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Hydro-meteorological droughts across the Baltic Region: The role of the accumulation periods

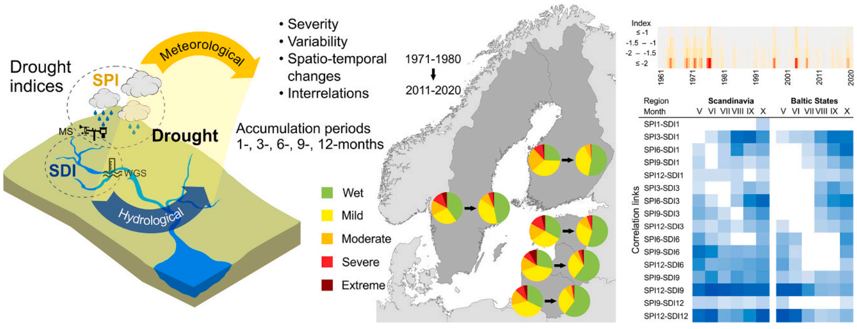
Diana Meilutytė-Lukauskienė[a,*], Serhii Nazarenko[a], Yaroslav Kobets[b], Vytautas Akstinas[a], Alireza Sharifi[c], Ali Torabi Haghighi[c], Hossein Hashemi[d], Ilga Kokorīte[e,f], Baiba Ozolina[f]

[a] *Lithuanian Energy Institute, Lithuania*
[b] *Tallinn University of Technology, Estonia*
[c] *University of Oulu, Finland*
[d] *Lund University, Sweden*
[e] *University of Latvia, Latvia*
[f] *Latvian Environment, Geology and Meteorology Centre, Latvia*

HIGHLIGHTS

- The study fills the gap in the joint analysis of the drought indices SPI and SDI in the Baltic Region.
- Droughts were studied over different accumulation periods, spatial and temporal scales.
- Relationships between the indices provide information on changes in water resources due to meteorological droughts.

GRAPHICAL ABSTRACT



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ABSTRACT

Based on the physical and geographical conditions, the Baltic Region is categorised as a humid climate zone. This means that, there is usually more precipitation than evaporation throughout the year, suggesting that droughts should not occur frequently in this region. Despite the humid climate in the region, the study focused on assessing the spatio-temporal patterns of droughts. The drought events were analysed across the Baltic Region, including Sweden, Finland, Lithuania, Latvia, and Estonia. This analysis included two drought indices, the Standardized Precipitation Index (SPI) and the Streamflow Drought Index (SDI), for different accumulation periods. Daily data series of precipitation and river discharge were used. The spatial and temporal analyses of selected drought indices were carried out for the Baltic Region. In addition, the decadal distribution of drought classes was analysed to disclose the temporal changes and spatial extent of drought patterns. The Pearson correlation between SPI and SDI was applied to investigate the relationship between meteorological and hydrological droughts. The analysis showed that stations with more short-duration SPI or SDI cases had fewer long-duration cases and vice versa. The number of SDI cases (SDI ≤ -1) increased in the Western Baltic States and some WGSs in Sweden and Finland from 1991 to 2020 compared to 1961–1990. The SPI showed no such

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[*] Corresponding author.
E-mail address: diana.meilutyte-lukauskiene@lei.lt (D. Meilutytė-Lukauskienė).

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tendencies except in Central Estonia and Southern Finland. The 6-month accumulation period played a crucial role in both the meteorological and hydrological drought analyses, as it revealed prolonged and widespread drought events. Furthermore, the 9- and 12-month accumulation periods showed similar trends in terms of drought duration and spatial extent. The highest number of correlation links between different months was found between SPI12-SDI9 and SPI12-SDI12. The results obtained have deepened our understanding of drought patterns and their potential impacts in the Baltic Region.

1. Introduction

The world is constantly facing a range of unprecedented meteorological and hydrological extremes, with drought being one of the most destructive phenomena. Droughts are an inherent and inevitable part of the climate system and occur in different regions of the world. They can occur at any time of the year and affect both areas with high precipitation levels and those with deficits. Droughts pose major challenges to sectors such as agriculture, energy and forestry, and result in significant economic losses (Ding et al., 2011; Maracchi et al., 2005; Logar and Van Den Bergh, 2013; Torabi Haghighi et al., 2020). Unlike other meteorological events, drought is a complex phenomenon as its onset and duration cannot be easily determined. The impacts of meteorological conditions accumulate over an extended period of time, making it challenging to determine the exact beginning and duration of a drought. Furthermore, droughts cannot be measured directly, so the use of drought indices is necessary for identification. These indices provide tools for assessing and monitoring drought conditions by considering various meteorological and hydrological factors.

Europe is not immune to the devastating impacts of drought, which is recognised as one of the most destructive natural disasters on earth. In recent years, droughts became a critical hydro-meteorological hazard with significant consequences (Spinoni et al., 2018; Ionita et al., 2022). Combined with high air temperature anomalies, precipitation deficits have led to significant environmental, economic, and social costs, as observed in 2003, 2010 and 2018 (Bastos et al., 2020). At the beginning of 2022, many regions in Europe were hit by a severe drought, which exacerbating the situation (European Commission and Joint Research Centre, 2022). The dry conditions were characterised by a persistent and severe lack of precipitation, accompanied by a heat wave since May. This significant decrease in precipitation had a profound impact on river discharge across Europe. For example, the BBC reported that the first six months of 2021 in the UK were the driest since 1976. According to the UK Environment Agency, water levels in over 2000 rivers decrease by up to 80 % during the summer. In the same year, Northern Italy faced its worst drought in 70 years, while neighbouring France experienced its worst drought since records began in 1958 (European Commission and Joint Research Centre, 2022). Portugal also endured the hottest July on record, with 99 % of the country affected by severe or extreme drought. These examples illustrate the severity and far-reaching impacts of drought events in Europe. The combination of reduced precipitation and rising temperatures has led to severe consequences for ecosystems, economies, and communities across the continent.

Typically, droughts are classified as meteorological (Böhnisch et al., 2021), agricultural (García-León et al., 2021), hydrological (Peña-Angulo et al., 2022), groundwater (Brauns et al., 2020; Babre et al., 2022), and socioeconomic (Musolino et al., 2017), and depending on the type, drought monitoring is usually carried out through a wide range of different drought indices. Some of them have been developed and used only in one region or country to better reflect unique local conditions. These indices are used to determine the characteristics of drought – duration (onset and end), severity, intensity, return period, and prevalence in the area. They also allow comparison of the extent of drought in time and space and visualization of drought on a map. There are several input parameters (precipitation, air temperature, evaporation, streamflow, groundwater, etc.) that need to be stored for the calculation of the index values.

Meteorological drought indices belong to the first generation of drought indices that emerged when the measurement of meteorological elements began. These drought indices are primarily associated with precipitation (liquid, solid, and mixed), but also with other meteorological parameters such as air temperature, humidity, and etc. The most commonly used meteorological drought indices are SPI (standardized precipitation index) and SPEI (standardized precipitation and evapotranspiration index). The use of both indices for drought analysis in different parts of Europe produced the same or very similar results (Spinoni et al., 2015; Jaagus et al., 2022). A comparison of meteorological droughts using SPI and SPEI showed a strong correlation on the same time scales (Ojha et al., 2021). Many scientific papers use SPI exclusively for drought estimation, analysis, and assessment. For example, SPI has been used to analyse meteorological droughts (Diani et al., 2019; Bayer Altin and Altin, 2021) or as a drought indicator to detect drought during different growing seasons of maize (Rolbiecki et al., 2022). Furthermore, this index could also be used for future drought analyses (Won and Kim, 2020). The main advantage of using the SPI is its simplicity. We only need the precipitation data and it can be calculated for different time steps (Darabi et al., 2023). Using SPI, Blauhut et al. (2022) studied two droughts of 2018 and 2019 across 28 European countries. The results showed a great diversity in the perception of droughts in Europe. In addition, the study found that there is an urgent need to further reduce the impact of droughts by implementing a drought governance approach.

Hydrological drought indices play a crucial role in assessing the impact of meteorological conditions on water availability and water levels in surface waters. They are used to quantify and understand drought conditions in river basins and are particularly relevant for managing water resources during periods of low water availability (Torabi Haghighi et al., 2020). Among the hydrological drought indices, the streamflow drought index (SDI) is a widely preferred choice among scientists. For example, Ali et al. (2020), Jahangir and Yarahmadi (2020), Malik et al. (2021), and Simsek (2021) have used the SDI in their research. Some specific examples include the 40-year analysis of hydrological droughts in the Tigris River basin (Ozkaya and Zerberg, 2019) and the assessment of hydrological droughts in the Struma River basin (Nikolova and Radeva, 2019). Additionally, Kubiak-Wójcicka and Bąk (2018) studied hydrological droughts in the Vistula River basin using the SDI, and Simsek (2021) used it to analyse hydrological droughts in the Mediterranean basins. Overall, the streamflow drought index (SDI) is a valuable tool for hydrological drought analysis as it is based on streamflow data and can summarise different processes that influence water availability in river basins.

While different countries in the Baltic Region have conducted various studies to analyse and understand drought patterns and their magnitude. However, only little attention has been paid in the past to the analysis of drought events analysis in the entire Baltic Region. Since then, there is a growing interest in studying long-term changes in both hydrological and meteorological droughts in this region. Studies in Sweden have mainly focused on analysing the hydrological characteristics of droughts (Hisdal et al., 2004; Tallaksen and van Lanen, 2004), accurately calculating drought indices for streams (Vicente-Serrano et al., 2012), and estimating the number, duration, and severity of stream droughts (Teutschbein et al., 2022). Most of these studies have been conducted at local to regional scales and do not cover the entire country (Drobyshev et al., 2011; Seftigen et al., 2013). Finnish scientists have focused on analysing long-term changes in drought (Korhonen and Kuusisto, 2010), inter-annual variability of meteorological drought using the Standardized Precipitation Index (SPI) (Irannezhad et al., 2015), and assessing different drought indicators during the summer season (Gao et al., 2016), with summer drought recently considered as a constraint for agriculture (Mustafa et al., 2022). In Lithuania, scientific works have referred to drought analysis (Valiukas, 2012; Nazarenko et al., 2022a; Nazarenko et al., 2022b), or drought dynamics (Rimkus et al., 2012; Rimkus et al., 2013; Stonevičius et al., 2018) using different drought indices. However, hydrological droughts have not been analysed specifically for Latvian rivers. Long-term changes in meteorological drought indices have been estimated only in a joint publication with other European countries (Jaagus et al., 2022). A trend analysis of extreme temperature and precipitation events was performed by Avotniece et al. (2010, 2012). Research in Estonia has mainly focused on the analysis of overall droughts (Tammets and Jaagus, 2013), spatial and temporal variability of droughts (Domínguez-Castro et al., 2017), and changes in drought indices (Jaagus and Aasa, 2018). In addition, some studies have combined different countries/regions. The estimation of drought dynamics in the Baltic Sea region by Rimkus et al. (2012) and the drought analysis in the eastern Baltic Sea region (Rimkus et al., 2017) were conducted using different indices. Bakke et al. (2020) studied extreme drought in northern Europe from climatological and hydrological perspective using two indices (SPI and SPEI). Long-term changes in these indices were determined over the period 1949–2018, focusing on warm (June–August) and cold (from November to March) seasons in Eastern and Central Europe (Jaagus et al., 2022). These studies demonstrate a growing interest in understanding the dynamics and impacts of drought in the Baltic Region. The use of various drought indices and approaches allows for a comprehensive analysis of drought patterns and long-term changes in the hydrological and meteorological conditions in the region.

Meteorological and hydrological droughts were selected for analysis because their interaction allows for a more comprehensive assessment of drought events in the Baltic Region, which is essential for gaining an overall picture of drought risks in the target area. Moreover, by studying both meteorological and hydrological droughts, we can gain a comprehensive understanding of drought dynamics. The research outlined in this paper has several main objectives: (1) to evaluate different drought indices (SPI, SDI) and analyse drought characteristics in the Baltic Region (Sweden, Finland, Lithuania, Latvia, and Estonia) in the period 1961–2020; (2) to evaluate the drought phenomenon in different accumulation periods (1-, 3-, 6-, 9-, and 12-month); (3) to evaluate the relationship between selected drought indices; and (4) to identify the main drought patterns on a temporal scale and in the analysed countries. By assessing different drought indices and studying drought characteristics over time, the study aims to provide insights into ongoing changes in drought conditions. Understanding the relationship between the drought indices can help in formulating strategies to mitigate drought risk and improve water resource management in the region. At the same time, analysing the relationships between the drought indices of countries will help to understand the origin of hydrological drought in the Baltic Region.

2. Research area and data

The Baltic Region, consisting of Sweden, Finland, Lithuania, Latvia, and Estonia, was selected as the study area (Fig. 1). According to the Köpper-Geiger climate classification, the study area mainly belongs to the zones Dfb – humid continental climate with warm summers (Estonia, Latvia, Lithuania, and southern Sweden) and Dfc – humid continental climate with cold summers (central and northern Sweden, and Finland) (Beck et al., 2018). Geographically, the area extends between the maritime-temperate and the continental-cold climate zones in a west-easterly direction. The climate diversity of the region is characterised by high spatial and temporal variability, which is strongly influenced by large-scale atmospheric variability.

Sweden is characterised by diverse physico-geographical features, ranging from mountains and highlands to lowlands in the coastal regions. The elevation varies from 0 on the coast to over 2000 m above sea level (a.s.l.) in the Scandinavian Mountains in the northwest. The average annual precipitation for the entire country ranges from 500 to 800 mm, with the western coastal regions receiving the highest annual precipitation and the eastern coastal regions receiving the lowest. The average monthly temperature varies widely between −7 and 15 °C with an annual average of 5 °C. Most of the Finland's territory is below 200 m a.s.l., and only in the northern part does the topography vary from 200 to 400 m in altitude. The average annual precipitation ranges from 500 mm in the north to 700 mm in the south. In the northern region, almost half of the precipitation falls as snow during the winter season. The perennial monthly average temperatures vary from −9 °C in winter to 16 °C in summer. The mainland of the Baltic States (Lithuania, Latvia, and Estonia) is mostly flat and lies on average 82 m above a.s.l., with altitude differences ranging from 0 to 317 m. Annual precipitation ranges from 550 mm in the middle lowlands to 900 mm in the highlands near the coast. The average monthly air temperature varies between −4 and 18 °C throughout the year.

From a hydrological point of view, the Swedish territory is divided into ten major river basins covering an area of >18,000 km^2 and 118 sub-basins defined by the Swedish Meteorological and Hydrological Institute (SMHI). Most Finnish rivers flow into the Baltic Sea, and some rivers flow into Russia and Norway and end in the Arctic Ocean. Almost all rivers have a lowland nival regime. Eight river basin districts in Finland have been identified under the EU Water Framework Directive. The rivers of the Baltic States (Lithuania, Latvia, and Estonia) belong to eight river basin districts and are divided into three categories according to the hydrological regime: marine, transitional, and continental. The main source of feeding the marine rivers is precipitation. For continental rivers, the amount of water from snowmelt is almost equal to that from groundwater. The primary source of water for the transitional rivers is a combination of snowmelt and precipitation.

The variability of the hydrological drought indices was analysed based on data from 89 water gauging stations (WGS) in the studied Baltic Region (24 in Sweden, 15 in Finland, 16 in Lithuania, 17 in Latvia, and 17 in Estonia). For each WGS, a meteorological station closest to the catchment area was selected. Due to the lower density of meteorological stations, some of them were linked to several hydrological stations. Generally, daily precipitation data from 51 meteorological stations (MS) throughout the study area (15 in Sweden, 12 in Finland, 6 in Lithuania, 6 in Latvia, and 12 in Estonia) were used to indicate meteorological drought. The daily precipitation and discharge data were used to calculate drought indices – SPI and SDI, respectively. The analysis was performed for the period 1961–2020. In Sweden, the daily hydrometeorological data were taken from Swedish Meteorological and Hydrological Institute (SMHI). In Finland, the daily meteorological data were taken from the Finnish Meteorological Institute (FMHI), and the daily discharge data were downloaded from the Finnish Environmental Institute's (SYKE) Hertta environmental information management system. Lithuanian daily discharge and precipitation data were obtained from the Lithuanian Hydrometeorological Service (LHMT) yearbooks. In Latvia, national monitoring data of daily discharge and precipitation were obtained from the Latvian Environment, Geology, and Meteorology Centre (LVGMC). The Estonian Environmental Agency (ESTEA), a state authority under the Ministry of the Environment of the Republic of Estonia, carries out hydrological monitoring in Estonia. All data on daily discharges are available on the ESTEA website (https://www.ilmateenistus.ee/). For Sweden, Finland, and the Baltic States, the data were aggregated to monthly averages for further calculation of drought indices.

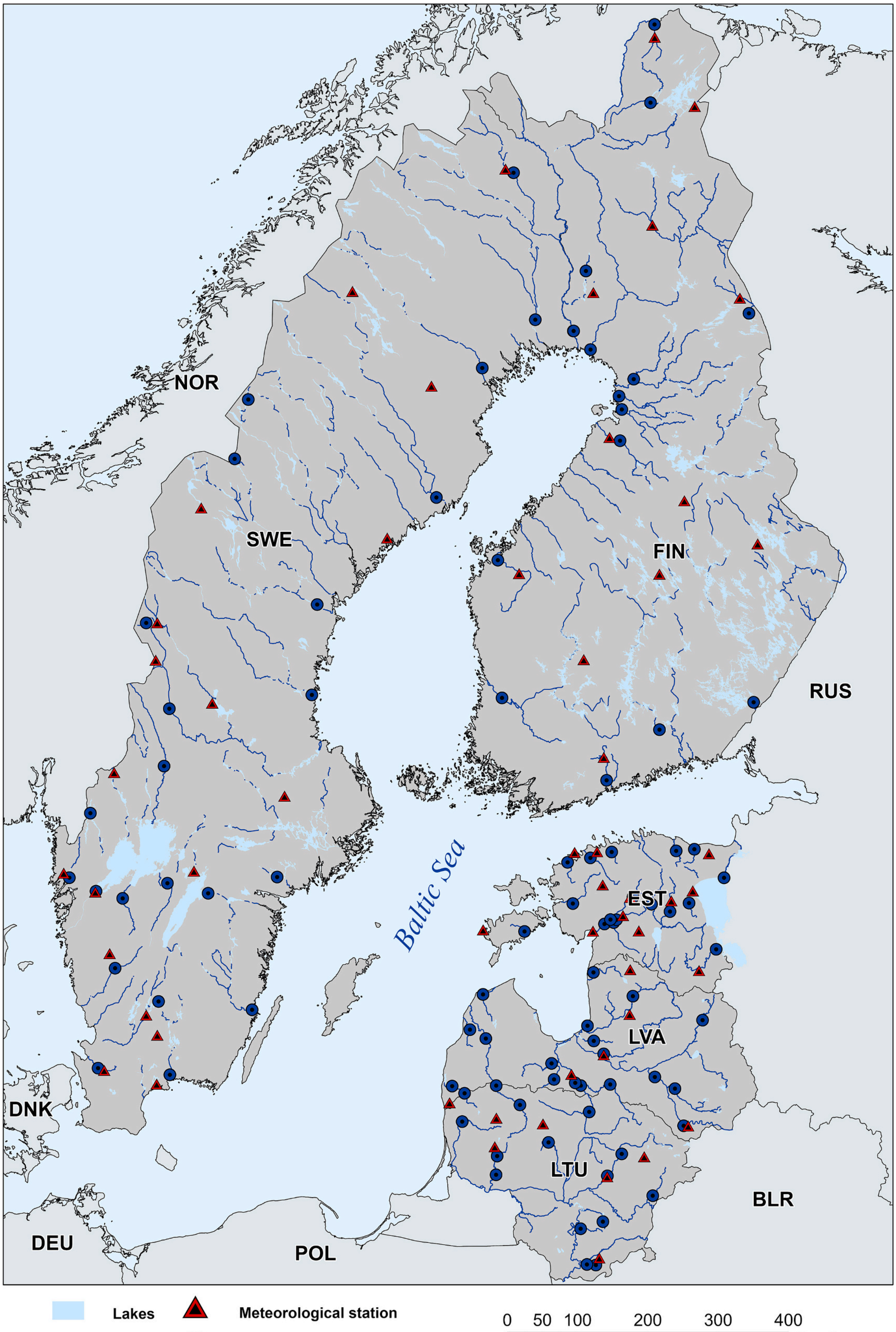


Fig. 1. Study area with selected meteorological and water gauge stations in the Baltic Region.

3. Methods

As part of the study, drought in the Baltic Region was analysed using drought indices. Daily data from 89 water gauging stations in the Baltic Region were collected for the study. The statistical period chosen for the analysis covered 60 years, from 1961 to 2020, and this period was applied to all regional stations. The drought indices, namely the SPI and the SDI, were used to assess and analyse drought accuracy. The *DrinC – Drought Indices Calculator* (https://drought-software.com/download/) software was used to perform the necessary calculations for the drought indices.

The Standardized Precipitation Index (SPI) was developed to quantify the precipitation deficit for several time scales (McKee et al., 1993). In this study, the SPI was calculated for five specific time scales (1-, 3-, 6-, 9-, and 12-month) corresponding to the past 1, 3, 6, 9, and 12 months of observed precipitation totals, respectively, to obtain a comprehensive understanding of drought conditions for different rime periods. This index is defined for each of the above time scales as the difference between monthly precipitation on a 1-, 3-, 6-, 9- or 12-month time scale (x_i) and the mean value ($\overline{x}$), divided by the standard deviation (s):

$$\mathrm{SPI} = \frac{x_i - \overline{x}}{s}$$

Where x_i – monthly rainfall amount $\overline{x}$ and s are the mean and standard deviation of rainfall, respectively, calculated from the whole time series of monthly values. McKee et al. (1993) used the classification system in Table 1 to categorize drought intensities based on the SPI.

During the study, several data analysis methods were used to explain and investigate the calculated data. First, a spatial analysis was used for the overall analysis of the numerous data sets, which was applied to both indices and performed in ArcMap 10.5 software.

For the Streamflow Drought Index (SDI), the cumulative flow rate of the river is calculated as follows (Nalbantis and Tsakiris, 2009):

$$Q_{i,j} = \sum_{j=1}^{3k} q_{i,j}$$

Where $i = 1, 2, 3 \ldots; j = 1, 2, 3 \ldots, 12; k = 1, 2, 3, 4$. $Q_{i,j}$ are the cumulative values, and $q_{i,j}$ is the total streamflow volumes for the i-th hydrological year and the k-th reference period. The subscript "*j*" refers to the month in the hydrological year ($j = 1$ for September and $j = 12$ for August). The values of k are $k = 1$ for October–December, $k = 2$ for October–March, $k = 3$ for October–June, and $k = 4$ for October–September.

The SDI is thus defined for each reference period k of the i-th hydrological year as follows:

$$\mathrm{SDI}_{i,k} = \frac{Q_{i,k} - \overline{Q_k}}{S_k}$$

where $\overline{Q_k}$ and S_k are the average and the standard deviation of the cumulative volume of the streamflow for the reference period of k and in a long period, respectively. With this definition, $\overline{Q_k}$ is considered the threshold level. The SDI is equivalent to the river's standardized streamflow volume. Instead of the volume, the mean river flow rate data are used as well. According to Nalbantis and Tsakiris (2009), Table 2 displays the classification of hydrological drought using the SDI.

The analysis of drought characteristics (short duration, long duration, and maximum duration) involved several key parameters to assess their spatio-temporal variability and distribution. These parameters were applied to both the SPI and SDI indices. The SPI or SDI indices with short duration represented the total number of cases when the continuous duration in months of the index value of ≤–1 was less than or equal to the 1961–2020 average. SPI or SDI with long duration meant the total number of cases but differed in that the continuous duration in months of the index value of ≤–1 was greater than the 1961–2020 average. The characteristic of the maximum duration of SPI or SDI is described by the maximum continuous duration in months for the index value ≤ –1 in 1961–2020. Additionally, the changes between two climatic norms (1961–1990 and 1991–2020) were estimated. The difference in the total number of cases of continuous duration of the index (≤–1) was calculated for 1991–2020 from 1961 to 1990. To analyse the droughts by decade, the results of the drought index calculations were divided into six ten-year periods. The percentage distribution of each drought class within a decade differs from the standard distribution of the entire period, thus providing the opportunity to identify periods with the highest concentration of the targeted drought class.

To investigate the relationship between the meteorological and hydrological drought, and to clearly visualize this relationship, the Pearson correlation coefficient (PCC) was calculated between each period of SPI and SDI at different time scales. PCC is the most common statistical method to show how strongly pairs of variables are related (Adler and Parmryd, 2010; Giavarina, 2015). The correlation analysis was performed for each month of the warm period (May–October), an example of this correlation is presented in Fig. 2. The analysis was conducted for a 60 years data set and between indices with different accumulation periods (1-, 3-, 6-, 9-, and 12-month). If the correlation reached a value of >0.7, it was considered high and used for further calculation of the year with a high correlation. To compare the correlation relationships of indices between countries, the number of rivers was converted into percentages of the maximum number of analysed rivers in each country.

4. Results

4.1. Spatio-temporal variation of drought indices in the Baltic Region

The criteria for the evaluation of the Standardized Precipitation Index (SPI) and the Drought Index (SDI) involved the analysis of the total number of continuous cases of SPI and SDI indices in each meteorological and water gauging station during the period from 1961 to 2020. These cases were considered across various selected accumulation periods, including short, long, and maximum durations, as well as the changes in 1991–2020 compared to 1961–1990.

The short duration of SPI indicated the total cases of SPI index in each meteorological station where the continuous duration of SPI value of ≤–1 was less than or equal to the 1961–2020 average of a certain accumulation period (Fig. 3a–e). For short accumulation periods (1- or 3-month), the highest number of short SPI cases was observed in the southern part of Sweden and in the central part of Finland. In these

Table 1
Classification of meteorological drought based on the SPI (McKee et al., 1993; Dehghani et al., 2017).

SPI value	Class	Probability (%)
SPI ≥ 2.0	Extremely wet	2.3
1.5 ≤ SPI < 2.0	Severely wet	4.4
1.0 ≤ SPI < 1.5	Moderately wet	9.2
0.0 ≤ SPI < 1.0	Mildly wet	34.1
−1.0 ≤ SPI < 0.0	Mild drought	34.1
−1.5 ≤ SPI < −1.0	Moderate drought	9.2
−2.0 ≤ SPI < −1.5	Severe drought	4.4
SPI < −2.0	Extreme drought	2.3

Table 2
Classification of hydrological drought based on the SDI (Nalbantis and Tsakiris, 2009).

State	Description	Criterion	Probability (%)
0	Non-drought	SDI ≥ 0.0	50.0
1	Mild drought	−1.0 ≤ SDI < 0.0	34.1
2	Moderate drought	−1.5 ≤ SDI < −1.0	9.2
3	Severe drought	−2.0 ≤ SDI < −1.5	4.4
4	Extreme drought	SDI < −2.0	2.3

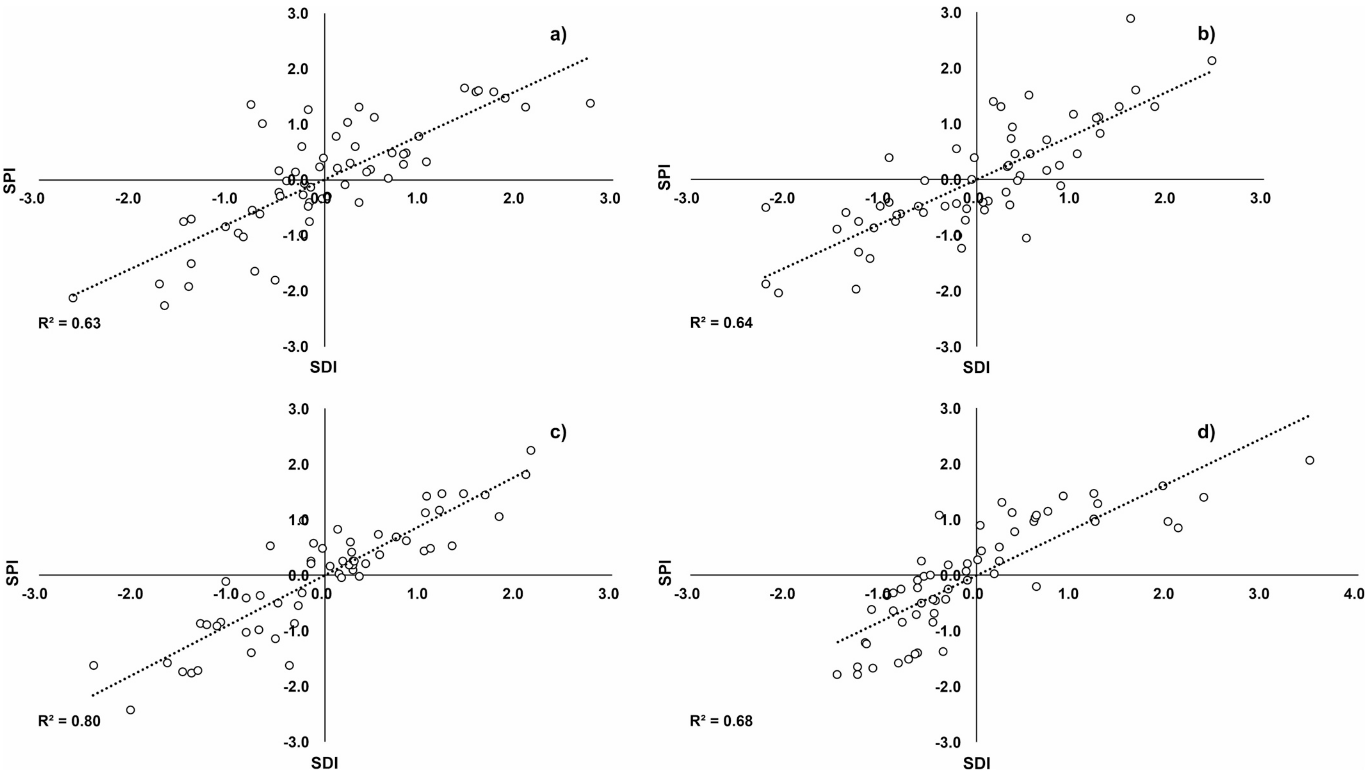


Fig. 2. Examples of SPI-SDI correlations: a) Sweden, correlation between SPI9 and SDI6 for the Assman River in June; b) Finland, correlation between SPI12 and SDI9 for the Ounasjoki River in October; c) Lithuania, correlation between SPI12 and SDI12 for the Jūra River in May; d) Estonia, correlation between SPI6 and SDI3 for the Tõrve River in August.

areas, the number of cases reached 88 for a 1-month SPI accumulation period and 52 for a 3-month SPI. Conversely, the Baltic States and mountainous regions of Sweden had the lowest number of cases with short duration SPI. For the SPI accumulation periods of 6- and 9-month, the distribution across the analysed region was not clear. However, the SPI with accumulation period of 12-month showed the highest number of cases (19 or more) in the southern part of Sweden, in several mountainous meteorological stations, and in most of Finland's area. On the other hand, the northern part of the Baltic Region and some meteorological stations in the Baltic States had the lowest number of cases mentioned (<14).

The SPI of long duration for different accumulation periods was determined by analysing the number of SPI index cases that had a continuous SPI value of ≤–1 above the 1961–2020 average (Fig. 3f–j). The results showed contrasting patterns compared to the short-duration SPI. For the accumulation periods of 1- and 3-month, the southern part of Sweden and the central part of Finland had a relatively lower number of cases (<15) of long-duration SPI. This differed from the short-duration SPI, where these areas had more cases. Similar tendencies/trends were observed for longer SPI accumulation periods (6-, 9-, and 12-month). Meteorological stations with a high number of short-duration SPI cases had a relatively lower number of long-duration SPI cases, and vice versa. The local conditions at each meteorological station played an important role in the accuracy of this effect. These conditions influenced that the number of short-duration SPI cases was higher and the number of long-duration SPI cases was lower, or vice versa. This pattern was particularly evident with longer accumulation periods.

The SPI maximum duration represents the maximum continuous duration, expressed in months of the SPI index when its value was ≤–1 for the period of 1961–2020. The durations for different accumulation periods are displayed in Fig. 3k–o. For 1-month accumulation period of the SPI, some exceptional meteorological stations had a maximum duration of the SPI of >5-month. The largest differences were observed for the 6-month accumulation period of the SPI. In Estonia, three meteorological stations had a maximum SPI duration between 19 and 29 months, while the rest of the Baltic Region had a maximum SPI duration of <12 months. For the longest SPI accumulation period of 12-month, the meteorological stations in Finland showed a maximum SPI duration of no >18 months, while in the Baltic States a relatively longer maximum SPI duration was recorded.

The difference between the two climatic norms of 1961–1990 and 1991–2020 showed changes in the total number of continuous SPI (≤–1) cases during the last thirty years period (Fig. 3p–t). A decrease in the total number of SPI cases was observed for most accumulation periods (1- to 9-month) in 1991–2020. The largest decrease in drought cases was observed mainly in the southern part of Sweden, at individual meteorological stations in the Baltic States and in the central part of Finland. The average decrease included 6 to 12 cases, but for the accumulation period of 3-month the number of cases reduced up to 30. As for the increase in the total number of SPI cases, no clear patterns were evident, except for the 12-month accumulation period, which showed an increase of up to 7 cases for the period 1991–2020 in the south-western part of Finland.

In this study, hydrological droughts were assessed using the SDI. Similar to the calculations for the SPI, the number of SDI short-duration cases was determined for different accumulation periods in the period from 1961 to 2020 (Fig. 4a–e). For short accumulation periods (1- to 6-month), the highest number of short-duration SDI cases (ranging from 23 to 45) was observed in water gauging stations (WGSs) in the western part of the Baltic States. The further one moves away from the Baltic Sea, the more the number of SDI short duration cases decreases in the WGS. In Sweden and Finland, no clear patterns for short SDI accumulation periods were detected, with the exception of some WGSs in central Finland, which had a relatively high number of cases (up to 45) for the 3-month accumulation period. Regarding the long accumulation periods, a higher number of short-duration SDI cases was observed in the south-

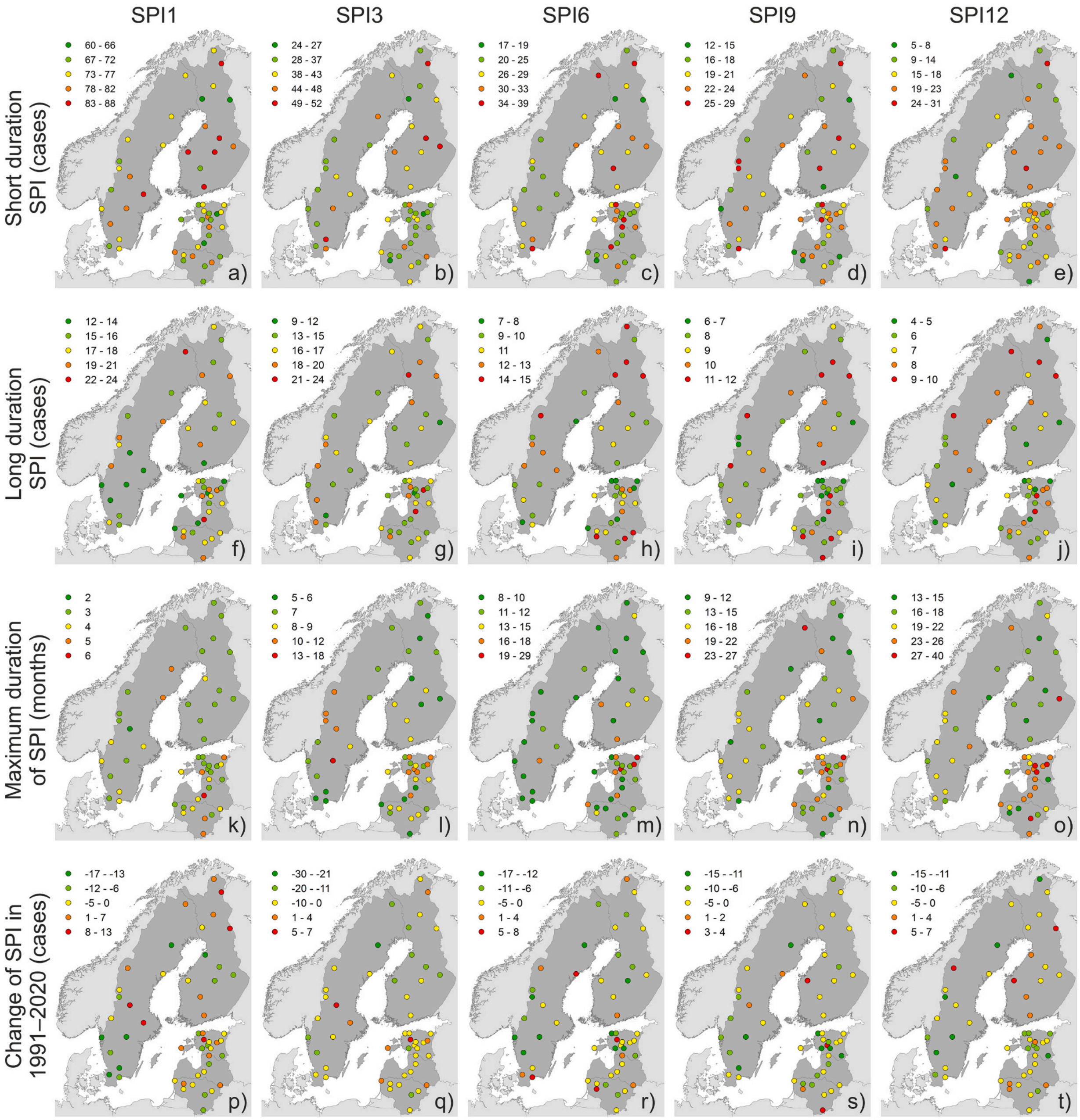


Fig. 3. Distribution of cases and maximum duration of SPI index for different accumulation periods (1-, 3-, 6-, 9-, and 12-month) on MS in the Baltic Region in 1961–2020 and change in 1991–2020 compared to 1961–1990.

western and mountainous regions of Sweden. However, in the WGSs of the Baltic States, the number of short-duration SDI cases decreased rapidly compared to the short accumulation periods. The relation between the SDI and SPI indices for a short duration was only observed in the southern part of Sweden and the central part of Finland. In the Baltic States, the indices matched only in the western part of Estonia for accumulation periods of 6- and 9-month.

The long-duration SDI exhibited an opposite effect in selected WGSs compared to the short-duration SDI (Fig. 4f–j). Most WGSs with a high number of cases of short-duration SDI had a lower number of cases of long-duration SDI. This trend was particularly evident in the WGSs of the Baltic States for accumulation periods of 3- and 6-month and in the WGSs of Sweden and Finland for accumulation periods of 1- and 3-month. Conversely, for accumulation periods of 9- and 12-month, the number of long-duration SDI cases (up to 11 cases instead of the previous 2–5 cases) increased in most WGSs of the Baltic States, especially those further inland. These differences in the number of cases could be attributed to the predominant groundwater feeding of these rivers, which delays the response time (Kriauciuniene et al., 2012; Akstinas et al., 2022). As a result, short drought events may not have a significant impact on them. However, prolonged droughts that develop over long periods of unfavourable conditions, are more evident in the long-duration SDI for accumulation periods such as 9- or 12-month.

The maximum duration of the SDI with the value ≤ –1 was used to identify the WGSs with the longest hydrological drought durations in the period from 1961 to 2020 for different accumulation periods (Fig. 4k–o). The eastern part of Estonia stood out with the longest maximum durations for most SDI accumulation periods, ranging from 39 to 58 months depending on the accumulation period considered. In contrast, the other WGSs had shorter maximum durations, typically ranging from 10 to 20 months. The WGSs in the western part of the Baltic States and in the northern regions of Sweden and Finland had the shortest durations. For

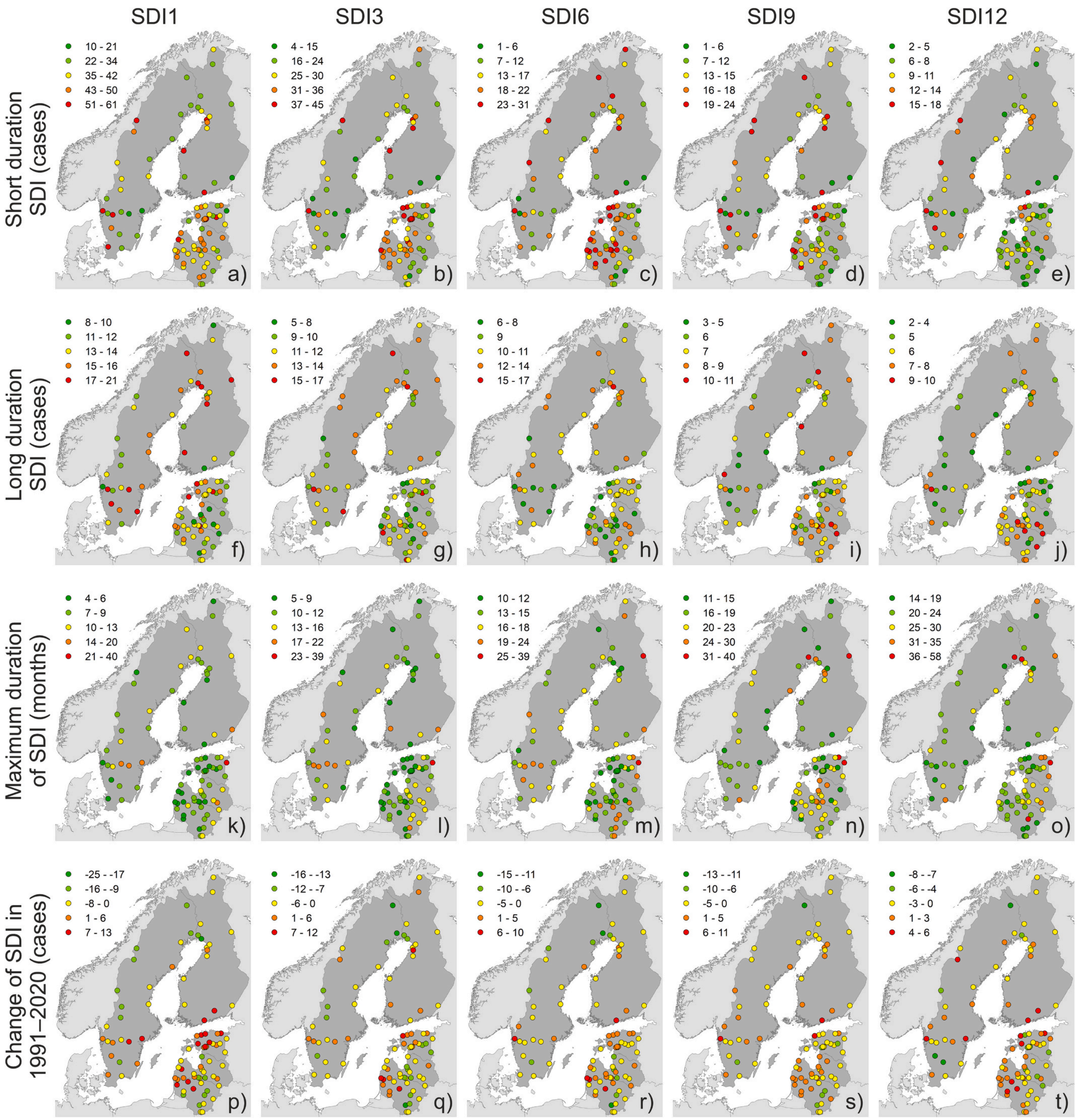


Fig. 4. Distribution of cases and maximum duration of SDI index for different accumulation periods (1-, 3-, 6-, 9-, and 12-month) on WGS in the Baltic Region in 1961–2020 and change in 1991–2020 compared to 1961–1990.

accumulation periods of 1- to 6-month, southern Sweden recorded a relatively average maximum duration of SDI. However, for longer accumulation periods, such as 9- and 12-month, the duration shortened.

The comparison of changes in the number of continuous cases of the SDI between the 1961–1990 and 1991–2020 periods revealed that the number of drought cases has increased over the last thirty years in many selected WGSs (Fig. 4p–t). The magnitude of the increase varied, ranging between 1 and 13 cases per period, depending on the specific accumulation period of the SDI index. In all accumulation periods, the number of hydrological droughts increased in the catchments close to the coastline in the western part of the Baltic States, as well as in the southern part of Finland and the south-eastern part of Sweden. In the remaining parts of the Baltic Region, a decrease in the number of SDI cases was defined for the period 1991–2020. The largest decrease in the number of drought cases occurred in the WGS of inland rivers. Interestingly, the changes in SDI in most regions did not match the patterns observed in the SPI, especially for shorter accumulation periods. The hydrological processes in the rivers usually have a certain delay period or are influenced by particular conditions (anomaly wet or dry) of the previous season, in contrast to the relatively rapidly changing meteorological conditions. However, there have been some exceptions, such as in southern Finland and in some parts of Estonia, where an increase in

SPI cases coincided with an increase in SDI.

These results revealed that the changes in hydrological drought conditions are influenced by factors beyond precipitation patterns and highlight the complexity and local variability of drought responses across the Baltic Region. The study disclosed the importance of considering both precipitation and discharge data when assessing the drought variability in different regions over time.

The timelines of selected drought indices by different accumulation periods showed how many meteorological stations (MS) with specific SPI intervals (Fig. 5) and how many WGS with specific SDI intervals (Fig. 6) were covered in the countries of the study area on a monthly basis. With a relatively short accumulation period of 1-month, a high number of meteorological stations across the Baltic Region experienced an SPI value ≤ –1 in almost every other year (Fig. 5). However, meteorological droughts with an SPI ≤ –2, which were more spatially distributed, were only indicated in certain years such as 1964, 1993, 1994, and 2015. In comparison, the hydrological droughts, even with a 1-month accumulation period (Fig. 6), had a slightly longer duration and were widespread. The high number of WGS with an SDI value ≤ –1 extended over several continuous months, as seen in the period from 1968 to 1977. Increasing the accumulation period to 3-month did not change the distribution of the SPI index between MS compared to the 1-month accumulation period. However, several years, such as 1963, 1964, and 1996, were characterised by an increase in the duration of spatially extended meteorological droughts affecting a large number of MS (Fig. 5). There were also no significant changes in the hydrological droughts for the 3-month accumulation period of SDI. Only the number of WGS with SDI values ≤ –2 increased (Fig. 6).

The 6-month accumulation period was a breaking point for the SPI analysis of MS coverage, as it prolonged periods of high levels of meteorological drought in MSs analysed (Fig. 5). These prolonged periods of drought occurred in months of 1963, 1964, and 1976, as well as in late 1995, and early 1996, and a similar pattern was observed for 2002 and 2003. During these periods, meteorological drought conditions persisted for a significant duration. The SDI with a 6-month accumulation period also revealed several periods when hydrological droughts lasted for a few or more years in many WGSs (Fig. 6). In particular, the periods 1971–1972, 1975–1977, and 2002–2003 were characterised by a high number of coincident WGS with SDI index values ≤ –1, indicating extended and prolonged hydrological drought conditions. The SPI index during the longest accumulation periods of 9- and 12-month showed a similar number of covered MS with an additional peak between 2018 and 2019 (Fig. 5). For the SDI of the 9- and 12-month accumulation periods, the overlapping WGS represented a large spatial extent to the pattern observed for the 6-month accumulation period (Fig. 6).

These results indicated that the 6-month accumulation period was particularly important for both the meteorological and hydrological drought analyses. During this period, the study area experienced prolonged and widespread droughts, and the patterns observed for the 9- and 12-month accumulation periods showed similar trends in drought duration and spatial extent.

The differences in the drought indices between the countries were illustrated by indicating the change over time in the monthly values less than or equal to −1 (Fig. 7 and Fig. 8). Moreover, the absolute minimum and median values were displayed to reveal the drought events of a wider extent and the interval of SPI values observed in at least half of the monitoring stations of a certain country. The drought indices were analysed for 6- and 12-month accumulation periods, as these periods indicated the highest change in spatial and temporal changes and the longest lasting drought events. The meteorological drought events of 1963, 1964, 1975 and 1976 showed similar tendencies in all analysed countries, except in Finland for the SPI index of the 6-month accumulation period (Fig. 7). Despite the similar lower boundary of the SPI, most meteorological stations in Finland had a relatively higher median SPI, which did not fall below −1.5, while in other countries it reached −3 in individual years. In addition, the droughts of the aforementioned years were less dense in the northern Sweden MS. In the later decades, the differences of a widespread drought in 1996 were observed. The most pronounced difference was found in Sweden, where the SPI value dropped to −3 and below in half of the MS, while it fluctuated between −1 and −1.5 in the other countries. In contrast, the droughts of 2002/2003 and 2006 showed the opposite character, when lower SPI values were observed in a large number of MS in the eastern part of the Baltic Region. On the western side of the Baltic Region (Sweden), low SPI values were only recorded in a few occasional MS in these years. The tendencies changed slightly when looking at a longer accumulation period of 12-month (Fig. 7). The prolonged droughts of 1963–1965 were widespread in the Baltic States, as −2 and lower SPI values were found in half of the MS. The SPI in Sweden and Finland fluctuated in a wide range. However, extremely low values were obtained in less than half of all MS. The overlap of similar results between the selected countries was only observed in 1976, when SPI values were below −1.5 in more than half of all MS. The differences between latitudes in the SPI values and their distribution among the selected MSs were determined in 1996 and 2006. These years showed that the SPI in the eastern part of the Baltic Region decreased from south to north.

The SDI index showed similar patterns for the years 1976, 2003 and 2006, especially in relation to the 6-month accumulation period (Fig. 8). The SDI fluctuated on average between −2 and −3 in at least half of the selected WGS in the mentioned years. The main difference was that the SDI decreased more evenly and the median values of the WGSs were more clearly reflected in the temporal scale. At the beginning of the analysed period, widespread hydrological drought was only indicated in Latvia and Estonia in 1964. Similar tendencies were observed in 1996. However, the minimum value of the SDI was relatively lower and included a higher number of WGS compared to the SPI index and its MSs. In contrast, in 1972 the widespread hydrological droughts were found in the majority of WGS of all Baltic States. The SDI of the 12-month accumulation period showed similar patterns as the 6-month period. The only difference was more pronounced and generalised drought events indicating prolonged deficit conditions. The extended accumulation period emphasised the distributional regularities that were evident in decreasing SDI values towards the north. This was the case in 1976 and especially in 2006. The hydrological drought events became less frequent in northern countries, e.g., Estonia and Finland. Moreover, fewer hydrological drought events and higher SDI values occurred in the northern part of Sweden than in the central and southern parts. Furthermore, not all cases with low SDI values overlapped with low SPI values. This was clearly seen in 1963 and 1964, when SPI values were below −2 in most MS, while SDI values in WGSs did not react that much and only coincided in Latvia and Estonia in 1964. General tendencies showed that the smallest differences and similar tendencies were obtained between Lithuania, Latvia and Estonia. In Sweden and Finland, however, the distribution of separate drought events was different from the other countries.

4.2. *Analysis of drought indices by decade*

The analysis of 10-year decades (which were divided from 60-year period) of droughts in the Baltic Region has provided valuable insights into the temporal variations in the occurrence of droughts in different countries (Appendix A, Fig. A.1–A.6). The results showed clear patterns in the intensity of drought events over time. The first three decades, covering the earlier period of the study, showed a higher percentage of severe and extreme drought events. The peak of drought occurrence was observed in the second decade from 1971 to 1980 (Figs. 9, 10). During this decade, the SPI for the 12-month accumulation period showed the prevalence of different types of droughts throughout the Baltic Region, ranging from wet conditions to extreme droughts (Fig. 9). It is noteworthy that only a handful of stations had predominantly mild drought and wet conditions during this period. The southern part of Sweden in

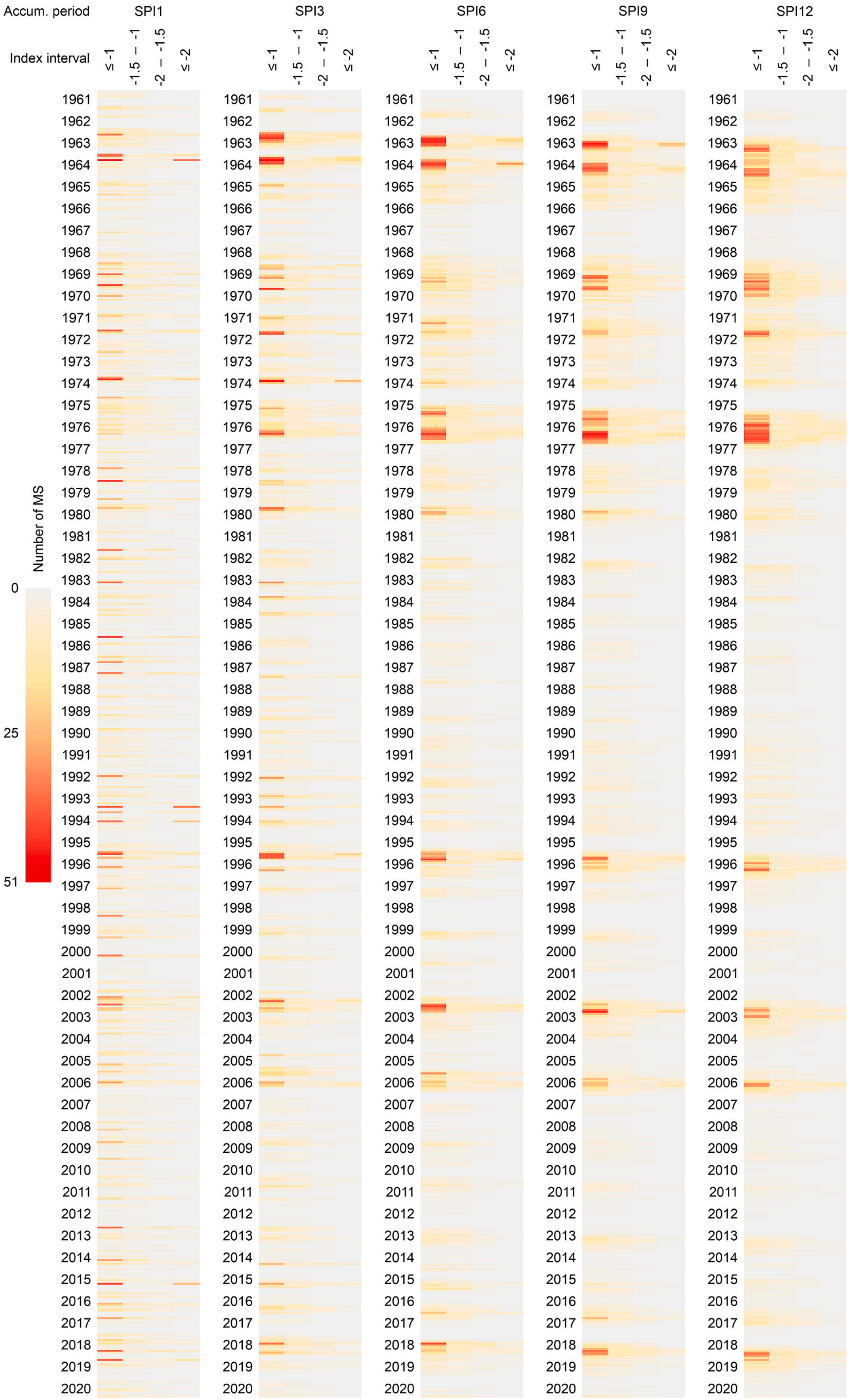


Fig. 5. Temporal change in MS number when monthly SPI values of specific intervals were observed for the period 1961–2020 according to different accumulation periods (1-, 3-, 6-, 9-, and 12-month) across the study area.

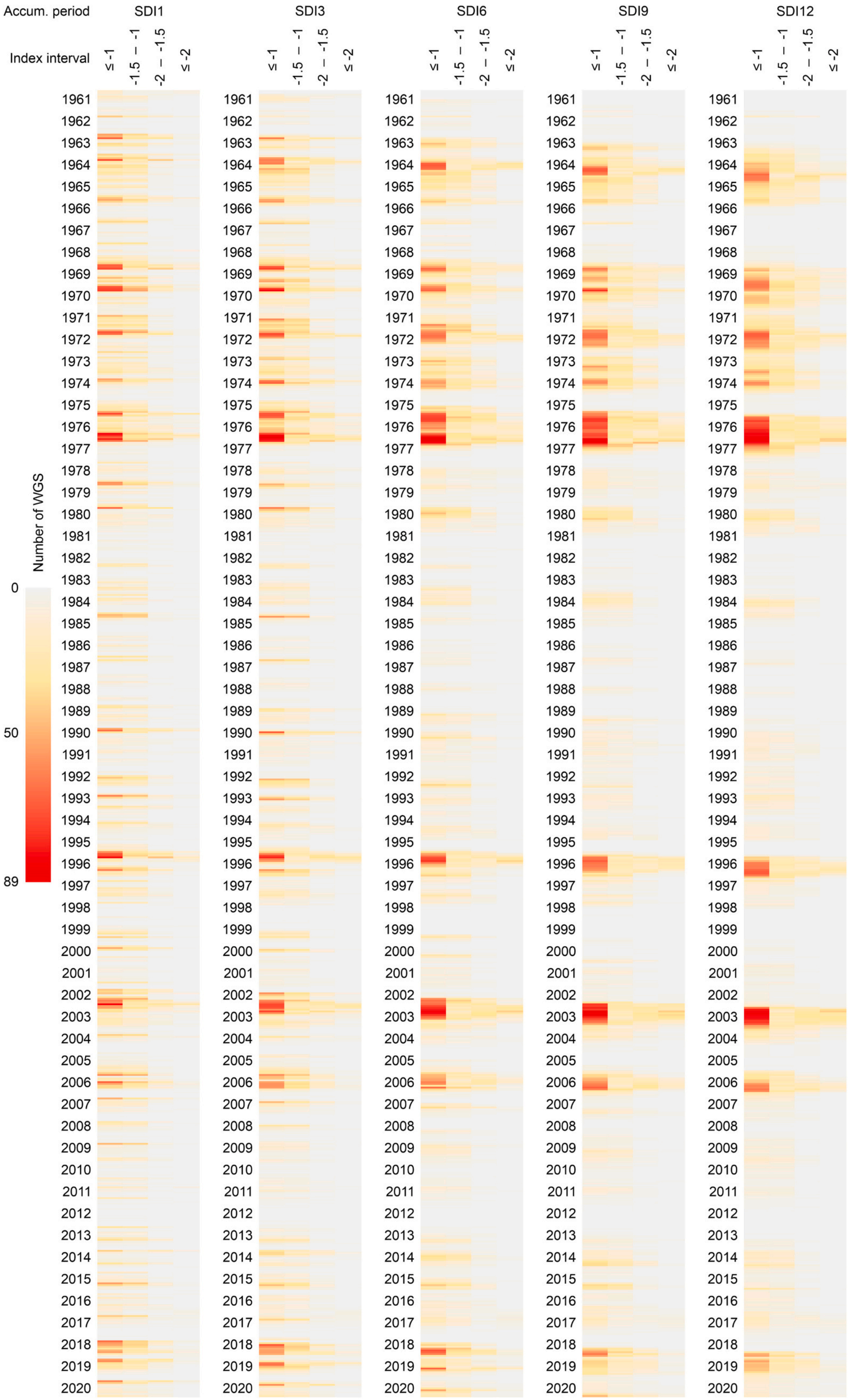


Fig. 6. Temporal change in WGS number when monthly SDI values of specific intervals were observed for the period 1961–2020 according to different accumulation periods (1-, 3-, 6-, 9-, and 12-month) across the study area.

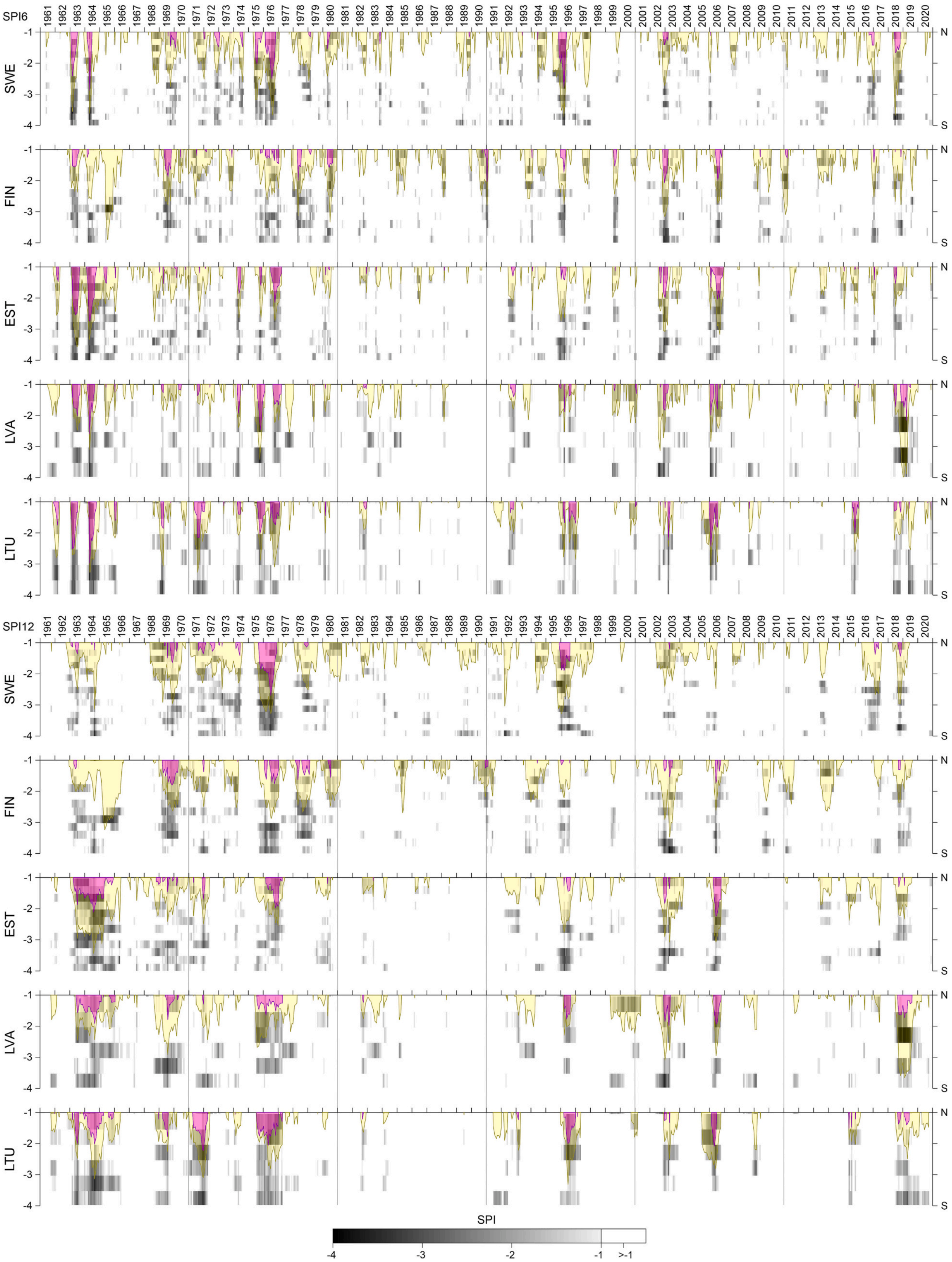


Fig. 7. Temporal change in the SPI index of selected MS within the specific country for the period 1961–2020 according to two accumulation periods (6- and 12-month). The horizontal matrix shows the SPI index value in selected MS in order from south to north in each country. The yellow chart shows the minimum value of the SPI, while the pink chart shows the median value of the SPI in the MS of a specific country.

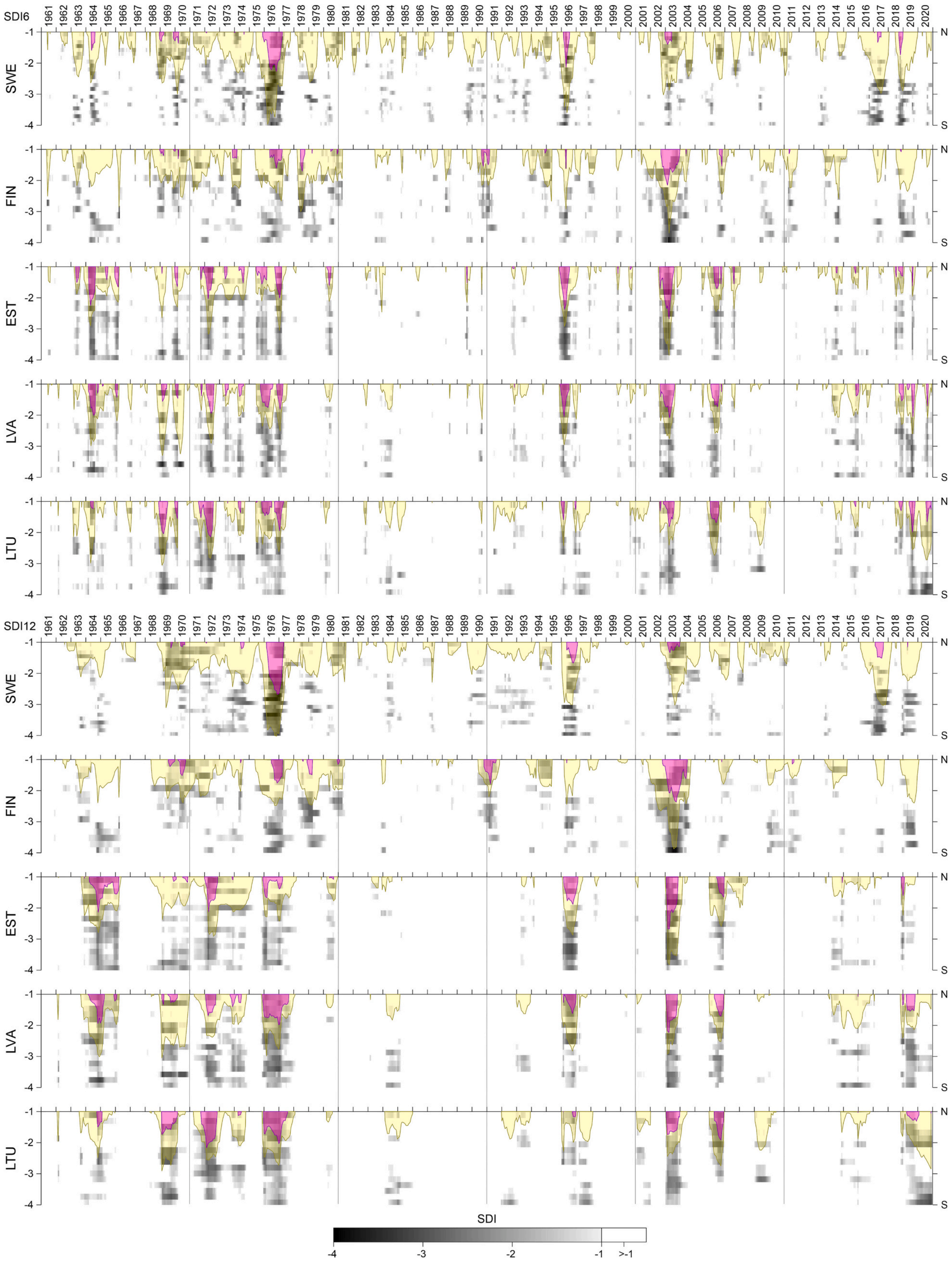


Fig. 8. Temporal change in the SDI index of selected WGS within the specific country for the period 1961–2020 according to two accumulation periods (6- and 12-month). The horizontal matrix shows the SDI index value in selected WGS in order from south to north in each country. The yellow chart shows the minimum value of the SDI, while the pink chart shows the median value of the SDI in the WGS of a specific country.

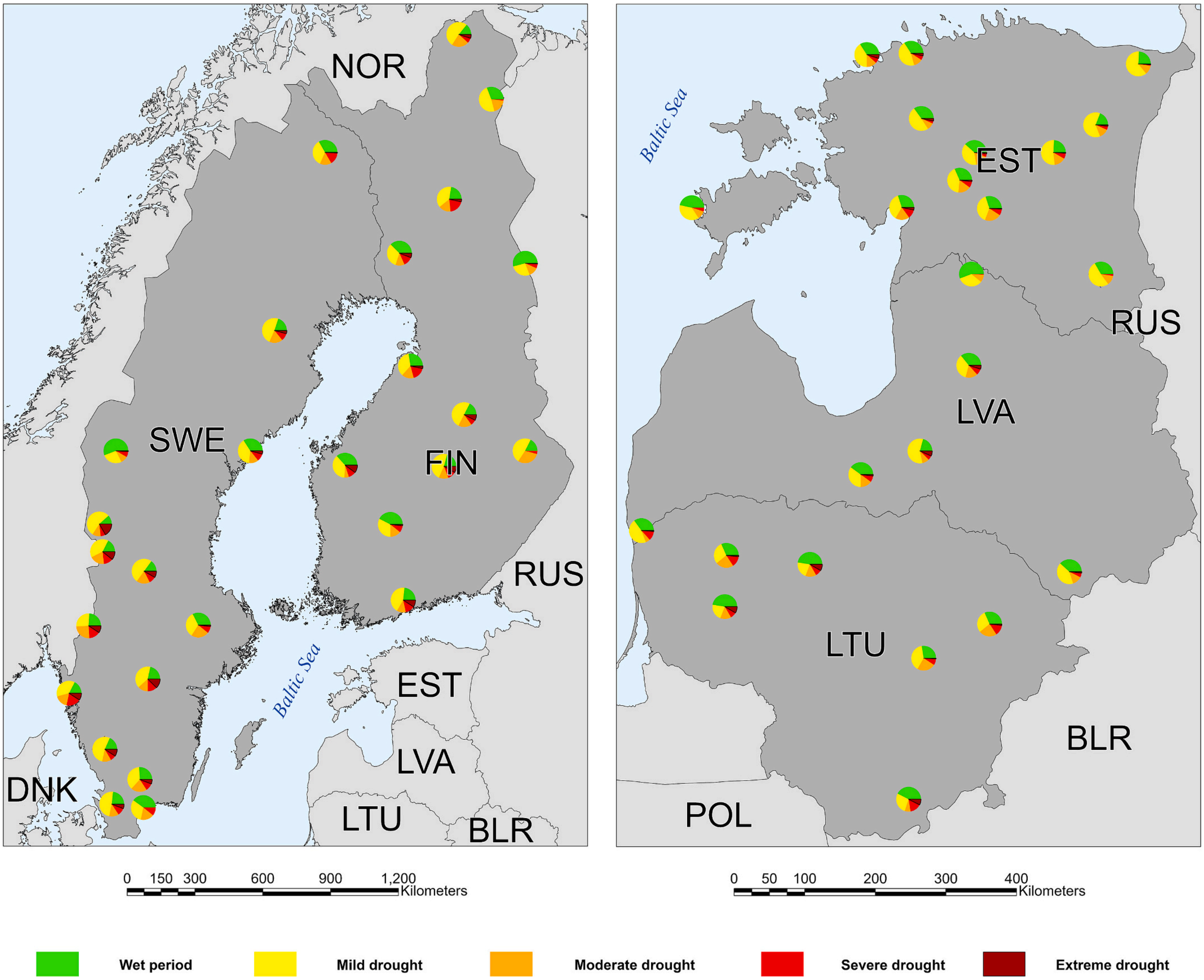


Fig. 9. Distribution of meteorological droughts by the SPI index of the 12-month accumulation period for the selected period of the 1971–1980 decade.

particular experienced a considerable number of extreme drought events (average extreme value 8.11 %). In contrast, the Baltic States experienced extreme droughts throughout the region, with the exception of the south-east, where mild droughts prevailed. This marked variability in drought patterns illustrates the regional differences in climatic conditions during the decade indicated. The analysis of the SDI in this decade revealed a very similar distribution of droughts in selected regions as in the case of the SPI (Fig. 10). In this decade, we could see a distribution of droughts from wet to extreme in almost all countries selected for this analysis, but the number of extreme droughts is the highest compared to other decades (Appendix A, Fig. A.7–A.12). The highest amount of extreme droughts events was found in the southern and northern parts of Sweden (average extreme value 10.49 %) and Finland (average extreme value 5.38 %) as well as in the western parts of the Baltic States (average extreme value 5.42 %).

However, the second half of the study period showed a different SPI trend (Appendix A, Fig. A.4–A.6). It was characterised by a more even distribution of drought events and a greater number of wetter periods. This showed that the later decades had relatively more positive hydrological conditions with a lower percentage of severe and extreme droughts. The analysis of climatic droughts in the second half of the study period revealed a more variable and less consistent pattern. Climatic droughts in this period had a significant concentration of wetter periods interspersed with occasional severe and extreme droughts. This suggests that the short periods of climatic drought events during second half of the study period were more unpredictable and variable. Droughts occurred rapidly and were replaced by strong wet periods in a relatively short period of time, in contrast to the more consistent dry pattern observed in earlier decades (Appendix A, A.1–A.6).

The analysis of hydrological drought by decade in the Baltic Region showed a similar pattern to meteorological drought (Appendix A, Fig. A.7–A.12). The first three decades were characterised by the occurrence of extreme droughts in all countries studied (Appendix A, Fig. A.7–A.9). Among these decades, the period from 1971 to 1980 stood out as the longest and most severe (Fig. 10), during which most extreme drought events occurred. In contrast, the fourth and fifth decades showed no significant differences and were associated with a wetter period in which there were only a small number of extreme drought events. This period can be considered as one with relatively favourable hydrological conditions and a lower percentage of severe droughts. However, in the last decade (Appendix A, Fig. A.12), there was a higher percentage of extreme droughts, although these were more localised compared to previous decades. The extreme droughts were mainly concentrated in certain areas, particularly in the central and south-eastern regions of Lithuania and Latvia, as well as in the southern parts of Sweden and some smaller areas in Finland, especially in the

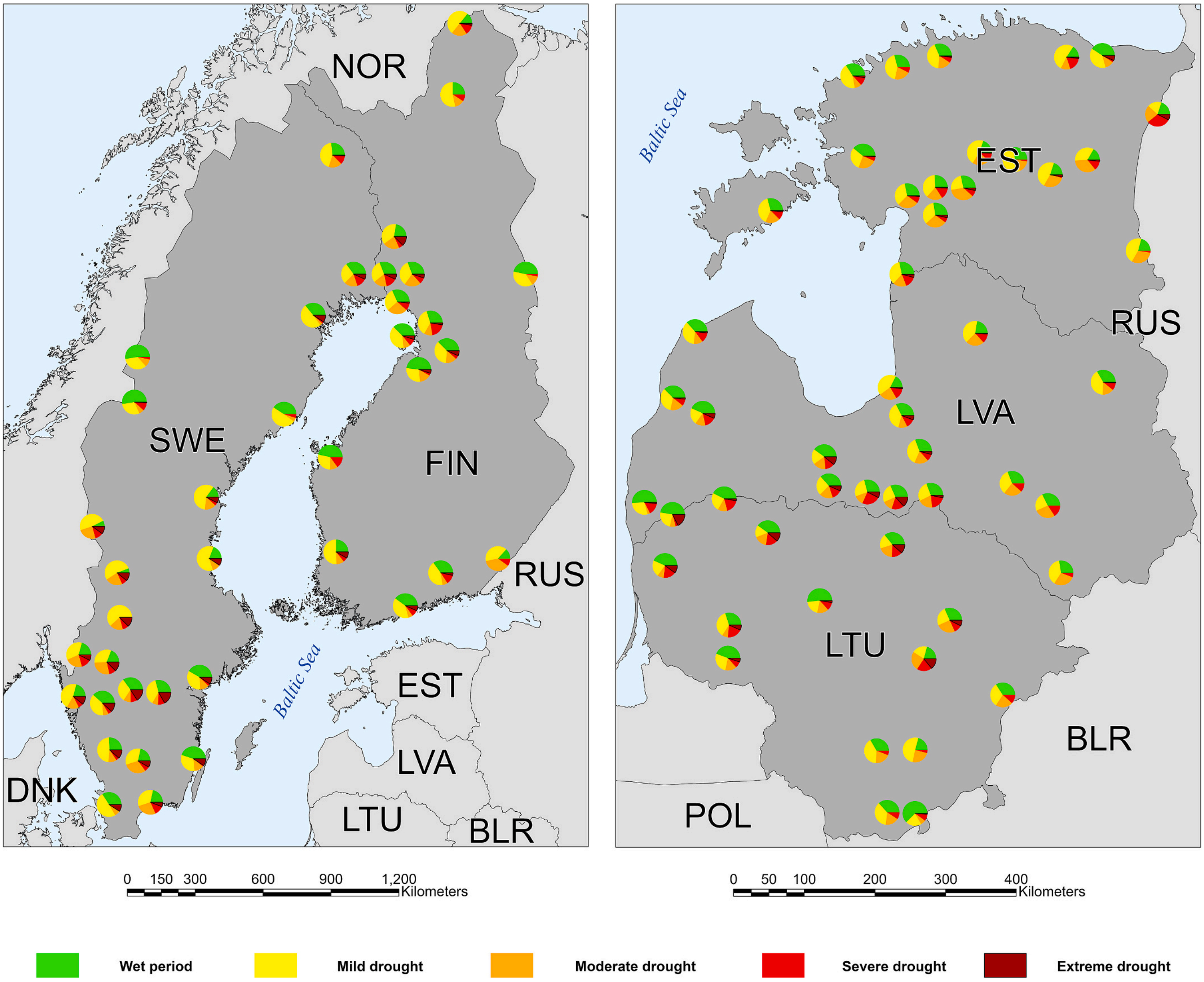


Fig. 10. Distribution of hydrological droughts by the SDI index of the 12-month accumulation period for the selected period of the 1971–1980 decade.

southwest.

The similarities between the hydrological and climatic drought patterns in the first three decades of the study period indeed show a strong relationship between the meteorological conditions and the subsequent hydrological response in the Baltic Region (Appendix A, Fig. A.1–A.3, A.7–A.9). The wetter conditions observed in the second half of the study period probably contributed to the reduction of extreme drought events and to a more consistent pattern of climatic drought events. The increased precipitation during this period led to more stable hydrological conditions and reduced the occurrence of severe droughts. However, the occasional occurrence of severe and extreme droughts during the wetter period also highlights the role of climate variability in influencing drought patterns in the region. Even during relatively wetter periods, the Baltic Region remains vulnerable to drought events, indicating the need for continuous monitoring and effective drought management strategies. The approach of analysing both hydrological and meteorological droughts provided a comprehensive understanding of drought dynamics in the Baltic Region.

Indeed, the results showed that the occurrence and severity of hydrological droughts in the Baltic Region have considerable variation over time. In the early to mid-20th century, more severe drought events occurred in the region, indicating drier conditions during this period. This was also underlined by a particularly intense drought period in the 1970s, when drought events peaked. However, in the later decades, the region experienced relatively wetter conditions and a decrease in the percentage of extreme drought events. This period was characterised by milder drought events compared to the earlier decades. In the last decade, however, the number of extreme droughts has decreased again, although they have tended to be localised to specific regions. This means that although droughts have been more frequent in recent years, their impacts have not been evenly distributed across the Baltic Region. The observed patterns indeed reveal the complex and dynamic nature of drought in the region, with variations in drought conditions over time.

4.3. *Comparative analysis of the relations between the drought indices*

Based on the fact that precipitation is the main driver of river flow, the relationship between climatic and hydrological drought doesn't require proof. At the same time, depending on the physico-geographic conditions, temperature, and latitude of the WGS, the amount of precipitation that is converted into river flow may vary. By examining the correlation between different months and accumulation periods, important conclusions can be drawn about how quickly the rivers respond to precipitation or lack thereof. To estimate this direct relationship in each country for each river, it was decided to examine correlation between SPI and SDI. Correlation was calculated for each month from the May–October season. Also, evaluation of these months was done between different accumulation periods (e.g., SPI with 3 accumulation months with SDI with 9 accumulation months, or SPI with 12 accumulation months with SDI with 12 accumulation months). As a result, for each country, the data matrix was done (Fig. 11), where the percentage of rivers with SPI-SDI correlation of >0.7 was presented in the grid for specific a month and relation.

The results in Fig. 11 show the similarities and differences between the two groups of countries based on the links between meteorological and hydrological drought indices. The first group included Lithuania, Latvia, and Estonia, while the second group consisted of Finland and Sweden. The analysis showed that the first group of countries (Lithuania, Latvia, and Estonia) had an almost identical distribution of dependencies by month, with correlations in 51–57 out of 96 possible variants. The streamflow drought index in these countries showed a high dependence on the standardized precipitation index in certain months and accumulation periods. For the three countries (Lithuania, Latvia, and Estonia), the SDI in May and June (and sometimes in July) was highly dependent on the SPI for the long-term accumulation period (SPI12-SDI9 and SPI12-SDI12). The highest number of correlations between SPI12 and SDI9 was found for Estonia in May and June (82.4 %), and the highest number of correlations between SPI12 and SDI12 was found for Lithuania in May (87.5 %). September and October were also strongly dependent on the SPI for short-term accumulation periods (1- and 3-month). This showed that in the first half of the warm period (spring and early summer), the meteorological conditions of the previous winter and autumn had a significant impact on hydrological drought. In contrast, in the second half of the warm period (late summer and early autumn), the climatic conditions of the summer were decisive for hydrological drought. Estonia stood out in this group, showing higher correlations between the SDI and the SPI in September and October, especially for the accumulation periods SPI6 (SPI6-SDI1 for September: 70.6 %; SPI6-SDI1 for October: 88.2 %) and SPI9 (SPI9-SDI3 for September: 58.8 %; SPI9-SDI3 for October: 64.7 %). This could indicate a stronger influence of climatic conditions on hydrological drought not only in summer but also in spring and winter. Furthermore, this could indicate that in Estonia, there is a greater time lag between the onset of meteorological drought and the onset of hydrological drought compared to the other countries in the group. This analysis highlights how hydrological drought patterns in the first group are influenced by different accumulation periods of meteorological drought and Estonia's specific characteristics in this respect. Overall, this analysis provided valuable insights into the relationships between meteorological and hydrological droughts in the above countries and their seasonal variations. In contrast to the first group of countries (Lithuania, Latvia, and Estonia), Finland and Sweden showed greater heterogeneity in their hydrological and meteorological drought relationships. This was shown by the lack of clear trends and a more diverse distribution of correlations by month.

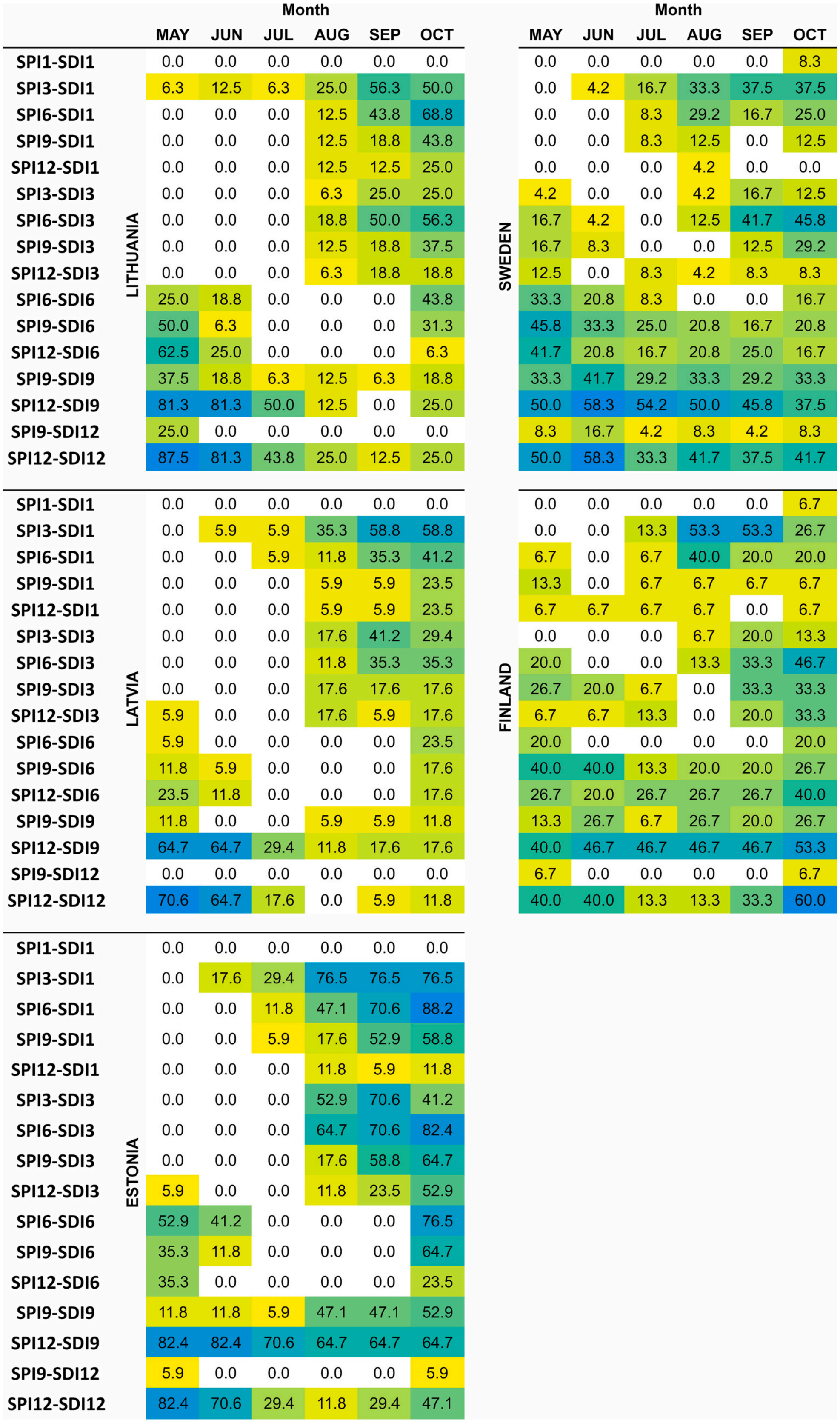
Of the 96 possible variations, Finland and Sweden had correlations for 71 and 72 variations, respectively, indicating a broader range of interactions between hydrological and meteorological conditions (Fig. 11). Finland and Sweden showed some similarities with Estonia. The similarities with Estonia, especially with respect to the SPI12-SDI9 and SPI12-SDI12 correlations, support the idea that meteorological conditions in the preceding months have a significant influence on hydrological drought during the warm period in all three countries. For a large proportion of the rivers studied in Finland and Sweden (over 40 %), there were high correlations between SPI9-SDI6 and SPI12-SDI6 in May. This indicates that the hydrological drought in May was influenced by the climatic conditions of the previous year. The persistence of meteorological conditions from the previous year may have a lasting effect on hydrological conditions in these countries. In Fig. 11, the SPI9-SDI12 dependence shows mostly random values for all countries, except for Sweden, where four rivers showed an atypical correlation. For these particular rivers in Sweden, the variations in hydrological drought are not primarily due to the preceding meteorological drought conditions.

A possible explanation could be that the main feeding source of these rivers was mainly from snow or glacier melt and that specific climatic conditions prevented sufficient supply melting waters, leading to an early hydrological drought. The greater heterogeneity of hydrological and meteorological drought conditions in Finland and Sweden may be related to their larger area, their elongated north-to-south shape, and their more northerly location. These geographical factors may result in different climatic and hydrological conditions in the region. With the exception of SPI9-SDI12 (for Sweden), no strong correlations were observed for other accumulation periods (where the SDI accumulation period is larger).

It is important to consider these results in the context of local climate, hydrological systems, and geographic characteristics of each country to fully understand the implications of the observed patterns. Several factors such as local hydrological processes, seasonal variations, and data availability could influence the lack of strong correlations between specific SPI and SDI accumulation periods. Using the Pearson correlation coefficient (PCC) to quantify the relationship between meteorological drought (measured by SPI) and hydrological drought (measured by SDI) was a valuable statistical approach. By calculating the PCC for different accumulation periods, the study gained insights into how changes in precipitation (meteorological drought) were associated with changes in discharge (hydrological drought) over different time periods. Additionally, this study can help to determine the time lag between hydrological and meteorological drought.

5. Discussion

In this study, both hydrological and meteorological droughts in the Baltic Region were estimated and analysed, providing valuable insights into the relationship between surface water content and precipitation deficits. The use of the SPI and SDI in drought analysis is well-established and has been used in various studies worldwide (Tefera et al., 2019; Chamorro et al., 2020; Erfurt et al., 2020; Torabi Haghighi et al., 2020; Kalbarczyk and Kalbarczyk, 2022; Niaz et al., 2022; Otop et al., 2023). The SPI has been recognised as a useful tool for analysing the drought occurrence based on meteorological and hydrological drought indices (Stagge et al., 2015; Karamuz et al., 2023). It allows comparisons between different climatic zones by normalising the index using a univariate probability distribution. In the context of central and southern Europe, Peña-Angulo et al. (2022) conducted a detailed assessment of changes in hydrological drought from 1962 to 2017. A newly developed and dense dataset of monthly streamflow observations was used for this naalysis. The study found a decrease in trends of hydrological drought in northern Europe and an increase in the remaining Europe. The changes in monthly streamflow trends showed a decrease in all months in southern Europe and in the warm months in northern Europe, along with an increase in the cold months in northern Europe. The observed positive trend in monthly streamflow, especially in winter, was attributed to a slight increase in precipitation over northern Europe (Caloiero et al., 2018). Additionally, the study highlighted the significant influence of increased atmospheric evapotranspiration demand and actual evapotranspiration in southern Europe (Tomas-Burguera et al., 2021), contributing to the hydrological drought trends in this region. Overall, these references and scientific studies demonstrate the wide application of drought indices such as SPI and SDI in assessing drought conditions and trends worldwide and their importance in understanding the hydrological and meteorological causes of drought events in different regions. In the context of the Baltic Region, the study provided valuable insights into the territorial distribution of droughts over different decades. In the decade from 1961 to 1970, Lithuania, Latvia, and Estonia experienced the most hydrological drought events. In 1971–1980, southern Sweden, western Lithuania, and Latvia had the highest concentration of extreme hydrological drought events. In the decade 1981–1990, central and southern Sweden had a higher



		Month					
		MAY	JUN	JUL	AUG	SEP	OCT
LITHUANIA	SPI1-SDI1	0.0	0.0	0.0	0.0	0.0	0.0
	SPI3-SDI1	6.3	12.5	6.3	25.0	56.3	50.0
	SPI6-SDI1	0.0	0.0	0.0	12.5	43.8	68.8
	SPI9-SDI1	0.0	0.0	0.0	12.5	18.8	43.8
	SPI12-SDI1	0.0	0.0	0.0	12.5	12.5	25.0
	SPI3-SDI3	0.0	0.0	0.0	6.3	25.0	25.0
	SPI6-SDI3	0.0	0.0	0.0	18.8	50.0	56.3
	SPI9-SDI3	0.0	0.0	0.0	12.5	18.8	37.5
	SPI12-SDI3	0.0	0.0	0.0	6.3	18.8	18.8
	SPI6-SDI6	25.0	18.8	0.0	0.0	0.0	43.8
	SPI9-SDI6	50.0	6.3	0.0	0.0	0.0	31.3
	SPI12-SDI6	62.5	25.0	0.0	0.0	0.0	6.3
	SPI9-SDI9	37.5	18.8	6.3	12.5	6.3	18.8
	SPI12-SDI9	81.3	81.3	50.0	12.5	0.0	25.0
	SPI9-SDI12	25.0	0.0	0.0	0.0	0.0	0.0
	SPI12-SDI12	87.5	81.3	43.8	25.0	12.5	25.0

		Month					
		MAY	JUN	JUL	AUG	SEP	OCT
SWEDEN	SPI1-SDI1	0.0	0.0	0.0	0.0	0.0	8.3
	SPI3-SDI1	0.0	4.2	16.7	33.3	37.5	37.5
	SPI6-SDI1	0.0	0.0	8.3	29.2	16.7	25.0
	SPI9-SDI1	0.0	0.0	8.3	12.5	0.0	12.5
	SPI12-SDI1	0.0	0.0	0.0	4.2	0.0	0.0
	SPI3-SDI3	4.2	0.0	0.0	4.2	16.7	12.5
	SPI6-SDI3	16.7	4.2	0.0	12.5	41.7	45.8
	SPI9-SDI3	16.7	8.3	0.0	0.0	12.5	29.2
	SPI12-SDI3	12.5	0.0	8.3	4.2	8.3	8.3
	SPI6-SDI6	33.3	20.8	8.3	0.0	0.0	16.7
	SPI9-SDI6	45.8	33.3	25.0	20.8	16.7	20.8
	SPI12-SDI6	41.7	20.8	16.7	20.8	25.0	16.7
	SPI9-SDI9	33.3	41.7	29.2	33.3	29.2	33.3
	SPI12-SDI9	50.0	58.3	54.2	50.0	45.8	37.5
	SPI9-SDI12	8.3	16.7	4.2	8.3	4.2	8.3
	SPI12-SDI12	50.0	58.3	33.3	41.7	37.5	41.7

		MAY	JUN	JUL	AUG	SEP	OCT
LATVIA	SPI1-SDI1	0.0	0.0	0.0	0.0	0.0	0.0
	SPI3-SDI1	0.0	5.9	5.9	35.3	58.8	58.8
	SPI6-SDI1	0.0	0.0	5.9	11.8	35.3	41.2
	SPI9-SDI1	0.0	0.0	0.0	5.9	5.9	23.5
	SPI12-SDI1	0.0	0.0	0.0	5.9	5.9	23.5
	SPI3-SDI3	0.0	0.0	0.0	17.6	41.2	29.4
	SPI6-SDI3	0.0	0.0	0.0	11.8	35.3	35.3
	SPI9-SDI3	0.0	0.0	0.0	17.6	17.6	17.6
	SPI12-SDI3	5.9	0.0	0.0	17.6	5.9	17.6
	SPI6-SDI6	5.9	0.0	0.0	0.0	0.0	23.5
	SPI9-SDI6	11.8	5.9	0.0	0.0	0.0	17.6
	SPI12-SDI6	23.5	11.8	0.0	0.0	0.0	17.6
	SPI9-SDI9	11.8	0.0	0.0	5.9	5.9	11.8
	SPI12-SDI9	64.7	64.7	29.4	11.8	17.6	17.6
	SPI9-SDI12	0.0	0.0	0.0	0.0	0.0	0.0
	SPI12-SDI12	70.6	64.7	17.6	0.0	5.9	11.8

		MAY	JUN	JUL	AUG	SEP	OCT
FINLAND	SPI1-SDI1	0.0	0.0	0.0	0.0	0.0	6.7
	SPI3-SDI1	0.0	0.0	13.3	53.3	53.3	26.7
	SPI6-SDI1	6.7	0.0	6.7	40.0	20.0	20.0
	SPI9-SDI1	13.3	0.0	6.7	6.7	6.7	6.7
	SPI12-SDI1	6.7	6.7	6.7	6.7	0.0	6.7
	SPI3-SDI3	0.0	0.0	0.0	6.7	20.0	13.3
	SPI6-SDI3	20.0	0.0	0.0	13.3	33.3	46.7
	SPI9-SDI3	26.7	20.0	6.7	0.0	33.3	33.3
	SPI12-SDI3	6.7	6.7	13.3	0.0	20.0	33.3
	SPI6-SDI6	20.0	0.0	0.0	0.0	0.0	20.0
	SPI9-SDI6	40.0	40.0	13.3	20.0	20.0	26.7
	SPI12-SDI6	26.7	20.0	26.7	26.7	26.7	40.0
	SPI9-SDI9	13.3	26.7	6.7	26.7	20.0	26.7
	SPI12-SDI9	40.0	46.7	46.7	46.7	46.7	53.3
	SPI9-SDI12	6.7	0.0	0.0	0.0	0.0	6.7
	SPI12-SDI12	40.0	40.0	13.3	13.3	33.3	60.0

		MAY	JUN	JUL	AUG	SEP	OCT
ESTONIA	SPI1-SDI1	0.0	0.0	0.0	0.0	0.0	0.0
	SPI3-SDI1	0.0	17.6	29.4	76.5	76.5	76.5
	SPI6-SDI1	0.0	0.0	11.8	47.1	70.6	88.2
	SPI9-SDI1	0.0	0.0	5.9	17.6	52.9	58.8
	SPI12-SDI1	0.0	0.0	0.0	11.8	5.9	11.8
	SPI3-SDI3	0.0	0.0	0.0	52.9	70.6	41.2
	SPI6-SDI3	0.0	0.0	0.0	64.7	70.6	82.4
	SPI9-SDI3	0.0	0.0	0.0	17.6	58.8	64.7
	SPI12-SDI3	5.9	0.0	0.0	11.8	23.5	52.9
	SPI6-SDI6	52.9	41.2	0.0	0.0	0.0	76.5
	SPI9-SDI6	35.3	11.8	0.0	0.0	0.0	64.7
	SPI12-SDI6	35.3	0.0	0.0	0.0	0.0	23.5
	SPI9-SDI9	11.8	11.8	5.9	47.1	47.1	52.9
	SPI12-SDI9	82.4	82.4	70.6	64.7	64.7	64.7
	SPI9-SDI12	5.9	0.0	0.0	0.0	0.0	5.9
	SPI12-SDI12	82.4	70.6	29.4	11.8	29.4	47.1

Fig. 11. Percentage representation plot of the number of correlation links between MS (SPI) and WGS (SDI) exceeding a threshold of correlation coefficient of 0.7, from the maximum number of possible relations for 1-, 3-, 6-, 9-, and 12-month accumulation periods; the data was analysed for each month during the May–October season.

percentage of drought events. Finally, in the decade from 2011 to 2020, Lithuania, Latvia, Estonia, southern Finland, and south-eastern Sweden had a higher number of hydrological drought events. This was also confirmed in other European regions, especially in north-central and north-eastern Europe (Blauhut et al., 2022). At the same time, the runoff indices of the Rhine and Danube showed that no severe or extreme drought was observed between 1976 and 2003 (Erfurt et al., 2020); in particular, runoff in 2003 and 2018 was classified as extremely low. This analysis suggests that different datasets provided different information about droughts that would have been missed if only one dataset was used. In Poland, the SPI indicated moderate drought for autumn 2018 and extreme drought for spring 2018 and summer 2019 (Kalbarczyk and Kalbarczyk, 2022). It is assumed that almost 60 % of Polish regions were affected by moderate, severe, or extreme drought in summer 2019. The assessment of droughts based on the SPI in the Lusatian Neisse catchment (Central Europe) showed extreme drought in the southern part of the region and severe drought in the rest of the region at the end of August 2018 (Otop et al., 2023). The cases of extreme meteorological drought, defined by SPI and SPEI, were also observed in eastern Germany in 2018–2019 (Conradt et al., 2023). Successive multi-year meteorological summer droughts in Central and Western Europe are characterised by two or more summers with below-average precipitation and above-average evaporative demand (Van Der Wiel et al., 2023). Worryingly, climate models predict a sharper increase in dry spells (Rousi et al., 2021) and multi-year droughts in Western Europe in response to ongoing global warming (Van Der Wiel et al., 2023). The current drought in Europe began in the summer of 2018 (Rousi et al., 2023). This particular year was characterised by extreme climatic conditions, including simultaneous heat waves and droughts across much of the continent.

This study also found that meteorological stations with many short-duration SPI index cases and water gauging stations (WGS) with many short-duration SDI index cases had fewer long-duration cases. Conversely, stations with many prolonged droughts had fewer short droughts. The SPI and SDI indices showed some agreement in specific regions across the Baltic Region, especially for 6- and 9-month accumulation periods, so that consistent drought information is available for these periods. There was an increase in SDI cases (SDI ≤ -1) for WGS in the western part of the Baltic States and occasional WGS in Sweden and Finland during 1991–2020, indicating a possible trend towards more frequent hydrological droughts in these areas. However, the SPI index did not show similar trends, except for the central part of Estonia and southern Finland, where some patterns were observed. These results are consistent with previous studies by Minea et al. (2022), who analysed drought trends in the Eastern European region for different time scales and highlighted droughts in the last two decades of the previous century. SPI was also used by Wicher-Dysarz et al. (2022) to assess meteorological drought uncertainty in identifying drought zones in Poland. The results revealed different zones of dryness across the country, ranging from normal ($-0.5 < \text{SPI} < 0.5$) to extremely dry ($\text{SPI} \leq -2.0$) conditions. Similarly, Chan et al. (2021) conducted an analysis of SDI in different time periods, providing valuable insights into the estimation and comparison of droughts. Additionally, a recent study focusing on Lithuania developed a hydrological drought index that identifies the most severe droughts over a 30-year period in 1992, 2002, 2006, 2019, and 2020 (Nazarenko et al., 2023). These various studies further contribute to the understanding of drought dynamics and patterns in the respective regions.

Analysis of drought indices with different accumulation periods has indeed revealed spatio-temporal patterns of meteorological and hydrological droughts. As noted by Hisdal et al. (2001), understanding the relationship between runoff patterns and drought events can be complex. Our study highlighted the importance of the 6-month accumulation period, which showed prolonged and more widespread drought events in the Baltic Region. The 9- and 12-month accumulation periods showed similar trends, indicating prolonged and widespread drought impacts. The role of monthly runoff in influencing the severity of hydrological droughts was evident, as droughts were caused by the accumulation of runoff deficits over time. These results are consistent with previous regional assessments that highlighted the complexity of drought patterns and the influence of runoff behaviour on drought occurrence (Dalezios et al., 2000; Hisdal et al., 2001; Van Loon and Laaha, 2015; Masseroni et al., 2021). Studies in Austria have shown that the duration and deficit of hydrological drought are influenced by several factors, with the deficit mainly related to wetness in the catchment and elevation characteristics (Van Loon and Laaha, 2015). In the Mediterranean, climate change since 1985 has resulted in consistently lower runoff compared to the 1950–2013 average (Masseroni et al., 2021). In addition, the results of Dalezios et al. (2000) showed a decreasing trend in drought in Greece from west to east, while Hisdal et al. (2001) found regionally varying drought deficits between 1962 and 1990, with deficits increasing in some areas (in Spain, the eastern part of Eastern Europe and large parts of the United Kingdom) and decreasing in others (in large parts of Central Europe and the western part of Eastern Europe).

The precise visualization of spatial variability is crucial to understanding regional weather patterns. The Baltic Region, which is characterised by different topographies and climate zones in several countries, poses a particular challenge. Determining the amount of meteorological data required is a well-considered decision based on the scientific objectives and spatial considerations of each study. This deliberate approach ensures that the data collection strategy is harmonised with the details of the meteorological processes under investigation, thereby increasing the precision and relevance of the scientific investigation in the context of regional weather patterns in the Baltic Region. Depending on the selected meteorological phenomenon and the extent of its distribution, the required number of meteorological stations is selected for the concrete analysis. Dyrrdal et al. (2021) highlight the need for a dense network of meteorological stations (MS), especially for the study of localised phenomena such as heavy rainfall. Heavy rainfall events occur on spatial and temporal scales that is some cases are inherently small and characterised by significant variability. To accurately characterise these events, a denser network of MS is essential. However, not all studies require a large amount of meteorological data. In contrast, the droughts analysed in our study are more widespread and regional in nature. Depending on the accumulation period applied, they last longer and indicate the state of the atmosphere over a certain period. Giaquinto et al. (2023) emphasise the sub-regional character of droughts with different accumulation periods. The four established sub-regions have both similarities and differences. For example, the Scandinavian peninsula has uniform south-eastern cluster covering southern and central parts of Sweden. Eastern Europe shows latitudinal subdivisions, especially in shorter accumulation periods. Fragmentation increases with the duration of accumulation, but does not necessarily lead to more sub-regions, but interrupts spatial continuity in the clusters. To summarise, it can be said that different patterns emerge in the regional clusters in the networks with different accumulation periods. In our study, each MS had a crucial link to the particular water gauging station (WGS). Accordingly, some of them covered several WGS. In our study, we used fifteen meteorological stations for Sweden, which together cover an area of 35.2 thous. km^2 per MS. Following Feiccabrino et al. (2013), who used nineteen uniformly distributed MS for surface-based methods in hydrological models, we recognise the importance of well distributed MS data. The study of spatial change from south to north is of central importance, as shown by Johansson and Chen (2003), who analysed 370 meteorological stations. Their results show that the largest precipitation scatter between MSs occurs in those up to an altitude of 200 m a.s.l., while the precipitation amount amplitude remained consistent in MSs located at 200–1000 m altitudes. Consequently, the previous study demonstrates that it is not necessary to have many MS, but that their spatial arrangement at different elevations and latitudinal distribution is more important.

Finland, which is characterised by gently rolling landscapes, stands out as an almost entirely flat country with a unique climate classification according to Köpper-Geiger (Beck et al., 2018). This topographic simplicity results in minimal precipitation variability, which contributes to the country's stable diurnal precipitation distributions (Lind et al., 2020). Finland's low altitude influences the regularity of precipitation patterns throughout the day, which is in contrast to regions with a more varied topography. Therefore, an area of 28.2 thous. km^2 per MS was chosen for Finland. For the Baltic States, the selected station density at low elevation is considered as quite good (Lithuania and Latvia – 10.8 thous. km^2 per MS; Estonia 3.8 thous. km^2 per MS). The number of meteorological stations we have chosen is sufficient to analyse the selected parameters in the contexts of prolonged droughts.

The presented methodology, where a specific meteorological station was assigned to each WGS, like any other methodology, has its limitations. Among the advantages, it can be noted that the nearest meteorological station with a long observation period allows for a better assessment of the relationship between meteorological and hydrological droughts. This leads to the use of fewer meteorological stations and, consequently, a lower density of meteorological data. At the same time, the use of raster-interpolated meteorological data may carry greater risks in accumulating errors due to the point - area of pixels connection (WGS and the modeled raster of interpolated/predicted meteorological data). However, the authors do not exclude the possible use of a similar approach, but it requires a more careful analysis of input data.

It is also worth noting that according to WMO recommendations for operational hydro-meteorological research, the density in coastal regions should be no <1 station per 9000 km^2. Considering these recommendations, as well as the understanding that drought has a broader spatial distribution than snow or rain, it can be considered that number of presented meteorological stations is sufficient for understanding trends and relationships between hydrological and meteorological droughts within the entire Baltic region. Undoubtedly, increasing the amount of input data will only improve clarity, but there is a significant problem with the availability of long-term observations.

Pearson's correlation coefficient has been used in several studies to show the linear relationship between variables (Bull and Morton, 1978; Coop et al., 2010). The test for a linear relationship between SPI and SDI in this study shows that Finland and Sweden, unlike the first group of countries (Lithuania, Latvia, and Estonia), have greater heterogeneity in their hydrological and meteorological drought relationships (of the 96 possible variations, they have correlations for 71 and 72 variations, respectively). Finland and Sweden show some similarities with Estonia. Like Estonia, they have a relatively high proportion of rivers where the hydrological drought index depends on the meteorological drought index throughout the warm season (SPI12-SDI9 and SPI12-SDI12). Eghtedar Nezhad et al. (2017) also assessed meteorological and hydrological droughts using the Reconnaissance Drought Index (RDI), SPI, and SDI, and found significant differences between SPI and RDI, while RDI and SDI had similar characteristics with strong correlations on the 48-month time scale. All these studies, as well as ours, have led to a more comprehensive understanding of how short- and long-term meteorological conditions influence the hydrological response to drought. These findings have helped determine whether meteorological droughts directly translate into hydrological droughts. Understanding the strength of this relationship is critical to developing effective drought monitoring and management strategies for the region.

Overall, the study aimed to understand how meteorological drought, driven by precipitation deficits, is related to hydrological drought, which reflects changes in water availability in the Baltic Region. By examining the relationship between these two types of droughts, researchers can gain insight into the vulnerability of regional water resources and provide better information on water management and strategies to mitigate the effects of climate change. The findings from this research can be beneficial in formulating drought mitigation strategies and improving water resource management in the Baltic Region.

6. Conclusions

The analysis of meteorological stations and water gauging stations in the Baltic Region revealed some interesting patterns regarding the duration of drought events and the correlation between the SPI and SDI indices. The meteorological stations with the highest number of short-duration SPI index cases and the WGSs with the highest number of short-duration SDI index cases had a lower number of long-duration cases. In contrast, stations with a relatively high number of long-duration droughts had fewer short-duration droughts.

The increase in the number of SDI cases (when $SDI \leq -1$) was observed for the WGS from the western part of the Baltic States and the occasional WGS of Sweden and Finland in 1991–2020 compared to 1961–1990. The SPI index did not show such tendencies except for the central part of Estonia and southern Finland. A clearer match between the change in the indices was obtained only for accumulation periods of 9- and 12-month.

The results for the spatio-temporal patterns showed that the 6-month accumulation period played a crucial role in both the meteorological and hydrological drought analyses. During this 6-month period, prolonged and widespread drought events occurred in the study area. Furthermore, the patterns observed for the 9- and 12-month accumulation periods showed similar trends in the duration and spatial extent of drought. The main regularities between the analysed countries emphasised the decreasing SPI and SDI values and their extent towards the north, which were clearly expressed in 1976 and 2006.

The wetter conditions observed in the second half of the study period likely contributed to the more consistent pattern of climatic drought events, with fewer extreme droughts observed. The increased precipitation during this period resulted in more stable hydrological conditions and a lower occurrence of severe droughts. However, the occasional occurrence of severe and extreme droughts during this period also highlighted the influence of climate variability on drought patterns in the region. Even during relatively wetter periods, the Baltic Region remained vulnerable to drought events, demonstrating the importance of understanding and managing drought risks. The comprehensive analysis of both hydrological and climatic drought provided a more holistic understanding of drought dynamics in the Baltic Region.

The dependence between SPI9 and SDI12 values was largely random in the Baltic Region. However, there was an interesting observation in Sweden, where four rivers showed an atypical correlation. The atypical correlation means that for these particular rivers in Sweden, hydrological drought seems to be less dependent on meteorological drought. This finding suggests that there might be other factors influencing hydrological drought in these particular rivers in Sweden. This could be related to local hydrogeological conditions, human interventions or other regional climate patterns that influence water availability in the rivers independently of meteorological conditions.

CRediT authorship contribution statement

Diana Meilutytė-Lukauskienė: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Serhii Nazarenko:** Writing – original draft, Methodology, Data curation. **Yaroslav Kobets:** Formal analysis, Data curation. **Vytautas Akstinas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Alireza Sharifi:** Formal analysis, Data curation. **Ali Torabi Haghighi:** Writing – review & editing, Methodology, Data curation. **Hossein Hashemi:** Writing – review & editing, Methodology, Data curation. **Ilga Kokorīte:** Writing – review & editing, Methodology, Data curation. **Baiba Ozolina:** Formal analysis, Data curation.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available from the paper authors upon reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169669.

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