



Meteorological drought in the upper Noteć catchment area (Central Poland) in the light of NDVI and SPI indicators

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Received: 12 January 2024 / Accepted: 3 June 2024 / Published online: 26 July 2024
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Abstract

The currently used standardised precipitation index (SPI) does not allow for a reliable assessment of the impact of drought due to the small and unevenly distributed network of meteorological stations. Hopes for developing methods to assess the impact of droughts are pinned on remote data acquisition and the use of analysis of aerial photographs and satellite scenes. The aim of this study is to assess the occurrence of drought based on the normalised difference vegetation index (NDVI) and SPI at multiple time scales (1-, 3-, and 6-, 9- and 12-month). NDVI values do not simply reflect meteorological drought. However, the spatial co-occurrence of meteorological drought with drought defined on the basis of the NDVI index was demonstrated. The study presents a new approach to identifying drought characterized by SPI and NDVI based on the bivariate choropleth map method, which can indicate the actual places of drought occurrence. The study was carried out for the upper Noteć catchment located in Central Poland.

Keywords Standardised precipitation index (SPI) · Normalised difference vegetation index (NDVI) · Remote sensing · Drought · Bivariate choropleth map · Central Poland

Introduction

The problem of extreme meteorological events is an increasingly important issue in the study of the natural and social environment. This is predominantly due to the large impact of these phenomena on ecosystems, man, and the economy (Nalbantis and Tsakiris 2009; Mahdavi et al. 2021; Kobrossi et al. 2021; Karamuz et al. 2021; Kubiak-Wójcicka 2021). The drought is considered in four categories: meteorological,

agricultural, hydrological, and socio-economic (Wilhite and Glantz 2009; Van Loon 2015; Kubiak-Wójcicka and Bąk 2018; Ozkaya and Zerberg 2019; Jamorska et al. 2019; Kubiak-Wójcicka et al. 2021a). Precipitation is the main factor influencing the onset and persistence of drought. Water is widely regarded as the main factor controlling the ecosystem structure (Notaro et al. 2010; Chen et al. 2020), its scarcity directly affects vegetation, and the transformations of vegetation are indicative of global and regional climate change (Zhu et al. 2016; Kubiak-Wójcicka and Machula 2020).

Studies over the past few decades have shown that the frequency and intensity of drought combined with air temperature have increased significantly in recent years (Groisman et al. 2005; Graczyk and Kundzewicz 2016; Kubiak-Wójcicka 2020) and are projected to rise further (Hanel et al. 2018; Spinoni et al. 2020). The lack of sufficient precipitation during the growing season significantly, and sometimes drastically, affects the vegetation of plants causing significant losses in yield and quality. Proper assessment of the extent of losses is essential to determine the amount of compensation for crop losses for insurers and farmers. Given the complexity of drought, there is a need for an objective approach to drought definition for management purposes. More than 100 different drought

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indicators can be found in the literature, which confirms that drought is an extremely complex phenomenon and the indicators used to assess it should be appropriately selected depending on the type of drought (Tigkas et al. 2019; Kchouk et al. 2021; Minea et al. 2022). One of the indicators recommended for drought monitoring is the standardised precipitation index (SPI), which is based on the amount of precipitation recorded at individual meteorological stations (WMO 2016; Burka et al. 2023). The SPI is the first link in the assessment of moisture condition for an area (Giaquinto et al. 2023). It reports on the magnitude, intensity, and duration of precipitation deficits (atmospheric drought) (Salimi et al. 2021). Increasingly, remote sensing analysis is being used for drought monitoring, especially for large areas that are difficult to access and lack a network of meteorological stations in the field, especially for crop monitoring, yield prediction, and production management in agriculture. Compared to in situ measurements, satellite measurements allow for the monitoring of larger areas (AghaKouchak et al. 2015). The most commonly used vegetation index for monitoring agricultural drought is the NDVI (Peters et al. 2002; Zhong et al. 2020; Vreugdenhil et al. 2022).

Both the SPI and the NDVI have their advantages and disadvantages. The disadvantages of the SPI arise from the uneven distribution of gauge stations in the field, which is associated with errors in assessing agricultural production losses in areas far from the stations. The application of the NDVI is, in turn, limited by the availability of satellite scenes meeting the technical criteria of usefulness for analysis (e.g. sufficiently low cloud cover) and the dependence of the spectral reflectance on factors not directly related to the degree of plant moisture (e.g. the species grown, the degree of plant development, the time of day when the satellite scene was taken), which makes it difficult or even impossible to calibrate the measurement results with the actual state of vegetation. Therefore, attempts are increasingly made to develop methods to assess the impact of meteorological drought on vegetation condition based on the analysis of various drought indices. Obtaining information on the actual state of drought is important because of the need to develop procedures for estimating damage in agriculture on the basis of which compensation will be paid.

The aim of this study is to investigate drought based on the normalised difference vegetation index (NDVI) and standardised precipitations index (SPI) at multiple time scales (1-, 3-, and 6-, 9- and 12-month). The procedure is based on the analysis of the relationship between the values of the NDVI index, which represents the differential vegetation condition, and the SPI, which is a traditional index for meteorological drought. The research was carried out for a case study—upper catchment area of the Noteć River (Central Poland).

Data and methods

Study area

The upper Noteć catchment is located in Central Poland, within the Kujawsko-Pomorskie and Wielkopolskie Voivodeships. Topographically, the area is located in a lowland and terrain height differences are small and about 100 m (SRTM 1 Arc-Second Global 2021). The catchment area is used for agricultural purposes. The largest area is occupied by agricultural land (75.99% of the area), followed by forests (deciduous, coniferous, and mixed occupy 11.43% in total), pastures (3.17%), water bodies (3.10%) (Corine Land Cover 2021) (Fig. 1).

The climate of the area is temperate with predominantly polar maritime air masses, resulting in cooler summers and milder winters compared to the eastern, more continental part of Poland. The area of Wielkopolska and Kujawy has been classified as one of the warmest regions in Poland, and as one of the driest in terms of precipitation. Evapotranspiration studies have shown that this is also the area with the greatest agricultural water shortages (Bąk 2003).

The analysed area includes the upper Noteć River catchment up to the water gauge station in Pakość and equals 2302.80 km² (Wektorowe warstwy tematyczne aPGW 2021). The mean long-term discharge of the Noteć River at the Pakość water gauge in the years 1951–2015 was 5.58 m³ s⁻¹, which translated into an outflow of 2.41 dm³ s⁻¹ km⁻² (Tomaszewski and Kubiak-Wójcicka 2021). This is the lowest value of outflow in Poland, which averages 5.5 dm³ s⁻¹ km⁻² (Kubiak-Wójcicka 2020).

Meteorological conditions in the upper Noteć catchment area are shown based on five meteorological stations: Izbica Kujawska, Pakość, Strzelno, Kołuda Wielka and Sompolno. Annual precipitation totals in the upper Noteć catchment in the years 1980–2016 ranged from 500.1 mm (Kołuda Wielka) to 542.5 mm (Strzelno) (Table 1). Both precipitation and discharge are among the lowest in Poland. Air temperature measurements were conducted only at the meteorological station in Kołuda Wielka. The mean annual air temperature at the station in the years 1980–2016 was 8.5 °C, and the highest mean annual air temperature occurred in 1989 (9.8 °C) (Kubiak-Wójcicka et al. 2021b). During the growing season (April–September), the average air temperature was 14.9 °C.

In the geographical and climatic atlases of Poland, the growing season is conventionally defined as the period from 1 April to 30 September (Lorenz 2005). The same dates of the beginning (1 April) and the end (30 September) of the growing season, according to the Act on Insurance of Agricultural Crops and Farm Animals, apply in the systems monitoring the conditions of growth

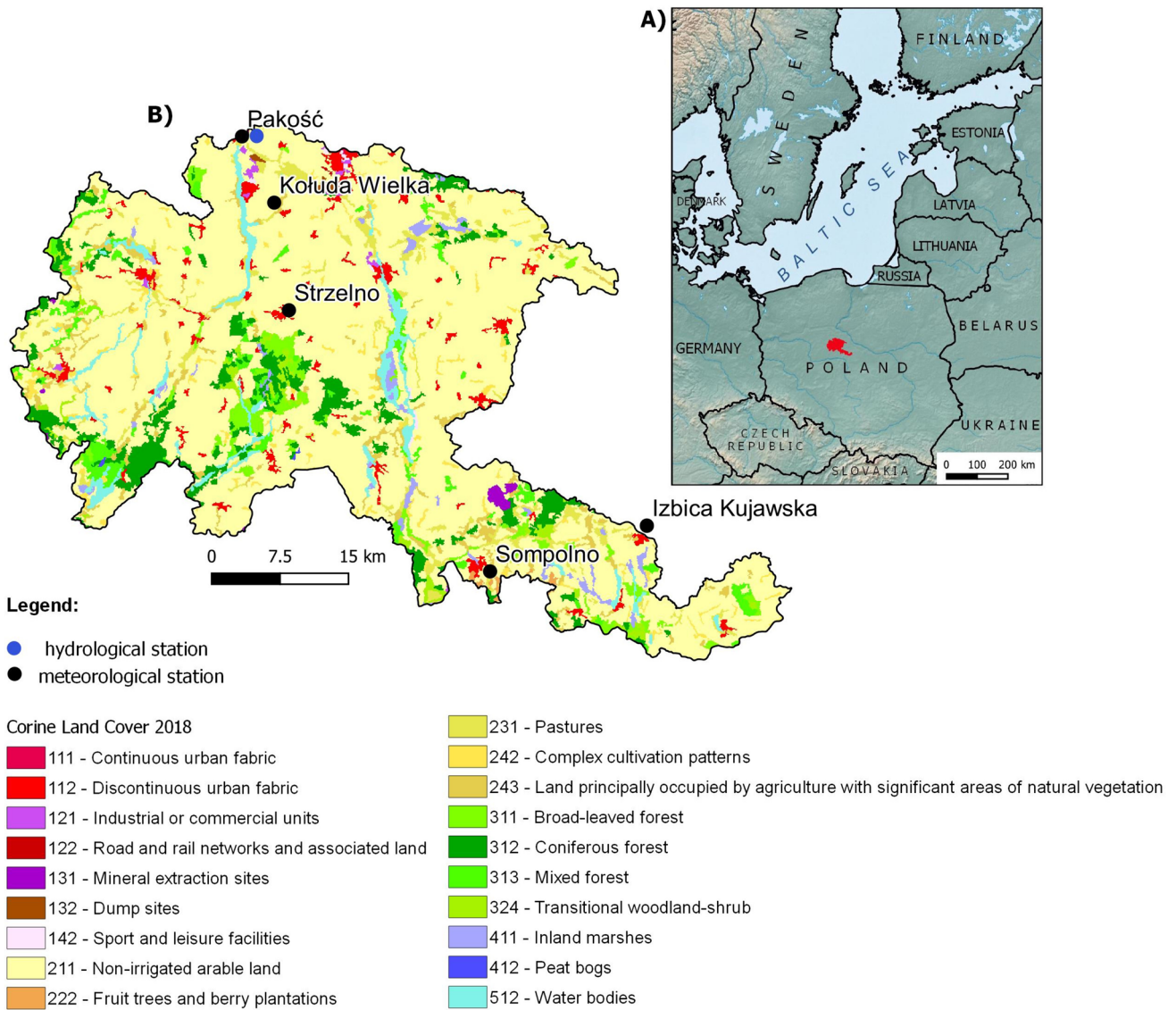


Fig. 1 Localisation of the study area and land use in the upper Noteć catchment

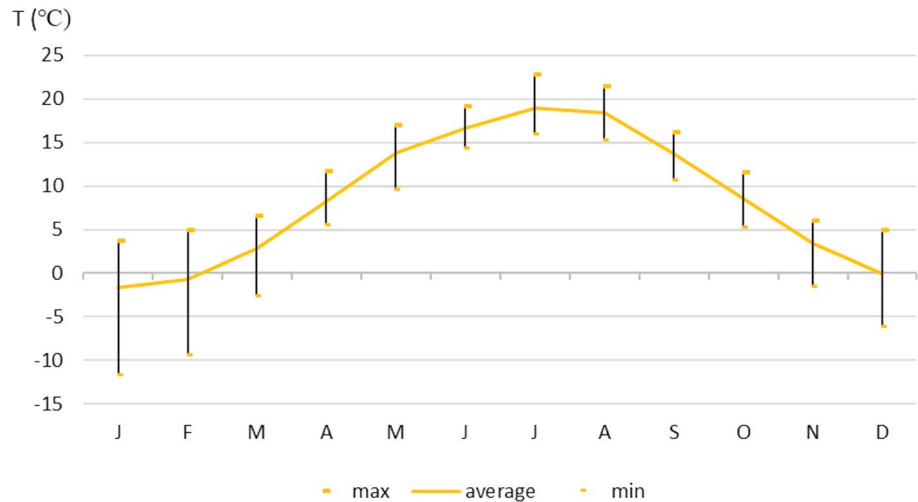
Table 1 Annual precipitation totals in the years 1980–2016

Measuring station	Altitude m a.s.l.	Latitude	Longitude	Total precipitation during the year (mm)
Izbica Kujawska	120	52 26 N	18 46 E	529.3
Pakość	75	52 48 N	18 05 E	513.5
Kołuda Wielka	85	52 44 N	18 09 E	500.1
Strzelno	105	52 38 N	18 11 E	542.5
Sompolno	96	52 23 N	18 31 E	516.0

and development of crop plants in Poland (Dąbrowska-Zielińska et al. 2011; Doroszewski et al. 2012). Thus, for the purposes of this study, the growing season is assumed

to be from April until September. In the analysed period 1980–2016, the highest average monthly air temperature

Fig. 2 Maximum, average, and minimum monthly air temperature at the Kołuda Wielka meteorological station in the years 1980–2016



values were recorded in July, and the lowest in January (Fig. 2).

The methodology for handling and processing the data

In order to test the usefulness of NDVI and SPI indices for assessing the co-occurrence of drought defined by these indices, a research procedure was proposed, the scheme of which is shown in Fig. 3. The description of the procedure's steps is included in the following subsections.

Standardised precipitation index (SPI)

Daily precipitation totals taken from the Institute of Meteorology and Water Management—National Research Institute were used for this study. Data were obtained for five meteorological stations, i.e. Izbica Kujawska, Strzelno, Sompolno, Kołuda Wielka and Pakość, which are situated within the upper Noteć catchment area. Based on the daily values, monthly and annual mean values were calculated for the period from 1980 to 2016. Monthly precipitation

values were used to calculate the SPI, which is used to identify meteorological drought. Meteorological conditions were complemented by data on air temperature which was measured exclusively at the Kołuda Wielka meteorological station.

The SPI, which was proposed by McKee et al. (1995), was used to determine meteorological drought in the upper Noteć River catchment between 1981 and 2016. This index is widely used as a reference drought index to monitor drought and assess its impact on vegetation condition (Shukla and Wood 2008; Stagge et al. 2015; Kubiak-Wójcicka 2019). It intuitively measures the departure of precipitation from the mean value of long-term records. The 30-year period used in hydrological calculations was taken as the minimum length of the calculation period (Hannaford et al. 2013).

The SPI was calculated on the basis of monthly precipitation totals for five meteorological stations in the upper Noteć catchment area (Izbica Kujawska, Strzelno, Kołuda Wielka, Sompolno and Pakość). In the study, matching to the normal distribution of homogenous series of precipitation has been achieved with use of the transformation function $f(P) = \sqrt[3]{x}$ (Bąk and Kubiak-Wójcicka 2017). To

Fig. 3 Acquisition and processing of data—research scheme

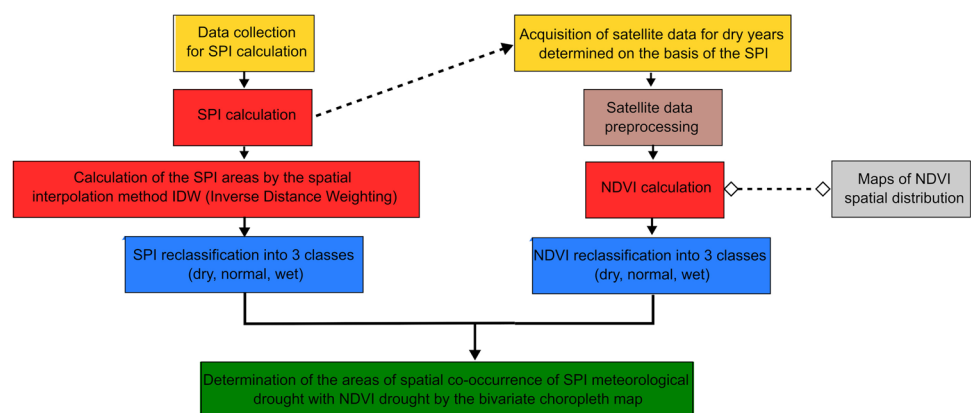


Table 2 Details of satellite images

Year	Data	Scene cloud cover	Land cover	Cloud sensor	Spatial resolution	Landsat mission
1989	15th May	0.00	0.00	TM	30 m	Landsat 5
	19th August	0.00	0.00			
2003	30th May	0.00	0.00	ETM+	30 m	Landsat 7
	23th June	2.00	2.00	TM		Landsat 5
2015	7th May	5.61	5.61	OLI	30 m	Landsat 8
	19th August	1.0	1.0	ETM+		Landsat 7

Source: Own elaboration based on EarthExplorer (2020) and Landsat Collection 1 Level-1 (2020)

Table 3 Pixel values adopted for cloud masking

Landsat mission	Sensor	Attribute	Pixel value
Landsat 5	TM	Cloud and	752, 756, 760, 764
		Cloud shadow—high	928, 932, 936, 940, 960, 964, 968, 972
Landsat 7	ETM+	Cloud and	752, 756, 760, 764
		Cloud shadow—high	928, 932, 936, 940, 960, 964, 968, 972
Landsat 8	OLI	Cloud and	2800, 2804, 2808, 2812, 6896, 6900, 6904, 6908
		Cloud shadow—high	2976, 2980, 2984, 2988, 3008, 3012, 3016, 3020, 7072, 7076, 7080, 7084, 7104, 7108, 7112, 7116

Source: Own elaboration based on U.S. Geological Survey: Landsat Collection 1 Level-1 Quality Assessment Band (2020)

calculate SPI values at different time scales (*n* months), it was necessary to obtain cumulative precipitation for each month and *n* months. A total of five different time series were analysed, i.e. 1, 3, 6, 9, and 12 months. The SPI shows the difference between the precipitation in a given month and the multi-year averages.

SPI values determine the deviation from the median expressed in standard deviation units calculated according to the formula:

$$SPI = \frac{f(X) - \mu}{\delta} \tag{1}$$

, where SPI—standardised precipitation index, *f(X)*—transformed sum of precipitations, μ —mean of normalised index *X*, δ —standard deviation of index *X*.

The proposed approach is based on the assessment of water resources under different hydroclimatic conditions and the establishment of different intensity classes. The adoption of standardised indices allowed for the classification of drought intensity. Extreme events were identified when the value of the index went above 1.0—wet periods, or dropped below −1.0—droughts.

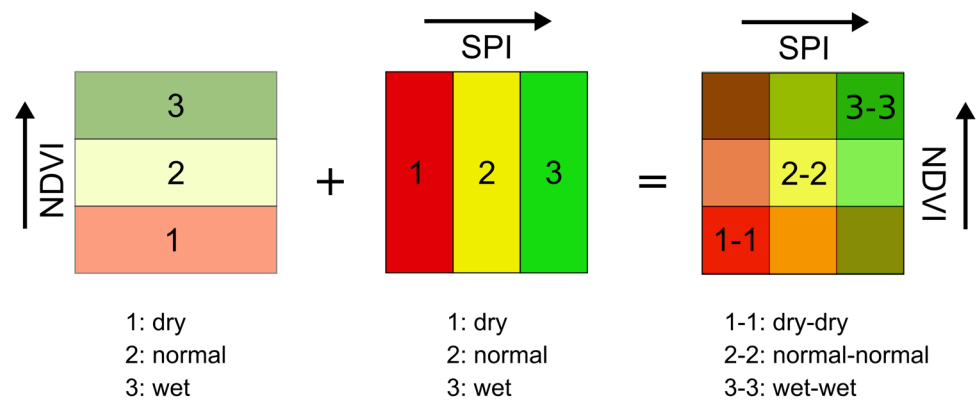
In addition, the use of the SPI allows us to differentiate between degrees of drought using a set of SPI thresholds of −1.0, −1.5 and −2.0, and 1.0, 1.5 and 2.0 for moderate, severe, and extreme drought and wetness, respectively (McKee et al. 1995). Precipitation is the main

factor controlling the onset and persistence of drought, but evapotranspiration should also be taken into account (Huang et al. 2023). Historical difficulties in quantifying evapotranspiration rates suggest that a general classification scheme is best limited to a simple measure of precipitation (Lloyd-Hughes and Saunders 2002).

Preprocessing of satellite scenes and calculation of the NDVI

The normalised difference vegetation index (NDVI) is used as one of the various remote sensing methods. It is widely applied to monitoring vegetation condition and assessing the impact of climate on vegetation dynamics. The NDVI was first used by Rouse et al. (1973). It is one of the oldest, best known and, because of its ease of calculation, widely used measures. It examines the chlorophyll and water content of plant tissues. It is used to collect information on photosynthetic intensity (Griffith et al. 2002), and helps predict yields as it detects changes in biomass (Wang et al. 2004). The NDVI is based on the contrast between the highest reflection in the near-infrared band and the highest absorption in the red range. It is calculated using the formula (Rouse et al. 1973):

Fig. 4 Construction of the legend of the bivariate choropleth maps developed for the study. Explanation of the construction of a bivariate choropleth map inspired by Stevens (2021)



$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} \quad (2)$$

, where R_{NIR} —near-infrared reflectance, R_{RED} —red reflectance.

The indicator takes values between -1.0 and 1.0 . The higher the near-infrared reflectance and the lower the red band reflectance, the greener the plants and the higher the NDVI value (Lu et al. 2021). This means that plants contain more chlorophyll, which absorbs red light, and spongy mesophyll (which stores water), which reflects infrared light. High values are associated with photosynthetic activity in plants (Rouse et al. 1973; Di Bella et al. 2004). A plant is considered to be in good condition and not exposed to stressors if the NDVI is above 0.6. Average values for vegetation range from 0.4 to 0.8 (Jarocińska and Zagajewski 2008). A value of -1.0 is characteristic of areas occupied by water bodies.

Based on the information about the occurrence of meteorological drought in a given year as defined by the value of the SPI index, a search of satellite scenes covering the analysed area during the growing season (April–September) was conducted. The study used satellite scenes (Landsat Collection 1 Level-1 2020), downloaded from EarthExplorer (2020). They were further verified based on the following conditions:

- The upper Noteć River catchment area (study area) should fit in a single scene.
- The cloud cover in the image should be between 0 and 10%.
- It should be possible to compare at least one pair of images in a given year.

Six satellite scenes meeting the above conditions were selected for the final analysis (Table 2).

After downloading, the satellite scenes were preprocessed in QGIS using the semi-automatic classification plugin (Congedo 2021). Preprocessing within this plugin included

scene conversion by TOA reflectance, DOS1 atmospheric correction, and cloud masking. Cloud masking was performed based on the BQA bands of each scene, reclassifying the BQA bands by indicating the pixel values corresponding to the cloud layer and cloud shadow (Table 3).

The preprocessing was followed by the main phase of calculating the normalised difference vegetation index (NDVI) with the use of a raster calculator according to the formulas provided at U.S. Geological Survey: Landsat normalised difference vegetation index (2020). The final maps showing the NDVI were trimmed to the catchment boundary. The results are presented at an interval of 0.1. Additionally, for the purpose of studying the co-occurrence of drought characterized by the SPI and the NDVI, a classification of the NDVI was established based on three size ranges. The first class includes the NDVI between 0 and 0.4 and characterizes drought, the second class between 0.4 and 0.6 is the normal condition, and between 0.6 and 1.0 is the wet condition.

Relationship between meteorological drought and vegetation condition

The bivariate choropleth map method was used to detect spatial relationships between the occurrence of meteorological drought and vegetation condition. The bivariate choropleth map method can be used only for two selected features, as taking into account more features may make visual and statistical interpretation difficult (Kozieł 1993). Moreover, the selection of the presented variables in a bivariate choropleth map is based on the existence of some kind of relationship between the variables, which relations may manifest themselves in a similar spatial distribution of phenomena, referred to as spatial co-occurrence (Leonowicz 2006). The bivariate choropleth map is more and more often used in research combining social and economic aspects with hydrological and meteorological phenomena (Vittal et al. 2020; Chakraborty et al. 2021). It should also be pointed out the

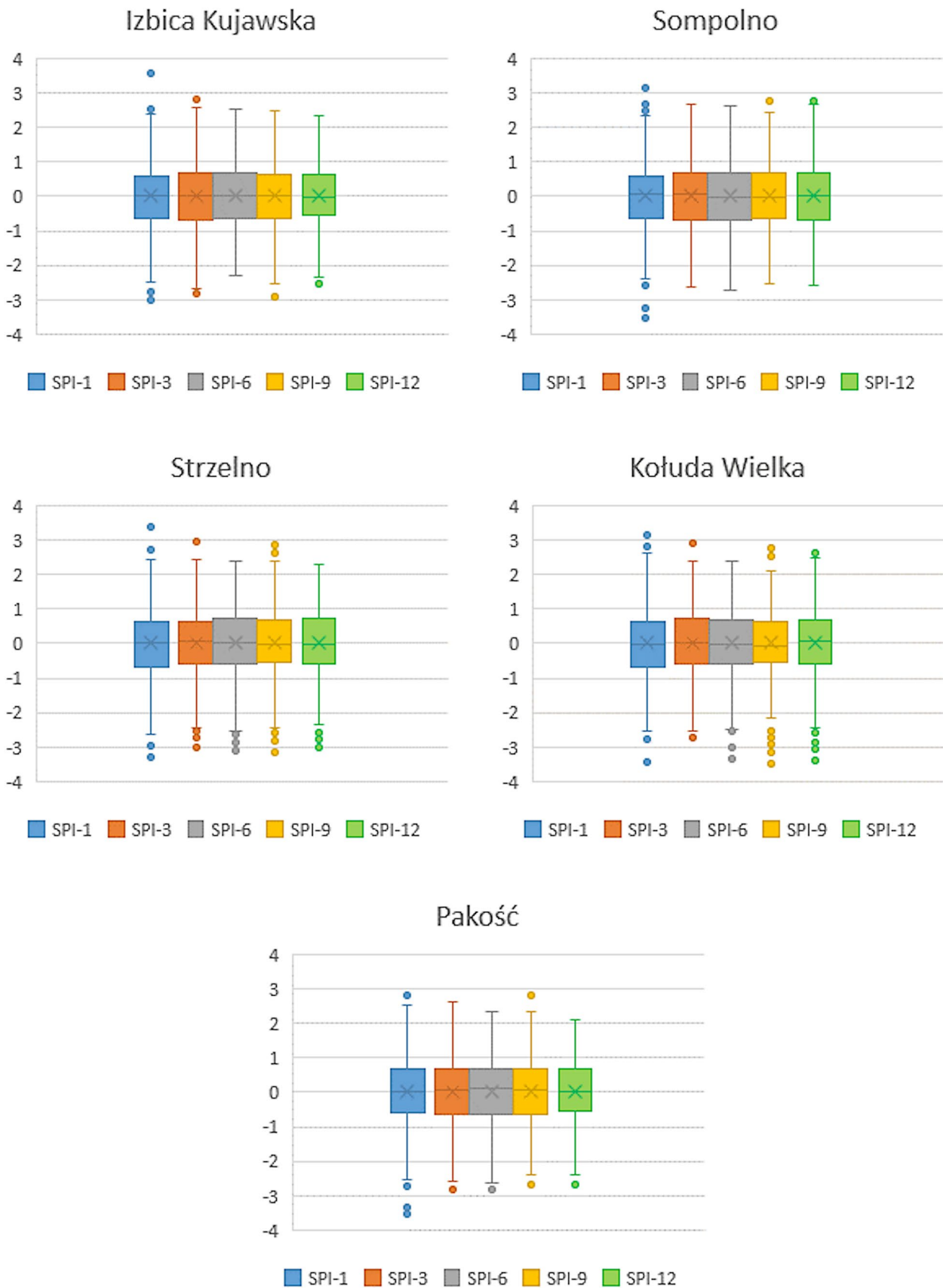
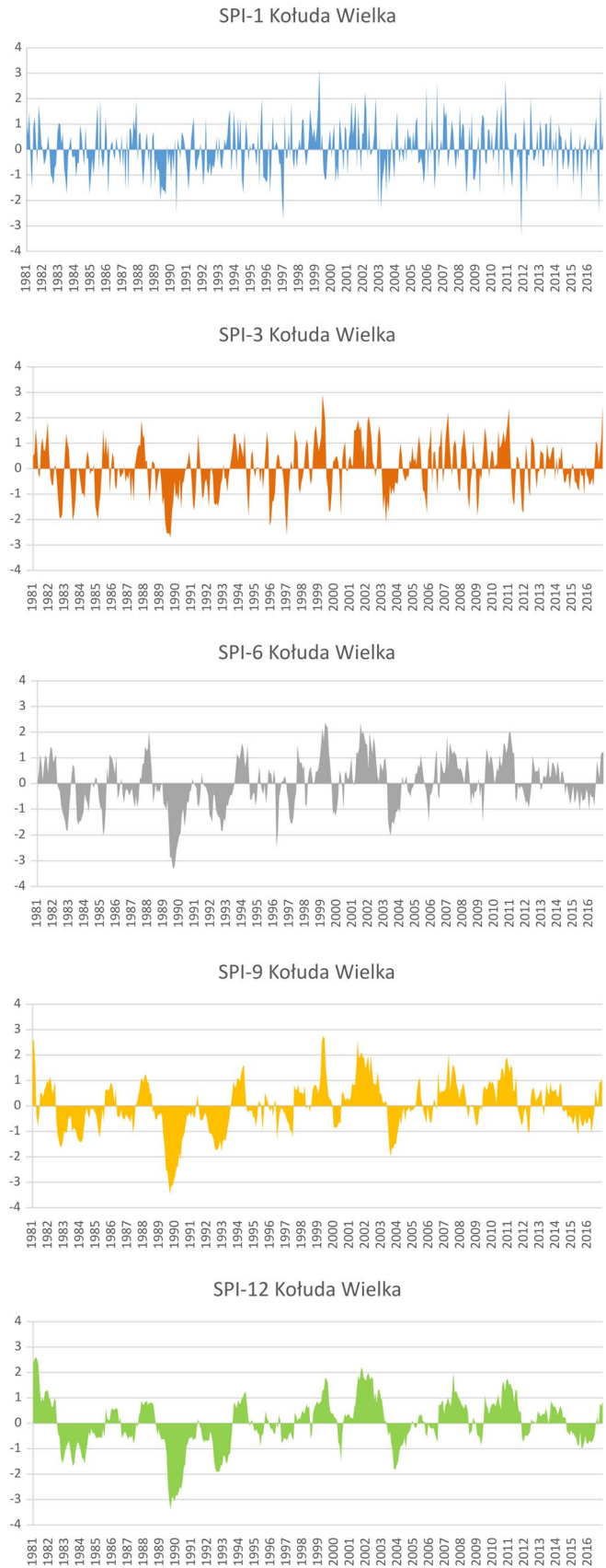


Fig. 5 Distribution of SPI values in the different accumulation periods (1, 3, 6, 9 and 12 months) between 1981 and 2016

Fig. 6 Course of meteorological droughts at the Kołuda Wielka meteorological station in the years 1981–2016 in various accumulation periods ($n = 1, 3, 6, 9$ and 12)



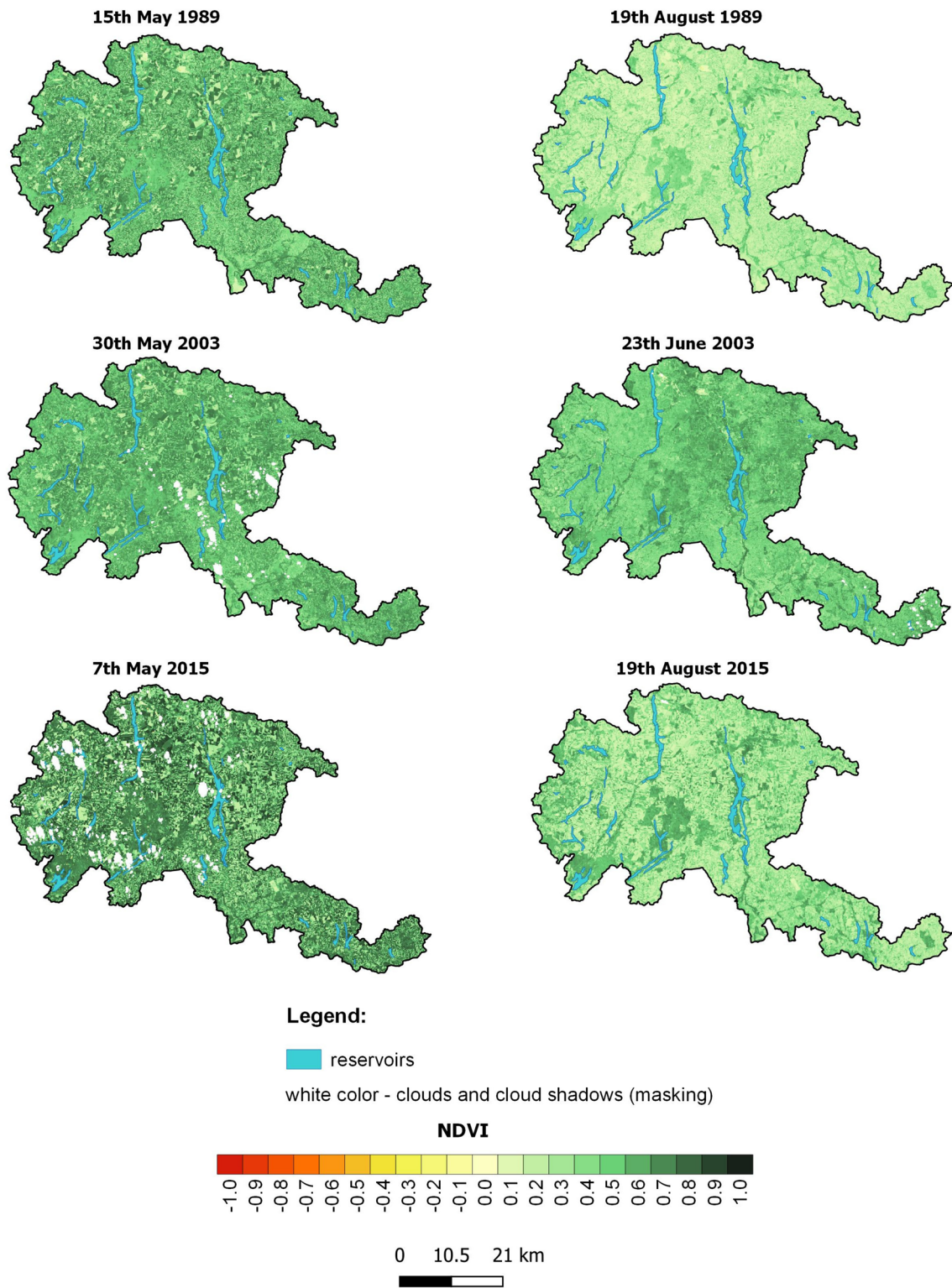


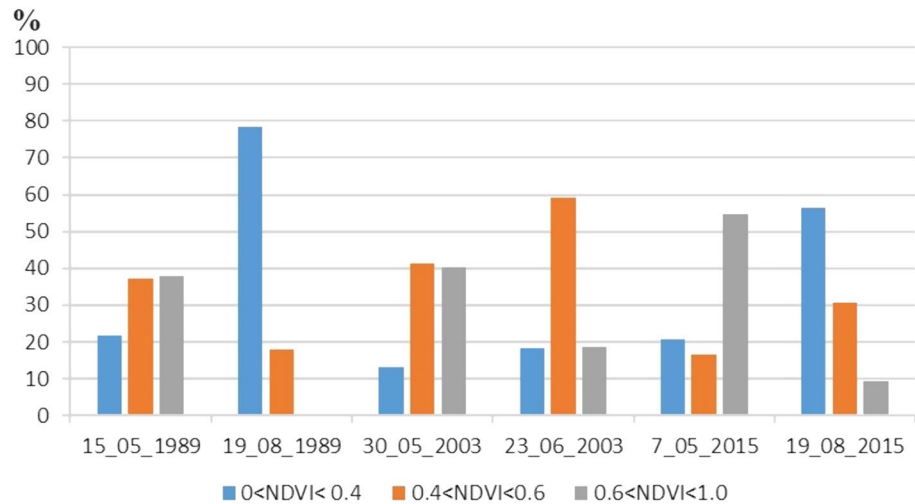
Fig. 7 Spatial variation of NDVI values

use of a bivariate choropleth map in the study by Sahana et al. (2021) about drought.

In this paper the bivariate choropleth map helped spatially define the co-occurrence of dry, normal, and wet conditions

from a meteorological point of view and the condition of the vegetation, divided into the following classes:

Fig. 8 Areas occupied by areas with given NDVI values at various dates in %



- Class 1 for dry-dry conditions: $SPI \leq -1.0$ and $NDVI$ 0–0.40.
- Class 2 defining normal-normal conditions: $SPI > -1.0$ and $SPI < 1.0$ and $NDVI$ from 0.4 to 0.60.
- Class 3 for wet-wet conditions: $SPI > 1.0$ and $NDVI$ 0.6–1.0

The construction of the bivariate choropleth map legend for the research conducted in this paper is shown in Fig. 4.

The co-occurrence analysis stage required the following essential preparatory steps so that the above bivariate choropleth map construction could be applied:

1. Creating raster layers representing the spatial variation of the SPI using inverse distance weighting (IDW) spatial interpolation.
2. Reclassifying raster layers representing the spatial variation of the SPI based on the division into classes representing wet, normal, and drought conditions.
3. Reclassifying the raster layer representing the spatial variation of the NDVI based on the division into classes representing wet, normal, and drought conditions.

The above activities were carried out using QGIS ver. 3.10.9 and QGIS ver. 3.10.9 with GRASS ver. 7.8.3. In addition GIMP ver. 2.10.18 and Inkscape ver. 1.0.1 were used to prepare the graphics. Also maps were made using mentioned softwares (without Inkscape ver. 1.0.1).

All maps in the paper are own elaboration and were elaborated in the coordinate system: WGS 84/UTM zone 34N. Figure 1: (a) was made with Natural Earth (2021) and Wektorowe warstwy tematyczne aPGW (2021); (b) was made with Wektorowe warstwy tematyczne aPGW (2021), Corine Land Cover (2021), Hydro IMGW-PIB (2021), QGIS Quick Map Services Plugin: OSM Standard (2021). Meteorological station Izbica Kujawska is out of catchment area according

to Table 1. Location of the hydrological station Pakość is caused by map symbol issues (Fig. 1).

Figures 7, 9, 10, 11, 12 and 13 were made with Wektorowe warstwy tematyczne aPGW (2021), Baza Danych Obiektów Ogólnogeograficznych (2021) and based on Landsat Collection 1 Level-1 (2020).

Results

Meteorological droughts on the basis of the SPI

The SPI was calculated for five meteorological stations located in the upper Noteć River catchment in different accumulation periods (1, 3, 6, 9 and 12 months) from 1981 to 2016. The highest amplitude of SPI values was recorded in a one-month period at the station in Sompolno (from -3.50 to 3.25). Over a longer accumulation period, the SPI range decreased, reaching its lowest amplitude in the 12-month period, which was recorded in Pakość (from -2.69 to 2.12). The range of SPI values in the analysed multi-year period is shown in Fig. 5.

The course of monthly SPI values at different time scales is similar at all five meteorological stations in the analysed multi-year period. This confirms that meteorological droughts which occurred at the station at Kołuda Wielka were also recorded at other meteorological stations in the upper Noteć catchment area. The correlation coefficient between SPIs cross-calculated for the five meteorological stations ranged from 0.81 to 0.92. The highest correlations were recorded between stations located in close vicinity, e.g. in the northern (Kołuda Wielka, Pakość) or southern part of the catchment area (Izbica Kujawska and Sompolno). Smaller correlations were found between stations that were further apart.

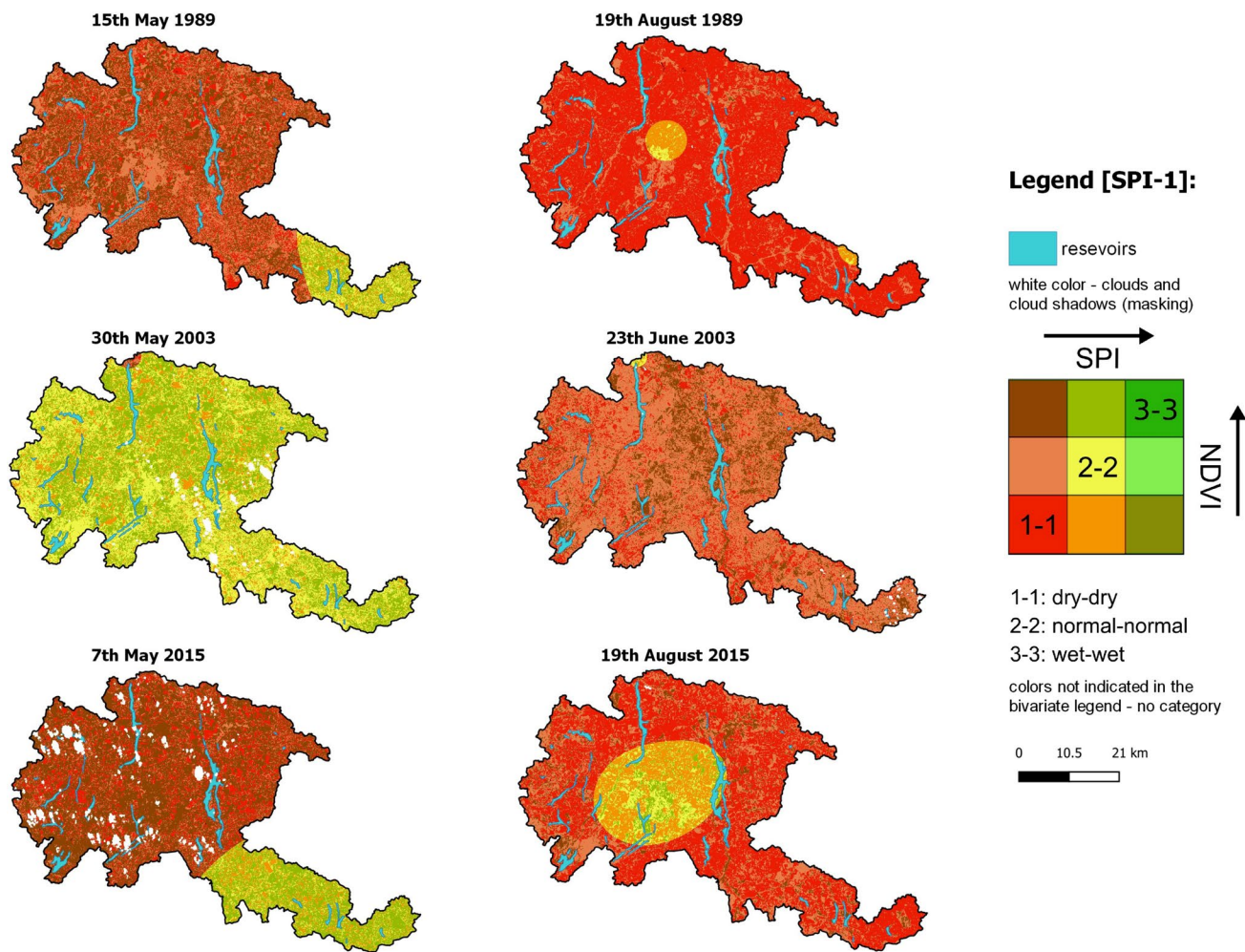


Fig. 9 Co-occurrence of meteorological drought (SPI-1) and vegetation condition (NDVI)

Figure 6 shows the course of SPI values in accumulation periods of 1, 3, 6, 9 and 12 months in the years 1981–2016 for the station at Kołuda Wielka. Depending on the accumulation period adopted, SPI values there ranged from 3.16 to –3.47. The lowest value among the adopted accumulation periods was recorded for the 1-month period (–3.43) in November 2011. Over longer periods of accumulation, the lowest values of the SPI in the Kołuda Wielka were recorded in September 1989 and were associated with an extreme meteorological drought that lasted from May to September. The 1989 drought also occurred at the other meteorological stations. The strongest and at the same time the longest-lasting drought was recorded at the stations in Kołuda Wielka and Strzelno.

During the analysed period of 1981–2016, the largest droughts occurred in 1989, 2003, 2011, 2012, and 2015. All SPI values (below –1.0) were grouped by drought class and then the percentage contribution to the time series was calculated (Fig. 6). The total number of months with SPI values

below –1.0 ranged from 25 to 38, accounting for between 11.6 and 17.6% of all months in the growing season during the analysed period. Normal-class droughts accounted for the largest percentage, with SPI values ranging from 28.3 to 34.3% of all months over the entire period. The smallest percentage was taken by extreme droughts that lasted from 9 to 20 months (i.e. from 1.7 to 3.7% over all analysed months). The longest extreme meteorological drought (3.7%) was detected for SPI-6. The predominant SPI values in the growing season months (April–September) were between –1.0 and 1.0 (normal). They accounted on average for 70% of the length of the growing season in the studied multi-year period.

Spatial variation of the NDVI

The analysis of areas occupied by individual classes of NDVI values indicates that the largest area occupied by vegetation in poor condition (NDVI < 0.4) was recorded on

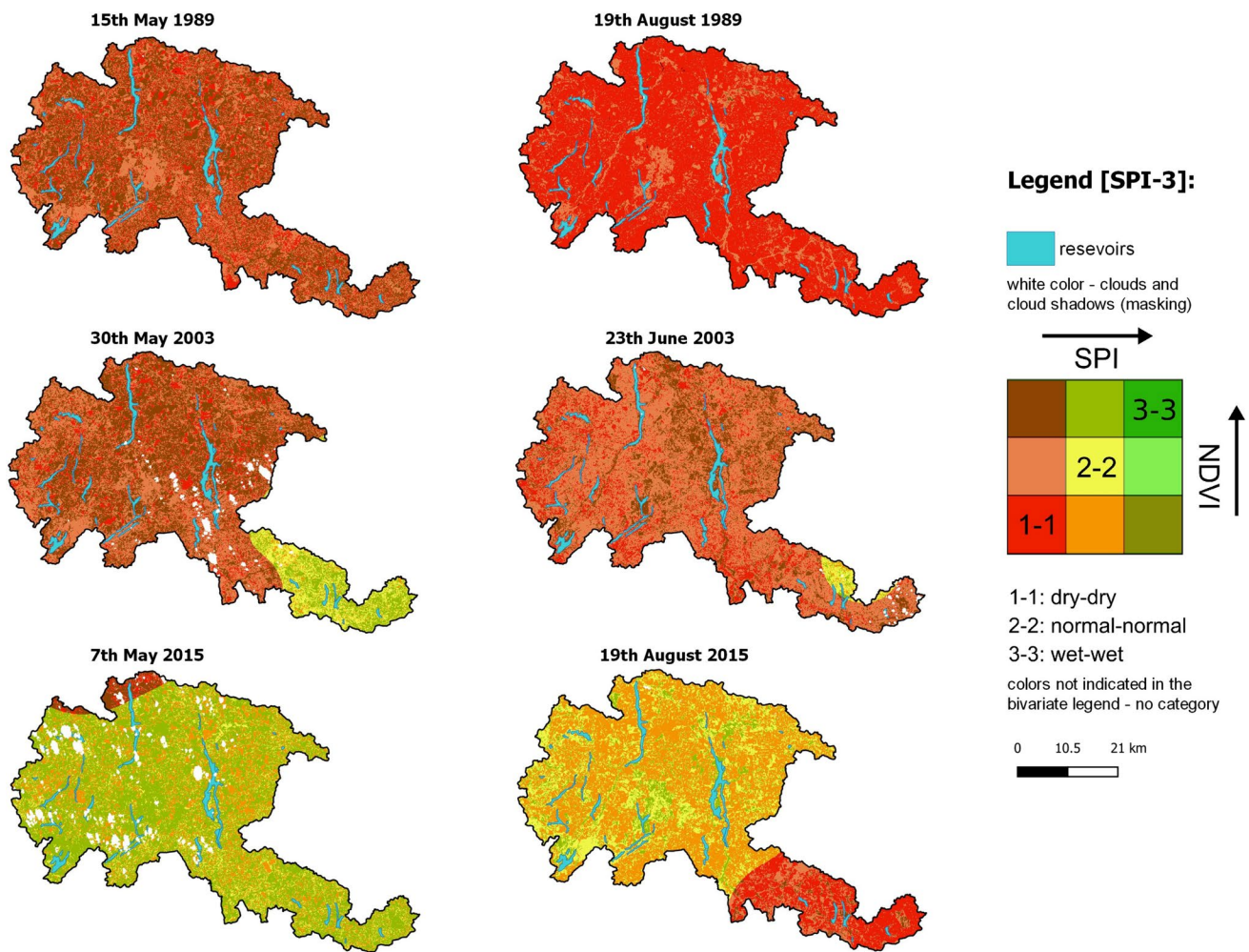


Fig. 10 Co-occurrence of meteorological drought (SPI-3) and vegetation condition (NDVI)

19 August 1989, when drought covered as much as 78.2% of the area in question (Fig. 8). During the spring period, i.e. on 15 May 1989, dry areas accounted for only 21.6% of the study area. A slightly smaller area compared to 19 August 1989 was occupied by drought on 19 August 2015 (56.5%), despite the fact that in the spring period (7 May 2015) the dry area was similar to that of 1989 at 20.7%. Dry areas ($NDVI < 0.4$) in 2003 in May and June were 13.0% and 18.2% of the analysed area, respectively. The absence of a satellite scene from August 2003 prevented us from determining whether the space occupied by dry areas was similar to that of 1989 or 2015. The 1989 results are related to a prolonged and intense meteorological drought (Fig. 6). The impact of the meteorological droughts of 2003 and 2015 on vegetation condition was less pronounced (Fig. 7). These droughts were shorter and less intense (Fig. 8).

Co-occurrence of meteorological drought (SPI) and vegetation condition (NDVI)

The visualisations obtained by the bivariate choropleth map method (Figs. 9, 10, 11, 12, and 13) indicate that the most uniform areas of spatial co-occurrence of SPI meteorological drought with NDVI drought occurred on 19 August 1989 (for all SPI accumulation periods). A similar feature of the uniformity of drought co-occurrence areas can be observed for 19 August 2015, except that for accumulation periods of 3, 6, and 9 months it is mainly the area of the South-Eastern and Eastern part of the analysed catchment (for accumulation periods of 6 and 9 months it also covers a small fragment in the vicinity of the Pakość station).

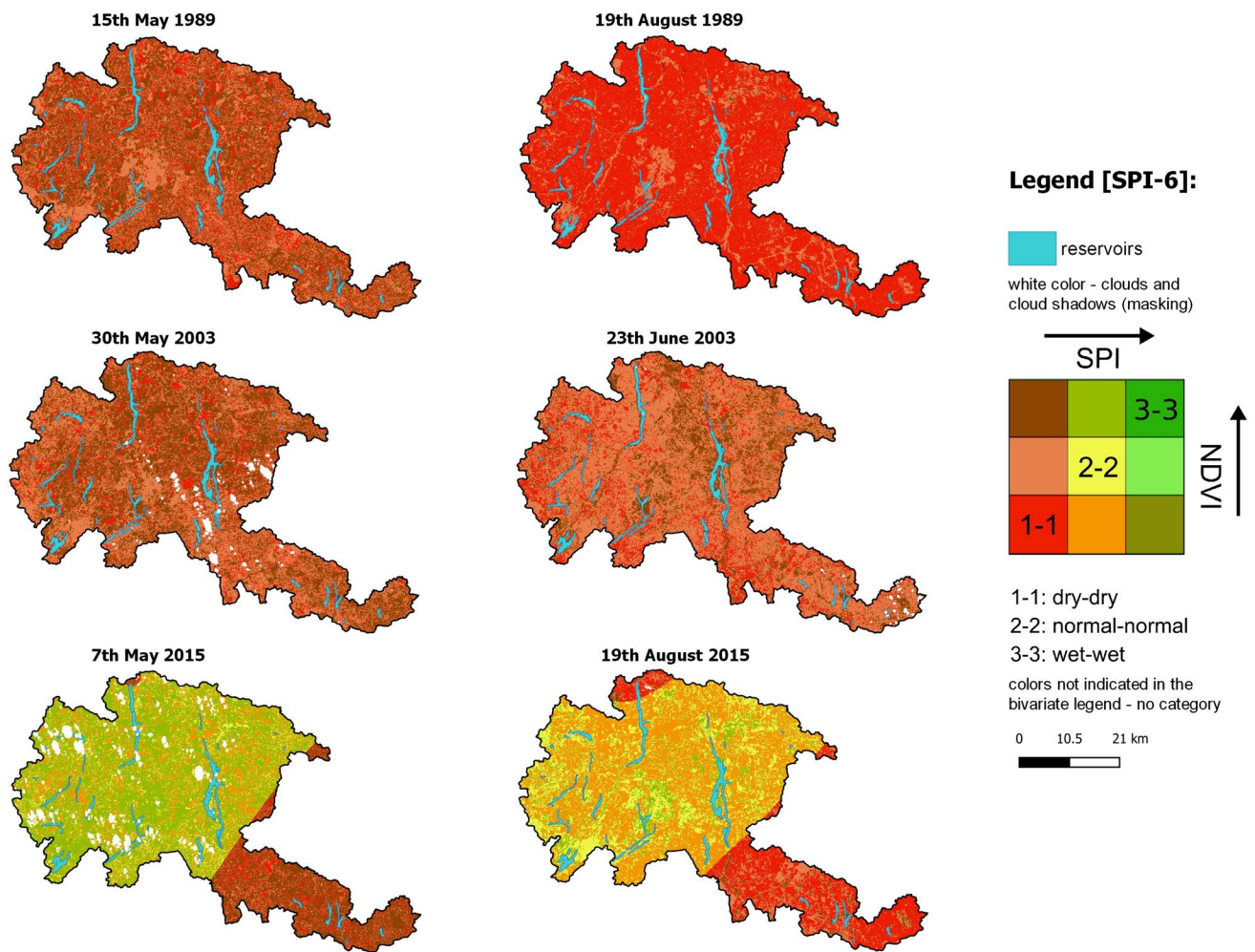


Fig. 11 Co-occurrence of meteorological drought (SPI-6) and vegetation condition (NDVI)

The obtained visualisations highlighted the fact that the area of co-occurrence of SPI meteorological drought SPI with NDVI drought for individual days representing May varied in range and was internally fragmented (granular). The variable co-occurrence and non-co-occurrence of droughts in the south-eastern part of the study area can also be observed. In addition, the visualisations highlighted the particular intensity and duration of the 1989 SPI meteorological drought and its spatial co-occurrence with the NDVI drought.

Droughts did not spatially co-occur (over the whole catchment area) on 30 May 2003 for the 9- and 12-month accumulation periods, on 15 May 1989 for the 12-month accumulation period, and on 23 June 2003 for the 12-month accumulation period. The same was true for the 1-month accumulation period on 30 May 2003 and for the 3-month

accumulation period on 7 May 2015, except for small parts of the northern catchment area.

Discussion

The methodology of calculating the SPI index is extremely simple, and the results are obtained in absolute values, which enables the comparison of droughts in different climatic regions (Kubiak-Wójcicka and Juśkiewicz 2020). In addition, SPI uses 1 parameter, which is the monthly sums of precipitation performed in situ. Its application could give reliable results, but is limited by the sparse network of gauge stations measuring the necessary meteorological parameters.

A solution to this situation is to use remote sensing indicators, e.g. the NDVI. In contrast to the SPI, the NDVI has the advantage of representing the drought phenomenon for

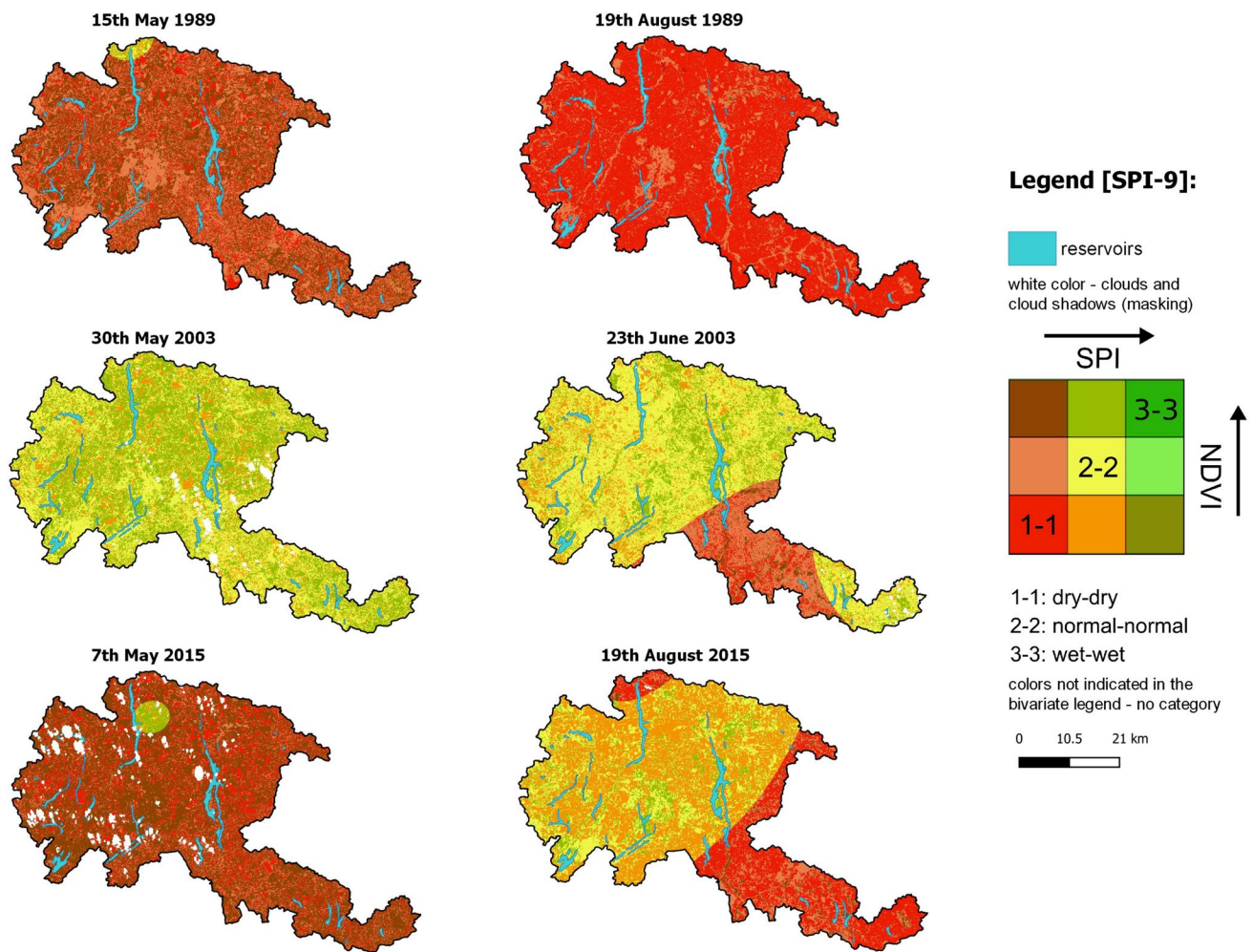


Fig. 12 Co-occurrence of meteorological drought (SPI-9) and vegetation condition (NDVI)

the whole area, and not only in individual meteorological stations. Remotely sensed vegetation condition allows for near real-time drought monitoring to help decision-makers assess local drought and take mitigating actions, without many of the limitations of more traditional drought monitoring methods (Mu et al. 2013). According to different authors, the NDVI has its limitations, such as: reaching the maximum NDVI value before plants reach maximum biomass, breaks in data continuity related to the number of cloudless sky days, and the short period of satellite observations (Tucker 1979; Pinzon and Tucker 2014). It can be concluded that the NDVI can be used to assess drought severity and crop damage, but seasonality should be taken into account (Ji and Peters 2003). The index should be used together with other indicators identifying drought e.g. standardised precipitation evaporation index, palmer drought severity index the climatic water balance. The NDVI was also applied in temperate areas in the Eastern Baltic Sea region. According

to Rimkus et al. (2017), maximum NDVI values are reached in June and July. The value of the NDVI begins to fall in August. This is due to the fact that crops are dominated by annual species that have a short vegetation cycle, with crops being harvested as early as August and September. There is a clear relationship between the NDVI value and the growing season and crop type. The simultaneous use of different methods to assess drought severity should overcome the disadvantages of using only one indicator. However, studies carried out for the upper Noteć River indicate that the inclusion of the SPI and the NDVI in a single test procedure for drought assessment in combination with vegetation condition did not yield clear results. Only in the case of prolonged and intense droughts (e.g. 1989) was the co-occurrence of meteorological drought with poor vegetation condition evident. For the short-lived but intense meteorological droughts recorded in 2003 and 2015 in the upper Noteć catchment such co-occurrence was not observed. The state of vegetation development is strongly associated with the onset of the

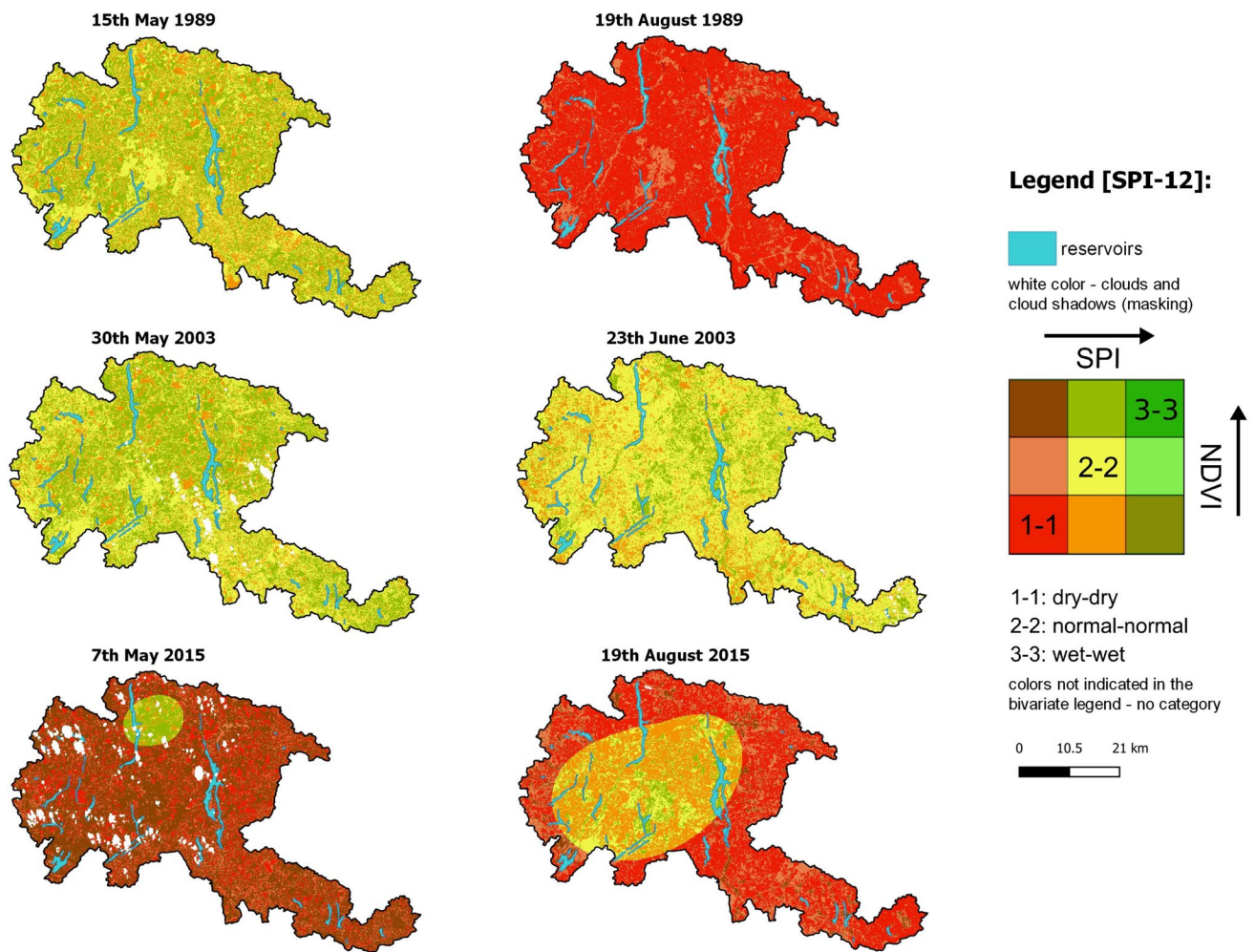


Fig. 13 Co-occurrence of meteorological drought (SPI-12) and vegetation condition (NDVI)

meteorological growing season (mean daily air temperature greater than or equal to 5.0 °C) (Jones and Briffa 1995). Due to climate change, the onset of vegetation starts earlier and the growing season lasts longer (Tomczyk and Szyga-Pluta 2017). It should be mentioned that due to the early start, the peak of vegetation is usually also reached earlier, and an early start of vegetation does not always lead to an increase in above-ground production (Livensperger et al. 2016). These phenomena make it difficult to simply correlate results obtained from indicator and remote sensing methods when analysing longer time series. On the other hand, by means of a bivariate choropleth map, we are able to combine the results obtained from the SPI and NDVI methods into one cartographic image (the analysis of spatial co-occurrence). The obtained image makes it possible to supplement the information on the occurrence of the drought phenomenon in areas diversified in terms of relief and land use, where

in situ meteorological observations are not carried out. Therefore, future research directions should focus on the correlations of SPI with other remote sensing or pedological indices (Secu et al. 2022; Ngo et al. 2022).

Conclusion

Based on the analysis of the bivariate choropleth map, the co-occurrence of meteorological drought with drought defined on the basis of the NDVI was demonstrated. However, the results obtained are not conclusive. NDVI values do not easily reflect meteorological drought. Results may be misinterpreted due the timing of the measurements, among other things. At the early vegetation stage (May–June), NDVI values obtained in temperate climates are overestimated with respect to meteorological drought.

On the other hand, in the late growing season NDVI values are underestimated compared to meteorological drought. The main reason for this phenomenon is the biology of the species grown (cereals) and the cycle of agricultural work (harvesting and ploughing that expose the soil). Differences in spectral reflectance between different crop types constitute an additional factor contributing to erroneous readings of NDVI values. This is related to the different degree of ground cover by the crops grown. A precise correlation between SPI and NDVI values is also difficult to obtain due to the different timing of the start of the growing season ($T > 5\text{ }^{\circ}\text{C}$), which varies from year to year in temperate climates. A proper assessment of vegetation condition would require the application of corrections to take account of crop structure. Finding a correlation between meteorological drought and vegetation condition probably requires that other meteorological factors, mainly temperature, are also included in the analysis.

The result of the analyses carried out is that the NDVI is not suitable for use as an independent, simple, fast and remote (no field visit required) method of estimating agricultural losses related to drought. However, the proposed procedure for assessing drought occurrence based on the analysis of spatial co-occurrence of drought defined on the basis of NDVI and SPI indices makes it possible to eliminate some of the errors in assessing drought occurrence resulting from the use of these indices separately.

Funding The authors received no specific funding for this work.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent to participate All authors gave explicit consent to participate in this study.

Consent for publication All authors gave explicit consent to publish this manuscript.

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References

- AghaKouchak A, Farahmand A, Melton FS, Teixeira J, Anderson MC, Wardlow BD, Hain CR (2015) Remote sensing of drought: progress, challenges and opportunities. *Rev Geophys* 53:452–480. <https://doi.org/10.1002/2014RG000456>
- Bąk B (2003) Warunki klimatyczne Wielkopolski i Kujaw [climatic conditions of Wielkopolska and Kujawy]. *Water Environ Rural Areas* 3(9):11–38
- Bąk B, Kubiak-Wójcicka K (2017) Impact of meteorological drought on hydrological drought in Toruń (Central Poland) in the period of 1971–2015. *J Water Land Dev* 32(1):3–12. <https://doi.org/10.1515/jwld-2017-0001>
- Baza Danych Obiektów Ogólnogeograficznych (2021). https://mapy.geoportal.gov.pl/imap/Imgp_2.html?locale=pl&gui=new&sessionId=5160004. Accessed 15 July 2021
- Burka A, Biazin B, Bewket W (2023) Drought characterization using different indices, theory of run and trend analysis in Bilate River watershed, rift valley of Ethiopia. *Front Environ Sci* 11:1098113. <https://doi.org/10.3389/fenvs.2023.1098113>
- Chakraborty L, Thistlethwaite J, Minano A, Henstra D, Scott D (2021) Leveraging hazard, exposure, and social vulnerability data to assess flood risk to indigenous communities in Canada. *Int J Disaster Risk Sci* 12(6):821–838. <https://doi.org/10.1007/s13753-021-00383-1>
- Chen Z, Wang W, Fu J (2020) Vegetation response to precipitation anomalies under different climatic and biogeographical conditions in China. *Sci Rep* 10:830. <https://doi.org/10.1038/s41598-020-57910-1>
- Congedo L (2021) Semi-automatic classification plugin: a Python tool for the download and processing of remote sensing images in QGIS. *J Open Source Softw* 6(64):3172
- Corine Land Cover (2021) Raster data retrieved from: <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download>. Accessed 3 Jan 2021. ©European Union, Copernicus Land Monitoring Service 2021, European Environment Agency (EEA)
- Dąbrowska-Zielińska K, Ciołkosz A, Malińska A, Bartold M (2011) Monitoring of agricultural drought in Poland using data derived from environmental satellite images. *Geoinf Issues* 3:87–97. <https://doi.org/10.34867/gi.2011.7>
- Di Bella CM, Paruelos JM, Becerra JE, Bacour C, Baret F (2004) Effect of senescent leaves on NDVI based estimates of FAPAR: experimental and modelling evidences. *Int J Remote Sens* 25(23):5415–5427
- Doroszewski A, Jadczyński J, Kozyra J, Pudełko R, Stuczyński T, Mizak K, Łopaska A, Koza P, Górski T, Wróblewska E (2012) Podstawy systemu monitoringu suszy rolniczej. *Water Environ Rural Areas* 12(2):77–91
- EarthExplorer (2020). <https://earthexplorer.usgs.gov/>. Accessed Dec 2020
- Giaquinto D, Marzocchi W, Kurth J (2023) Exploring meteorological droughts' spatial patterns across Europe through complex network theory. *Nonlinear Process Geophys* 30:167–181. <https://doi.org/10.5194/npg-30-167-2023>
- Graczyk D, Kundzewicz ZW (2016) Changes of temperature-related agroclimatic indices in Poland. *Theor Appl Climatol* 124:401–410. <https://doi.org/10.1007/s00704-015-1429-7>
- Griffith JA, Martinko EA, Whistler JL, Price KP (2002) Interrelationships among landscapes, NDVI, and stream water quality in the U.S. Central Plains. *Ecol Appl* 12(6):1702–1718
- Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvayev VN (2005) Trends in intense precipitation in the climate record. *J Clim* 18(9):1326–1350. <https://doi.org/10.1175/JCLI3339.1>

- Hanel M, Rakovec O, Markonis Y, Máca P, Samaniego L, Kyselý J, Kumar R (2018) Revisiting the recent European droughts from a long-term perspective. *Sci Rep* 8:9499. <https://doi.org/10.1038/s41598-018-27464-4>
- Hannaford J, Buys G, Stahl K, Tallaksen LM (2013) The influence of decadal-scale variability on trends in long European streamflow records. *Hydrol Earth Syst Sci* 17:2717–2733. <https://doi.org/10.5194/hess-17-2717-2013>
- Huang YF, Ng JL, Fung KF, Weng TK, Dahoul NA, Ahmed AN, Sherif M, Chaplot B, Chong KL, Elshafie A (2023) Space–time heterogeneity of drought characteristics in Sabah and Sarawak, East Malaysia: implications for developing effective drought monitoring and mitigation strategies. *Appl Water Sci* 13:205. <https://doi.org/10.1007/s13201-023-01989-0>
- Hydro IMGW-PIB (2021). <https://hydro.imgw.pl/#map/19.5,51.5,7,true,true,0>. Accessed 13 and 15 July 2021
- Jamorska I, Kubiak-Wójcicka K, Krawiec A (2019) Dynamics of the status of groundwater in the Polish Lowland: the River Gwda catchment example. *Geologos* 25(3):193–204. <https://doi.org/10.2478/logos-2019-0021>
- Jarocińska A, Zagajewski B (2008) Korelacje naziemnych i lotniczych teledetekcyjnych wskaźników roślinności dla zlewni Bystrzanki. *Teledetekcja Śr* 40:100–124
- Ji L, Peters AJ (2003) Assessing vegetation response to drought in the Northern Great Plains using vegetation and drought indices. *Remote Sens Environ* 87:85–98
- Jones PD, Briffa KR (1995) Growing season temperatures over the former Soviet Union. *Int J Climatol* 15(9):943–959. <https://doi.org/10.1002/joc.3370150902>
- Karamuz E, Bogdanowicz E, Senbeta TB, Napiórkowski JJ, Romanowicz RJ (2021) Is it a drought or only a fluctuation in precipitation patterns? Drought reconnaissance in Poland. *Water* 13:807. <https://doi.org/10.3390/w13060807>
- Kchouk S, Melsen LA, Walker DW, van Oel PR (2021) A review of drought indices: predominance of drivers over impacts and the importance of local context. *Nat Hazard Earth Syst Sci*. <https://doi.org/10.5194/nhess-2021-152>
- Kobrossi J, Karam F, Mitri G (2021) Rain pattern analysis using the standardized precipitation index for long-term drought characterization in Lebanon. *Arab J Geosci* 14:44. <https://doi.org/10.1007/s12517-020-06387-3>
- Kozieł Z (1993) Barwny kartogram złożony jako metoda badań i prezentacji wybranych zjawisk geograficznych. Uniwersytet Mikołaja Kopernika, Toruń
- Kubiak-Wójcicka K (2019) Dynamics of meteorological and hydrological droughts in the agricultural catchments. In: Research for rural development, annual 25th international scientific conference: proceedings, vol 1, pp 111–117. <https://doi.org/10.22616/rrd.25.2019.017>
- Kubiak-Wójcicka K (2020) Variability of air temperature, precipitation and outflows in the Vistula basin (Poland). *Resources* 9:103. <https://doi.org/10.3390/resources9090103>
- Kubiak-Wójcicka K (2021) Assessment of water resources in Poland. In: Zelenáková M, Kubiak-Wójcicka K, Negm AM (eds) Quality in water resources in Poland. Springer International Publishing, Cham, pp 15–34. https://doi.org/10.1007/978-3-030-64892-3_2
- Kubiak-Wójcicka K, Bąk B (2018) Monitoring of meteorological and hydrological droughts in the Vistula basin (Poland). *Environ Monit Assess* 190:691. <https://doi.org/10.1007/s10661-018-7058-8>
- Kubiak-Wójcicka K, Juśkiewicz W (2020) Relationships between meteorological and hydrological drought in a young-glacial zone based on standardised precipitations index (SPI) and standardised runoff index (SRI). *Acta Montan Slovaca* 25(4):517–531. <https://doi.org/10.46544/AMS.v2514.07>
- Kubiak-Wójcicka K, Machula S (2020) Influence of climate changes on the state of water resources in Poland and their usage. *Geosciences* 10:312. <https://doi.org/10.3390/geosciences10080312>
- Kubiak-Wójcicka K, Nagy P, Zeleňáková M, Hlavatá H, Abd-Elhamid HF (2021a) Identification of extreme weather events using meteorological and hydrological indicators in the Laborec River catchment, Slovakia. *Water* 13:1413. <https://doi.org/10.3390/w13101413>
- Kubiak-Wójcicka K, Pilarska A, Kamiński D (2021b) The analysis of long-term trends in the meteorological and hydrological drought occurrences using non-parametric methods—case study of the catchment of the upper Noteć River (Central Poland). *Atmosphere* 12:1098. <https://doi.org/10.3390/atmos12091098>
- Landsat Collection 1 Level-1 (2020). <https://earthexplorer.usgs.gov/>. Accessed Dec 2020. Landsat 4–5 TM DOI: <https://doi.org/10.5066/F7N015TQ>, Landsat 7 ETM+ DOI: <https://doi.org/10.5066/F7WH2P8G>, Landsat 8 OLI/TIRS 436 DOI: <https://doi.org/10.5066/F71835S6>
- Leonowicz AM (2006) Kartogram jako forma prezentacji zależności zjawisk geograficznych. *Prace Geograficzne PAN IGIpZ*, 206, Warszawa
- Livensperger C, Steltzer H, Darrouzet-Nardi A, Sullivan PF, Wallenstein M, Weintraub MN (2016) Experimentally warmer and drier conditions in an Arctic plant community reveal microclimatic controls on senescence. *Ecosphere* 10(4):e02677. <https://doi.org/10.1002/ecs2.2677>
- Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. *Int J Climatol* 22:1571–1592. <https://doi.org/10.1002/joc.846>
- Lorenz H (2005) Atlas klimatu Polski. IMGW, Warszawa
- Lu L, Shen X, Cao R (2021) Elevational movement of vegetation greenness on the Tibetan Plateau: evidence from the landsat satellite observations during the last three decades. *Atmosphere* 12:161. <https://doi.org/10.3390/atmos12020161>
- Mahdavi P, Kharazi HG, Eslami H, Zohrabi N, Razaz M (2021) Drought occurrence under future climate change scenarios in the Zard River Basin, Iran. *Water Supply* 21(2):899–917. <https://doi.org/10.2166/ws.2020.367>
- McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. Preprints of the 9th conference of applied climatology, 1995, Dallas, pp 233–236
- Minea I, Iosub M, Boicu D (2022) Multi-scale approach for different type of drought in temperate climatic conditions. *Nat Hazards* 110:1153–1177. <https://doi.org/10.1007/s11069-021-04985-2>
- Mu Q, Zhao M, Kimball JS, McDowell NG, Running SW (2013) A remotely sensed global terrestrial drought severity index. *Am Meteorol Soc* 94(1):83–98. <https://doi.org/10.1175/BAMS-D-11-00213.1>
- Nalbantis I, Tsakiris G (2009) Assessment of hydrological drought revisited. *Water Resour Manag* 23:881–897. <https://doi.org/10.1007/s11269-008-9305-1>
- Natural Earth (2021). <https://www.naturalearthdata.com/downloads/10m-cultural-vectors> and <https://www.naturalearthdata.com/downloads/10m-raster-data>. Accessed 28 Jan 2021. 6–7 Feb 2021
- Ngo HL, Nguyen HD, Loubiere P, Tran TV, Şerban G, Zelenakova M, Breţcan P, Laffly D (2022) The composition of time-series images and using the technique SMOTE ENN for balancing datasets in land use/cover mapping. *Acta Montan Slovaca* 27(2):342–359. <https://doi.org/10.46544/AMS.v27i2.05>
- Notaro M, Liu Z, Gallimore RG, Williams JW, Gutzler DS, Collins S (2010) Complex seasonal cycle of ecohydrology in the South-west United States. *J Geophys Res* 115:G04034. <https://doi.org/10.1029/2010JG001382>
- Ozkaya A, Zerberg Y (2019) A 40-year analysis of the hydrological drought index for the Tigris Basin, Turkey. *Water* 11(4):657. <https://doi.org/10.3390/w11040657>

- Peters AJ, Walter-Shea EA, Ji L, Vina A, Hayes M, Svoboda MD (2002) Drought monitoring with ndvi-based standardized vegetation index. *Photogramm Eng Remote Sens* 68:71–75
- Pinzon JE, Tucker CJ (2014) A non-stationary 1981–2012 AVHRR NDVI_{3g} time series. *Remote Sens* 6:6929–6960. <https://doi.org/10.3390/rs6086929>
- QGIS Quick Map Services Plugin: OSM Standard (2021) Plugin was used on 13 and 15 July 2021. Author of the plugin: NextGIS. Base map from: OpenStreetMap and OpenStreetMap Foundation. Detailed information about copyright and license of the OpenStreetMap is available online on: <https://www.openstreetmap.org/copyright>
- Rimkus E, Stonevicius E, Kilpys J, Maciulytė V, Valiukas D (2017) Drought identification in the Eastern Baltic region using NDVI. *Earth Syst Dyn Discuss* 8:627–637. <https://doi.org/10.5194/esd-2017-5>
- Rouse JW Jr, Haas RH, Schell JA, Deering DW (1973) Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation. *Prog. Rep. RSC 1978-1*, Remote Sensing Center, Texas A, M Univ., College Station, nr E73-106393, 93 (NTIS No. E73-106393). <https://ntrs.nasa.gov/api/citations/1973017588/downloads/19730017588.pdf>
- Sahana V, Mondal A, Sreekumar P (2021) Drought vulnerability and risk assessment in India: sensitivity analysis and comparison of aggregation techniques. *J Environ Manag* 299:113689. <https://doi.org/10.1016/j.jenvman.2021.113689>
- Salimi H, Asadi E, Darbandi S (2021) Meteorological and hydrological drought monitoring using several drought indices. *Appl Water Sci* 11:11. <https://doi.org/10.1007/s13201-020-01345-6>
- Secu CV, Stoleriu CC, Lesenciu CD, Ursu A (2022) Normalized Sand index for identification of bare sand areas in temperate climates using landsat images, application to the South of Romania. *Remote Sens* 14(15):3802. <https://doi.org/10.3390/rs14153802>
- Shukla S, Wood W (2008) Use of a standardised runoff index for characterizing hydrologic drought. *Geophys Res Lett* 35:L02405. <https://doi.org/10.1029/2007GL032487>
- Spinoni J, Barbosa P, Bucchignani E, Cassano J et al (2020) Future global meteorological hot spots: a study based Cordex data. *J Clim* 33(9):3635–3661. <https://doi.org/10.1175/JCLI-D-19-0084.1>
- SRTM 1 Arc-Second Global (2021). <https://doi.org/10.5066/F7PR7TFT>. Retrieved from: <https://earthexplorer.usgs.gov/>. Accessed 3 June 2021
- Stagge JH, Tallaksen LM, Gudmundsson L, Van Loon AF, Stahl K (2015) Candidate distributions for climatological drought indices (SPI and SPEI). *Int J Climatol* 35(13):4027–4040. <https://doi.org/10.1002/joc.4267>
- Stevens J (2021). <https://www.joshuastevens.net/cartography/make-a-bivariate490choropleth-map>. Accessed 2 June 2021
- Tigkas D, Vangelis H, Tsakiris G (2019) Drought characterisation based on an agriculture-oriented standardised precipitation index. *Theor Appl Climatol* 135:1435–1447. <https://doi.org/10.1007/s00704-018-2451-3>
- Tomaszewski E, Kubiak-Wójcicka K (2021) Low-flows in Polish Rivers. In: Zelenakova M, Kubiak-Wójcicka K, Negm AM (eds) *Management in water resources in Poland*. Springer, Cham, pp 205–228. https://doi.org/10.1007/978-3-030-61965-7_11
- Tomczyk A, Szyga-Pluta K (2017) The period of intense vegetation growth and maturing of plants in north-western Poland. *Badania Fizjograficzne, Seria A, Geografia Fizyczna* A68:223–232. <https://repozytorium.amu.edu.pl/server/api/core/bitstreams/bdc302a4-85d6-4cb6-b475-a5b96637ef46/content>
- Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens Environ* 8:127–150
- U.S. Geological Survey: Landsat Collection 1 Level-1 Quality Assessment Band (2020). <https://www.usgs.gov/core-science-systems/nli/landsat/landsat-collection-1-level-1-quality-assessment-band>. Accessed Dec 2020
- U.S. Geological Survey: Landsat Normalized Difference Vegetation Index (2020) https://www.usgs.gov/core-science-systems/nli/landsat/landsat-normalized-difference-vegetation-index?qt-science_support_page_related_con=0#qt502science_support_page_related_con. Accessed Dec 2020
- Van Loon AF (2015) Hydrological drought explained. *WIREs Water* 2:359–392
- Vittal H, Karmakar S, Ghosh S, Murtugudde R (2020) A comprehensive India-wide social vulnerability analysis: highlighting its influence on hydro-climatic risk. *Environ Res Lett* 15(1):014005. <https://doi.org/10.1088/1748-9326/ab6499>
- Vreugdenhil M, Greimeister-Pfeil I, Preimesberger W, Camici S, Dorigo W, Enenkel M, van der Schalie R, Steele-Dunne S, Wagner W (2022) Microwave remote sensing for agricultural drought monitoring: recent developments and challenges. *Front Water* 4:1045451. <https://doi.org/10.3389/frwa.2022.1045451>
- Wang J, Rich PM, Price KP, Kettle WD (2004) Relations between NDVI and tree productivity in the central Great Plains. *Int J Remote Sens* 25(16):3127–3138. <https://doi.org/10.1080/0143116032000160499>
- Wektorowe warstwy tematyczne aPGW (2021) Retrieved from: <https://dane.gov.pl/pl/dataset/599/resource/672,wektorowe-warstwy-tematyczne-apgw/table> [12 July 2021]. Data provider: Państwowe Gospodarstwo Wodne Wody Polskie. License link: <https://creativecommons.org/licenses/by/4.0/legalcode.pl>
- Wilhite DA, Glantz MH (2009) Understanding: the drought phenomenon: the role of definitions. *Water Int* 10:111–120
- World Meteorological Organization (WMO); Global Water Partnership (GWP) (2016) *Handbook of drought indicators and indices*. In: Svoboda M, Fuchs BA (eds) *Integrated drought management tools and guidelines series 2. Integrated Drought Management Programme (IDMP)*: Geneva, Switzerland
- Zhong F, Cheng Q, Wang P (2020) Meteorological drought, hydrological drought, and NDVI in the Heihe River Basin, Northwest China: evolution and propagation. *Hindawi Adv Meteorol* 2020(1):2409068. <https://doi.org/10.1155/2020/2409068>
- Zhu ZC, Piao SL, Myneni RB, Huang MT, Zeng ZZ, Canadell JG, Ciais P, Sitch S, Friedlingstein P, Arneeth A et al (2016) Greening of the earth and its drivers. *Nat Clim Change* 6:791–795. <https://doi.org/10.1038/nclimate3004>

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