

Meteorological and agricultural drought indices used in drought monitoring in Poland: a review

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Abstract: In the article, a brief review is presented of the definition of meteorological and agricultural droughts, drought indices and the operational systems of monitoring droughts in Poland. Drought is a widespread and frequent disaster which occurs more often within humid climate zones. Meteorological drought is the result of deficiencies in precipitation. Agricultural drought is an effect of various characteristics of meteorological and hydrological drought in agriculture comprising the reduction of evapotranspiration, soil water deficits, and reduced crop yield. Drought indicators are the common measures for drought assessment. The paper contains an inventory of drought measures (indicators) that are applied to evaluate meteorological and agricultural drought in Poland. For meteorological drought monitoring and the assessment of its intensity, four different indices have been used in Poland: relative precipitation index (*RPI*), effective drought index (*EDI*), standardised precipitation index (*SPI*) and climatic water balance (*CWB*). Agricultural drought is monitored by soil moisture index (*SMI*), agricultural drought index (*CDI*) and the potential reduction of final yield (yield reduction ratio *YR*). The working drought monitoring systems give information for the whole country or for a specific region but they are directed to some specific drought analyses. Four different drought monitoring systems have been under operation in Poland since 2005. The Institute of Meteorology and Water Management (IMGW) conducts the system called “POSUCH@”. The Institute of Soil Science and Plant Cultivation conducts the agricultural drought monitoring system. The Institute of Technology and Life Sciences (ITP) has developed two systems: the regional drought monitoring system in the Kujawy region and the nationwide system of monitoring and forecasting water deficit and surplus in agriculture.

Keywords: drought indices, meteorological drought, agricultural drought, monitoring, operational system

Submitted 20 March 2014, **revised** 21 November 2014, **accepted** 25 November 2014

1. Introduction

According to recent studies and investigations, droughts should be defined as a natural but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, and resulting in diminished water resources availability (Pereira et al. 2002; Paulo, Pereira 2006). Generally the definitions state that drought is due to the breakdown of the rainfall regime. Meteorological drought is most often expressed in terms of rainfall in relation to some average amount and the duration of the dry period and can be defined as a period with a lack of precipitation or with rainfall lower than average, lasting sufficiently to cause hydrological and agricultural hazards.

The negative effect of meteorological droughts is complex and can be observed in various branches of the national economy. It is particularly visible in agriculture. The effect in agriculture is differentiated and depends on the duration and intensity of meteorological drought before and during an agricultural drought. Droughts negatively affect crops, but the effect varies for various plants, soils

and geographic regions. A crop decrease is a final effect of agricultural drought and depends largely on the duration and intensity of the drought. Autumn and early spring droughts usually cause a decrease in winter crops while spring droughts cause a decrease in spring crops, the first hay cut and pasture efficiency. Summer droughts usually negatively affect potato crops, the second hay cut and field fodder crops.

Meteorological drought is expressed solely on the basis of the degree of dryness (usually related to the departure of rainfall from the average) and duration of a dry period. Agricultural drought links various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits etc. Any realistic definition of agricultural drought should account for the variable susceptibility of crops at different stages of crop development. Most commonly agricultural drought is defined as soil water deficit of a particular crop at a particular time period or moment, affecting crop yield and leading to a significant decline in crop yield.

The object of the paper is meteorological and agricultural drought defined in this way. The article reviews the measures for meteorological and agricultural drought used in drought monitoring systems operating in Poland.

2. Meteorological drought

Many indices and methods have been developed and are used to identify and determine the intensity of meteorological drought (Vogt, Somma 2000). Among them the standardised precipitation index *SPI* has received special attention in recent years since its introduction by McKee et al. (1993, 1995). It was applied to the analysis of regional droughts in Portugal (Paulo et al. 2002; Alfonso 2005; Paulo, Pereira 2006;), in Crete (Tsakiris, Vangelis 2004), in Sicily (Bonaccorso et al. 2003), in Hungary (Szalai, Szinell 2000; Szalai et al. 2000) and for the whole of Europe (Lloyd-Hughes, Saunders 2002). It is widely recommended as a very simple and objective measure of meteorological drought (Vermes 1998; Vermes et al. 2000; U.S. National Drought... 2014).

For meteorological drought monitoring and the assessment of its intensity four different indices have been used in Poland: relative precipitation index (*RPI*), effective drought index (*EDI*), standardised precipitation index (*SPI*) and climatic water balance (*CWB*). The *RPI*, *EDI* and *SPI* calculation is based on long-term (at least 30-year) precipitation records.

1. Relative Precipitation Index (*RPI*) is the ratio of precipitation sum for the given period P and the long-term average for the same period \bar{P} expressed in percent :

$$RPI = \frac{P}{\bar{P}} \cdot 100\% \quad (1)$$

According to Kaczorowska (1962) and Tomaszewska (1997) three classes of dry periods in terms of precipitation conditions are distinguished (Tab. 1).

Table 1. Classes of dry periods (according to Kaczorowska (1962), Tomaszewska (1994))

Period	Percent of the average in:	
	month	quarter, year
Extremely dry	0-24.9	0-49.9
Very dry	25.0-49.9	50.0-74.9
Dry	50.0-74.9	75.0-89.9
Average	75.0-125.9	90.0-110.9

2. Effective Drought Index (*EDI*) is a measure of precipitation needed for a return to normal conditions (To-

karczyk, Szalińska 2013). The concept of the *EDI* is a standardised daily difference between weighted precipitation accumulation over a defined preceding period and its multi-year mean value for each calendar day. It is calculated with a daily time step. *EDI* values are standardised, which allows for the comparison of drought severity at different locations regardless of climatic differences among them. The 2-category classification (Tab. 2) of dry periods is used in the drought monitoring system called "POSUCH@" conducted by the Institute of Meteorology and Water Management (IMGW) (<http://posucha.imgw.pl/>).

Table 2. Classification of *EDI* values and precipitation conditions, according to <http://posucha.imgw.pl/>

<i>EDI</i>	Precipitation conditions
(0.7 ÷ -0.7)	normal
[-0.7 ÷ -1.5]	dry
≤ -1.5	very dry

3. Standardised Precipitation Index (*SPI*) is a standardised deviation of precipitation in a particular period from the median long-term value of this period (McKee et al. 1993, 1995). *SPI* is calculated for each calendar month at 1-, 2-, 3-, 6-, 12-, 24-, 36- and 48-month time scales using long-term series of precipitation measurements at different meteorological stations all over the country. *SPI* values for periods longer than 1 month are calculated for moving totals of precipitation. For each month of the calendar year a new series is created with elements equal to corresponding precipitation moving sums. For example, the 3-month *SPI* calculated for June 2013 utilised the precipitation total of April 2013 through June 2013 in order to calculate the index. Likewise the 12-month *SPI* for June 2013 utilised the precipitation total for July 2012 through June 2013. Thus, *SPI* values describe meteorological drought at the end of a month, caused by a deviation of precipitation during 1-, 2-, 3-, 6-, 12-, 24-, 36- and 48-month time periods in relation to the median value (values with 50% probability).

SPI is calculated using the normalization method. Precipitation is a random variable with a lower limit and often positive asymmetry, and does not conform to the normal distribution. Most often periodical (10-day, monthly or annual) sums of precipitation conform to the gamma distribution and therefore the precipitation sequence is normalised with the transformation function $f(P)$:

$$f(P) = u = \sqrt[3]{x} \quad (2)$$

where: x – the element of precipitation sequence.

Values of the *SPI* for a given P are calculated from the equation:

$$SPI = \frac{f(P) - \bar{u}}{d_u} \quad (3)$$

where: SPI – standardised precipitation index, $f(P)$ – transformed sum of precipitation, \bar{u} – mean value of the normalised precipitation sequence, d_u – standard deviation of the normalised precipitation sequence.

The negative values of SPI are compared with the boundaries of different classes of drought. There are many classifications used by different authors. Originally McKee et al. (1993) distinguished 4 categories of drought: mild, moderate, severe and extreme, with the threshold value of SPI for the mild drought category equal to $SPI = 0$ (tab. 3). Agnew (2000) writes that in this classification all negative values of SPI are taken to indicate the occurrence of drought – this means that for 50% of the time, drought is in occurrence. He concluded that this was not rational and suggested alternative, more rational thresholds. According to Vermes (1998) three categories are proposed, with the first class starting at $SPI = -1$. The class of mild drought ($-1 < SPI < 0$) was aggregated with the slightly wet class ($0 \leq SPI \leq 1$) into the near normal class. Because of the great variability of precipitation in Poland, modification of SPI in the scope of the threshold of the moderate drought class was proposed (Łabędzki 2007). This was an attempt to apply this index to detect periods of mild drought, especially in shorter periods, e.g. months. According to this the threshold value of the first class of drought was changed to $SPI = -0.5$ (Tab. 4). Nowadays two classifications are used in Poland: the 3-category classification according to Łabędzki (2007) in the drought monitoring system called “POSUCH@” conducted by the Institute of Meteorology and Water Management (IMGW) (<http://posucha.imgw.pl>)

Table 3. Classification of the SPI values and meteorological drought category

SPI	Meteorological drought category according to	
	McKee (1993)	Vermes (1998)
0 to -0.99	mild drought	near normal
-1.00 to -1.49	moderate drought	moderate drought
-1.50 to -1.99	severe drought	severe drought
≤ -2.00	extreme drought	extreme drought

Table 4. Classification of SPI values and meteorological drought category, according to Łabędzki (2007)

SPI	Meteorological drought category
0.50 to -0.49	normal
-0.50 to -1.49	moderate drought
-1.50 to -1.99	severe drought
≤ -2.00	extreme drought

and the 4-category classification as shown in Table 5 used in the system of “Monitoring and forecasting water deficit and surplus in agriculture” (<http://agrometeo.itp.edu.pl>) conducted by the Institute of Technology and Life Sciences (ITP).

Table 5. Classification of SPI values and meteorological drought category used by ITP (www.agrometeo.itp.edu.pl)

SPI	Meteorological drought category
0.50 to -0.49	normal
-0.50 to -1.00	mild drought
-1.00 to -1.49	moderate drought
-1.50 to -1.99	severe drought
≤ -2.00	extreme drought

source: own study

4. Climatic Water Balance (CWB) is the other indicator used in Poland for meteorological drought monitoring and the assessment of its intensity. Meteorological drought is a phenomenon manifested by precipitation deficit in relation to average values. It is the most common approach in the defining and identification of this type of drought. However, a broader approach to this phenomenon is needed. A parameter which provides a more complex characteristic of meteorological drought is climatic water balance. It describes moisture conditions determined by atmospheric precipitation as water input, and evaporation as water loss. Climatic water balance, therefore, is a comprehensive indicator which includes all basic meteorological factors that are decisive for meteorological drought generation, i.e. precipitation and evaporation. A balance of precipitation and evaporation is also essential in terms of meteorological drought impact on the development of successive drought stages, i.e. soil drought, agricultural and hydrological drought. Unlike precipitation based assessment, climatic water balance can weaken or strengthen drought evaluation through the incorporation of essential additional information about moisture conditions.

Climatic water balance is calculated as the difference between precipitation total and the reference evapotranspiration total in a particular period:

$$CWB = P - ET_o \quad (4)$$

where: CWB – climatic water balance in a given period [mm], P – precipitation in a given period [mm], ET_o – reference evapotranspiration in a given period [mm] calculated using the Penman-Monteith method.

Similar to SPI , standardised climatic water balance ($SCWB$) is also used. It is a standardised deviation of climatic water balance values in a given period from the

median long-term value of this period (Łabędzki, Bąk 2004; Łabędzki 2006; Wibig 2012). It is calculated using the normalization method which normalises the historical time series of climatic water balance. Next, the standardised value is calculated using the following formula:

$$SCWB = \frac{CWB_n - \overline{CWB_n}}{d_{CWB_n}} \quad (5)$$

where: $SCWB$ – standardised climatic water balance, CWB_n – normalised time series of climatic water balance (mm), $\overline{CWB_n}$ – mean value of normalised time series of climatic water balance [mm], d_{CWB_n} – standard deviation from the normalised time series of climatic water balance [mm].

The 3-category classification as shown in Table 6 was used in the regional system of drought monitoring conducted by the Institute of Technology and Life Sciences (ITP) in the Kujawy region.

Table 6. Classification of meteorological drought according to standardised climatic water balance ($SCWB$)

$SCWB$	Meteorological drought category
0.50 to -0.99	normal
-1.00 to -1.49	moderate drought
-1.50 to -1.99	severe drought
≤ -2.00	extreme drought

source: own study

3. Agricultural drought

Agricultural drought is frequently described in terms of drought indices, which are convenient and relatively simple to use. An agricultural drought index should be based on crop water balance simulation modeling. Crop water simulation-based analysis of drought is necessary for the identification of agricultural drought because it accounts for evapotranspiration, soil water capacity, current soil moisture, water deficit and other parameters of the soil-plant-atmosphere continuum essential in drought development.

Many indices and methods have been developed and are used to identify and determine the intensity of agricultural drought (Vogt, Somma 2000; Boken et al. 2005). Index-based assessment of agricultural drought has been used in Poland within the conducted drought monitoring systems since 2005. The indices and the soil-crop parameters are estimated through the use of different models, for example the CROPBALANCE model, which was developed at the Institute of Technology and Life Sciences (Łabędzki 2006; Łabędzki et al. 2008).

The following indices have been used.

1. Crop Drought Index CDI is used to quantify agricultural drought intensity (Brunini et al. 2005; Narasimhan, Srinivasan 2005; Tian, Boken 2005; Łabędzki 2006). It indicates the reduction of evapotranspiration in relation to potential evapotranspiration due to soil water deficit and is calculated as:

$$CDI = 1 - \frac{ET}{ET_p} \quad (6)$$

where: ET – actual evapotranspiration under soil water deficit [mm], ET_p – potential evapotranspiration under sufficient soil moisture content [mm].

CDI assumes the values within the range $\langle 0,1 \rangle$:

$$CDI = 0 \text{ when } ET = ET_p$$

$$CDI < 1 \text{ when } ET < ET_p$$

$$CDI = 1 \text{ when } ET = 0$$

The actual and potential evapotranspiration is calculated using reference evapotranspiration and the crop and water stress coefficient approach and also the methodology described by Allen et al. (1998).

The actual evapotranspiration is calculated in ten-day periods, months and whole growing seasons as a sum of daily values. Evapotranspiration ET^t in a day t is calculated as:

$$ET^t = k_s^t k_c^t ET_0^t \quad (7)$$

where:

ET_0^t – reference evapotranspiration in a day t , according to the Penman-Monteith equation (Allen et al. 1998) [$\text{mm}\cdot\text{d}^{-1}$];

k_c^t – crop coefficient (dimensionless);

k_s^t – water stress coefficient (dimensionless).

Under excellent soil water conditions $k_s^t = 1$ and

$$ET^t = ET_p^t = k_c^t ET_0^t \quad (8)$$

where:

ET_p^t is potential evapotranspiration in a day t [$\text{mm}\cdot\text{d}^{-1}$].

Reference evapotranspiration incorporates the effect of weather conditions on evapotranspiration. Crop coefficient k_c^t predicts evapotranspiration under standard conditions, i.e. under excellent agronomic and soil water conditions. The effect of soil water stress on crop evapotranspiration is described by reducing the value of the crop coefficient, and then multiplying it by the water stress coefficient k_s^t . The water stress coefficient is calculated as:

$$k_s^t = \frac{ASW_p^t}{(1-p)TASW_r} \quad (9)$$

where:

ASW_p^t – available soil water in the root zone at the beginning of a day t [mm];

$TASW_r$ – total available soil water in the root zone [mm];

p – soil water depletion fraction, fraction of $TASW_r$ that a crop can extract from the root zone without suffering water stress (dimensionless), according to Allen et al. (1998).

Total available soil water $TASW$ is calculated in 10-cm layers as the difference between the water content at field capacity ($pF = 2.0$) and wilting point ($pF = 4.2$), using the formula:

$$TASW = SWC_{pF2.0} - SWC_{pF4.2} \quad (10)$$

where:

$SWC_{pF2.0}$ and $SWC_{pF4.2}$ – the soil water content [in mm] at $pF = 2.0$ and $pF = 4.2$;

$TASW_r$ – is calculated in the root zone, changing in time according to the root depth d .

The estimation of water stress coefficient k_s^t requires a daily water balance computation for the root zone. It is calculated as:

$$ASW_p^t = ASW_k^{t-1} = ASW_p^{t-1} + P^{t-1} - ET^{t-1} \quad (11)$$

where:

ASW_k^{t-1} , ASW_p^{t-1} – available soil water in the root zone at the end and at the beginning of a day $t-1$ [mm];

P^{t-1} – precipitation in a day $t-1$ [mm];

ET^{t-1} – evapotranspiration in a day $t-1$ [mm].

This simple procedure assumes that the infiltration of daily precipitation to the root zone is within the same day, as well as that the time of deep percolation from the root zone when soil water content exceeds field capacity is also 1 day.

To categorise and evaluate the severity of drought, CDI should be compared with the limits of different classes of drought. There is no unique, commonly acceptable classification of agricultural drought according to CDI . The three-category drought classification is used (moderate, severe, and extreme drought), with the threshold value for

Table 7. Classification of agricultural drought according to CDI

Agricultural drought category	CDI
Moderate drought	0.10 ÷ 0.19
Severe drought	0.20 ÷ 0.49
Extreme drought	0.50 ÷ 1.00

source: own study

the moderate drought category equal to $CDI = 0.1$ (Tab. 7). This means that a 10% reduction of evapotranspiration in relation to potential evapotranspiration is not considered as a drought effect.

2. Soil Moisture Index SMI is used to evaluate soil moisture conditions and to quantify soil drought intensity. It is calculated as (Hunt et al. 2009):

$$SMI = -5 + 10 \frac{ASW_a}{TASW} \quad (12)$$

where:

ASW_a – actual available soil water [mm],

$TASW$ – total available soil water [mm].

This method is based on the assumption that evapotranspiration becomes limited below the midpoint between field capacity and wilting point, or at 50% of total available water. No reduction in ET occurs until soil water falls below 50% of field capacity. Below 50% of field capacity the reduction in ET is linear below 50% of field capacity.

The four-category classification of soil moisture conditions is used and two categories of soil drought are distinguished within it (moderate and severe drought), with the threshold value for soil drought equal to $SMI = 0.00$ (Tab. 8).

Table 8. Classification of soil moisture according to SMI index

Soil drought category	SMI
No drought – excessive moisture	≥ 5.00
No drought – optimal moisture	[0.00; 5.00)
Moderate drought	[-2.00; 0.00)
Severe drought	[-5.00; -2.00]

source: own study

3. Crop Yield Reduction YR is used to quantify the effect of water stress and agricultural drought on a crop and is calculated from the equation (Raes 2004; Raes et al. 2006):

$$YR = \left(1 - \frac{Y_{re}}{Y_p} \right) = 1 - \prod_{i=1}^N \left[\prod_{j=1}^M \left(1 - k_y \left(1 - \frac{ET}{ET_p} \right) \right)^{\frac{\Delta t_j}{L}} \right] \quad (13)$$

where: Y_{re} – actual yield reduced due to water stress, Y_p – potential yield that can be expected under the given growing conditions for non-limiting water conditions, k_y – yield response factor, ET – actual evapotranspiration under soil water deficit, ET_p – potential evapotranspiration under non-limiting water conditions, N – total number of growth stages, M – number of time steps with length Δt_j (days)

during the growth stage i , Δt_j – the length of the period j in the growth stage i (days), L_i – the total length of the growth stage i (days), j – the number of the period in the growth stage i .

Table 9. Classification of agricultural drought according to yield reduction YR

Agricultural drought category	YR [%]
No drought – small yield loss	[0; 10)
Moderate drought – moderate yield loss	[10; 20)
Severe drought – heavy yield loss	[20; 50)
Extreme drought – very heavy yield loss	[50; 100]

source: own study

The three-category drought classification is used (moderate, severe, and extreme drought), with the threshold value for the moderate drought category equal to $YR = 0.1$ (Tab. 9). This means that a 10% reduction of crop yield in relation to potential yield is not considered as a drought effect.

4. Drought monitoring systems in Poland

Four different drought monitoring systems have been in operation in Poland since 2005. The Institute of Meteorology and Water Management (IMGW) conducts the system called “POSUCH@”. The Institute of Soil Science and Plant Cultivation conducts the agricultural drought monitoring system. The Institute of Technology and Life Sciences (ITP) has developed two systems: the regional drought monitoring system in the Kujawy region and the nationwide system of monitoring and forecasting water deficit and surplus in agriculture.

Hydrometeorological drought monitoring and prediction system “POSUCH@”. The system is conducted by the Institute of Meteorology and Water Management – National Research Institute IMGW-PIB (Tokarczyk, Szalińska 2013; IMGW 2014). The main objective of the system was to create a comprehensive, multipurpose application for drought hazard assessment supporting the operational work of hydrological forecasts offices. Operational drought hazard assessment includes meteorological and hydrological drought detection, analysis of drought intensity, duration and extension, as well as assessment of susceptibility to drought and drought hazard prediction. The data come from the measurements of meteorological and hydrological conditions, available within the monitoring network operated by IMGW-PIB. Its historical climatological database contains information from 350 meteorological stations and 1680 precipitation stations

(with daily data from 333 stations) while its historical hydrological database contains data from 900 gauge stations with records of daily discharges from around 30% of the stations. Operational data are obtained from the network of meteorological and hydrological stations supplied with telemetry facilities.

A scheme of drought hazard assessment includes the following components: estimation of meteorological drought indices, evaluation of susceptibility to drought, drought hazard assessment, and generation of products. Two meteorological drought indices are used for the system of drought hazard assessment and prediction: *EDI* (effective drought index) – meteorological drought detection, intensity and duration analysis, temporal variability presentations, hazard evaluation; and *SPI* (standardised precipitation index) – mapping spatial distribution of meteorological drought, inferring regional susceptibility to drought. The system does not deal with agricultural drought. The resulting products of the system are presented on the website <http://posucha.imgw.pl/>.

Agricultural Drought Monitoring System (ADMS).

The ADMS for Poland is provided by the Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB) on behalf of the Ministry of Agriculture and Rural Development (Doroszewski et al. 2008, 2012; ADMS 2014). ADMS supports the fulfillment of an insurance policy established by the Polish Government, according to the Act of 7 July 2005 on subsidies to the insurance of agricultural crops and farm animals (Dz. U No. 150, item 1249, 2006, No. 120, item 825). ADMS is designed to identify areas where there are crop losses caused by drought conditions, which are listed in the “Act on subsidies to insurance of agricultural crops and farm animals”.

In the Agricultural Drought Monitoring System, meteorological conditions that cause droughts are evaluated by the climatic water balance (*CWB*). The *CWB* Index expresses the difference between the precipitation and potential evapotranspiration calculated with the Penman equation.

In the system, drought is defined by losses in crop yields caused by the occurrence of climatic water balance (*CWB*) in the 6 consecutive ten-day periods below a defined value for an individual species or group of cultivated plants, as well as the soil category in the period from 1 April to 30 September. In determining the areas affected by a drought, besides the value of climatic water balance, the characteristics of soil retention are determined by soil category, and are identified based on soil and agricultural maps. In this way, a strong diversification of the susceptibility of Polish soil cover to the effects of a shortage of

water is taken into account. Spatial differentiation of soil cover in Poland according to a susceptibility of different categories of soil to drought comprises the categories: a very light soil (very susceptible), light soil (susceptible), medium-heavy soil (medium susceptible), heavy soil (less susceptible).

The appearance of a specified value of *CWB* causes on average a 20% reduction in the yield – this relates to the value of the long-term average. Critical values of the climatic water balance mean the appearance of drought for plant species or groups of cultivation plants and soil categories and periods of development.

A table with critical values of *CWB* and monitoring results are presented on the website <http://www.susza.iung.pulawy.pl/en/>.

The “**Monitoring meteorological and agricultural drought in Kujawy region**” system. The system was developed and operated by the Kujawsko-Pomorski Research Centre of the Institute of Technology and Life Sciences in 2008-2012, in the Kujawy region of central Poland (Fig. 1). The region is the driest region in Poland, where periods of short or long-term drought are very common. The results of the monitoring of meteorological and agricultural drought were presented on the ITP website.



Fig. 1. Location of Kujawy region

Drought monitoring was carried out using the network of automatic stations for measuring agrometeorological and agrohydrological elements (Fig. 2).

Meteorological drought was monitored using the relative precipitation index (*RPI*), the standardised precipitation index (*SPI*) and the standardised climatic water balance (*SCWB*). Agricultural drought monitoring was carried out using the crop drought index (*CDI*).

Examples of monitoring results, which were presented every 10 days on the website, are shown in Tables 10 and 11.

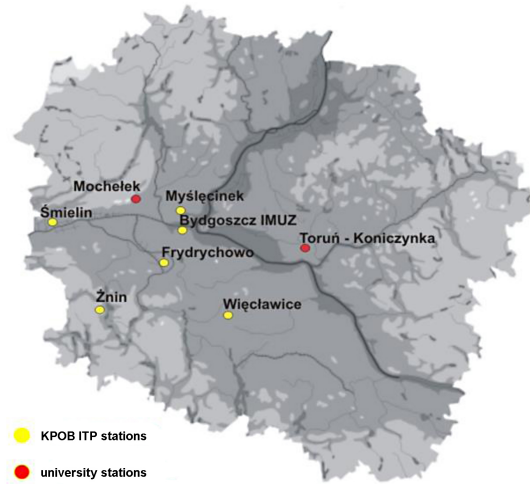


Fig. 2. Location of measurement stations

The monitoring helped to estimate the spatial variability of drought intensity. Using this information and meteorological forecasts, the progress of drought was predicted. The monitoring and estimation of drought supported decision-making and activities in agricultural production, water management in the rural areas, irrigation and natural resource protection in river valleys used agriculturally. Since 2012 the regional system has been included in the nationwide system of monitoring water deficit and surplus in agriculture.

Table 10. Meteorological drought intensity in 2009

Period	<i>P</i> [mm]	<i>CWB</i> [mm]	Drought intensity according to		
			<i>RPI</i>	<i>SPI</i>	<i>SCWB</i>
01.04-30.04	31	-30	extreme drought	extreme drought	extreme drought
11.04-10.05	38	-35	extreme drought	severe drought	severe drought
21.04-20.05	47	-38	severe drought	moderate drought	no drought
01.05-31.05	50	-49	no drought	no drought	no drought
11.05-10.06	50	-59	no drought	no drought	no drought
21.05-20.06	52	-61	no drought	no drought	no drought
01.06-30.06	58	-54	no drought	no drought	no drought
11.06-10.07	66	-45	no drought	no drought	no drought
21.06-20.07	76	-36	no drought	no drought	no drought
01.07-31.07	82	-32	no drought	no drought	no drought
11.07-10.08	77	-33	severe drought	no drought	no drought
21.07-20.08	67	-36	severe drought	severe drought	severe drought
01.08-31.08	62	-30	extreme drought	extreme drought	severe drought
11.08-10.09	57	-23	severe drought	no drought	no drought
21.08-20.09	53	-15	severe drought	no drought	no drought
01.09-30.09	43	-11	severe drought	no drought	no drought

P – mean precipitation in 1945-2008; *CWB* – mean climatic water balance in 1945-2008

extreme drought	moderate drought
severe drought	no drought

Table 11. Agricultural drought intensity in 2009

Period	TASW	Meteorological drought intensity according to SPI	Root crops		Grassland sites		
			late potatoes	sugar beet	wet	drying	dry
IV-V	120 mm				-	-	
	200 mm						
IV-VI	120 mm				-		
	200 mm						
IV-VII	120 mm						
	200 mm						
IV-VIII	120 mm						
	200 mm						
IV-IX	120 mm						
	200 mm						

TASW – available soil water; - no significant relationship between meteorological and agricultural drought; explanation see Table 10

The “**Monitoring and forecasting water deficit and surplus in agriculture**” system. Since 2012 Institute of Technology and Life Sciences has led national agrometeorological monitoring in rural areas (ITP 2014). The project is financed by the Polish Ministry of Agriculture and the Rural Development Programme: *The Monitoring and Prediction of Progress and Risk of Water Deficit and Surplus in Rural Areas, 2011-2015*. The system has been developed using the experiences gathered during the operation of the regional drought monitoring system for the Kujawy Region in Poland. The present nationwide system provides current and forecast evaluation of water deficit and surplus for agriculture in selected representative agricultural ecosystems and estimates potential reduction of crop yield due to water shortage. Required meteorological data are provided by a network of automatic stations located in 13 regions on Polish territory. Weather forecasts, necessary for the development of predictions of water deficit or surplus in a subsequent 10- and 20- day period, come from the meteorological service of MeteoGroup Poland.

Monitoring of water deficit and surplus and their consequences is carried out using an indicator method. Precipitation conditions are monitored using the standardised precipitation index *SPI*; soil moisture is monitored with the soil moisture index *SMI*; the deficit of water for crops with the agricultural drought index *CDI*; and the potential reduction of final yield with the yield reduction ratio *YR*.

The *SPI* is calculated on the basis of precipitation data from 35 meteorological stations (Fig. 3). at 1-, 2-, 3-, 6-, 12-, 24-, 36- and 48-month time scales, and for the 30/31-day periods moved every 10 days by 10 days. Using the forecast precipitation for the forthcoming 10 and 20 days the predictions of the 30-day *SPI* are created.

Soil moisture (soil moisture index *SMI*), deficit of water for crops (agricultural drought index *CDI*) and potential yield reduction (*YR*) are evaluated every 10/11 days for

the previous 10/11 days and forecast for the next 10 and 20 days. The assessment is done in 13 regions distinguished on the basis of diversity of climate and agro-climatic conditions in Poland (Fig. 4). The total area of the selected region under monitoring is 204 000 km².



Fig. 3. Location of meteorological stations in Poland for which the *SPI* is calculated

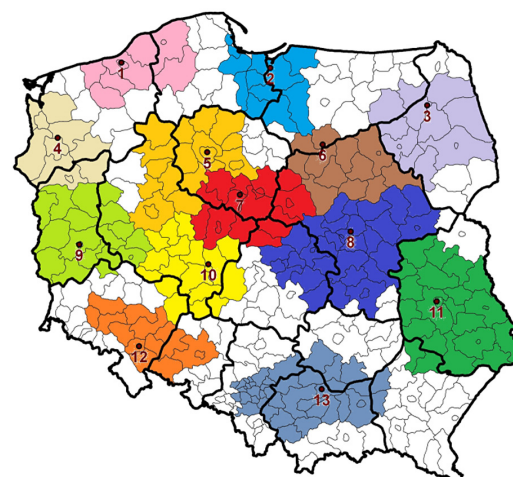


Fig. 4. Selected agricultural regions in Poland and meteorological stations

Table 12. Comparison of the currently operating monitoring systems in Poland

System	Conducting institution	Monitored area	Monitored drought type	Indices used	Monitored period/frequency	Forecast
POSUCH@	Institute of Meteorology and Water Management	whole country (312 000 km ²)	meteorological	<i>EDI</i> (Effective Drought Index)	365 days/ 1 day	3 days
				<i>SPI</i> (Standardised Precipitation Index)	1 month/ 1 month	-
Agricultural Drought Monitoring System	Institute of Soil Science and Plant Cultivation	whole country (312 000 km ²)	agricultural	<i>CWB</i> (Climatic Water Balance)	60 days/ 10 days	-
Monitoring and forecasting water deficit and surplus in agriculture	Institute of Technology and Life Sciences	204 000 km ²	meteorological	<i>SPI</i> (Standardised Precipitation Index)	1, 2, 3, 6, 12, 24, 36, 48 months/ 1 month	-
				<i>SPI</i> (Standardised Precipitation Index)	30 days/ 10 days	10 and 20 days
			agricultural	<i>SMI</i> (Soil Moisture Index)	10 days/ 10 days	10 and 20 days
				<i>CDI</i> (Crop Drought Index)	10 days/ 10 days	10 and 20 days
				<i>YR</i> (Yield Reduction)	10 days/ 10 days	10 and 20 days

The results of the monitoring and forecasts are presented as tables and maps on the Internet at www.agrometeo.itp.edu.pl.

Among all operating agrometeorological monitoring systems in Poland, the nationwide system of monitoring and forecasting water deficit and surplus created by researchers from ITP is distinctive from other operating systems by supplying a broader range of information, including precipitation and soil moisture conditions, agricultural drought intensity and potential crop yield reduction as a final effect of agricultural drought. Moreover the system has enhanced the module of medium- and long-term forecasting.

A summary of the monitoring systems currently in operation is given in Table 12. It contains information on the area being monitored, the types of monitored drought, the drought indices used in the systems, the monitored periods and the frequency with which it is updated. Two systems give forecasts of the indices and of drought intensity.

5. Summary and concluding remarks

In this article, a brief review is presented on the definition of meteorological and agricultural droughts, common drought indices and the operational systems for monitoring droughts in Poland.

Drought is a widespread and frequent disaster. This climate anomaly becomes very characteristic in many countries within humid climate zones. Droughts can be divided into meteorological, hydrological, agricultural, and socio-economic varieties. Meteorological drought is the result of deficiencies in precipitation. Hydrological drought is associated with the effects of precipitation deficit on surface or subsurface water resources. Agricultural drought is the effect of various characteristics of meteorological and hydrological drought in agriculture, comprising a reduction in evapotranspiration, soil water deficits, and reduced crop yield.

Drought indicators are the common measures for drought assessment. They should provide a concise overall measure of the phenomena on the basis of available and easily measured hydro-climatic, soil and crop data. The paper contains an inventory of drought measures (indicators) that are applied to evaluate meteorological and agricultural drought in Poland. Nowadays in Poland no one uniform system of drought assessment exists. The presented systems give information for the whole country or for a specific region but they are directed to some specific drought analyses. They play a complementary role. The preference for particular methods and indices for drought monitoring depends on the particular application. For meteorological drought monitoring, the recently

developed standardised precipitation index *SPI* is preferable. This index has a multiple time-scale capability and various other advantages compared to the other indices. It is recommended by the World Meteorological Organization. For agricultural drought monitoring *SPI* should be combined with real-time monitoring of soil moisture deficit, crop water stress and the evaluation of possible crop yield reduction. For this aim different methods and indices are applied in the presented systems. Some of them have gained wide acceptance across Europe and the wider world (*SMI*, *CDI*, and *YR*, according to Raes). The method used in the Agricultural Drought Monitoring System for Poland (ADMS), based on the relationships between climatic water balance and crop yield reduction, has more of a regional applicability.

The information supplied by the existing drought monitoring systems can support decision-making and activities aimed at the mitigation of the negative impacts of droughts, effective use of water resources, irrigation scheduling and other human activities that are connected with the climate.

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