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Potential of remote sensing techniques for integrated spatio-temporal monitoring and analysis of drought in the Sana River basin, Bosnia and Herzegovina

Luka Sabljić [1,*], **Tin Lukić** [2], **Slobodan B. Marković**[2,3,4,5], and **Davorin Bajić** [1]

[1]*University of Banja Luka,*
Faculty of Natural Sciences and Mathematics
Mladena Stojanovića 2, 78000 Banja Luka, Bosnia and Herzegovina

[2]*University of Novi Sad,*
Faculty of Natural Sciences,
Department of Geography, Tourism and Hotel Management
Trg Dositeja Obradovića 3, 21000 Novi Sad, Serbia

[3]*Serbian Academy of Sciences and Arts,*
Kneza Mihaila 35, 11000 Belgrade, Serbia

[4]*University of Technology,*
Institute of Physics – Centre for Science and Education,
Division of Geochronology and Environmental Isotopes,
Konarskiego 22b, 44100 Gliwice, Poland

[5]*University of Montenegro,*
Faculty of Philosophy,
Danila Bojovića bb, 81400 Nikšić, Montenegro

[*]*Corresponding author E-mail: luka.sabljic@pmf.unibl.org*

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Abstract— The subject of the research paper is the exploration of the potential of remote sensing techniques for enhanced spatio-temporal monitoring and analysis of drought impacts within the Sana River basin area in Bosnia and Herzegovina (B&H). The aim is to identify meteorological, hydrological, agricultural, and socio-economic drought occurrences by processing remote sensing "products". An integral part of this aim involves calculating the standardized precipitation index (SPI), temperature condition index (TCI), vegetation condition index (VCI), and vegetation health index (VHI). Meteorological drought monitoring was carried out using the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) dataset processed through the Google Earth Engine (GEE) platform. A 42-year period (1981–2023) was compared with reference years

(2016 and 2017). The occurrence of meteorological drought (lack of precipitation) was identified, and SPI was calculated. The period with reduced precipitation and negative SPI values during 2016 and 2017 coincided with the pattern of decreasing water levels in the main stream of the Sana River, confirming the impact of meteorological drought on the occurrence of hydrological drought. Agricultural drought monitoring was conducted using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, namely MOD13Q1 and MOD11A2, to calculate TCI, VCI, and VHI. The results indicate negligible drought occurrence for 2016, while extreme agricultural drought was observed in the basin area for 2017. The consequences of agricultural drought on the occurrence of socio-economic drought were examined. The results show an extreme decrease in yields of wheat, barley, corn, potatoes, pears, and plums during 2017 compared to 2016. The research contributes to a better spatio-temporal understanding of drought phenomena, and the presented data and results are significant for numerous practical issues related to monitoring, mitigation, and/or prevention of negative consequences of drought in river basin areas.

Key-words: drought, hazard, remote sensing, geographic information systems, mapping, Sana River basin, Bosnia and Herzegovina.

1. Introduction

Drought is an exceptionally complex natural disaster (*Xie* and *Li*, 2020a). According to *Hao* and *Singh* (2015) and *Dong et al.* (2022), drought is one of the most common natural disasters in terrestrial ecosystems, characterized by wide coverage, frequent occurrences, and negative impacts, which directly or indirectly cause significant economic losses at regional and global levels. Drought leads to widespread exhaustion of natural and artificial water resources over an extended period (*Rossi,* 2000). Over the past few decades, under the influence of climate change, the impact of drought on agriculture, economy, and society has intensified (*Council*, 1992; *Wilhite et al.,* 2007; *Orimoloye*, 2022). Drought leads to a negative impact on agricultural productivity, desertification, forest degradation, and other socio-economic problems (*Li et al.,* 2020a,b; *Xie* and *Li,* 2020b).

Depending on the type of drought, its impacts vary in space and time (*Žurovec et al*., 2017). According to *Wilhite* (1985), the following types of droughts exist: meteorological, hydrological, agricultural, and socio-economic. Meteorological droughts are closely related to reduced or lack of precipitation (*Wilhite*, 2000; *Gabrić* and *Plavšić*, 2019). According to *Liu et al.* (2023), meteorological drought, caused by insufficient precipitation, high temperatures, and significant evapotranspiration, can lead to water shortages, manifested through soil moisture deficits. Traditional monitoring of meteorological drought relies on meteorological data from meteorological stations (MS) (*Robock et al.,* 2000; *Hashim* et al., 2016). However, in areas with disparate distribution of MS, access to long-term and reliable data for monitoring meteorological drought is limited (*Tan et al*., 2017; *Tian et al.,* 2018). Uneven spatial distribution of MS and discontinuous precipitation data trends are characteristic of developing countries, such as Bosnia and Herzegovina (B&H). Consequently, there is a shortage of research concerning meteorological droughts within the borders of B&H, particularly related to specific geographic environments. The lack of an adequate number and uneven distribution of MS can be overcome by an alternative approach using satellite meteorological data. According to *Ezzine et al.* (2014) and *Tang et al.* (2020), satellite meteorological data offer the possibility of identifying conditions for drought occurrence on various surfaces, as well as suitability for monitoring large-scale droughts in real-time with high accuracy and implementation. *Zhu et al.* (2019) highlight the abundance of various satellite precipitation data and their wide application in meteorological drought analysis (*Gao et al*., 2018; *Tladi et al.,* 2022; *Feng et al.,* 2023; *Kourtis et al.,* 2023; *Torres-Vázquez et al*., 2023; *Zhang et al*., 2023; *Oukaddour* et al., 2024). According to the authors of this study, satellite meteorological data have not been used to investigate meteorological drought in the territory of B&H thus far. According to *Wilhite* (2000), meteorological drought can act as a "trigger" for the occurrence of other types of droughts. *Lee et al.* (2022) emphasize that this type of drought directly influences the occurrence of hydrological drought. The mentioned drought is traditionally detected through field observations of river flow, surface or groundwater levels, providing direct evidence of water scarcity (*Nalbantis* and *Tsakiris*, 2009; *Zhu et al.,* 2016).

According to *Spinoni et al.* (2018), there is an established consensus about recent trends of meteorological and hydrological droughts in Europe: in the last decades, southern Europe experienced increasing drought frequency and severity (*Briffa et al*., 2009; *Vicente-Serrano* et al., 2014; *Gudmundsson* and *Seneviratne*, 2015; *Spinoni et al.,* 2015a,b), with the Mediterranean region as a hotspot (*Hoerling et al.,* 2012), especially in spring and summer (*Spinoni et al*., 2017). Drought has been present several times in the territory of B&H during the past two decades (*Žurovec et al*., 2017). During the period from 2000 to 2021, extreme drought occurred eight times: in 2003, 2007, 2011, 2012, 2013, 2015, 2016, and 2017 (*Trbić et al*., 2022). *Trbić et al*. (2013) emphasize that in the future, a greater number of hot/tropical days, along with reduced precipitation and the occurrence of dryness or aridity, will increase the likelihood of drought in the territory of B&H. In this regard, the negative impacts of droughts observed in the past may be significant for the future, making areas where more frequent severe droughts are expected a very important subject of research (*Spinoni et al*., 2018).

Meteorological and hydrological droughts, intensified by high temperatures, contribute to soil moisture deficits, thereby causing agricultural drought (*Liu et al*., 2016). *Wilhite* (2000) emphasizes that due to soil moisture deficits, agriculture is the first economic sector affected by drought, especially if the period of moisture deficiency is accompanied by high temperatures and windy conditions. By processing remote sensing "products" in the form of satellite imagery, it is possible to generate various indices for monitoring agricultural drought. Specifically, *Yoon et al*. (2020) highlight that for the identification, monitoring, and analysis of agricultural droughts, remote sensing-based indices have proven to be the most helpful supplementary data due to their simplicity, low cost of synoptic display, and reliability. The use of indices such as the normalized difference vegetation index (NDVI), temperature condition index (TCI), and vegetation condition index (VCI) for identifying agricultural drought is globally recognized (*Nicholson* and *Farrar*, 1994; *Kogan*, 1995a; *Seiler et al.*, 2000; *Wang* et al., 2001). The uniqueness of these indicators lies in their autonomy from various environmental conditions (*Anyamba et al.*, 2001; *Ji* and *Peters*, 2003), allowing for effective monitoring of agricultural drought in any geographic environment. Agricultural drought has a significant impact on reducing agricultural production and yields, leading to the manifestation of socio-economic drought, which, according to *Wilhite* and *Glantz* (1985), involves considering the effects that the mentioned drought has on the supply and demand of economic goods such as fruits, vegetables, grains, and meat.

The primary objective of this study is to improve drought monitoring in the Sana River basin (B&H) through the utilization of remote sensing techniques. This involves conducting integrated spatio-temporal analysis and exploring potential mitigation strategies. A fundamental part of this goal involves identifying meteorological and hydrological droughts, mapping agricultural drought as a causal consequence, and examining environmental impacts through the identification and monitoring of socio-economic drought. The research is based on the application of modern technologies such as Geographic Information Systems (GIS) and remote sensing. The presented methodology is significant for identifying and understanding drought as a natural disaster. The research results can be beneficial to relevant institutions in policy-making and planning activities in the areas of monitoring, prevention, and/or mitigation of the harmful effects of drought in the geographic environment.

2. Study area

The study area comprises the river basin of the Sana River, which stretches across the northwest of B&H [44.18° N – 45.09°N; 16.29° E – 17.09° E] (*Fig. 1*). The Sana River originates from three karstic sources on the border of the municipalities of Ribnik and Mrkonjić Grad. The mentioned river is a tributary of the Una River and belongs to the larger river basin of the Sava River with a surface participation of 3.55%. The length of the Sana River is 146 km, its source is located at an altitude of 414 m a. s. l., and its mouth at 122 m a. s. l. It is characterized by the Posavina variant of the pluvio-nival water regime, which is characterized by high water levels in April, and lower levels in August (*Gnjato*, 2018). Based on data from the hydrological station (HS) Prijedor (1961–2014), the highest flow rates on the Sana River were recorded in the spring season (119.7 m^3/s), and the lowest in the summer season (42.6 m^3/s). The total area of the river basin according to the HydroSHEDS database (https://www.hydrosheds.org/) is 3470 km^2. The average elevation of the river basin is 505 m, while the average slope is 10.9°. Based on data from MS Novi Grad, Prijedor, Sanski Most, and Ribnik (1981–2023), the average annual precipitation in the river basin area is 1043.42 mm, while the average annual temperature is 11.09 °C. According to the Köppen-Geiger climate classification (*Kottek* et al., 2016), the Sana River basin belongs to the Cfb climate type, which is characterized by moderately cold winters and warm summers.

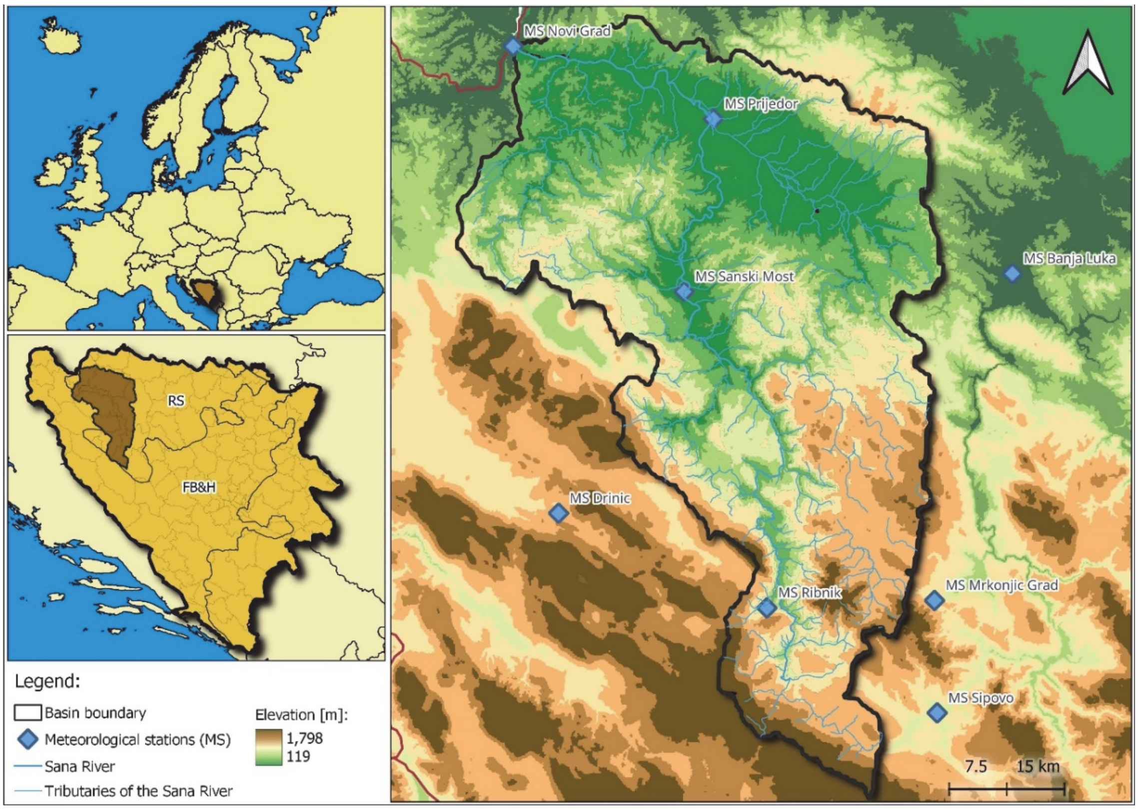

Fig. 1. Location of the study area with meteorological stations used in this study.

The Sana River basin extends across both entities in B&H: Republic of Srpska (RS) and the Federation of Bosnia and Herzegovina (FB&H). It partially or entirely covers the following municipalities in RS: Novi Grad, Kostajnica, Prijedor, Oštra Luka, Banja Luka, Ribnik, Mrkonjić Grad, Krupa on Una, as well as municipalities in FB&H: Bosanska Krupa, Sanski Most, and Ključ. According to the latest population census in B&H from 2013, these municipalities had a combined population of 454,000 inhabitants (*Agency for*

Statistics of Bosnia and Herzegovina, 2016), which also represents the total population in the basin area. Based on the Corine Land Cover database from 2018 (https://land.copernicus.eu/), concerning land use within the study area, built-up areas occupy 38.68 km^2, arable land covers 1514.09 km^2, forested areas cover 1830.82 km^2, and water bodies cover 21.79 km^2. The significant participation of arable land, accounting for 43.64% of the basin area, indicates that agriculture as the primary economic sector is exceptionally significant for the economic development of this geographical environment.

3. Methods and data

Monitoring drought in the research is based on processing remote sensing "products" in the form of satellite imagery. The Google Earth Engine (GEE) platform, based on cloud technology, was used for processing. In order to identify the period of meteorological drought within the research, satellite precipitation estimate data called Climate Hazards Group InfraRed precipitation with Station data (CHIRPS) were used. The mentioned data are of a global nature, with relatively high spatial resolution (0.05°× 0.05° ~ 5.3 km) and long-term temporal coverage (1981 – almost real-time) (*Funk et al.*, 2015). Before using CHIRPS data, they were validated based on data from the meteorological stations. The validity of CHIRPS data based on MS data has been confirmed in several studies (*Katsanos et al.*, 2016; *Hsu et al.,* 2021; *Alsilibe et al.*, 2023), and they have been used in drought analyses (*Rivera et al.*, 2018; *Habitou et al.*, 2020). At the study area level, CHIRPS data were previously validated in a research by *Sabljić et al.* (2023). According to the methodology of the mentioned authors, the validity assessment process involved comparing the average precipitation amount of CHIRPS and meteorological data from MS Prijedor and Sanski Most (1992–2022). In this research, and according to the mentioned methodology, during the validity assessment process, meteorological data from a larger number of MS stations were additionally taken into account, and a longer time period was observed (1981–2023). Meteorological data were obtained from the Republic Hydro-Meteorological Institute of the Republic of Srpska (RHMIRS) and the Federal Hydro-Meteorological Institute of the Federation of Bosnia and Herzegovina (FHMIFB&H). Meteorological data from MS stations located within the basin area were considered, as well as data from MS stations located in its immediate vicinity (*Table 1*). The reason for including MS stations located outside the basin boundaries is explained by the lack of such stations at higher elevations within the basin.

Table 1. MS stations whose data were used in the validity assessment process

Row number	Name	Location	Time period	Elevation (m)
1	Novi Grad	45°05’ N; 16°37’ E	1981–2023	122
2	Prijedor	44°97' N; 16°71' E	1981–2023	133
3	Banja Luka	44°79’ N; 17°20’ E	1981–2020	150
4	Sanski Most	44°46’ N; 16°42’ E	1981–2022	158
5	Ribnik	44°40’ N; 16°81’ E	2000–2023	293
6	Šipovo	44°28’ N; 17°09’ E	1999–2023	454
7	Mrkonjić Grad	44°41’ N; 17°08’ E	1981–2023	570
8	Drinić	44°50’ N; 16°46’ E	1981–2023	722

Meteorological drought is characterized by a lack of precipitation, and to establish its occurrence, a comparison is made between the 42-year average precipitation (1981–2023) and the average precipitation of reference years (2016 and 2017). Therefore, following the recommendations of the World Meteorological Organization, the meteorological element covering one full climatological cycle was observed (*Lukić et al.,* 2021). The aim of this process is to identify the time period during the reference years when the precipitation was below the 42-year average. The time period during which a lower amount of precipitation than the average is observed is characterized by the occurrence of meteorological drought.

The occurrence of meteorological drought was further analyzed by calculating the standardized precipitation index (*SPI*). This indicator, presented by *McKee et al.* (1993), represents the deviation *z* from the mean value in units of standard deviation. In the research, *SPI* was calculated based on CHIRPS precipitation data at the location of each pixel composite period for each year during the reference period (*Fig. 2*). The formula for calculating *SPI* is as follows:

$$SPI_{ijk} = \frac{(P_{ijk} - \overline{P_{ij}})}{\sigma_{ij}}, \tag{1}$$

where SPI_{ijk} is the *z*-value for the pixel (*i*) during timeframe (*j*) for year (*k*), P_{ijk} is the precipitation value for pixel (*i*) during timeframe (*j*) for year (*k*), P_{ij} is the mean for pixel (*i*) during timeframe (*j*) over *n* years, and σ_{ij} is the standard deviation of pixel (*i*) during week (*j*) over *n* years.

Meteorological drought acts as a trigger for the occurrence of other types of droughts. Hydrological drought arises from meteorological drought (lack of precipitation), often developing slowly and lasting for months, with serious consequences for ecosystems, the environment, agricultural production, and water resource systems (*Van Loon*, 2015). Within the scope of the study, the impact of meteorological drought on the occurrence of hydrological drought was established through the analysis of the water level of the main stream of the Sana River. The average mean water level on the main stream of the Sana River was calculated, incorporating data from the HS Prijedor and Sanski Most for the studied time period (2001–2019). The average mean water level of the 18-year period was compared with the average mean water level of the reference years (2016 and 2017). Months during which a lower average mean water level than the 18-year average was evident are characterized by the occurrence of hydrological drought.

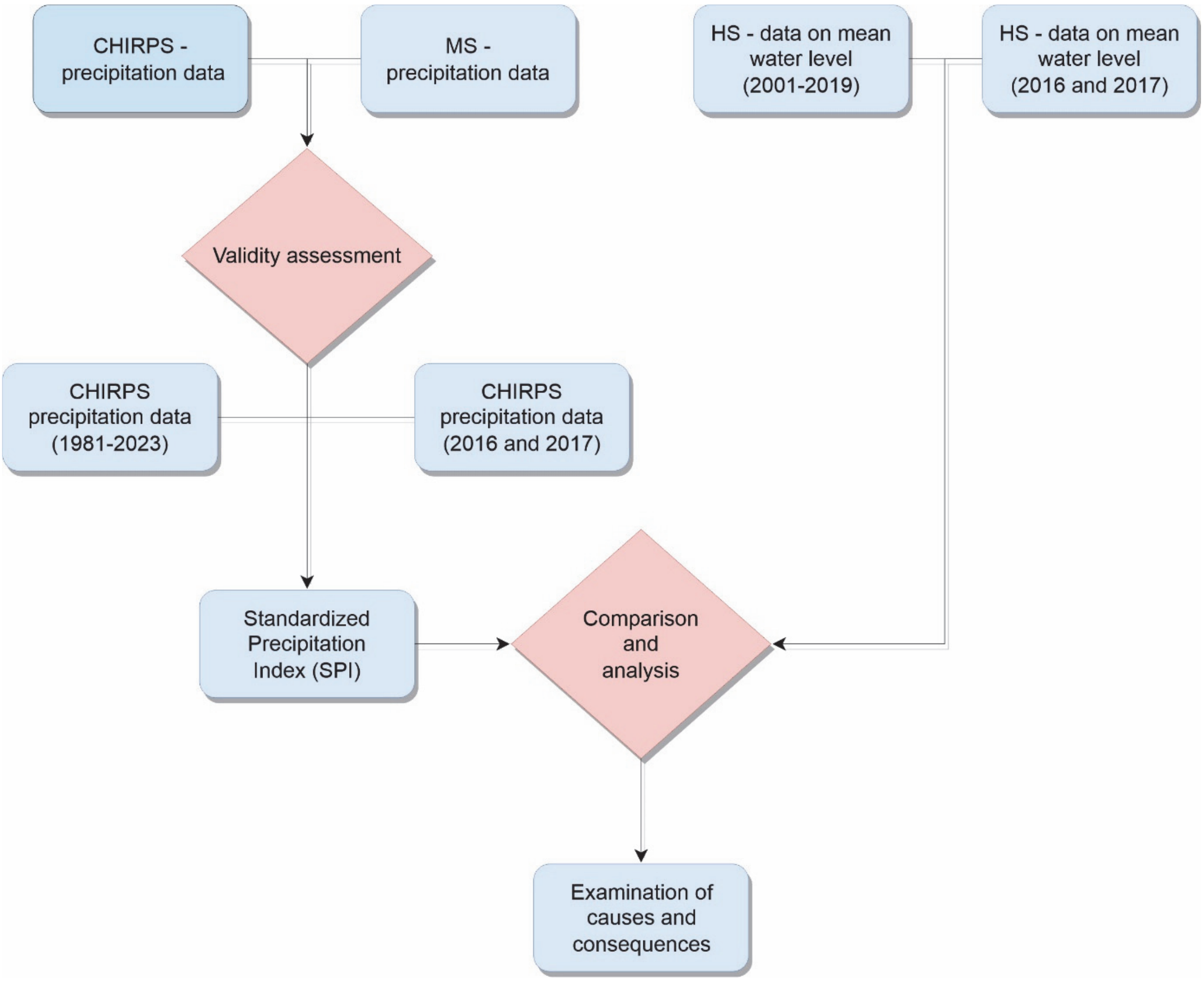

Fig. 2. Methodology for processing and monitoring meteorological and hydrological droughts.

The time periods characterized by clear differences in the amount of received precipitation, negative *SPI* values, as well as periods with significant decreases in the water level of the main stream of the Sana River, represent the basic temporal data for the process of identification and mapping of agricultural drought at the study area level. The process of mapping agricultural drought is based on the computation of *TCI* and *VCI*, and the results of these indices are used to calculate *VHI* (*Fig. 3*). The mentioned indices are computed by processing remote sensing data in the form of satellite data through the GEE platform. In this regard, Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data were used, specifically: MOD13Q1 and MOD11A2. An overview of the characteristics of these satellite data is provided in *Table 2* (*Didan,* 2021; *Wan et al*., 2021).

Table 2. Overview of MOD13Q1 and MOD11A2 satellite data characteristics

COLLECTION		**GRANULE – MOD13Q1**	
Characteristic	**Description**	**Characteristic**	**Description**
Collection	Terra MODIS	Number of science dataset (SDS) layers	12
Temporal resolution	Multi-Day	Columns/Rows	4800 × 4800
Temporal extent	2000-02-18 – now	Pixel size	250 m
Spatial extent	Global	**GRANULE – MOD11A2**	
Coordinate system	Sinusoidal	**Characteristic**	**Description**
Datum	N/A	Number of science dataset (SDS) layers	12
File format	HDF-EOS	Columns/Rows	1200 × 1200
Geographic dimensions	1200 ×1200 km	Pixel size	1000 m

TCI represents the initial indicator of water stress and drought. It was developed by *Kogan* (1995a) using the thermal bands of the Advanced Very High Resolution Radiometer (AVHRR) to determine vegetation stress caused by temperature, as well as stress induced by excessive moisture. The input satellite data for calculating *TCI* is the MOD11A2 satellite data. The formula for calculating *TCI* according to the previously mentioned author is:

$$TCI_j = \frac{(TCI_j - TCI_{min})}{(TCI_{max} - TCI_{min})} \times 100 \, , \tag{2}$$

where TCI_{max} and TCI_{min} are the maximum and minimum values of *TCI* in a multi-year dataset. *j* is the *TCI* value of the current month in the calculation.

VCI is applied when assessing the status of agricultural drought. Its component is *NDVI*. It was developed by *Kogan* (1995a, 1997). *VCI* estimates the current *NDVI* by comparing it with a range of values observed during previous years. The input data for its calculation is the MOD13Q1 satellite data. The result of *VCI* is expressed in numerical values, where lower values indicate poorer vegetation conditions, while higher values indicate better vegetation conditions.

According to *Kogan* (1997) and *Bento et al.* (2018), the calculation of *VCI* for each pixel and period during the reference years is based on the formula:

$$VCI_j = \frac{(NDVI_j - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \times 100 \ , \tag{3}$$

where $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum values of NDVI in a multi-year dataset. *j* is the *NDVI* value for the current month in the calculation.

VHI represents an index used in monitoring agricultural drought. According to *Bhuiyan et al*. (2006), *VHI* takes into account local biophysics (soil and slope) as well as climatic conditions, making it highly applicable in monitoring drought in various agrometeorological regions. *Prasad et al.* (2006) and *Kogan et al.* (2012) emphasized that the results of *VHI* are highly correlated with crop yields, particularly during critical phases of crop growth. To be successfully calculated, its computation requires the integration of the results of the two previously mentioned sub-indices: *VCI* and *TCI*, and the final formula for calculation is:

$$VHI = \alpha \times VCI + (1 - \alpha) \times TCI \ , \tag{4}$$

where α is the "weight" for measuring the contribution of *VCI* and *TCI* in assessing drought status. Generally, the value of α is set to 0.5 due to challenges arising in differentiating the contributions of surface temperature and *NDVI* during vegetation stress measurements.

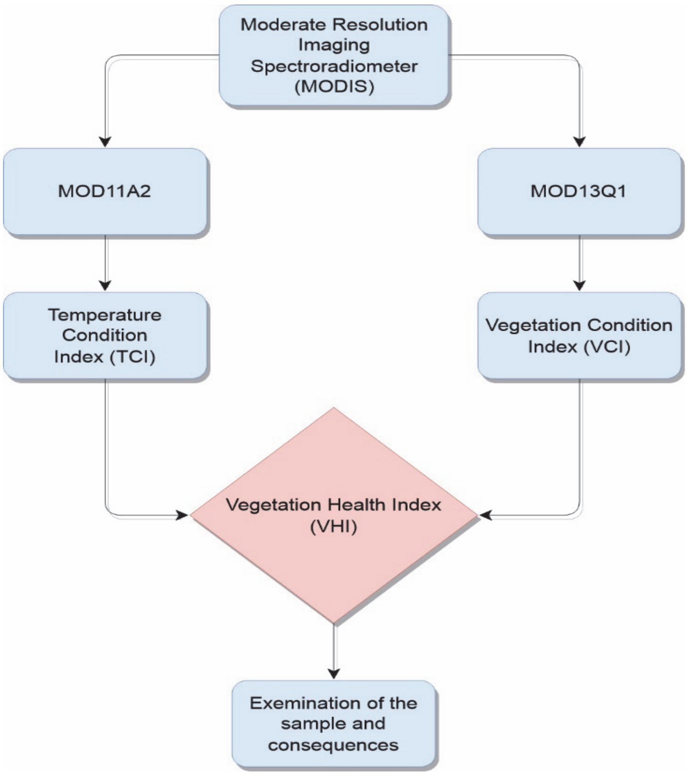

Fig. 3. Data processing methodology for identifying and mapping agricultural drought.

The results of the mentioned indices (*TCI*, *VCI*, and *VHI*) range from -1 to 1. Negative values indicate the occurrence of drought, while positive values indicate the absence of drought. In the study, following recommendations (*Kogan*, 1990, 1995b) and previous research (*Monteleone et al.,* 2020; *Zeng et al.,* 2022), the standardization of these indices was performed through their reclassification into values from 0 to 100, in an equal number of drought categories (*Table 3*).

Table 3. Categorization of drought types

Row number	Value	Drought type
1	< 10	Extreme drought
2	< 20	Severe drought
3	< 30	Moderate drought
4	< 40	Mild drought
5	>= 40	No drought

The consequences of identified agricultural drought are examined through the occurrence and analysis of socio-economic drought. This type of drought was identified by analyzing statistical data on crop yields during the reference period. The data were obtained from the Institute of Statistics Republic of Srpska (ISRS) and Federal Institute of Statistics of the Federation of Bosnia and Herzegovina (FISFB&H). Data on yields at the municipal level within the Sana River basin were considered, including: Bosanska Krupa, Ključ, Sanski Most, Banja Luka, Novi Grad, Kostajnica, Prijedor, Oštra Luka, Ribnik, and Mrkonjić Grad. Yield data were compared for the reference years (2016 and 2017) for the following crops: wheat, maize, barley, potatoes, apples, pears, and plums, and the causes and consequences of this type of drought were examined.

4. Results and discussion

The validation of CHIRPS satellite precipitation data was performed according to the previously described methodology. A comparison of the average precipitation quantity between CHIRPS and the MS indicates a high degree of validity of the satellite data (*Fig. 4*). December is characterized by 89.40% agreement between satellite and real data. Five out of twelve months (April, May, September, October, and November) are characterized by >90% agreement, while six out of twelve months (January, February, March, June, July, and August) are characterized by >95% agreement between satellite and real data.

Fig. 4. Evaluation of meteorological data validity (1981–2023).

The average annual precipitation (1981–2023) aligns with the data obtained from the MS stations at a rate of 94.95%, while the total precipitation matches at a rate of 98.19%. Previous research (*Sabljić et al*., 2023) assessing the validity of the average annual precipitation (1992–2022) for the Sana River basin resulted in a match of 92.63%, as well as 92.38% for total precipitation. Considering the inclusion of a greater number of MS stations at different altitudes, as well as the observation over a longer time period, led to more accurate results in the validation process of satellite precipitation data. Taking into account that HM data relates to seven points in space representing MS stations, while satellite data covers the entire area, along with the spatial resolution factor of satellite data, it is concluded that satellite data is valid for the research and monitoring of meteorological drought.

According to the methodology described earlier, to identify meteorological drought, a comparison was made between the average precipitation for a 42-year period (1981–2023) and the average precipitation for the years 2016 and 2017 (*Fig. 5*). During the year 2016, lower precipitation amounts (*Fig. 5a*) were identified in April (-15.27 mm), September (-19.7 mm), October (-5.85 mm), and December (-85.67 mm). On the other hand, during the year 2017, lower precipitation amounts (*Fig. 5b*) were identified in May (-9.21 mm), June (-22.57 mm), July (-20.92 mm), August (-30.85 mm), and October (-12.75 mm).

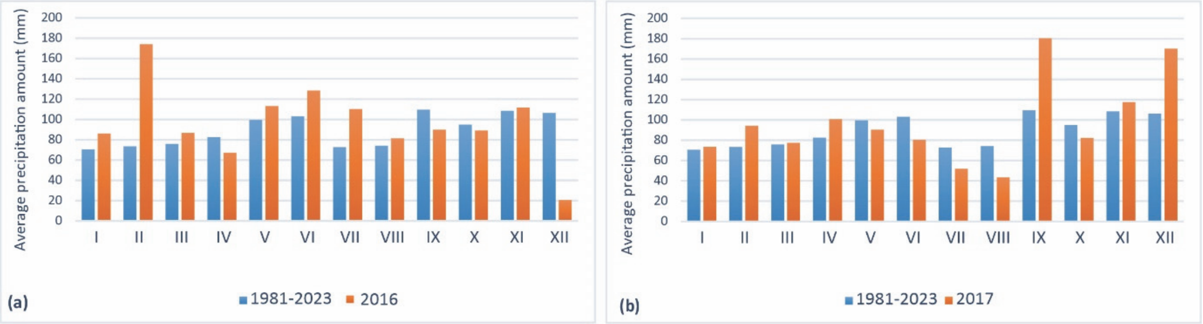

Fig. 5. Comparison of average precipitation amounts per month (1992–2022) with the reference years (2016 and 2017)

To confirm the occurrence of meteorological drought, the *SPI* was calculated. The input meteorological data for *SPI* calculation are previously validated CHIRPS data. *SPI* was calculated for the years 2016 and 2017 (*Fig. 6*). The *SPI* values for 2016 range from -1.73 to 2.69, and for 2017, they range from -0.85 to 1.25. According to *McKee et al.* (1993), drought occurs when the *SPI* value is less than 0. During 2016, *SPI* <0 was identified in April (-0.75), August (-0.14), September (-0.21), October (-0.24), and December (-1.73). For 2017, *SPI* <0 was identified in May (-0.31), June (-0.63), July (-0.85), August (-0.81), and October (-0.31).

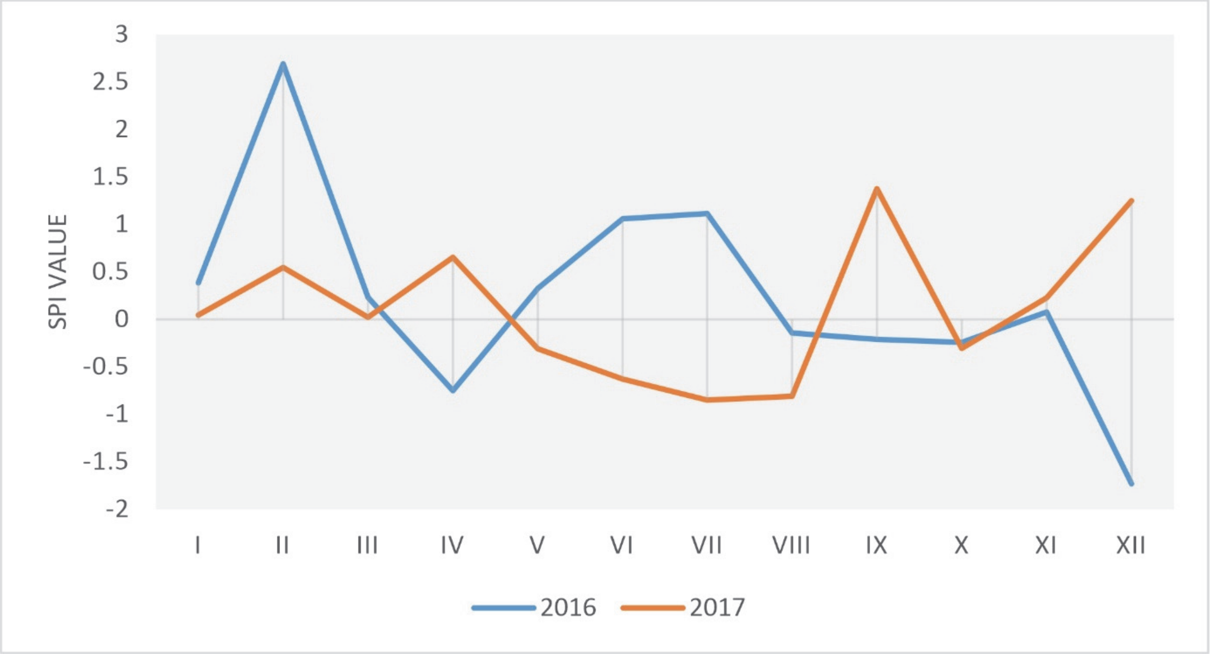

Fig. 6. Monthly *SPI* values (2016 and 2017).

To identify hydrological drought, a comparison of the average water level for 18-year period (2001–2019) with the average water level of 2016 and 2017 was conducted (*Fig. 7*). During 2016, at the location of the hydrological station in Prijedor (*Fig. 7a*), lower average water levels were identified in January (-12 cm), April (-72.7 cm), June (-27.1 cm), September (-4.1 cm), and December (-94.9 cm). In the same year, at the location of the hydrological station in Sanski Most (*Fig. 7b*), lower average water levels were identified in January (-21.1 cm), March (-4.5 cm), April (-55.2 cm), June (-31.6 cm), July (-0.4 cm), August (-2.7 cm), September (-11.3 cm), November (-1.6 cm), and December (-62.3 cm). During 2017, at the location of the hydrological station in Prijedor (*Fig. 7c*), lower average water levels were identified in January (-80.5 cm), June (-45.7 cm), July (-12.4 cm), August (-12.1 cm), and October (-7.4 cm). Similarly, in the same year, at the location of the hydrological station in Sanski Most (*Fig. 7d*), lower average water levels were identified in January (-58.1 cm), March (-6.5 cm), April (-23.2 cm), May (-13.4 cm), June (-35.6 cm), July (-41.4 cm), August (-41.7 cm), September (-31.3 cm), October (-24.5 cm), and November (-19.6 cm).

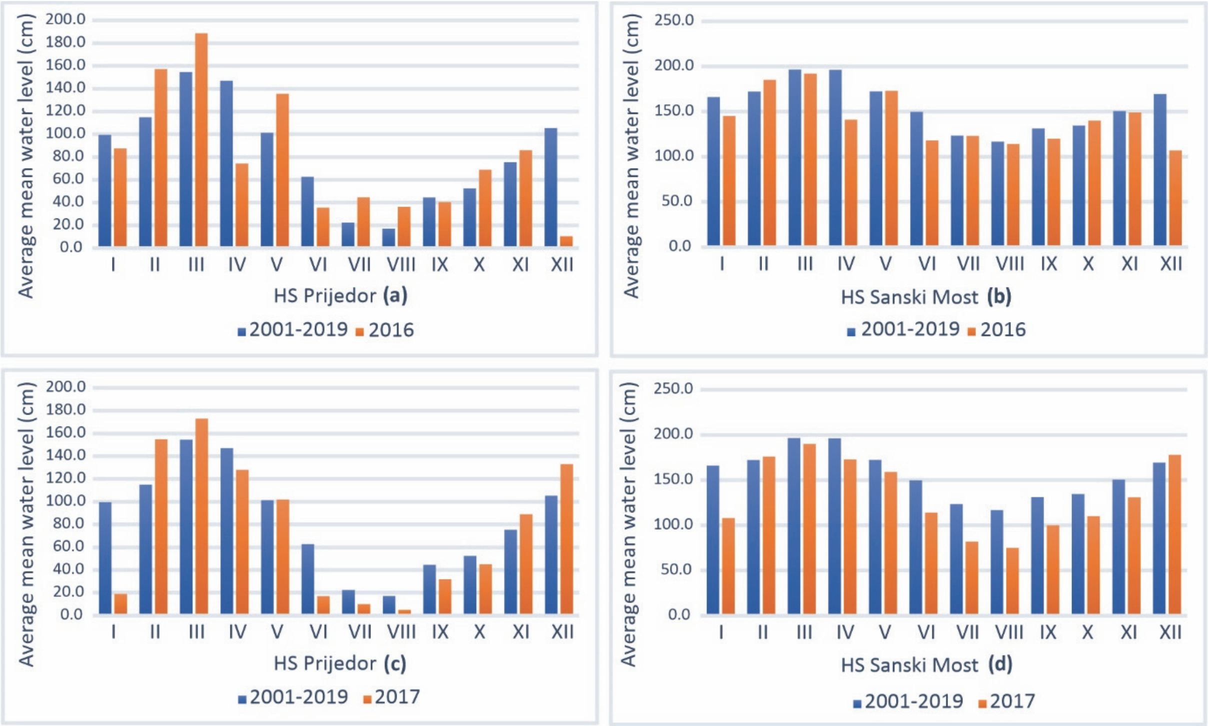

Fig. 7. Comparison of average mean water level (2001–2019) with the reference years (2016 and 2017) at the Prijedor and Sanski Most hydrological stations.

According to the results of *Ducić et al.* (2014), frequent occurrences of severe and extreme meteorological droughts have been evident in B&H during the last decades. There has been an increasing number of dry days, while the number of days with intense rainfall has also increased (*Trbić et al.*, 2013, 2014;

Popov et al., 2019). The occurrence of these phenomena in B&H, coupled with rising temperatures, leads to more intense and extreme droughts, especially during the summer period (*Trbic et al.*, 2022). During the past decade (2001–2010), *Žurovec et al.* (2011) identified 24 months as dry in central B&H. In the recent past, *Điderlija et al.* (2023) identified a lack of precipitation, negative *SPI*, and high temperatures during 2017 in the Sarajevo canton area of B&H. Similarly, in the basin of the Sana River, during 2016 and 2017, deficiencies in precipitation and negative *SPI* were observed at the monthly level, indicating the occurrence of meteorological drought. Considering the time series, these occurrences were not temporally continuous during 2016, and therefore did not show characteristics of severe meteorological drought. In contrast, during 2017, reduced precipitation and negative *SPI* were identified continuously over a four-month period (from May to August). The occurrence of meteorological drought with this duration can have serious consequences for the geographical environment and the occurrence of other types of droughts. According to the results of *Čadro et al.* (2017), in the time period from 1961 to 2010, the occurrence of hydrological drought was noted several times in the lower course of the Sana River. Within the results of this research, there is a clear temporal coincidence of periods with lower precipitation and lower water levels in the main course of the Sana River during 2016 and 2017. This phenomenon indicates that meteorological drought influenced the occurrence of hydrological drought. Taking into account the presented results regarding the occurrence of meteorological and hydrological droughts during 2016 and 2017, as well as the agricultural potential of this geographical environment (*Korjenić*, 2012), it is assumed that these occurrences could have significantly affected the occurrence of agricultural, as well as socio-economic drought during the reference years.

The identification, mapping, and monitoring of agricultural drought at the study area level were conducted by calculating the *TCI, VCI*, and *VHI* indicators. Taking into account the planting and harvesting calendar of major crops in B&H (*Bajić et al.*, 2022), agricultural drought monitoring with the calculation of these indicators was performed with an instantaneous assessment in July of the reference years.

Monitoring agricultural drought involved creating maps categorizing drought according to *TCI* and *VCI* values (*Fig. 8*). The initial results of *TCI* and *VCI* (*Fig. 8a-d)* range numerically from -1 to 1. According to *Karnieli et al.* (2006), negative *TCI* values indicate vegetation stress. In this regard, high temperatures can worsen vegetation dryness, leading to elevated vegetation stress levels. Similarly, negative *VCI* values indicate stress and poor vegetation conditions. Conversely, positive values of these indices represent healthy or "unstressed" vegetation, indicating areas free from agricultural drought. Spatially, negative *TCI* values (< 0) during 2016 (*Fig. 8a*) prevail in the southern part of the river basin, while during 2017 (*Fig. 8b*), they dominantly cover the entire river basin area, indicating pronounced drought. On the other hand, negative *VCI* values (<0) during 2016 (*Fig. 8c*) are negligibly present in the southern part of the river basin, while during 2017 (*Fig. 8d*), they are present throughout the river basin area, with dominant spatial outlines in the valley of the main stream of the Sana River.

Values of spatially represented indices (ranging from -1 to 1) were reclassified according to the recommendation of *Kogan* (1995a) into the following categories: extreme drought, severe drought, moderate drought, mild drought, and areas without drought (*Fig. 8e-h*). During 2016, according to the *TCI* results (*Fig. 8e*), mild and moderate droughts were identified in the river basin area, with these types of drought present in the southern, eastern, and central parts of the basin. Similar results during the same year were observed with the *VCI* indicator (*Fig. 8g*). "Small signs" of drought with negligible consequences are visible in the southern and southwestern parts of the basin. During 2017, according to the *TCI* results (*Fig. 8f*), a dominant spread of severe and extreme droughts was identified throughout the river basin area. These results were confirmed by the *VCI* results (*Fig. 8h*), based on which the occurrence of severe and extreme drought in the river basin area was identified. The lack of precipitation, low *SPI* values, and a decrease in the water level of the main stream (from May to August) are the main causes of the occurrence of extreme vegetation stress, manifested by the deterioration of vegetation "health" throughout the basin, especially in the northeastern, western, and southeastern parts of the basin. The occurrence of extreme drought is dominant in the valley of the main stream of the Sana River.

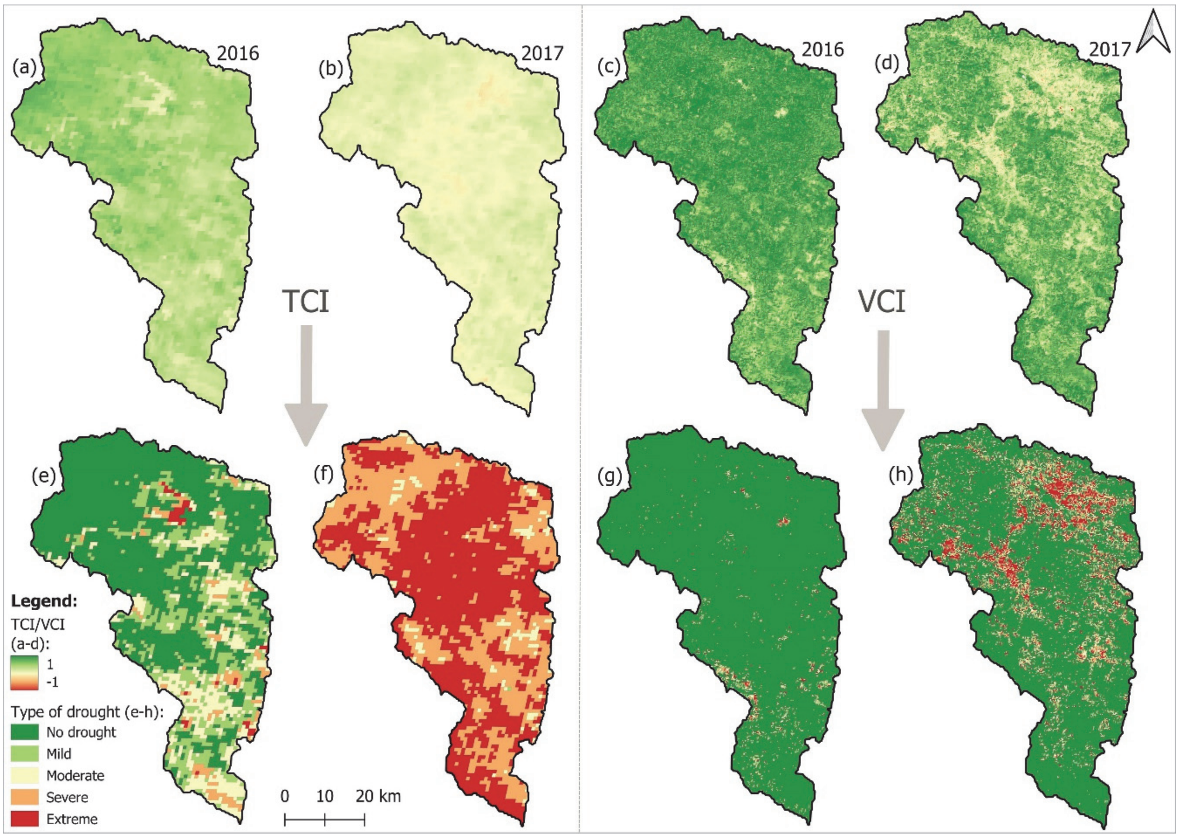

Fig. 8. Mapped and reclassified results of *TCI* and *VCI* for the year 2016 and 2017.

The overall “picture” of the negative impact of agricultural drought at the river basin level was obtained by calculating the *VHI* and creating a map of different drought types based on the results of this index (*Fig. 9*). The initial results of *VHI*, like other indices, range numerically from -1 to 1, where negative values indicate poor vegetation conditions, and positive values indicate good vegetation conditions. During 2016 (*Fig. 9a*), negative values were noticeable in a negligible spatial extent in the southern part of the river basin. In contrast, during 2017 (*Fig. 9c*), negative values were noticeable throughout the entire river basin area. Like *TCI* and *VCI*, the *VHI* index was reclassified into different drought categories according to the recommendation of *Kogan* (1995a) (*Fig. 9b,d*). According to the results from 2016 (*Fig. 9b*), the category representing areas without drought dominates the entire river basin area. The presence of mild and moderate agricultural drought categories is observed in the southern part. On the other hand, according to the results from 2017 (*Fig. 9d*), a significant drought occurrence is visible. Almost the entire river basin area is affected by some category of drought (mild, moderate, severe, or extreme). Severe and extreme droughts predominate in the area of the main stream of the Sana River.

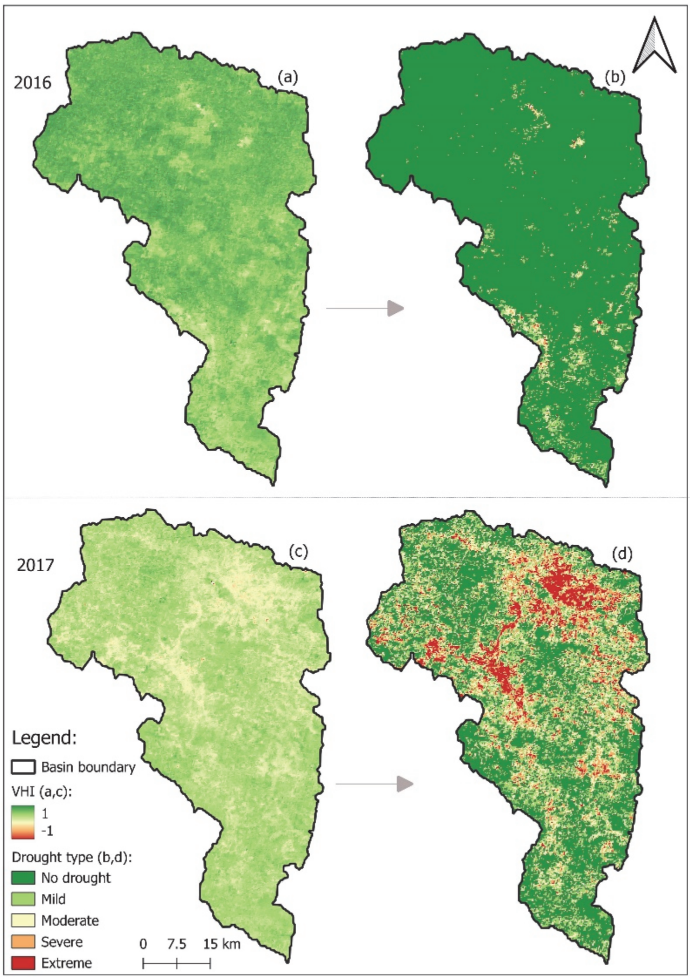

Fig. 9. Comparison of *VHI* indicator results (2016 and 2017)

Seiler et al. (1998) confirm in their research results that the *VHI* (by combining *TCI* and *VCI*) closely aligns with precipitation patterns in the studied areas, and it is of crucial importance in characterizing the spatial extent and severity of agricultural droughts. Additionally, *Tsiros et al.* (2004) and *Parviz* (2016) have confirmed in their research results that *VCI* and *TCI* in combination yield satisfactory outcomes at the global level when used for drought identification, assessing the impact of weather on droughts, and evaluating vegetation conditions. According to *Gidey et al.* (2018), previous studies have shown that low values of *VCI* and *TCI*, or warm weather, largely indicate stressful conditions for vegetation and eventually the occurrence of agricultural droughts. Similarly to the results of the mentioned authors, through the results of this research at the level of the Sana River basin, a high degree of mutual alignment of *TCI, VCI,* and *VHI* has been demonstrated, as well as alignment with precipitation patterns and water level. The calculation of *SPI* successfully identified the occurrence of meteorological drought, and the consequent occurrence of hydrological drought. These droughts acted as triggers for the occurrence of agricultural drought, which was successfully identified by calculating *TCI, VCI,* and *VHI. Marufah et al.* (2017) have shown through their research results that it is possible to establish the duration, spatial distribution, severity, and category of agricultural drought using VHI. Similarly, during 2016 and 2017, the spatial extent of agricultural drought was identified in the Sana River basin. Moderate drought was observed in 2016 to a negligible extent, while severe and extreme drought were observed dominantly in the Sana River valley in 2017.

During 2017, agricultural drought resulted in the manifestation of socio-economic drought. According to the report of the Ministry of Foreign Trade and Economic Relations in Bosnia and Herzegovina (MOFTER, 2017), there was a decrease in yields and total production of crops, vegetables, fruits, and grapes at the national level. The most significant negative impact of the drought was observed in the corn crop, with a yield of 3.7 t/ha, which was 39% lower than the yield achieved in the previous year. The reduced corn yield per hectare also led to a 40% decrease in the total corn production. The yield of wheat was lower by 6%, with a yield of 4.1 t/ha, while the yield of potatoes was lower by 21%, with a yield of 9.6 t/ha, during 2017 compared to 2016. Additionally, according to the aforementioned report, significant crops with a decline in yields included: soybeans (-36.95%), carrots (-35.92%), green corn (-33.35%), peas (-29.51%), grass-clover mixtures (-29.40%), cabbage (-26.15%), tobacco (-23.97%), white onion (-23.40%), black onion (-21.45%), alfalfa (-21.21%), tomatoes (-19.10%), clover (-18.56%), peas (-13.27%), green lettuce (-11.07%), peppers (-10.85%), cucumbers (-10.79%), strawberries (-4.19%), and watermelons (-2.13%).

Monitoring of socio-economic drought at the level of the Sana River basin was conducted by comparing agricultural yields at the study area level for the period of 2016 and 2017 (*Fig. 10*). Yield data were aggregated at the municipal level and included the yields of the following crops: wheat, corn, barley, potatoes, apples, pears, and plums. During 2017 compared to 2016, a decrease in potato yield by 26.39% (18707 – 13770 t), corn by 41.36% (92803 – 54416 t), barley by 1.13% (6885 – 6807 t), potatoes by 20.76% (61692 – 48882 t), pears by 19.57% (4507 – 3625 t), and plums by 63.07% (25650 – 9472 t) was identified. A negligible increase in apple yield was observed during the observed period, specifically by 2.02% (9134 – 9287 t).

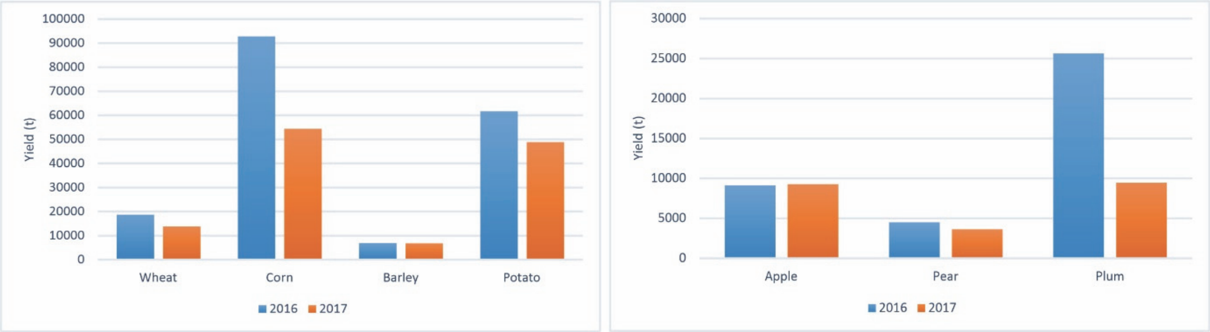

Fig. 10. Comparison of agricultural production yields for selected crops

The presented data clearly indicate that the occurrence of agricultural drought had serious consequences for agricultural yields in 2017, and that it also contributed to the manifestation of socio-economic drought. The sensitivity of the agricultural sector to drought is largely reflected in its dependence on land and water resources affected directly or indirectly by drought. Additionally, according to *Zurovec et al*. (2015), significant challenges for the agricultural sector in B&H stem from the complex governance structure, whereby all levels of authority (from local to national) have jurisdiction over planning and management in agriculture. For these reasons, it is necessary to invest additional efforts in activities, measures, processes, and plans aimed at mitigating drought. Some examples of good practices and implemented activities include establishing methods for calculating drought indices, processing time series data, analyses and mapping (using GIS), as well as using software for irrigation planning during crisis situations. By enhancing the capacity for drought preparedness and management, including the formulation of comprehensive manifestation plans at the local and national levels, B&H could further develop comprehensive vulnerability assessment approaches that incorporate remote sensing methods and techniques for drought monitoring and management. This would entail the implementation of effective mitigation strategies, as well as the creation and improvement of policies for planning and responding to crisis situations.

5. Conclusion

Modern technologies and data collection methods, such as GIS and remote sensing, offer the possibility of advanced monitoring of natural disasters like droughts. Using these technologies, it is possible to identify and track negative occurrences in space, conduct assessments of their harmful impact, and assist in the development of projects to rehabilitate degraded areas. So far, there is a limited number of drought studies in the territory of B&H, while integrated research based on remote sensing about droughts, their causes, and consequences is almost non-existent for now.

Spatio-temporal monitoring at the study area level for a defined time period (2016 and 2017), through satellite data processing, identified the onset of drought. CHIRPS satellite precipitation data, available from 1981 to nearly real-time, enabled efficient monitoring of precipitation changes over a wide time range (1981–2023). Based on the mentioned data, a precipitation deficit was identified for the observed time period (2016 and 2017), the standardized precipitation index, SPI, was calculated, and the occurrence of meteorological drought was established. The lack of precipitation led to a decrease in the average mid-level water level of the Sana River, and consequently, the the occurrence of hydrological drought. These events directly impacted the manifestation of agricultural drought during the period of intensive agricultural activities (planting and harvesting). Processing MOD13Q1 and MOD11A2 satellite data calculated various temperature and vegetation indices, and the occurrence of agricultural drought was identified and mapped. It should be noted that higher spatial resolution of satellite data for mapping agricultural drought would contribute to more precise results of spatial drought identification compared to those presented in this study. The identified agricultural drought affected agricultural production, through reduced yields, and consequently led to the onset of socio-economic drought. By analyzing statistical yield data, socio-economic drought was identified in the study area, with a deficit in yields of wheat, maize, barley, potatoes, pears, and plums.

The results of the research can be valuable to relevant institutions for drought monitoring, timely warning of its occurrence, and for the development of studies for drought adaptation and mitigation in river basin areas. Further advancement in research based on the presented results would involve the application of supervised classification processes of land use with elements of precision agriculture. This process would entail detailed classification of various agricultural crops in the study area. Integrating this type of classification into the presented research would contribute to a clearer spatial identification and reflection of agricultural drought on individual agricultural crops in the study area.

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