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TOOL FOR DROUGHT MONITORING IN THE DANUBE REGION – METHODS AND PRELIMINARY DEVELOPMENTS

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Abstract

Drought is a naturally recurring phenomenon of the climate system that affects virtually all regions of the world. During the past decades extreme droughts with extensive negative effects on ecosystems became evident also in the Danube region. At the moment regional capacity to monitor drought is still very diverse and not synchronised among different countries. In this is paper, we present a recently developed drought monitoring tool – the Drought User Service (DUS) for the Danube region using remote-sensing products which aims at offering a more accurate and in near-real-time monitoring via different drought indices. The DUS was created as the monitoring tool of the risk-based paradigm, which seeks to give information in near real-time about the location and severity of droughts throughout the Danube region. Satellite remote sensing products meet the requirements for operational monitoring because they are able to offer continuous and consistent measurements of variables, which can be used to assess the severity, spatial extent and impacts of drought. In the DUS three different variables – vegetation, soil moisture and precipitation – are monitored with earth observation products. The condition of vegetation and soil moisture is tracked with two simple indicators computed as long-term anomalies of the NDVI and SWI products made available through EU's Copernicus Global Land Service. The importance of DUS and of the developed methods for faster detection of drought onset as useful foundation for establishing a better pro-active drought management in order to mitigate the negative effects of drought in the region is discussed.

Keywords: drought monitoring, drought impacts, drought management, satellite data, Drought User Service

INTRODUCTION

Drought has been a recurrent phenomenon in the Danube region and its characteristics in the last decades are changing. It has become more intense and is developing more frequently. According to recent findings related to climate change, drought is likely to become more frequent and severe in the 21st century in many regions of the world, especially in water-scarce and already vulnerable areas that include parts of Europe (IPCC, 2014). In the current climate, summer water scarcity is already a problem in the Danube basin but its duration and magnitude are projected to increase especially in the southern and eastern part of the Danube basin (Bisselink et al., 2018; van Lanen and Vogt, 2018). Despite the impacts on the economy and welfare of people caused by drought in the last decades, drought is still not considered an issue of high priority, people remain reactive in their actions and any measures are carried out only when drought has already developed. In the last years, there have been important efforts both in the scientific and technical field in relation to drought. Unfortunately, a universal definition of drought is difficult to formulate due to the range of drivers and impacts that a drought event may have (Sepulrce-Canto et al., 2012). Drought projects increase the knowledge on drought in different research areas and regions, providing additional monitoring tools and management experiences for policy-makers and water related managers in the EU i.e. DROUGHT-R&SPI (Drought - R&SPI, 2015), DEWFORA (Dewfora project, 2013), PESETA (Watkiss et.al., 2009) and regional cooperation programmes such as EUROCLIMA (European Commission, 2018), as well as several national initiatives. Findings from the projects have advanced the knowledge base with better access to information, guidelines and services on (van Lanen et al., 2017): drought monitoring, prediction and early warning, drought impacts and links with the hazard, drought risk assessment, risk reduction and drought response and policy, and planning for drought preparedness and mitigation across sectors.

As a result, a range of indicators is used to detect and monitor agricultural drought, which are typically based on meteorological observations and estimates from remote sensing and modelling. The status of drought monitoring in the Danube region is still in its early stages, characterised by cross-border inconsistency with products that are often not delivered on time. Furthermore, methodologies for drought risk assessment and drought impact assessment are not harmonised across the region. Drought management in the region is reactive, dealing mainly with losses and damages, cooperation among key actors is missing and formal legislation considers drought only partially and insufficiently. Aiming at overcoming these weaknesses was the main motivation for launching of the project DriDanube – Drought Risk in the Danube Region (DriDanube, 2018). The paper presents some of its results, focusing on a new monitoring tool – the Drought User Service (DUS) that makes use of the earth observation operational products from the EU's Copernicus Global Land Service: the Soil Water Index (SWI) and the Normalized Difference Vegetation Index (NDVI). SWI and NDVI long-term anomalies can be used as indicators for operational drought monitoring and early warning across 10 countries in Danube basin. The DUS presents to the public near-real-time information on drought via an online portal: www.droughtwatch.eu. Timely, relevant and reliable drought information will be vital for detection and alert systems at the core of response activities in the Danube region.

RESEARCH AREA

To provide context for the consideration of drought detection, an overview of the regional climate is given. The research area covers almost the entire catchment area of the Danube River and includes the territories of 10 countries: Czech Republic, Slovakia, Austria, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro and Romania (Fig. 1). Generally, most of the Danube basin is dominated by a continental climate, only the western parts of the upper basin and its southwestern part are influenced by the Atlantic climate or by the Mediterranean climate, respectively. Annual precipitation depends mainly on orographic features and ranges from less than 200 mm per year to over 2000 mm per year. The rivers fed by water and moisture from the wet mountains help to balance evapotranspiration deficits, typical for the Pannonian plain and the delta, in the dry lowlands (Danube Regional project, 2012). Eight extreme drought events that have occurred across various parts of the Danube region since 2000 have caused extensive damage to natural ecosystems and diminution of agricultural production and in many countries also disturbance of surface and groundwater supplies.

REMOTE SENSING DATA AND DROUGHT INDICATORS

Recently developed platform called Drought User Service (DUS) is an innovative web-based tool for the viewing and analyses of the drought related spatial datasets. The purpose of the tool is to upgrade the systems for monitoring of the drought in the Danube region with the goals of mitigating the effects of drought and preparing potential users for timely reaction. The development was followed a pre-set plan, roughly composed of three consecutive phases. First, we were interested in the ideas and demands of potential users. We collected these with a web-based questionnaire comprising of 35 questions related to the basic information about the user, information about their experience in working with Earth Observation data, and questions concerning the components of the planned system, its tools, and data usage (analyses). We have sent the questionnaires to all project partners and other potential users, including national hydrological and meteorological services,

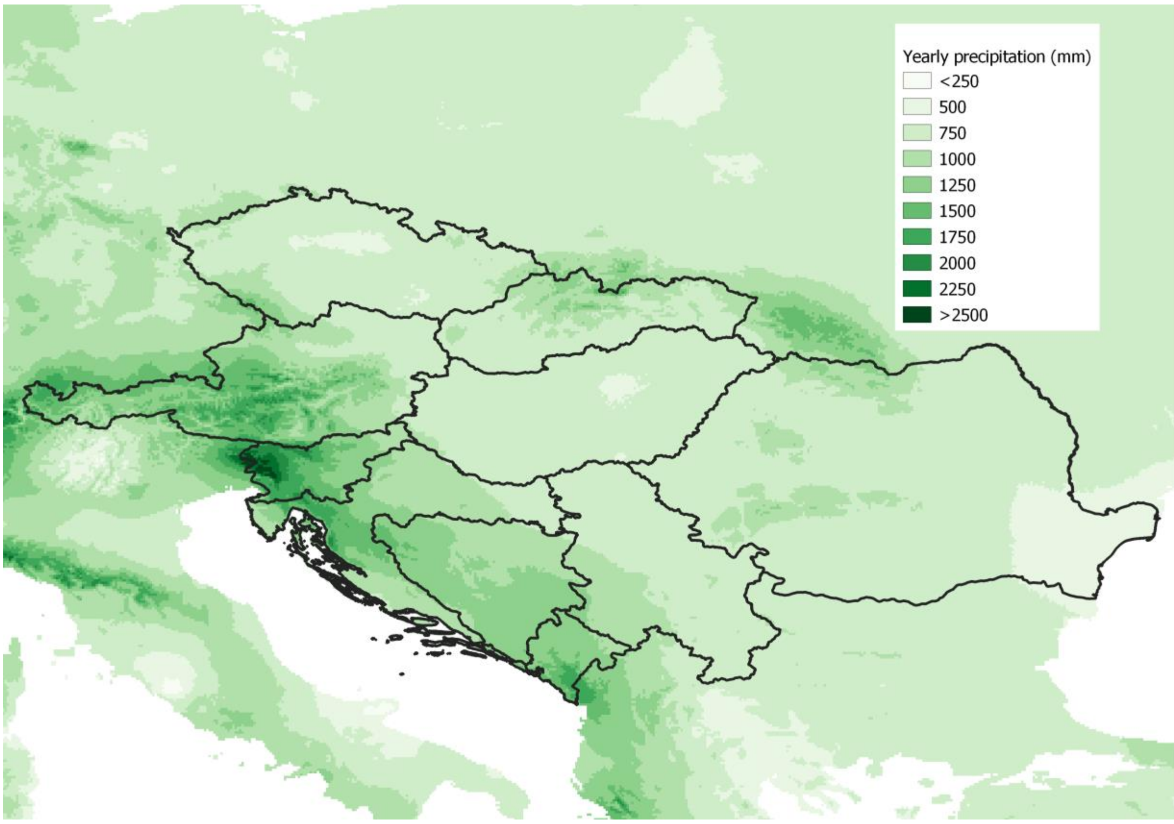

Fig. 1 Annual precipitation map (shades; average for period 1971-2000) and political boundaries (black line) of the region and countries, participating in preparation of Drought User Service (Source of precipitation data: worldclim.org; Fick and Hijmans, 2017)

environmental agencies, other governmental agencies, international and non-governmental organizations, and research institutions. 47 institutions from 10 European countries responded. The analysed results were translated into the priority scale of the requirements, based on the MoSCoW method, in which the requisites are divided into four categories: must-have, should-have, could-have and will-not-have requirements (Bittner and Spence, 2004).

DUS offers near real-time information about drought conditions with two remotely sensed indices: the Soil Water Index (SWI) and the Normalized Difference Vegetation Index (NDVI). This section describes these indices, their usefulness and implementation for drought monitoring in the Danube region. The data source for both SWI and NDVI products are made available through the Copernicus Global Land Service (GLS).

Soil Water Index (SWI) anomalies for soil moisture monitoring in drought conditions

Soil moisture (SM) is an important element in the Earth's system. Its key role in the hydrological, carbon and energy cycles and their interaction led to its recognition as an Essential Climate Variable in 2010 by the Global Climate Observing System (e.g. Leghates et al., 2011; Seneviratne et al., 2010). Furthermore, soil moisture is one of the indicators used to monitor, forecast and characterise drought. Operational online drought monitoring tools around the world incorporate information on soil water content from modelled and/or remote-sensing-based estimates: e.g. the US Drought Monitor, the European Drought Observatory (Vogt et al., 2011), the African Flood and Drought Monitor.

SM estimates are available from in-situ measurements, atmospheric and hydrological models, and satellite imagery and are characterised by method-specific advantages and limitations (e.g. Leghates et al., 2011; Nghiem et al., 2012; Petropoulos et al., 2015). The satellite-based SM products are most commonly retrieved from microwave activate and passive sensors (e.g. SMOS – Kerr et al., 2010; SMAP – Entekhabi et al., 2010; AMSR-E – e.g. Njoku et al., 2003; ERS and ASCAT– e.g. Wagner, 1998) and offer the advantage of continuous temporal and spatial measurements (in contrast to e.g. point-measurements from in-situ networks which are not representative over an area due to the high spatial variability of soil moisture).

The Copernicus SWI product provides global daily information on moisture conditions at different soil depths at a spatial resolution of 0.1 degrees (Paulik, 2017). The SWI data used to calculate the SWI anomalies displayed in DUS uses as input the ASCAT-25km surface soil moisture (SSM), a remote-sensing product (Bartalis et al., 2008) provided operationally in near real-time by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The ASCAT scatterometer on board the Metop satellites (Metop-A and Metop-B) is a real aperture radar that operates at 5.255 GHz (C-band) and uses six vertically polarised antennas for transmission and reception of long pulses that after several specific steps (as described in e.g. EUMETSAT, 2015; Wagner et al., 2013) become backscatter coefficients (σ^0) given in units of decibels (dB). Exploring the underlying high sensitivity of microwaves to the water content in the most upper layer of the soil (1-2 cm) these backscatter measurements are then transformed into surface soil moisture estimates with the TU Wien method by Wagner et al. (1999a,b,c) originally developed for the ERS-1/2 AMI instruments and further improved by Bartalis (2006, 2007) and Naeimi et al. (2009a,b). However, besides soil moisture, the microwaves are sensitive also to other factors such as the surface roughness and vegetation cover; the TU Wien's SSM retrieval model is a change-detection model which minimises these effects by interpreting changes in backscatter (σ^0) over time as detailed in Wagner et al. (2013).

SWI gives information on the moisture conditions available to plants in their root-zone which has proved to be useful for characterising agricultural drought (e.g. Gouveia et al., 2009). Based on the method proposed by Wagner (1999b), the SWI algorithm uses an infiltration model that describes as a function of time the relation between the soil moisture observed at surface and the profile soil moisture. Thus, using a two-layer water balance model, the SSM observations are transformed into SWI with Eq. (1).

$$\mathrm{SWI}_{(t_n)} = \frac{\sum_i^n \mathrm{SSM}_{(t_i)} e^{\frac{t_n - t_i}{T}}}{\sum_i^n e^{-\frac{t_n - t_i}{T}}}, \text{ for } t_i \leq t_n \quad (1)$$

where t_n is the observation time of the current measurement and t_i are the observation times (in Julian days) of the previous measurements; all SSM observations made before t_n are summed up and exponentially weighted. The factor T determines the weights (e.g. for T = 5 the weight is equal to 0.135; where 10 is the number of days SSM was taken before t_n) and how much SSM observations taken in the past influence the current SWI value.

For near real-time operations, the SWI can be calculated with a recursive formulation (Eq. 2) (Albergel et al., 2008, Paulik, 2017):

$$\mathrm{SWI_T}(t_n) = \mathrm{SWI_T}(t_{n-1}) + \mathrm{gain_T}(t_n)(\mathrm{SWI}(t_n) - \mathrm{SWI_T}(t_{n-1})) \quad (2)$$

where t_n and t_(n-1) are the observation times of the current and previous SSM measurements, respectively.

Agricultural drought follows the meteorological drought and is characterised by drying of soil which results in a reduction in vegetation growth and in crop and biomass production (Mishra and Singh, 2010; Van Lanen et al., 2017). In DUS, long-term anomalies of SWI are used as indicator of drought. The long-term anomalies are used, rather than current absolute values as they reflect better the positive and negative variations in soil water content in a historical context, and thus of drought conditions. These are computed daily (Eq. 3) as the difference between the SWI (T=10) value for a certain day (e.g. 1 March 2018) and the long-term average for the same day over values since 2007 up to the last full year (e.g. for a value in 2018 the period considered is 2007-2017; Copernicus SWI product is available only since

2007). Before anomaly computation the data is masked for frozen soil and temporary water on the surface using the Surface States Flags (SSF) as described in Paulik (2017).

$$\mathrm{SWIanomaly_t} = \mathrm{SWI_t} - \overline{\mathrm{SWI}} \quad (3)$$

where $\mathrm{SWI_t}$ is the SWI value of day t of the current year, and $\overline{\mathrm{SWI}}$ is the long-term average of SWI. According to the definition of the SWI, the SWI Anomaly represents values expressed as units of degree of saturation. In the DriDanube's Drought User Service the SWI Anomaly values are displayed as daily maps. The maps depict with brown shades the SWI anomalies as percentage up to -25% less than long-term average and with blue shades up to 25% more than the long-term average; zero represents no change in soil moisture conditions from the long-term mean.

The SWI product has certain limitations, which have to be considered for the interpretation of SWI anomaly indicator presented here. These are related to the model definition of the SWI; e.g. soil texture that defines the relationship between value T and soil depth is not taken into account, and therefore the availability of values which allows the user to select and compare the best data. Also, evapotranspiration is not considered by the SWI algorithm which can lead to false high values when precipitation and satellite observation times coincide and the rainfall evaporates rather than infiltrate into the deeper layers of the soil. Furthermore, as already mentioned at the beginning, vegetation has a strong influence on the radar signal of which the annual cycle in the base product – the ASCAT SSM – is considered to be the same for each year; however, if this deviates significantly form the average the retrieval of SSM becomes biased.

The SWI product, as well as its underlying ASCAT SSM product, has been extensively validated in numerous studies against external data sets including in-situ soil moisture measurements in Paulik et al. (2017 and all other studies therein referenced). The products show good correlations with both modelled and ground measurements, except arid areas and for the northern latitudes. The accuracy of the product was reached for 75% of the sites when the target was set to 0.1 m^3/m^3, while a target of 0.2 m^3/m^3 was obtained for 98% of sites (Paulik, 2017). Furthermore, the SWI product has a good temporal consistency that reflects well the seasonal cycle with the exception of very dry conditions. The spatial consistency is also good, however, SWI estimates are not reliable over high altitudes, dense forest and desert areas; and cannot be estimated for frozen conditions.

Normalized Difference Vegetation Index (NDVI) anomalies for vegetation drought monitoring

NDVI is the most straightforward way of detecting and monitoring vegetation from satellite measurements (Anyamba and Tucker, 2012) and represents the starting point of satellite-based indicators for drought monitoring. This simple metric has been present since the 1980s and was first formulated for AVHRR imagery by Tucker et al. (1979). Given its early development almost 40 years ago, this indicator has been widely studied for its utility in various applications: e.g. land cover classification, agricultural monitoring, biomass estimation or is included as input in land-surface or biophysical models (Anyamba and Tucker, 2012); or combined with other variables into more advanced indices (e.g. the Vegetation Condition Index by Kogan and Sullivan, 1993). NDVI has also proven to be valuable for detecting drought-induced stress to vegetation and therefore included in the Handbook of Drought Indicators and Indices– a general guide on commonly used drought indicators for identifying the spatial extend, onset, duration and severity of droughts meant for practitioners who deal with drought management (WMO and GWP, 2016).

NDVI, an index without physical units, is calculated from measurements of the spectral reflectances in the red spectrum (RED) and near-infrared (NIR) regions of the electromagnetic spectrum (Eq. 4) (Brown et al., 2013). Theoretically, the NDVI values range between -1.0 and +1.0, where an increased NDVI is a sign of biomass abundance, while a low NDVI marks the lack of vegetation or decrease of photosynthetic activity.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \quad (4)$$

The Copernicus Normalized Difference Vegetation Index (NDVI) product (Smets et al., 2018) are generated based on the SPOT/VEGETATION C3 and the PROBA-V C1 data separately. The NDVI values are provided for every 10-day period at a spatial resolution of 1/112 degrees (~ 1km), and represent the best measurement selected from 10 consecutive days based on the criteria detailed in Swinnen et al. (2017).

The usual way of using NDVI for drought detection and monitoring is to compute NDVI anomalies (Anyamba and Tucker, 2012). In DUS, the NDVI Anomaly indicator is based on the difference from the long-term mean which shows the current drought severity in a historical context. It is produced for every 10-day period and is calculated as the difference between a certain 10-day NDVI value (e.g. first decade of July 2017) and the long-term average (Eq. 5) over values since 1998 (Copernicus NDVI product available since 1998) up to the last full year (e.g. for a value in 2018 the period considered is 1998-2017). Before anomaly computation, the data is masked for cloud and cloud shadow, snow or ice and water using the Quality Flags as described in Smets et al. (2018).

$$\mathrm{NDVIanomaly_t} = \mathrm{NDVI_t} - \overline{\mathrm{NDVI}} \quad (5)$$

In Eq. 5 $\mathrm{NDVI_t}$ represents the 10-day NDVI value of the current year, and $\overline{\mathrm{NDVI}}$ is the long-term average of NDVI. Negative NDVI anomalies represent lower than average NDVI values and are an indicator for vegetation stress and lower than average photosynthetic activity. In DUS, the anomalies are displayed as maps for every 10-day period (decade). The maps depict with brown shades the NDVI anomalies as percentage up to -25% less than long-term average and with green shades up to 25% more than the long-term average; zero represents no change of vegetation conditions from the long-term mean.

Similar to the SWI product, the NDVI product is not free of shortcomings which are sensor dependent – the well-known inability of optical sensors to penetrate through clouds; additional factors such as – variations in solar zenith and viewing angles, surface reflectance bidirectional effects, atmospheric conditions, topography, data dropouts in cold regions – also influence the NDVI values. A full description of how are these addressed is available in Smets et al. (2018). The overall performance of the product is rated as "good" based on validation studies carried out against similar products e.g. the NDVI from MODIS /Terra - NASA and from AVHRR/Metop – EUMETSAT (CGLS, 2018).

RESULTS AND DISCUSSION

The drought monitoring tool DUS (Fig. 2), being developed within DriDanube project, increases the amount of new data and improves accessibility of existing data used in predicting and managing drought and its effects. The combination of data, new tools and previous research (e.g. Ceglar et al., 2012) enables the planning of more efficient control mechanisms, spatial interventions and management practices in the Danube basin. On the other hand, DUS serves the end users, such as various ministries, agencies, and farmers, to make decisions and take action on the ground. Most of the service data covers the entire Danube region and, due to their nature (mostly satellite data), they have great potential for further development and geographic expansion. This opens the possibility for the competent departments of different countries to engage at a higher level of cooperation between the integrated regions of one of the major river basins in Europe.

18 requirements were created from the user survey. Four of these are general, related to the availability of the service and user support. Six requirements relate to the data, their quality, temporal and spatial resolutions, availability basic cartographic data and auxiliary data. The respondents requested eight usability requirements, referring to the interaction of the user with the service (Hasenauer et al., 2017). When the initial user requirements were met, the project consortium followed up with the user trainings where the service has been reviewed. The collected feedback was later reviewed, categorized and implemented.

The results of the survey were the basis for the design of the technical solution. The Drought User Service is implemented with a combination of modern tools and technologies for web application development. The graphical user interface is composed with the HTML5 markup language and CSS3 cascading style sheets. The service is written in the JavaScript programming language and the developed in Aurelia framework. The use of online maps is enabled through the OpenLayers 4.6.4 library, and MapServer 7.0.7 platform is used to display the drought-related data provided through our own Web Map Service (WMS). The technologies used facilitate potential service extensions and long-term compatibility with other web tools. They are also available without licencing fees, have a wide range of users, and are actively developed and updated in line with modern trends.

The web interface displays three types of data. The first type includes the basic cartographic layers: Google Maps (obtained 2018), OpenStreet Map (OSM, 2018) and the Satellite Image Mosaic, based on Sentinel-2 data and

Fig. 2 Appearance of the Drought User Service portal

provided by EOX GmbH (EOX, 2017). The second type includes the various vector layers of administrative boundaries at different NUTS levels for the area of the Danube River basin (Eurostat, 2018). The last type are raster data layers for the study of drought at a range of temporal and spatial resolutions, provided by various institutions. These form the core of the planned upgrade of the system, which will include the analysis of drought and its impact, and provide a drought early warning system.

Additional data will therefore include information layers developed during the project. These will show the state of drought and related phenomena. The system is designed modularly and enables quick and easy integration of new data; either in the application itself or through online services for displaying and transmitting geographic information, e.g. WMS, Web Coverage Service (WCS), Web Feature Service (WFS).

In the DUS first observational year drought index SWI and vegetation index NDVI showed good spatial matching. In Figure 3. we see long-term anomalies of SWI index from May to September 2018 with 1-month intervals and in Figure 4. long-term anomalies of NDVI index for the same time frame as SWI index. In May 2018 SWI showed that areas with a level of soil moisture saturation lower than long-term average were scattered across Danube area. In same time period vegetation index NDVI showed higher values than long-time average across Danube region which are mainly caused by the earlier development of green mass due to higher temperatures in spring in this area. In June SWI index increased in almost all investigated areas and especially in north and west became positive or higher than the long-term average. NDVI index in June lowered and in some areas in the north, central and east region became negative and showed good correlation with SWI index. In July and August situation changed and SWI index in the north part of the region become negative, especially deep in the Czech Republic. At the same time index rises in south and east areas and became much higher than the long-term average in Romania, Bulgaria and Serbia. NDVI index in July and August stay in negative zone in northern parts of the region and slowly worsened and spread in the west and central parts. At the same time in the south and east parts index became positive which correlate with SWI index. In September SWI index slightly improved in almost all investigated areas with exception of the areas along East Adriatic coast and central Danube region, while NDVI index showed more negative anomalies in the north and central parts and less positive in east and south parts of the region.

The goal of development is to take a step further from the creation of a web browser. The DUS therefore enables the user to analyse and compare the displayed data. It is possible to overlay multiple layers, modify their transparency, and remove the selected layer to display underlying layers. The user can query the values of individual pixels or display and export a timeline graph for the selected pixel. Users can also download data to a desktop computer and analyse them in a Geographic Information System. When selecting a vector layer object, the records in the attributes table of this object are displayed. Individual data layers are provided with the basic descriptive information while descriptions that are more detailed are accessible from the application in the form of fact sheets. These describe the purpose, usability, the production method, technical information and product quality of an individual data layer.

The DriDanube project's objective is to create a framework for relevant stakeholders in the Danube region to increase their capacity to prepare better in case of drought events; in other words, moving from the traditional post-event crisis management to a pro-active risk-based management of droughts which includes several actions such as: preparedness, monitoring, risk-mitigation and response. As presented in this paper the

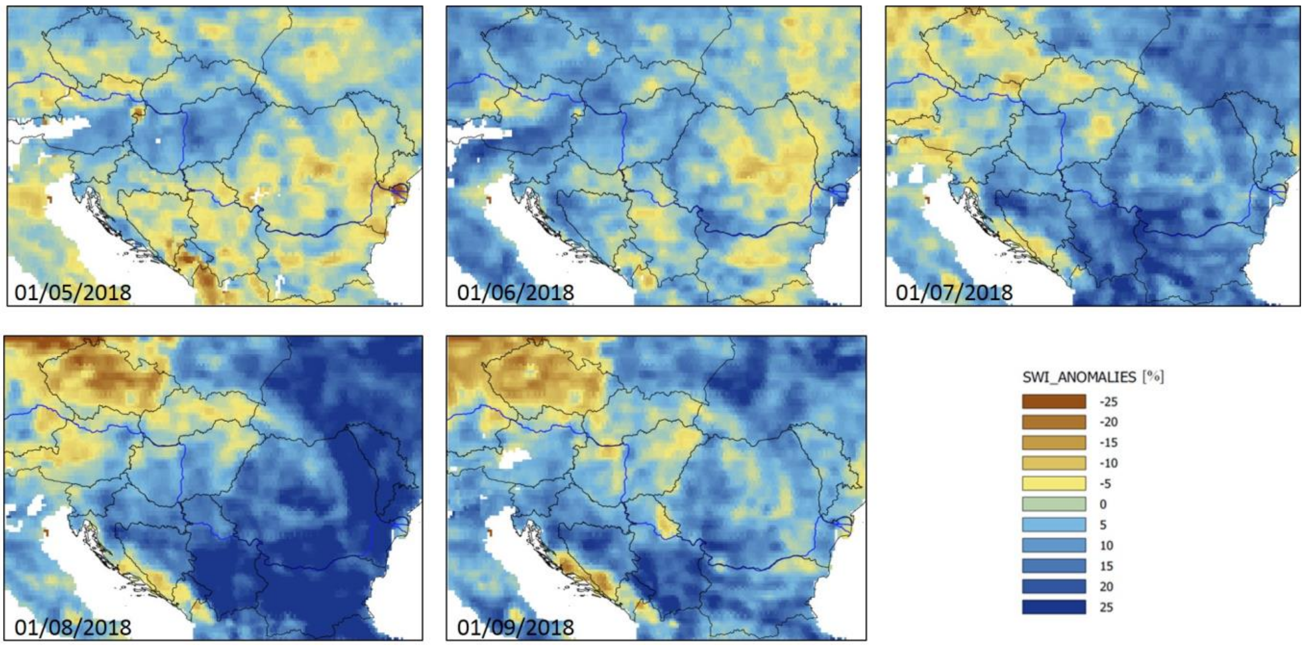

Fig. 3 SWI long-term anomalies on 1st of: May, June, July, August and September 2018 over the Danube region: brown shades represent lower than average soil moisture conditions and blue shades represent higher than average soil moisture conditions.

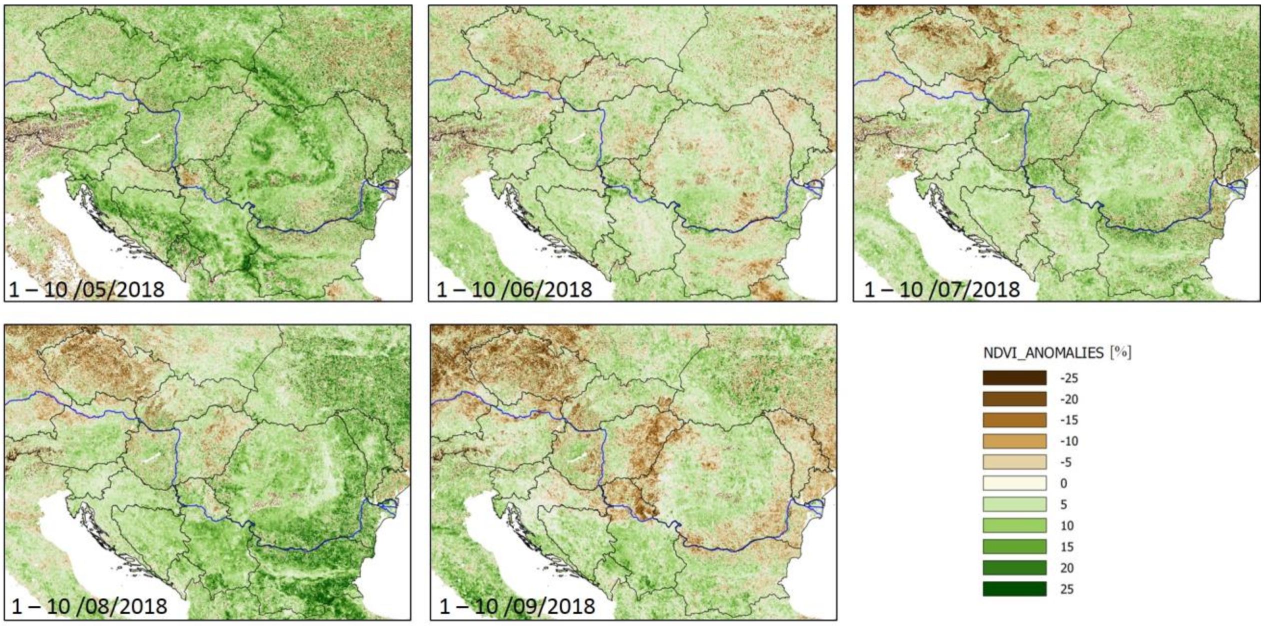

Fig. 4 NDVI long term anomalies for the 1st decade (1-10) of months: May, June, July, August and September 2018 over the Danube region: brown shades represent lower than average vegetation conditions and green shades represent higher than average vegetation conditions.

two indices were selected based on their well-known potential to characterised droughts. However, beside the limitations determined by their production (associated with sensor type, algorithm etc.), it is recognised that no one indicator or index can fully capture the complexity of droughts (e.g., Hayes et al., 2012). Additionally, in the DUS only long-term anomalies are available at the moment, however different other reference periods could be considered (10-days, weekly, monthly) and further investigated for their ability to monitor drought effects for example in relation to land cover types (e.g., crop types). Also, although the whole period available is considered for the calculation of NDVI and SWI anomalies, 19 and 11 year, respectively, it might still not be representative for drought events in the region. Considering different T values (at the moment $T = 10$ is used) for calculating anomalies could also be explored over different areas and land-cover types within the Danube region. Furthermore, one needs to take into account limitations of the earth observation products. For ASCAT surface soil moisture, the input of SWI, long-term positive trends have been observed over Europe especially located close to large cities. These positive trends in soil moisture, and thus backscatter, are likely caused by expansion of urban areas, where multiple scattering increases backscatter, and possibly Radio Frequency Interference. Currently, TU Wien is further investigating the source of these trends and how to correct for them.

In recent years, an increased demand for information at finer spatial resolution (field size) has emerged as in the case of agriculture monitoring. In the DUS, we have also presented for the first time SWI anomalies at 1 km spatial resolution which is based on the original SWI Anomaly indicator downscaled with parameters calculated from Sentinel-1. This approach combines the advantages of the Sentinel-1 high spatial resolution and that of the ASCAT high temporal revisit time and show promising results as described in Bauer-Marschallinger et al. (2018); the product is currently being prepared for operational dissemination through the Copernicus GLS (2018).

CONCLUSION

No single source of information is authoritative and comprehensive to identify potential drought area alone, especially given the climatological heterogeneity within the Danube basin. The DUS brings to the drought practitioners in the region indicators based on earth observation products that offer information on the current status of drought and enables them to compare current situation to past drought episodes. In addition to the near real-time monitoring, the portal also makes available the results of the impact and risks assessments carried out within the scope of the project. Conclusions on the drought situations are most confidently when many or all factors indicate a similar situation of dryness in a region. Any reduction of ambiguity associated with data and information used by DUS contributes to an improved linkage between early warning and early response. The drought monitoring approach improved by DUS through the integration of satellite data and developed impact databases can form the basis for decision support systems at a national level for producing reliable and useful information that is regional in scope and relevant for local decision-making.

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