

COMPARISON OF GEOVISUALIZATION METHODS FOR DROUGHT IMPACTS AND VEGETATION TRENDS USING COPERNICUS DATA

MASTER'S THESIS

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ChatGPT (OpenAI GPT-5.5) was used to support academic writing, language refinement, and assist with script development.

Hereby, I declare that this piece of work is entirely my own, the references cited have been acknowledged and the thesis has not been previously submitted to the fulfilment of the higher degree.

A handwritten signature in blue ink, reading "Emese Gojdár". The signature is written in a cursive style, with the first name "Emese" on the top line and the last name "Gojdár" on the bottom line.

I would like to express my sincere gratitude to my supervisors, Rostislav Néték (Department of Geoinformatics, Faculty of Science, Palacký University Olomouc) and Christoph Traun (Director of Studies, UNIGIS Professional, Department of Geoinformatics – Z_GIS), for their guidance, valuable feedback, and continuous support throughout the preparation of this thesis.

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Theses guidelines

The aim of the thesis is to develop, compare and evaluate different geospatial visualization methods for representing vegetation trends and drought impacts in Hungary, using Earth Observation data from the Copernicus programme. The focus is placed on the spatio-temporal geospatial analysis (e.g. NDVI). The goal of detecting changes in vegetation health over time and identifying areas most affected by water scarcity and environmental stress will be processed on technology/language selected by a student. The pilot study will identify and collect suitable Copernicus datasets covering Hungary. Then, various visualization approaches will be applied, including both static cartographic visualisation and interactive web maps. These methods will be designed, implemented, compared and evaluated in terms of their interpretability, clarity, and effectiveness in communicating results based on different target groups (expert and lay audiences, governments, media, ...). The thesis will reflect how geospatial visualization can support public awareness and decision-making related to environmental degradation and climate resilience. The expected outcome is a comprehensive set of visualization products accompanied by a critical assessment of their communicative strengths and limitations.

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LIST OF ABBREVIATIONS

ArcGIS	Geographic Information System platform
ArcPy	ArcGIS Python site package
CB	Copernicus Browser
CDI	Combined Drought Indicator
CDSE	Copernicus Data Space Ecosystem
CEMS	Copernicus Emergency Management Service
ECMWF	European Centre for Medium-Range Weather Forecasts
EDO	European Drought Observatory
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GIS	Geographic Information System
HDI	Hungarian Drought Index
IDW	Inverse Distance Weighting
JRC	Joint Research Centre
LAU	Local Administrative Unit
NDMC	National Drought Mitigation Center
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
OVF	National Directorate General for Water Management (Országos Vízügyi Főigazgatóság)
SMI	Soil Moisture Anomaly
SPI	Standardized Precipitation Index
SPI-1	One-month Standardized Precipitation Index
SPI-3	Three-month Standardized Precipitation Index
USDA	United States Department of Agriculture
USDM	United States Drought Monitor
VCI	Vegetation Condition Index
VHI	Vegetation Health Index

INTRODUCTION

Moving towards the interior of the European continent, Hungary also faces significant environmental challenges in terms of the daily lives of the population and the country's economy due to the environmental challenges of increasingly frequent droughts. Although there were also periods of outstanding drought at the end of the 20th century, which were sometimes followed by exceptionally good years or periods of flooding, these dry years did not show clear patterns until recent decades, which are mainly characteristic and stagnant after the 2000s and in the last 10 years or so. The decreasing precipitation and its uneven distribution have triggered environmental changes that are related to the country's topography and hydrology before the original river regulations. It is becoming increasingly clear that the effects of the drainage of the large Great Plain areas and the spatial changes of the river regulations after 1846 are having an impact today. At the same time, the impact of globalization, the spread of increasingly widespread invasive species and the displacement of native vegetation all lead to the conclusion that a strongly changing climate is currently developing in Hungary, and as a result, the Hungarian countryside as we know it is undergoing transformation. The continuously rising average temperature of the Earth's surface and the impact of weather extremes are also significant in the Carpathian Basin, and the factors listed so far are responsible for the fact that the water content of the soil in the country's areas and our rivers and canals are suffering from unprecedented degradation and reduction. The exceptionally dry year of 2022 and the significant lack of precipitation that year have shown that such intensive and large-scale processes may be initiated in agriculture, forestry, biodiversity and with regard to water resources and human well-being that they may be irreversible. (Kis et al., 2023) It is important to see from previous research but also from current trends that these environmental impacts no longer only affect agriculture, but also affect everyday life, from urban life to national parks, wetlands and mountain forests. Water scarcity and increasing droughts affect natural ecosystems, protected areas, floodplain forests, urban vegetation and landscape stability across the country. (Farkas et al., 2017)

Unfortunately, in the past 10 years, there has not been enough action at the decision-making level for rehabilitation, and in fact the opposite has happened with the neglect of the often unprofessionally managed water networks, and the concrete filling of canals in many places. Deforestation and untreated green areas without consulting or informing the population, as well as the urban heat island effects, all contribute to the increasingly difficult experience of summer heat. It is typical of the summers of recent years that the press and media's clickbait articles are full of various buzzwords such as "heat wave", "heat dome" and "tropical nights". Yet it seems that the population and political leaders do not trust or have not believed enough in researchers and scientific evidence. Although the current Hungarian meteorological service providers have drought monitoring systems, these are obtained from data sets produced by scientific institutions and most of the information remains for experts and researchers, these maps and radar images are often difficult to interpret and difficult to access for the average person. These drought maps provide data for scientific purposes with technical indicators and complex classifications, special queries. However, effective public communication of environmental changes is becoming increasingly important, as adaptation to climate change requires not only scientific knowledge, but also public awareness and understanding. Maps and appropriate data visualizations can bridge this gap by transforming complex environmental data sets into accessible and intuitive visual representations. (Farkas et al., 2017) The main objective of this thesis would be to develop visuals from accessible Copernicus data for drought mapping with freely available datasets provided by the Copernicus Emergency Services. And to create and find a cartographic solution that delivers information in an accessible and understandable way to ordinary people, based on which they can have adequate background knowledge to make objective decisions both from a political perspective and in terms of their own lives and adaptation strategies. All this is supplemented with maps that also illustrate the changes in vegetation by mapping the drought years examined, since the most direct effect can perhaps be observed in the behavior of grasslands and croplands during the summer periods.

1 OBJECTIVES

The primary objective of this thesis is to investigate how drought-related environmental information can be communicated more effectively using cartographic design and geovisualization, or mapping techniques. While numerous drought monitoring products are already available through academic institutions and operational monitoring services, relatively little attention has been paid to how user-friendly and popular different visualization methods are or how they influence the interpretation and understanding of drought-related information by non-expert audiences. The study focuses on the conditions in Hungary already discussed in the introduction and processes and uses two complementary Earth Observation datasets for mapping purposes. Mainly the study focuses on the conditions in Hungary already discussed in the introduction and processes and uses two complementary Earth Observation datasets for mapping purposes. The first dataset comes from the European Drought Observatory (EDO), which consists of the Combined Drought Indicator (CDI), which provides information on the frequency and severity of drought across Europe. The second dataset consists of vegetation change information from Sentinel-2 satellite images, using the Normalized Difference Vegetation Index (NDVI) provided by the Copernicus Data Space Ecosystem (CDSE) via the Copernicus Browser (CB). While the CDI dataset shows the progression and spatial distribution of drought areas, the NDVI-based analyses provide a direct representation of the vegetation response and environmental degradation associated with prolonged water shortages, which is expected to help map readers understand the direct impact of increasingly frequent drought years.

The current goal of the research is not to develop a new drought indicator or environmental remote sensing model, but to process and use currently available and available datasets in a way that focuses on visual communication and more effective transfer of information. The central research question is: *Which geovisualization method most effectively supports the understanding of drought impacts and vegetation trends for non-expert users?* To answer this question, cartographic products were developed using different visualization approaches, including point datasets and interpolation map layers following data processing and spatial analysis, from which the final products were static printed 2D maps and interactive web map outputs. The drought maps created depict the aggregated seasonal drought conditions between 2020 and 2025, covering the main drought periods from May to September. Instead of visualizing individual observation dates, the maps summarize the occurrence and severity of drought for each annual season, allowing the identification of recurring spatial patterns and long-term trends.

Several different mapping techniques were used and compared. The expected results would be a real-world demonstration of the differences that would help towards a more effective and popular drought interpretation. These maps include aggregated drought polygon maps with variable transparency and overlap symbolization, Wurman Dots intensity maps, and Statistical choropleth maps that depict drought risk levels at the settlement and county levels. Each visualization method aims for the simplest and most generalized representation. It emphasizes different aspects of the underlying drought data and therefore offers different advantages and limitations in terms of readability, pattern recognition, and information transfer. In addition to the types of maps depicting drought years, seasonal NDVI degradation maps were also produced for the same period, between 2020 and 2025. These visualizations are based on a comparison of vegetation conditions in early summer (May-June) and late summer (August-September). The resulting maps highlight areas where vegetation conditions deteriorated during the summer periods and provide an additional perspective on the environmental consequences. Rather than depicting vegetation density itself, these visualizations emphasize the spatial distribution and intensity of vegetation loss and stress. The resulting cartographic products are designed for both digital and physical distribution. In addition to traditional map layouts, the outputs were developed in the format of printed posters and fold-out leaflet-style maps, which can be used for public communication and education purposes. Interactive web maps and web-based mapping applications were also created to explore the potential of digital platforms to communicate drought-related information to a wider audience. Their differences, advantages, and limitations were also revealed during the study.

The final and main step was to compare the types and methods of the maps produced, both between cartographic types and in terms of static and interactive comparison. This issue was assessed by a quality assessment by different Geographic Information System (GIS) experts, from feedback from Hungarian university

professors and colleagues, as well as from opinions from other fields, e.g. journalists, editors and engineers working in other fields and some completely "inexperienced" testers who were not at all familiar with map reading or using web maps.

The final and main step was the comparison of the completed map types and methods, both between cartographic types and in terms of static and interactive comparison. This question set included a quality evaluation by different GIS experts, feedback from Hungarian university professors and colleagues, as well as opinions from other fields, e.g. journalists, editors and engineers working in other fields and some completely "inexperienced" testers who were not at all familiar with map reading or using web maps. The main questions focused on usability, interpretability and the amount of information provided. During the user test, people had to examine the maps based on predefined questions and criteria and give their opinions and learned information. This provided a broader result for the main question of the thesis, which could help to understand what visual methods could currently or in the future support more effective and representative educational materials for current and future generations about the drought situation affecting Europe and currently Hungary. The main goal of the thesis and the maps is to work with freely available Copernicus data and, after reproducible data processing, to produce effective visualizations for anyone.

2 STATE OF ART

2.1 Environmental monitoring of drought and vegetation dynamics

The increasing frequency and severity of drought events in recent decades has made drought monitoring necessary. It has become widespread primarily from the scientific sphere in the area of environmental management and climate change adaptation strategies. Past studies and future climate projections show that the increase in temperature will continue to develop and, along with it, the significant variability of precipitation may exacerbate drought periods in many regions of the world and in countries with vulnerable geographical conditions. In proportion to this, these environmental factors are currently and will continue to affect the daily lives of the population, so transparent and reliable monitoring systems are becoming increasingly important in the increasingly digital world.

Hungary is considered particularly sensitive and vulnerable to droughts due to its location in the Carpathian Basin. Analyses of retrospective climate indices show that a drying process following an emerging pattern is occurring with increasing frequency in a significant part of the country, mainly in the summer months - but in some years there are significant precipitation deficits even in early spring. Kis et al. (2023) projected a significant expansion of semi-arid conditions across Hungary, with steppe-like climatic conditions becoming increasingly dominant under high temperature scenarios. Their results also predict that climatic conditions favourable to beech forests could largely disappear from the country's mountainous regions by the end of the century, as these moisture-demanding species are simply unable to keep up with the continuously warming climate and the lack of precipitation for several years. (Kis et al., 2023) In addition to environmental impacts, drought also poses a spatially differentiated socio-economic challenge. Farkas et al. (2017) showed that vulnerability to climate change varies significantly across the Hungarian Southern Great Plain and that an effective assessment requires the integration of both environmental and socio-economic indicators. Their work highlights the importance of spatial analysis and regional-scale visualization in identifying hotspots of climate change vulnerability and supporting adaptation planning. (Farkas et al., 2017)

2.2 Copernicus-based solutions

Within Europe, the Copernicus Programme represents one of the most comprehensive operational Earth observation systems, including the European Drought Observatory (EDO), which operates within the Copernicus Emergency Management Service, providing drought monitoring information in the form of accessible data through a wide range of indicators derived from meteorological, hydrological and vegetation-related datasets. Among these products, the Combined Drought Indicator (CDI) has become one of the most widely used operational drought monitoring tools. (De Jager & Vogt, 2015; *Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx*, n.d.) The CDI was specifically developed to represent the progression of agricultural drought by integrating precipitation anomalies, soil moisture deficits, and vegetation response. De Jager and Vogt (2015) describe the indicator as a conceptual representation of drought development, where precipitation deficits first trigger a monitoring phase, followed by a warning phase associated with soil moisture depletion, and finally an alarm phase characterized by observable vegetation stress.

Vegetation monitoring is a vital component of drought assessment. Since vegetation reflects the cumulative effects of meteorological and hydrological conditions, vegetation indicators often provide direct evidence of the impact of drought on ecosystems and agriculture. In addition, Addabbo et al. (2016) emphasize the importance of Sentinel-2 for vegetation monitoring due to its high spatial resolution, short return time and vegetation-sensitive spectral bands. These features allow detailed observations of vegetation dynamics. (Addabbo et al., 2016) The integration of vegetation indices into drought monitoring frameworks predates the Copernicus programme. Owangi et al. (2011) showed that NDVI-derived indicators, including the Vegetation Condition Index (VCI) and the Vegetation Health Index (VHI), provide reliable measures of vegetation stress and can be effectively integrated to supplement drought maps. (Owangi et al., 2011) Similarly, Al-Bakri et al. (2019) found that the Combined Drought Index incorporating NDVI data showed stronger correlations with agricultural production than rainfall-based indicators alone and supported more effective drought mapping. (Al-Bakri et al., 2019)

2.3 Geovisualization as an analytical and communication tool

While many studies have investigated drought indicators and vegetation monitoring methods, relatively less attention has been paid to the systematic comparison of different mapping approaches using the same drought dataset. In recent years, the intensively digitized world and the rapid growth of Earth observation data have significantly increased the importance of data visualization and map development in environmental research. Modern environmental monitoring systems produce large amounts of multidimensional spatial data that require effective visual representations to support interpretation and decision-making. Complementing this, the diversity of visualization products has expanded from purely cartographic activities and analytical displays of research to more widely disseminated storytelling maps and data visualizations or infographics. Contemporary geovisualization research emphasizes that maps should not only display information, but also facilitate understanding, discovery, and communication. Effective visualization allows users to identify patterns, recognize anomalies, compare spatial relationships, and understand changes over time. This role is particularly important in drought monitoring, where environmental processes are characterized by strong spatial variability and continuous temporal evolution. According to Nakić et al. (2022), successful visualization depends heavily on user-centered design principles. (Nakić et al., 2022)

The usability of a map is not only determined by the quality of the processed data, but also by the appropriate symbolization, relevant color selection, and general visual hierarchy. For example, in environmental mapping, the popular choropleth maps provide a simple way to map variable values. In addition, Netek et al. (2018) describe heat maps as an increasingly popular geovisualization technique for depicting spatial concentrations and identifying hotspots. The method, based on kernel density estimation, transforms spatial features into continuous visual surfaces that can facilitate pattern recognition. Although originally applied to traffic accident mapping, the method is equally relevant for environmental datasets characterized by spatially varying intensity levels. (Netek et al., 2018) The interpretability and research potential of visualization is further illustrated by the work of Zeng et al. (2021), who combined drought indices with SOM-Kmeans clustering techniques to identify spatial drought patterns and classify regions according to predicted drought characteristics. Their work shows that visualization and classification are closely related processes. (Zeng et al., 2021)

These developments coincided with the emergence of interactive GIS platforms and web mapping technologies. In contrast to traditional static maps, modern web-based visualization interfaces allow users to dynamically explore spatial information using temporal scales, interactive custom queries, dashboards, and animated visualizations. Such approaches are particularly suitable for drought monitoring, as they show changes over time and facilitate communication with both expert and non-expert audiences. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

2.4 Operational Drought Visualization Platforms

Modern drought monitoring systems increasingly focus not only on producing representative indicators, but also on developing interactive visualization platforms. These modern developments are able to present complex environmental information in an accessible format, with data richness and easy-to-interpret visuals and explanations, even in an online format, requiring less background knowledge. One of the most notable examples is the Drought Aware application developed by ESRI and published through the ArcGIS Living Atlas platform. The Dashboard-type web tool shows the time-series drought situation of the United States on maps dating back to the 2000s. The map data layers are complemented by demographic, hydrological and agricultural data and their on-the-fly calculation in the user interface, where everything interactively responds to and displays the selected data or zones after navigating with the cursor. With this method, the map user can examine the drought exposure and its impacts in the United States from multiple perspectives. The Drought Aware application also demonstrates several modern trends in contemporary geovisualization, both in terms of map design and usability. Its main feature is that it presents more complex data and immediately visualizes the relationships between them, but not least its interactivity engages users in an enjoyable and playful way with time sliders, filter elements and clickable diagrams. This method can be used to communicate, for example, complex environmental impacts much more widely than with purely scientific maps. These features were the main inspiration for the current research, although

the current study focuses primarily on cartographic visualization techniques rather than dashboard-based analysis tools. The growing popularity of web-based environmental applications reflects a broader preference within showing spatial data for interactive and user-centered communication. These advances in modern maps are a result of recent years' advances in the use of maps, while printed maps often face significant limitations.

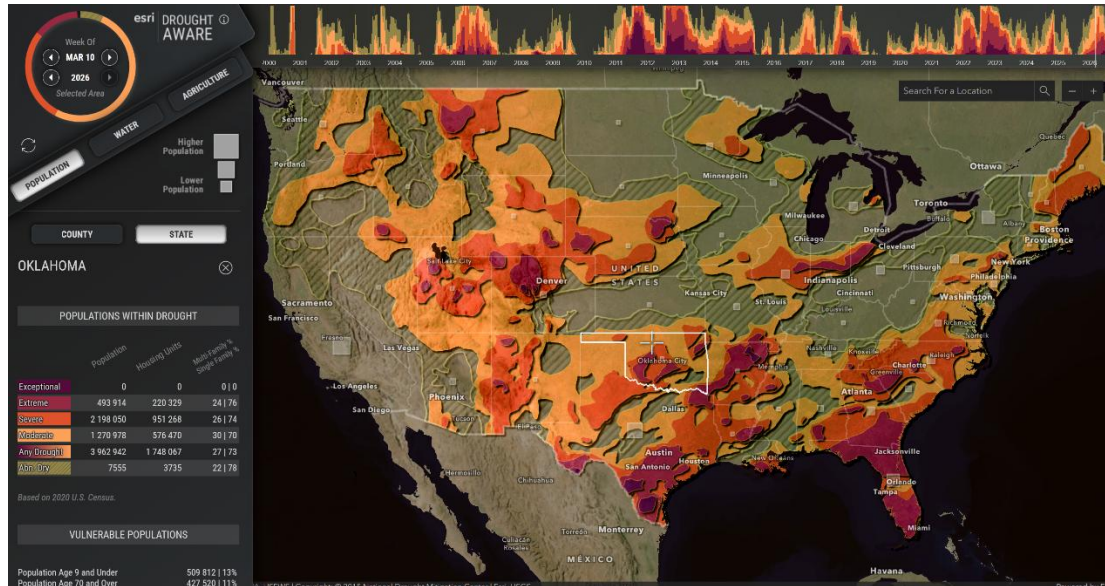


Figure 1. ESRI Living Atlas Drought Aware dashboard overview on desktop (Own screenshot)

The Drought Monitor dashboard map is based on data produced and provided by the United States Drought Monitor (USDM). The data available on their website is available in multiple file formats and can be downloaded for mapping and spatial analysis. The USDM is one of the most widely recognized drought monitoring products in the world, produced continuously since 1999 through a collaboration between the National Drought Mitigation Center (NDMC), the National Oceanic and Atmospheric Administration (NOAA), and the United States Department of Agriculture (USDA). The data is updated and uploaded weekly with national coverage and is labeled by layer category from D0 (extremely dry) to D4 (exceptional drought). These data are not derived from automated model-driven processing and are stored in multiple physical monitoring stations - including precipitation, soil moisture, water flow, reservoir levels, temperature and evaporation rates, and plant health. These field monitoring station measurements enable a quantitative drought assessment framework that is prepared and further developed through expert evaluation. Consequently, the use of the data is based on a solid scientific basis and is suitable for practical applications.

In addition, the USDM has also become an important decision-support tool in the country. Its classifications are used by federal and state agencies to support drought response measures, agricultural relief programs, disaster alerts, and water management decisions. The combination of regularly updated environmental monitoring data and user-oriented visual design is an important benchmark for contemporary drought visualization systems and has served as a significant inspiration for current research.

Another widely used drought visualization platform is Windy.com. This map depicts soil moisture anomalies on a global scale. Unlike drought monitoring systems such as USDM or EDO, Windy is primarily aimed at the general public. It integrates weather and environmental datasets into a single interactive map environment. Areas with below-average soil moisture are shown in a color scheme ranging from yellow to dark red. Areas with above-normal moisture are shown in green and blue. Although the platform provides limited methodological documentation, the description reveals that it relies on numerical weather forecasting and surface modeling datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF). Windy's popularity stems from its simple user experience and quick-to-interpret symbolization presented through visually intuitive and interactive interfaces. In this way, it is a popular platform for conveying information to a non-expert audience.

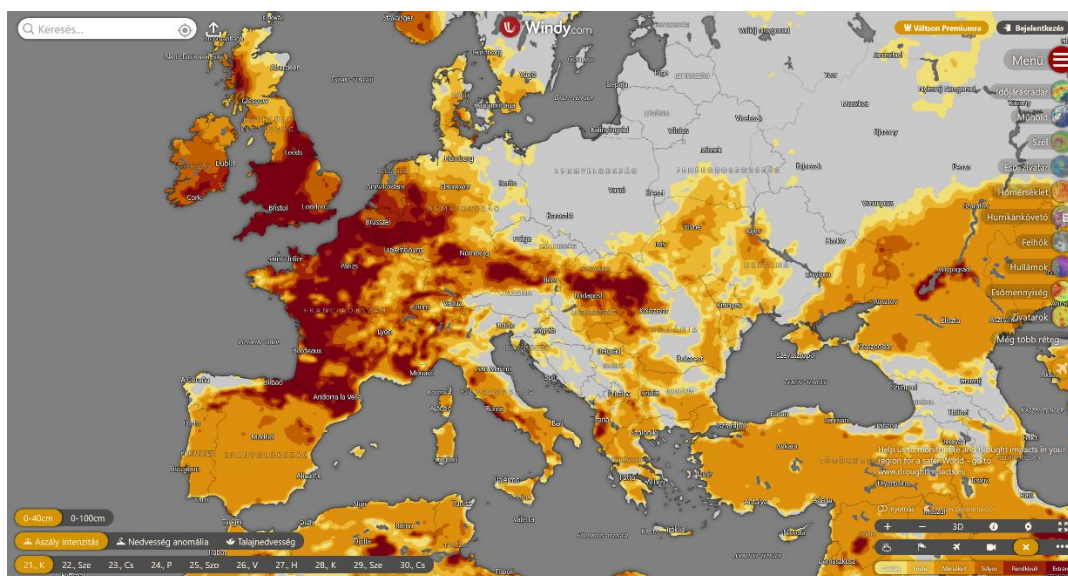


Figure 3. Map view of the Windy.com Drought Map on desktop (Own screenshot)

2.5 HungaroMet Agricultural Drought Information Service and the Operational Water Deficit Assessment and Forecasting System

To cite examples from Hungary, one of the most widespread drought monitoring map services is the Agricultural Drought Information Service operated by HungaroMet. The system provides continuously updated maps, which mainly focus on agriculture. This type of approach evaluates drought in terms of plant water supply and plant development. Agricultural drought is a situation in which the soil water supply is insufficient to meet the water demand of vegetation, resulting in irreversible stress, yield reduction and deterioration of crop quality. The data processing is provided by the calculated value and interpolation from daily soil moisture data on a 5x5km national grid. These are classified into three different soil depth classes (0–20 cm, 20–50 cm and 50–100 cm) and the resulting values are modeled, which are further weighted according to characteristics specific to different plant groups. The resulting data are classified into severity classes, ranging from no drought to severe conditions. (Aszálymonitoring, n.d.; HungaroMet, n.d.)

From a visualization perspective, the HungaroMet maps use a relatively traditional, interpolation representation, where drought categories are displayed as colored polygons that cover the entire territory of Hungary. The time-slice display allows arrows to switch between maps of previous drought data, thus allowing some temporal interpretation to detect drying areas on the map. However, it can be stated that there is no further interactive function on the map, there are no city or regional unit labels, and it is not possible to zoom in and select specific areas. Only a very simplified topographic map of Hungary is shown on a simple blue line map of the larger lakes and main watercourses. Although this map is available in digital form and has some minimal interactive functions, the visualization remains static and provides a limited display for the user. These Hungarian drought maps also illustrate the question of environmental monitoring. Although scientifically informative, the cartographic design prioritizes data delivery over user experience, storytelling, and public understanding. This approach has further motivated the further experimentation of alternative mappings that can more intuitively communicate the effects of drought to the population. (Aszály Információk - Agrometeorológia - Met.Hu, n.d.)

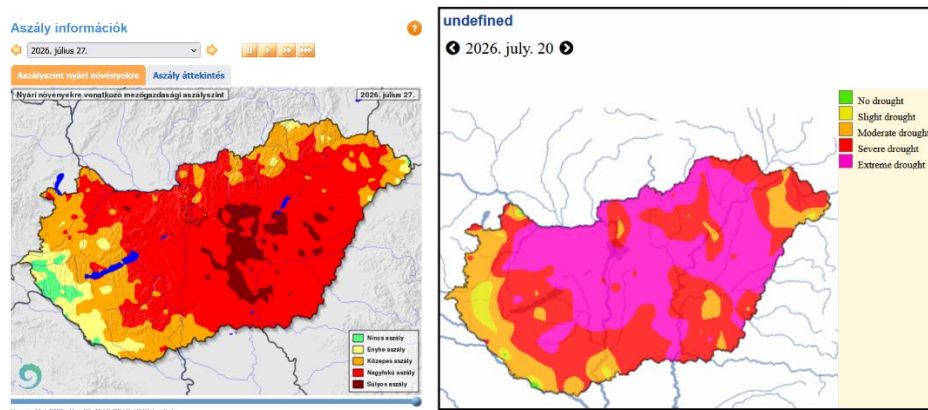


Figure 5. & 6. HungaroMet drought map viewer with timeslider on desktop and the map viewer of Operational Drought and Water Scarcity Management System (Own screenshot)

In 2016, the National Directorate General for Water Management (OVF) developed a web-based Hungarian drought monitoring system called the Operational Water Deficit Assessment and Forecasting System. This map database is based on a nationwide network monitoring system consisting of 127 automated measuring stations. These continuously collect hydrometeorological data, i.e. precipitation, air temperature and relative humidity along with soil moisture at multiple depths. These observations are integrated with soil moisture models and drought-related indicators, such as the Hungarian Drought Index (HDI). The application, which received a special award at the 2022 GDi Solutions Day conference, is one of the most advanced operational drought monitoring tools currently available in Hungary. (*Térinformatikai Díjat Nyert Az Aszálymonitoring Rendszer - Országos Vízügyi Főigazgatóság*, n.d.) The main feature of the platform is that it allows users to perform temporal and spatial analyses and display and download statistical queries and summaries. This interactive user interface is closer to modern expectations, but it should be noted that the interface requires prior knowledge of web mapping and is difficult to interpret even for a professional who is using it for the first time. The description of the legend is incomplete, the explanation of the marker values is absent or incomprehensible to a non-professional, as the queries of the different layers can also cause some complications before one can visualize the desired layers. Without a doubt, an extremely powerful and robust accessible web application has been developed, which stores and enables a lot of data suitable for research purposes, but unfortunately the usability of the map requires lengthy study and interpretation, which can reduce the level of motivation to work with the interface.

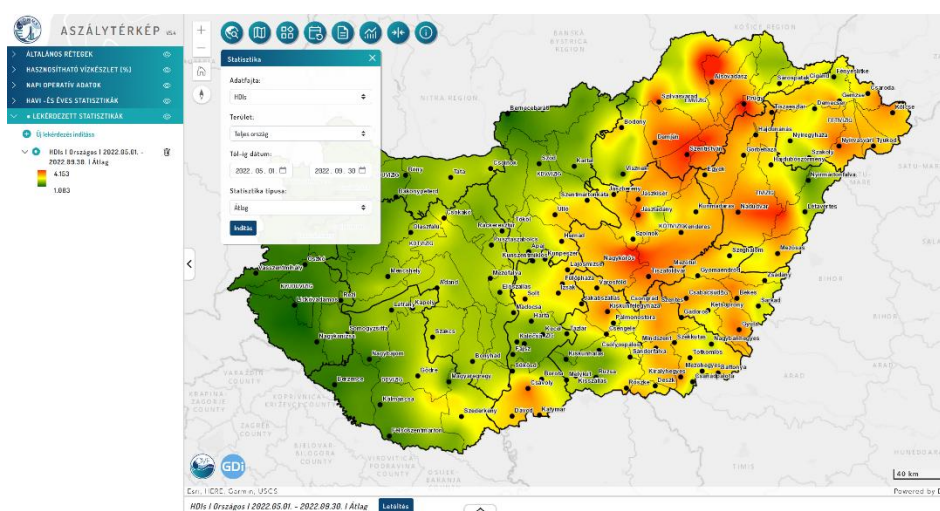


Figure 7. Map view of the Operational Water Deficit Assessment and Forecasting System on desktop (Own screenshot)

3 METHODOLOGY

3.1 European Drought Observatory and the CDI dataset

The main dataset used for the research is the Combined Drought Indicator (CDI) provided by the European Drought Observatory (EDO). This dataset is freely available through the Copernicus Emergency Management Service (CEMS) on their website. The entire service is maintained by the Joint Research Centre (JRC) of the European Commission. The EDO data provider serves as the official platform of the European Union and Europe-wide datasets can be downloaded from their website. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.) As drought is a complex environmental phenomenon affecting multiple components of the Earth system simultaneously, its assessment cannot rely on a single meteorological or hydrological variable. As a result, the CDI was developed as a composite indicator that combines information on precipitation deficit, soil moisture and vegetation greenness. (Cammalleri et al., 2021) The CDI was specifically designed for the detection and monitoring of agricultural droughts, thus providing information not only on current drought conditions, but also on areas exposed to drought impacts. Since a significant part of Hungary is agricultural land and under cultivation, it was justified to use this dataset for further mapping. Using this data, authentic visualizations could be created, which could provide valid values for information dissemination and even support political decision-making.

The dataset is created at a spatial resolution of 5 km and is updated every 10 days, enabling near real-time monitoring. (Cammalleri et al., 2021; Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.) Although the EDO platform is publicly available, its technical architecture and indicator-based approach are primarily aimed at researchers, environmental experts, policymakers and institutional users. The complexity of the web display and discovery map and the indicators may be a limitation for the non-expert audience, therefore its spread may be much smaller and is mainly widespread in the professional circles listed above.

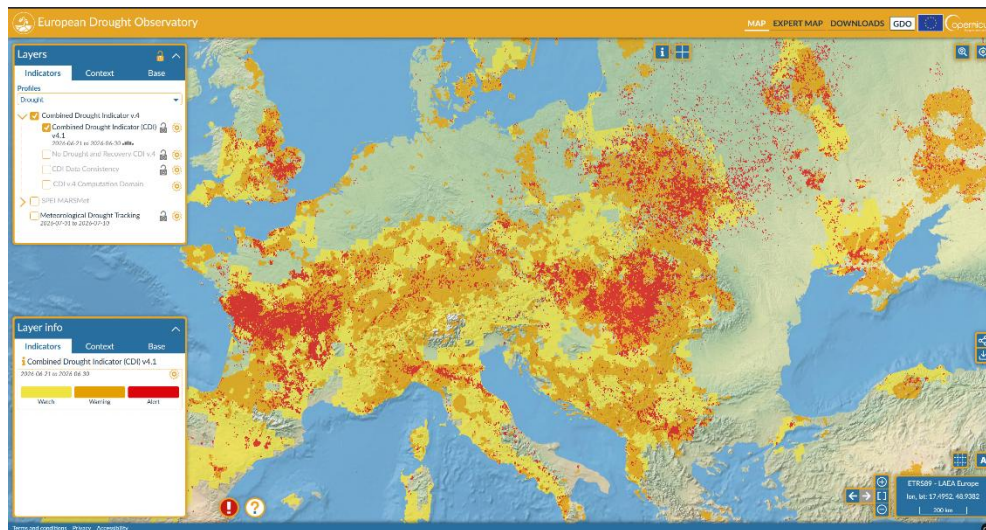


Figure 8. European Drought Observatory web view on desktop (Own screenshot)

The CDI is designed to develop agricultural drought as a cascade process. According to this model, a lack of precipitation initially creates meteorological drought conditions, which later lead to a decrease in soil moisture content. These processes ultimately manifest as vegetation stress. This causal relationship forms the basis of the indicator. (Cammalleri et al., 2021; Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

CDI variables:

- Standardized Precipitation Index (SPI)
- Soil Moisture Anomaly (SMI)
- Absorbed Photosynthetically Active Radiation Ratio (fAPAR) Anomaly

These variables collectively describe the environmental changes and the different stages of drought development, which are briefly described in this chapter. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

Standardized Precipitation Index (SPI)

It measures the deviation of precipitation from long-term climate averages. Two time scales are considered: the one-month SPI (SPI-1) and the three-month SPI (SPI-3). SPI-3 has been shown to correlate closely with vegetation response and is therefore particularly suitable for monitoring agricultural drought. SPI-1 allows the detection of short-term extreme droughts.

Soil Moisture Anomaly (SMI)

The soil moisture component is derived from the LISFLOOD hydrological model developed by the Joint Research Centre. It represents the deviation of soil water content from long-term average conditions and provides information on the hydrological response to precipitation deficits.

fAPAR Anomaly

The vegetation component is represented by anomalies in the fraction of photosynthetically active radiation absorbed (fAPAR). This is the proportion of incoming solar radiation from the satellite that is absorbed by vegetation for photosynthesis. Negative fAPAR anomalies provide direct evidence of plant health. (Cammalleri et al., 2021; Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

CDI Classification Scheme

The CDI does not provide a continuous numerical drought score. Instead, it represents drought conditions through a categorical classification system that describes the different stages of drought development. This data structure is important for the current study, as the entire geovisualization workflow was based on these CDI categories. The following classes served as thematic classes for the subsequent cartographic representation. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

Table 1. CDI Classification Scheme (Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.)

Code	Category	Description
0	No Drought	Normal environmental conditions
1	Watch	Precipitation deficit detected
2	Warning	Soil moisture deficit associated with drought development
3	Alert	Vegetation stress caused by drought conditions
4	Recovery	Return of precipitation and vegetation conditions to normal
5	Temporary Soil Moisture Recovery	Partial recovery of soil moisture conditions

6	Temporary Vegetation Recovery	Partial recovery of vegetation conditions
7	No Data	Missing or unavailable data

The three main drought classes describe increasing levels of drought severity. In the following and in the downloaded data, only these classes were used, and the fourth category was No data.

The *Watch* category is the earliest stage of drought development. It indicates the presence of a rainfall deficit. At this stage, the effects on soil moisture and vegetation are not yet significant. The *Warning* category indicates a rainfall deficit. At this stage, it has spread to the soil system and soil moisture content has moved in a negative direction. The *Alert* category corresponds to the most severe drought phase in the CDI framework. Vegetation stress indicates negative anomalies. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.) On the web map viewer, the classification system uses a simple color scheme ranging from yellow (*Watch*) to orange (*Warning*) to red (*Alert*).

Despite its widespread use and functionality, the CDI has several limitations that should be taken into account when interpreting the results. For example, this indicator is not suitable for assessing hydrological or socio-economic drought, as these can vary according to different mechanisms and time scales. (Cammalleri et al., 2021) Regarding the vegetation component, it is based on satellite observations. These can also be affected by cloud cover, seasonal vegetation cycles or land cover. Therefore, vegetation information should in some cases be intentionally excluded from the calculated index. (Microsoft Word - Copernicus_EDO_Factsheet_CDI_v3_20230515.Docx, n.d.) Due to these properties, the dataset was suitable for further visualizations and spatial analysis, but it should be noted that further processing was greatly complicated by the raster-based, significantly "noisy" dataset. Also, the processing of the EDO data required several separate and step-by-step processes to create the desired output layers, which will be discussed in more detail in the remaining parts of this chapter.

3.2 Sentinel-2-Based NDVI analysis for vegetation change assessment

Although the CDI includes the agricultural drought index and the effects on vegetation, it may sometimes be incomplete due to limitations in the calculation of the index. In addition, the spatial location of the most damaged vegetation cannot be directly detected. These are mainly clearly visible on satellite images and aerial photographs, or can be observed with the naked eye on site. Since this is a nationwide mapping, Sentinel-2 satellite images were chosen to observe the summer seasonal state of vegetation. By examining the normalized differential vegetation index (NDVI) derived from these raster datasets. Since the period examined was only the summer periods, long time-series satellite image analysis was not required to prepare the visualizations discussed in the thesis - although it is worth mentioning that Sentinel-2 satellite images are also widely used for agricultural monitoring and yield prediction due to the data density. Thus, vegetation degradation maps that complement drought maps can theoretically serve as a good complement to map readers in causal interpretation. Vegetation degradation represents the final stage of the drought development process described by the CDI framework (De Jager & Vogt, 2015; Owrangi et al., 2011), so vegetation degradation maps that complement drought maps can theoretically serve as a good complement to map readers in causal interpretation.

The NDVI data was based on images captured by the Sentinel-2 mission, part of the European Union's Copernicus Earth Observation Programme. It consists of two satellites, Sentinel-2A and Sentinel-2B, which provide systematic multispectral observations of land surfaces with return intervals suitable for environmental monitoring applications (5 days, but also 2-3 days) and multispectral resolution of 10m. Data have been available since the launch of Sentinel-2A in 2015, with full constellation coverage achieved after the launch of Sentinel-2B in 2017. (Addabbo et al., 2016)

3.3 Normalized Difference Vegetation Index (NDVI)

NDVI is one of the most widely applied remote sensing indicators for assessing vegetation condition and photosynthetic activity. The index exploits the characteristic spectral behavior of healthy vegetation, which strongly reflects near-infrared radiation while absorbing red light for photosynthesis.

NDVI is calculated as: where NIR represents reflectance in the near-infrared portion of the spectrum and Red corresponds to reflectance in the visible red band. The resulting values range theoretically between -1 and +1. Higher positive values indicate dense and healthy vegetation with strong photosynthetic activity, while lower values indicate sparse vegetation, stressed vegetation, bare soil, or non-vegetated surfaces. Numerous studies have demonstrated a strong relationship between NDVI-derived vegetation indicators and drought conditions. Vegetation indices are particularly valuable because they capture the cumulative effects of meteorological and hydrological stress on plant communities and agricultural systems. Consequently, NDVI has become a widely adopted tool for drought monitoring and environmental assessment. (Addabbo et al., 2016). For Sentinel-2 NDVI, the formula is the following:

$$NDVI = \text{Index}(B8, B4) = \frac{B8 - B4}{B8 + B4}$$



Figure 9. NDVI satellite imagery in the Copernicus Browser map view and index selection interface (Own screenshot)

Rather than analysing individual NDVI snapshots, the objective of this study was to identify seasonal vegetation decline associated with summer drought development.

For each year between 2020 and 2025, two representative seasonal periods were selected:

- May–June, representing peak spring and early-summer vegetation development,
- August–early September, representing late-summer conditions after the main drought period.

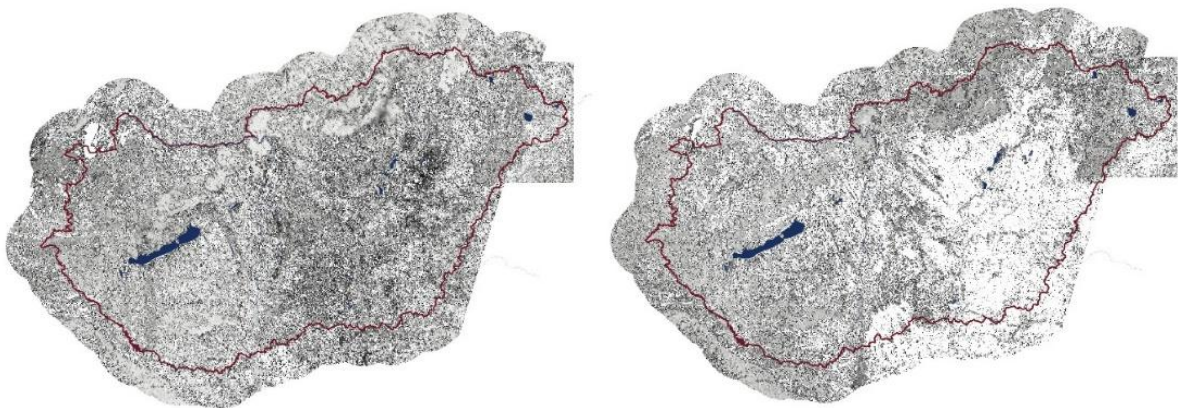


Figure 10. & 11. Generated NDVI mosaics of the year of 2022, early summer (left) and late summer (right)(Own figures)

The comparison of these periods was designed to capture vegetation changes occurring during the growing season. Under favorable climatic conditions, vegetation generally maintains relatively high NDVI values throughout the summer. By comparing early summer and late summer vegetation conditions, it becomes possible to quantify the spatial extent and magnitude of vegetation decline associated with drought stress.

3.4 Software and platform used

The workflow developed for the thesis involved several GIS, remote sensing and data processing environments. The primary EDO drought datasets were pre-processed and automated in Python using a Jupyter Notebook environment. This was complemented by ESRI ArcGIS Pro (version 3.7.0) geoprocessing tools and ModelBuilder batch workflows. All additional scripts were run in ArcPy Notebooks in ArcGIS Pro and uploaded to the GitHub platform, with future public access to open repositories. Following the drought data pre-processing, the additional vector dataset was obtained using data downloaded from OpenStreetMap, which was downloaded via the Overpass Turbo query service. These layers were processed and refined in QGIS (version 3.44.10), which was also used for exploratory analyses and preliminary testing of NDVI-based vegetation indices extracted from Sentinel satellite images downloaded from CB. All Python code development was done in Visual Studio Code (version 1.125.1). The final cartographic products were created and mapped in ArcGIS Pro, where the processed datasets were symbolized, analyzed, and prepared for publication on ArcGIS Online. In addition, the unique illustrations included in the thesis were created using Procreate (version 5.4.11) on an iPad and then refined using generative AI - ChatGPT 5.5 - which currently provides the cover and background image of the thesis website. The thesis summary poster was finalized in Canva, along with the original static maps. This combination of GIS, programming, and graphic design software allowed for a fully reproducible workflow.

3.5 Study area

The visualizations prepared cover the entire territory of Hungary and the processed data always provide national coverage - an exception to this is the areas not affected by drought. The country is geographically landlocked, located in the Carpathian Basin, in East-Central Europe. Its area is approximately 93,030 km², which is typically characterized by lower relief, a significant part of which is the Great Plain and the Lesser Plain regions used for agriculture and animal husbandry. The highest point in the country is Kékes (1014 m), which is located in the Northern Central Mountains, and there are also smaller mountains in Transdanubia and Southern Transdanubia, but these do not reach an altitude of 1000 meters above sea level. The country has a temperate continental climate, which can be influenced by continental, Atlantic and Mediterranean air masses throughout the year. During the summer, hot and dry air masses typically arrive and remain, while precipitation is unevenly distributed throughout the year, mainly in the form of late spring and early summer showers. These increasingly extreme changes demand serious climatic and lifestyle changes from the country's population and put pressure on the economy. The combination of relatively flat topography, geographical location, intensive agricultural land use and increasing climate variability makes Hungary particularly vulnerable to drought events. The situation of the past decades and the latest climate projections show rising summer temperatures, more frequent heat waves, and increasingly variable and rarer precipitation patterns. (Ács et al., 2015; *Magyarország Helyzete, Földtörténete, Domborzata*, n.d.)

4 DATA PREPROCESSING

4.1 Data acquisition

The data sets used in this research were obtained from two mentioned Copernicus services. Drought-related information was sourced from the European Drought Observatory (EDO), while vegetation data were derived from Sentinel-2 multispectral satellite imagery accessed through the Copernicus Browser platform.

For the drought analysis, the Combined Drought Indicator (CDI) v4.1 dataset was downloaded directly from the EDO download service in GeoTIFF format. Although the full CDI classification scheme includes both drought and recovery classes, only the three primary drought categories - Watch, Warning, and Alert - were utilized in this study, as these classes directly represent drought severity and formed the basis of the subsequent cartographic visualizations. The study period covered the years 2020–2025, corresponding to the temporal scope of the drought analysis. Since the indicator is produced at a ten-day temporal resolution, three raster datasets were typically available per month, representing drought conditions during the beginning, middle, and end of each month from May until September each year. All datasets were obtained in their original spatial resolution and format.

Satellite images suitable for vegetation monitoring were downloaded from the web platform CDSE Copernicus Browser. Here, after selecting the Level-2A images from the available Sentinel-2 satellite images, only manually selected bands of satellite images "masked" to the desired geometry were downloaded using a shapefile covering Hungary. That is, the B04 (Red) and B08 (Near-Infrared) bands in the case of the Sentinel-2 satellite. The manually selected data download was performed with a free user account on the CB interface. During the image selections, a maximum of 30% cloud cover and the dates were considered. Due to the spatial extent of the study area, approximately nine Sentinel-2 scenes were needed for the full national coverage in each data collection period.

4.2 EDO data processing

The downloaded CDI data was prepared for visualization by preprocessing. And although the main topic of the thesis is not data processing, due to the downloaded format and data volume, several automated steps were required until the desired vector file format was produced. The goal of the preprocessing was to create a reproducible workflow and model during the test phase, using which any person with GIS knowledge can create maps similar to Drought Aware and get creative with various symbolizations. After the preparations, the following steps were performed.

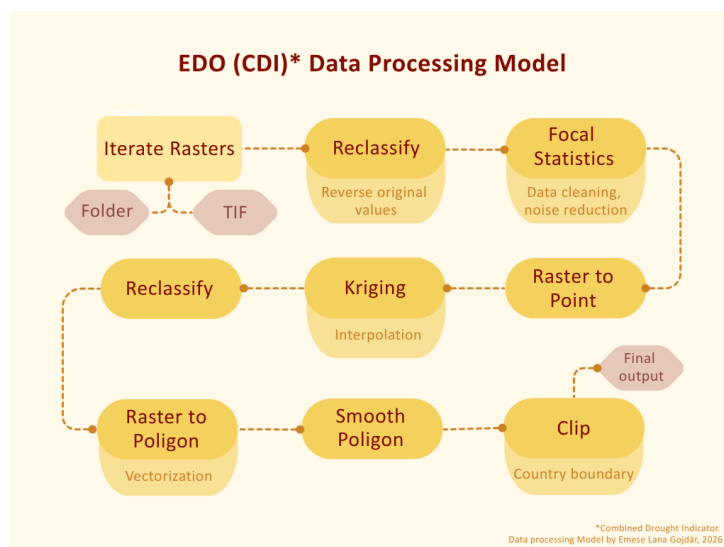


Figure 14. Illustrated workflow of the created ArcGIS Modelbuilder modell used for EDO data preprocessing (Own figure)

A Python script developed specifically for this purpose in Jupyter Notebook Clipped all EDO .tif format data with the 50 km buffered border of Hungary. This was important so that the entire national coverage would be ensured during the subsequent Interpolation generation. This way, the generated data would reflect accurate data along the borders. After that, a filter was applied to the cropped rasters, which selected the summer months (May-September), thus reducing the amount of data. This process resulted in 75 raster layers. The following steps were created mainly using ArcGIS Pro (version 3.6.3) ModelBuilder. A batch run model consisting of 8 toolbars was created, which created several different output files from the already clipped raster files. At the end of the process, interpolation rasters, vector point layers and smoothed polygon layers with a structure similar to DW were created separately for each date. Toolboxes within the model itself process the data in a multi-step process, where first values are assigned to pixels (the values stored in the original EDO raw files had to be replaced and reclassified into pixel values. It is important to note that values between 0 and 2 were treated as NoData in the original dataset and were therefore excluded from the reclassification process.) Then a Focal Statistics tool performed noise reduction and cleaning on the pixels. This process is done by moving a 3x3 neighborhood window through a raster grid (a statistical function is calculated for each central cell based on the values of the surrounding cells in the neighborhood), so the data is much more generalized and less noisy.

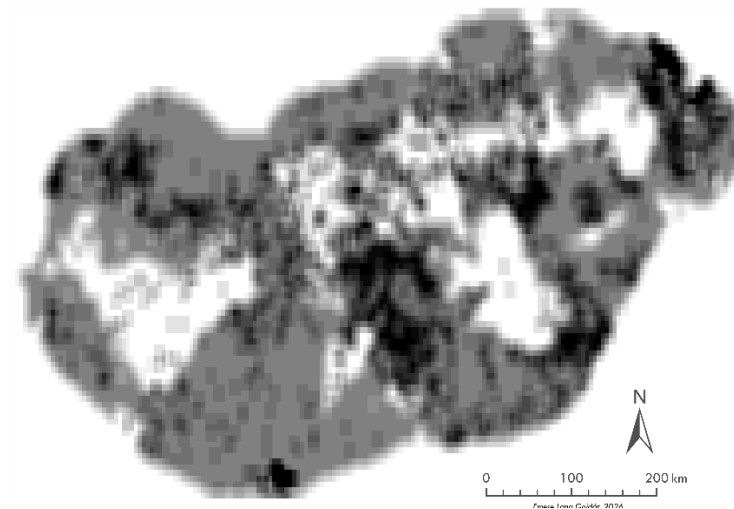


Figure 15. Reclassified EDO data after Focal Statistics raster cleaning (Own figure)

This spatial smoothing process significantly improved the homogeneity of the raster regions. Cleaning noisy data here is a critical step before vectorization. Omitting this step would generate too many small polygons, which would disrupt the visual experience and mapping. The following step in the workflow was to assign spatially explicit values to the raster cells and generating vector points from that output. This resulted in an already representative phase of the data, with coherent drought categories. With this step, an accurate layer generated a vector point for each pixel grid that gave the opportunity to experiment with further different map types later. The next step was the Interpolation.

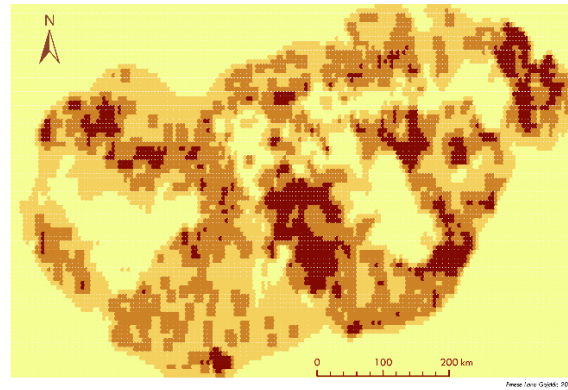


Figure 16. Vectorized point based data during the preprocessing modell run (Own figure)

Interpolation is a method for performing spatial analysis to estimate unknown values. It predicts and generates the surface of areas in unknown locations from spatial points containing data. Using this logic, points that are closer to each other are more likely to have similar values than those that are further away. Several interpolation methods were tested from the previously generated point data, including Inverse Distance Weighting (IDW), Spline interpolation and Kriging. (*Understanding Interpolation Analysis—ArcGIS Pro | Documentation*, n.d.) The use of a 50 km buffer zone previously used around the country border proved to be extremely useful in this step. Without this extended area, the interpolation process would rely exclusively on points located strictly within the country borders, which could lead to distortions. Kriging gave the most effective and visually desirable result. This is a geostatistical interpolation technique that not only takes into account the distance between points but also models the spatial structure of the data using a semivariogram (a statistical graph measuring how data difference grows with distance). It also appears from online sources that it is one of the most popular methods for drought prediction, along with IDW. It is also widely used in environmental sciences and meteorological data analysis.

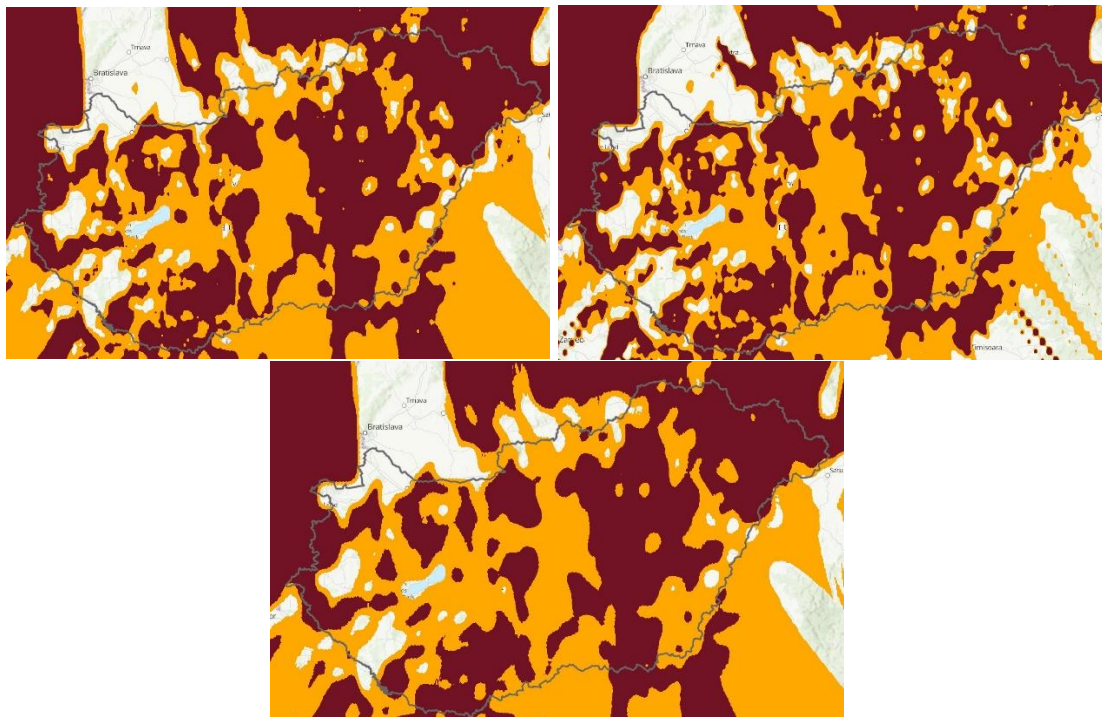


Figure 17., 18. & 19. Interpolation method testing with IDW (upper left), Spline (upper right) and Kriging (bottom) (Own figures)

After the interpolation was completed, another reclassification was required, as shown in the model flow chart. The generated prediction surfaces were again in raster format, which had to be converted back into discrete integer classes. From these, the final vector polygon layers could be created, which were almost in the desired geometry. In this step, they were created using the Raster to Polygon tool, fine-tuned using the Smooth polygon tool - using the Polynomial Approximation with Exponential Kernel (PAEK) algorithm - and clipped to the size of the country using the Clip tool. (*How Smooth Line and Smooth Polygon Work—ArcGIS Pro | Documentation*, n.d.) It should also be mentioned that certain topological errors occurred at the end of the vectorization process. The gaps between the polygons belonging to different classes did not generate overlapping polygons, but the vectorization covering the entire country took place "in one plane", so to speak. For this reason, in some parts, after sufficient magnification, it may become visible that the edges of the polygons do not touch each other 100% - these mainly resulted in different sizes during the Smoothing processing. In the final results, these errors are negligible due to the nationwide coverage, and this error value was considered acceptable for the results. At the planned scale of the visualization, these artifacts do not compromise the readability or interpretability of the drought severity maps, therefore they were not subjected to further topological correction.

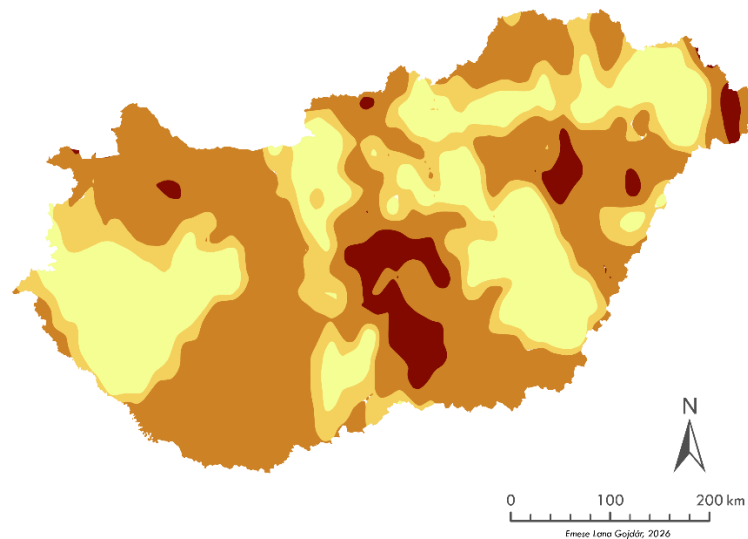


Figure 20. Example of one of the final outputs from EDO data processing modell (Own figure)

The vector drought polygons being created were ready for mapping and a time series display format was also proposed. Animated, i.e. layer-by-date - switchable maps have become increasingly common in recent years when both commercial and open-source map service software and programs offer the option to display them. Since the dates in the data names belonged to each layer, a timeslide ready for further data processing was also created using ArcPy Notebooks. Here, using ArcGIS Pro, it is easy to enable time-strip display and date-based animation, but this was not included in the media to be compared in the thesis. It is important to mention that the possibility of this display form is given and possible from the data produced.

4.3 NDVI Preprocessing Workflow

Following data collection, the downloaded Sentinel-2 images underwent a multi-step preprocessing workflow. The goal was to map and compare spatial, seasonal vegetation changes and annual trends between 2020 and 2025. To do this, an NDVI dataset had to be created in advance. The workflow is performed by ArcPy scripts developed in the Jupyter Notebook environment. As a first step, all downloaded zipped files were automatically extracted using the 7-Zip File Manager. After this step, all satellite images were placed in a date-based directory structure.

Each date had two separate bands, band 4 (red) and band 8 (near-infrared), from which the NDVI was calculated. An ArcPy notebook went through all extracted image folders, identified the corresponding spectral bands, and generated unique NDVI raster datasets. The next step was the full national coverage, which was created from the already calculated rasters, a so-called mosaic image made of several neighboring Sentinel tiles. Images taken in May and early June were combined into a spring mosaic, which represents the blooming season and the greening period of trees. While images taken in August and early September were created into a late summer mosaic. This image depicts vegetation conditions following the main drought period. The mosaicing process minimized temporal differences between adjacent frames and imposed few limitations on the mapping phase. Images taken in May and early June were combined into a spring mosaic, which shows the blooming season and the greening period of trees. While images taken in August and early September were created in a late summer mosaic. This image depicts vegetation conditions after the main drought period. The mosaic process minimized temporal differences between adjacent frames and had few limitations during the mapping phase. The mosaic images were then subjected to further filtering, where pixel values that were not representative of vegetation cover were removed. This removed pixels with values between -1 and 0.5, which showed water, cloud, or built-up areas. Although the procedure does not qualify as a formal cloud masking workflow based on Sentinel's quality assessment layers, it significantly reduced the impact of non-vegetative pixels. Consequently, the subsequent NDVI difference calculation was not performed on unnecessary pixels. There, only the pixels covering vegetation were processed, i.e. the mosaic of early summer NDVI was subtracted from the late summer NDVI coverage. This calculation was also performed using ArcPy Notebooks and the final output data was called NDVI delta. The resulting raster represented the extent of degradation during the vegetation period and served to further illustrate the loss associated with summer drought conditions.

Despite the applied preprocessing procedures, there were several limitations. Due to the lack of precise cloud masking workflow, some residual pixels related to clouds remained in the final mosaics. This problem is particularly visible in the 2025 dataset. Here, cloud pollution in parts of Northwestern Hungary resulted in anomalous NDVI difference values. These do not reflect the actual vegetation loss by the end of summer. The same calculation operation gave good results for all other data, so we considered them acceptable as the final result of the mapping. The resulting NDVI difference rasters were then used as the primary input dataset for the vegetation change visualizations presented in the next section.

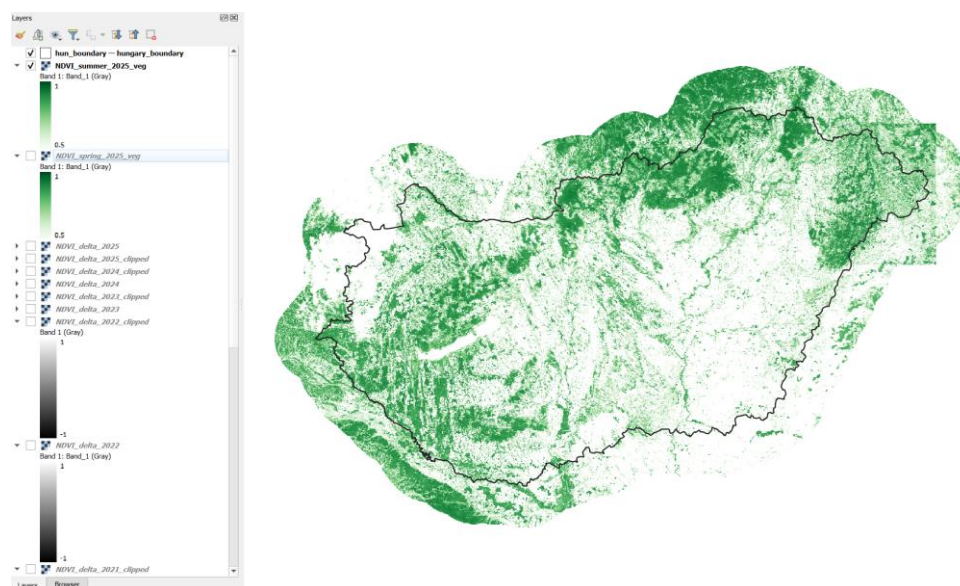


Figure 21. Screenshot during the NDVI data preprocessing in QGIS (Own figure)

5 GEOVISUALIZATION AND MAP DESIGN

5.1 Area Polygon and Outline maps

The first visualization map types were derived from the Combined Drought Indicator (CDI) after the layers were smoothed drought polygons. Instead of displaying individual drought events separately, as previously discussed, each element of these layers had to be created in an aggregate seasonal visualization for each year starting in 2020. The summer drought period covers the period from May to September, which has already been processed, every year. This cartographic concept is a visual style used by Esri Cartographer John Nelson for his experimental environmental mapping designs. I drew inspiration from and reproduced these drought maps, still following the Drought Aware mapping principles. This layer visualization allows you to identify areas where drought conditions have occurred repeatedly over a given period. It also allows you to distinguish occasional areas where drought conditions have occurred less frequently.

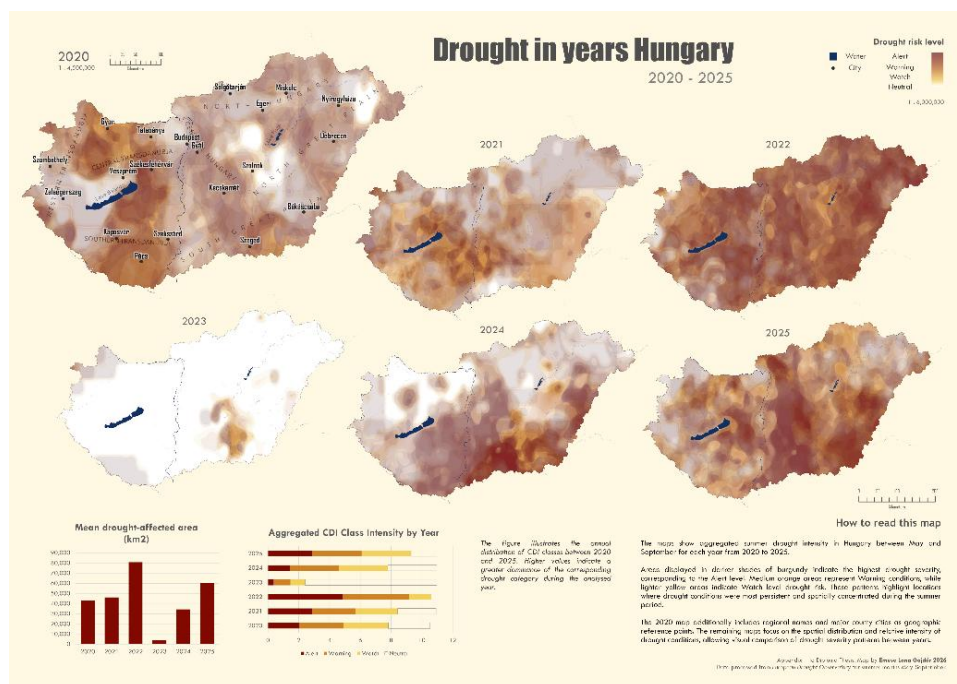


Figure 22. Final layout of the static Area Polygon map (Own figure)

The symbolization here uses a combination of color intensity and layer transparency to represent the severity and frequency of drought. Darker shades of burgundy represent areas falling under the 'Alert' category, while lighter shades of orange and yellow correspond to 'Warning' and 'Watch' conditions. Areas missing in the white patches are shown as 'No data', i.e. areas uncovered on the maps. (This is especially true for 2023, which resulted in a much wetter year after the outstanding 2022, which resulted in a significantly less significant drought summer in the EDO data. These will also appear on the other map types.) The emphasis on the areas most severely affected by drought is given by the fact that as the slightly transparent layers are stacked on top of each other, the color intensity increases, and the repetition can be used to deduce how severely the area under study is exposed to drying out. This approach can have several visible advantages compared to traditional and date-varying drought maps. Since it makes the drought polygons visible at the same time - with the possibility of even creating a full-year visualization - it can perhaps generate a more pronounced focus in the map reader and in understanding the problem. At the same time, multi-year visualization makes it easier for laypeople to compare environmental and climate patterns spanning several years. This question will also be addressed in the later comparative user feedback chapter.

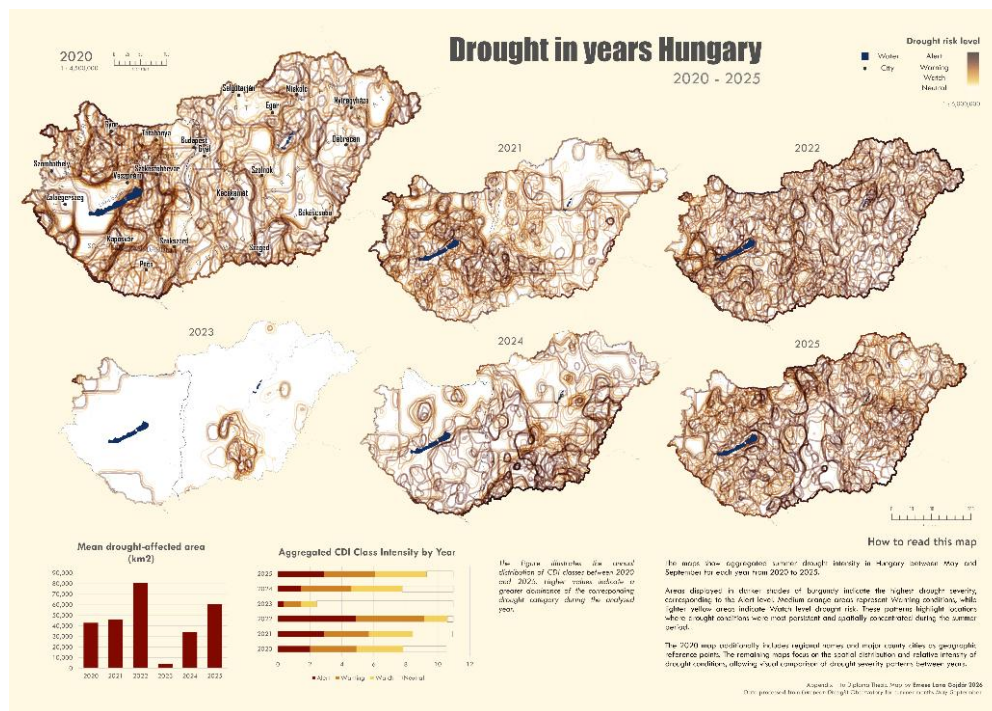


Figure 23. Final layout of the static Outlines map (Own figure)

From the same dataset and data structure, another experimental mapping format inspired by John Nelson was tried out. Here, instead of filling in the previously symbolized polygons, only their outer outline edges were colored and made somewhat transparent during the design. The resulting maps generated a very individual and unusual visualization product, which is worth examining mainly from a graphical and artistic point of view. The legend and the overlapping of the lines follow the same logic as in the previous map type. The "areas" formed inside the darker lines are the most severely droughted areas, while the lighter and less frequently overlapping line networks indicate less frequent drought periods. However, this mapping method was also included among the visuals to be compared, since the question arises here too; *“Could one of the more artistic drought maps be interpreted at the level of information transfer and communication?”*

5.2 Wurman Dots map

Among the following visualization methods, the Wurman point approach is one of the most influential alternatives to traditional thematic mapping techniques. The original method originated in the work of Richard Saul Wurman and Joseph R. Passonneau. It was originally a grid-based point representation, presented in the book *Urban Atlas: 20 American Cities*. Wurman's goal was to improve the communication of complex urban data sets by providing a clear and visually intuitive cartographic representation. (Passonneau & Wurman, 1967) Rather than relying on administrative boundaries or continuous overlays, the method represents quantitative information by means of a regular arrangement of circular symbols whose size reflects the magnitude of the variable being mapped. The technique was originally intended for visualization of population density and other urban indicators. Each grid cell contains a fixed reference circle that represents the maximum possible value. Within this, an inner circle is scaled proportionally to the observed value. This design allows users to compare relative intensities across space while maintaining a consistent visual structure. For the present drought map, an alternative form of this method was developed, where only the inner circle is displayed. The vector and aggregate polygon layers created during the data processing described in Section 5.2.1 were used for preprocessing the data. For this design, a 200 square kilometer hexagon grid was generated over the national surface using the *Generate Tessellation* ArcGIS Pro tool. The frequency of the areal coverage of the polygons within each grid was then calculated. This resulted

in an aggregated area value normalized to area, which produced the desired symbolization and the main patterns became recognizable for this type of map.

However, since statistical information is rarely labeled according to these grid cells, the original values must be redistributed or aggregated. Consequently, the method represents a compromise between geographic accuracy and spatial comparability. Regional patterns are better captured this way, rather than administrative or geographic boundaries. Another limitation of the display is that the labels for cities and larger regions were subject to software errors, because unfortunately the dotted displayed "grid" covered the labels in some unavoidable way. Some transparency was set on the colored points, so the region labels became somewhat visible, but the limited possibilities of the software made it a bit difficult to create the desired mapping design for this visualization. The layers representing water cover also required manual correction, here the vector points covering the lakes had to be deleted one by one from the symbolization, so that Lake Balaton and Lake Tisza became visible.

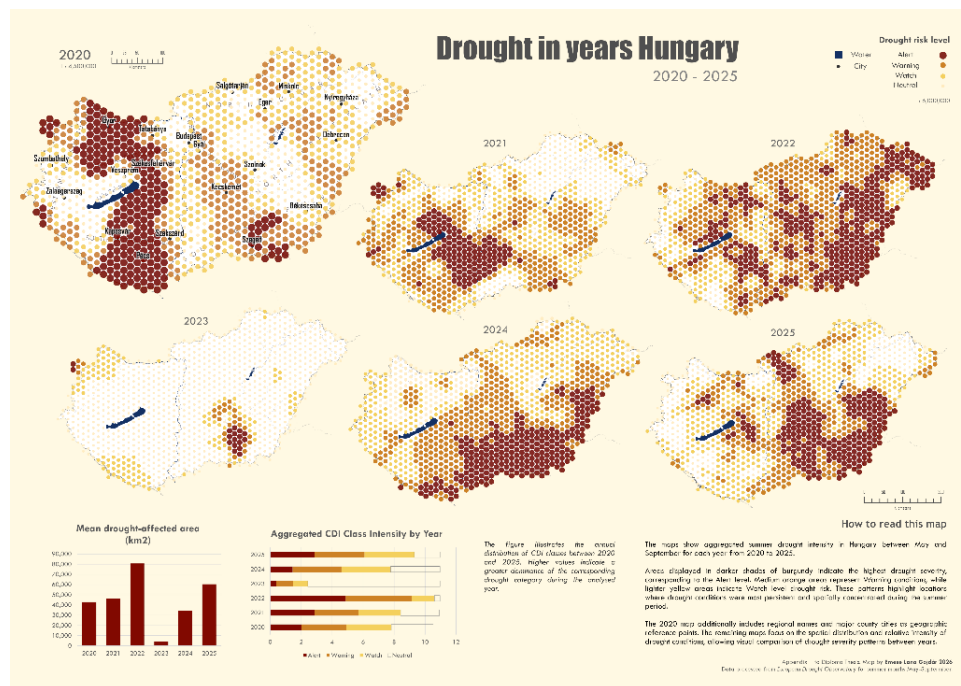


Figure 24. Final layout of the static Wurman Dots map (Own figure)

5.3 Statistical choropleth map with piechart diagrams

Choropleth maps are the most widely used technique in thematic cartography for visualizing the diversity of statistical data. The method is based on assigning color values to predefined spatial units according to the magnitude of an attribute. This allows for a quick and intuitive identification of regional differences. Due to their simplicity, they are popular map types for communicating environmental, demographic and socio-economic information. On these maps, drought intensity was visualized at the LAU 2 (local administrative unit) level, which corresponds to the settlement boundaries of Hungary. The displayed values came from the same aggregated CDI dataset that was also used in the Wurman Dot visualization. Here, however, instead of a separately generated hexagon grid, the polygons of the settlements provided the so-called "grid". Within these areas, the intensity of drought frequency was prepared using the same logic, with area-based normalization and zonal statistical analysis. Thus, the similar pattern could be achieved and symbolized again from the obtained values. Administrative units provide recognizable geographical references. Therefore, in theory, allowing users to directly connect drought patterns to settlements and regions they already know. In the hypothetical testing result, the best results were expected for this visualization form. The area-based coloring was complemented by pie charts representing county-level representation, which displayed the same intensity values, calculated for the entire county. Within this, they

wanted to illustrate the spatial distribution of drought for counties, even more so from statistical aspects and data visualization purposes. These values to be visualized were prepared after numerous Spatial Join and Dissolve functions, the process was achieved through manual calculations and connections to achieve the desired displayable attributes. The result is a drought intensity index calculated for each of the 4 drought categories, taking into account the area coverage. The appropriate workflow requires some testing, but the final format was a regenerated polygonised layer, where the LAU 2 areas with the same intensity of drought formed a consolidated unit, and after intersections with the counties we got the expected result.

The combination of a colored choropleth surface and pie charts allow for regional comparison and multivariate analysis on a map. Users can use the color scheme to identify areas with drought intensity and the pie charts to identify the relative distribution of categories. This approach increases the information content of the map. Additional supplementary figures are not or only minimally needed.

However, choropleth maps also have well-known cartographic limitations. Environmental factors such as drought do not fit administrative boundaries. Therefore, the symbolized spatial method does not fully reflect reality and can even be misleading in more precise studies. Since the formation of continuous and transitional surfaces, considering all the factors of drought, is best visualized, this aggregated and averaged representation is a very simplified way to display the summer seasonally aggregated data. After mapping, neighboring settlement boundaries may be significantly different, for example, despite having similar geographical and weather characteristics.

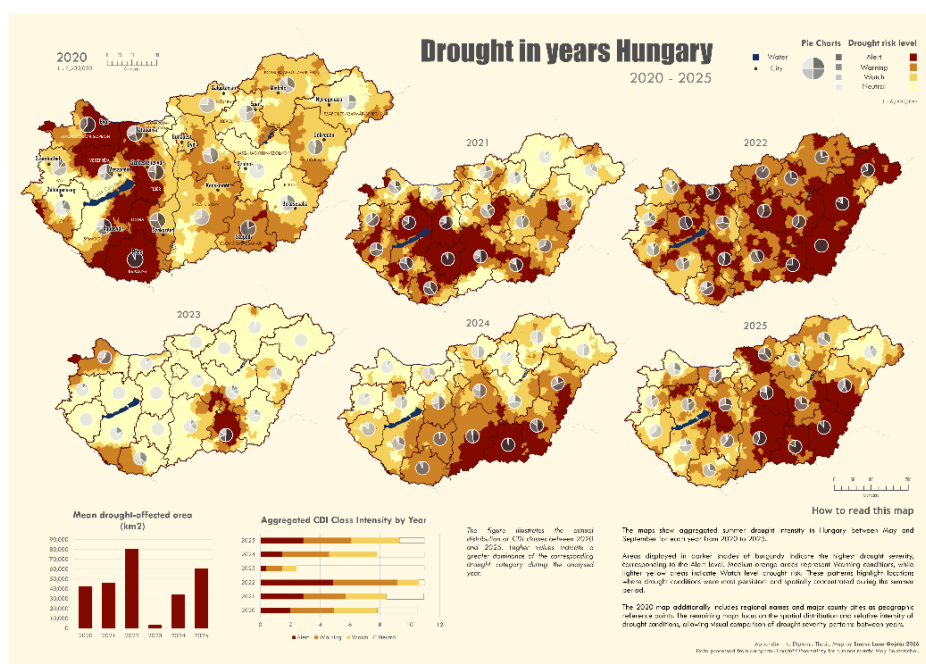


Figure 25. Final layout of the static Statistical map (Own figure)

5.4 Heat Map Visualization (Excluded Alternative)

Heatmaps based on Kernel Density Estimation (KDE) processing were among the original map types to be compared. However, heatmaps generated from drought data created as a test from pre-processed data did not prove to be a good enough basis for comparison. Especially in high-altitude years, where aggregated whole-summer high drought frequencies should have been applied with this method, the overlapping zones would have shown too small difference due to the model, so this map type was discarded from the further comparison process. Although the method produced visually good results in some cases - for example, we could get better generated surfaces for drought for a single given date, the other mapping methods were made from aggregated averaged seasonal

visualization, so the heatmap approach was excluded from the final cartographic outputs and remained only as an exploratory visualization experiment.

5.5 Cartographic Design Process

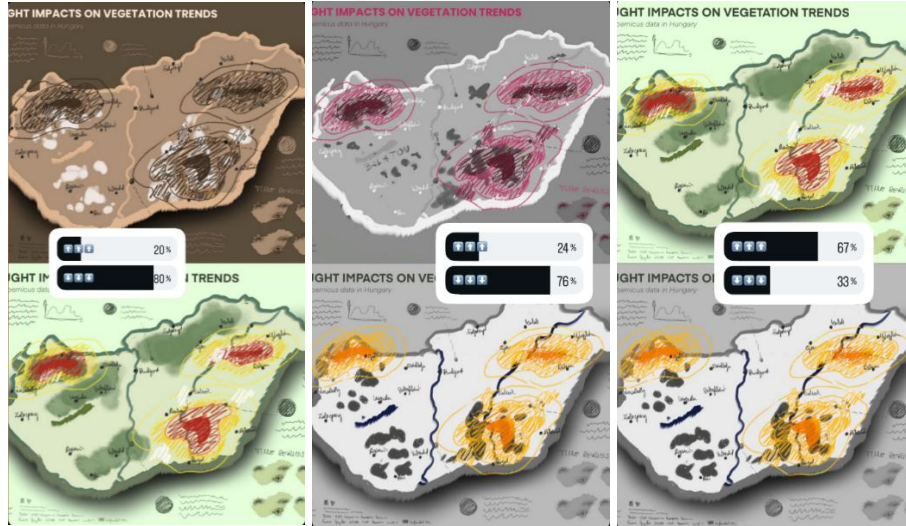


Figure 26., 27. & 28. Screenshots of the interactive voting taking place in Instagram Story on a phone screen (Own screenshot)

In the initial phase of the visual design planning, some user-oriented testing phases were scheduled. More than 60 users on the creator's Instagram profile voted for their preferred drought map display style using the posted Story voting feature. These included the original large drought map layout and various color combinations, including gray and magenta monochrome, a drought color scale ranging from reddish to yellow on a greenish background - similar to the original foreign and Hungarian drought maps - and warm earthy palettes. In the 2-round voting, users could first choose from 4 types of hand drawn illustration compositions, and then based on the voting between the two final color schemes, the dark red and yellow symbolization marked with natural primary colors proved to be the most popular. It is worth mentioning that already at this stage of the design planning, there were applicants to test the maps in the coming comparison phase. For online followers, following a process often means much more than just evaluating the final results. This can be observed in many creative processes, where users feel more involved when they are part of a development process, and are therefore more willing to participate in, for example, testing the completed maps. These sketches were very minimal designs that were drawn digitally by hand in the app Procreate on an iPad. Although this evaluation cannot be considered a formal usability study, it provided valuable feedback in the early design phase. The final version was then prepared based on additional cartographic approach requirements and layout tests. The following figures show the experimentation phase and design elements.

The most popular design used a light pastel green background, complemented by a custom drought color palette. This combination ranged from light yellow to orange to dark burgundy, representing increasing intensity. This palette was later refined using Adobe Color to improve harmony and contrast. Emphasizing clear distinctions between classes was an important consideration. The final color scheme was used together for both the static and interactive web applications. The development of polygon-based drought visualizations was strongly inspired by the cartographic work of - the aforementioned - John Nelson (Esri). His mapping techniques demonstrate how simple color palettes, transparency, and overlapping polygon geometries can convey complex spatial patterns. Wurman Dots and Statistical Maps also attempted to carry similar stylistic elements where possible.

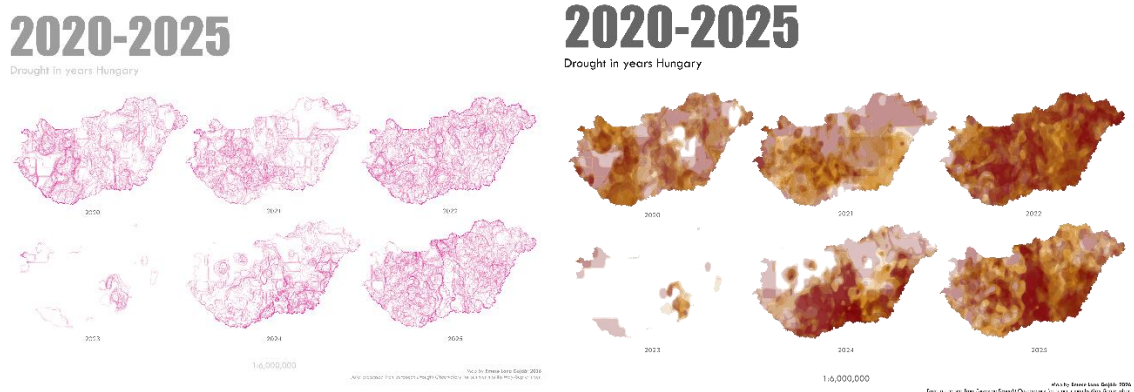


Figure 29., 30. & 31. Layout design testing maps (Own figures)

5.6 Printed Map Products

The visualizations developed in this study were primarily designed as printed cartographic products, not necessarily as digital maps. The original idea was to create a single large poster with infographic elements and explanatory figures, speech bubbles and images. However, this idea did not materialize, as for comparative maps of several years, the layout would not have supported the appearance of having the main map of a given year on the plan, and the following years only appearing in miniature, very minimalist and simple representations in one corner of the map. Although graphically understandable and interpretable designs were created, this design idea was not suitable for cartographic and educational purposes, so a much more minimalist map design had to be created. In addition to the posters, the idea of a leaflet-style printed map was also considered, and eventually worked with an intermediate solution, where the poster design was also suitable for a map that could be folded and unfolded after printing. This allowed the posters to be produced in printed form, while foldable printed maps could also be produced. The main page always showed the type of drought map in question, while the complementary NDVI map appeared on the back. Some infographic elements were also incorporated to help interpret the data displayed on the map. These included the legend and scale cartographic elements, as well as a short “How to read this map” section, which aims to improve accessibility for non-expert users. In addition to the ratio to drought areas calculated in annual breakdowns, the drought intensities are also broken down by category in terms of spatial intensity diagrams.

Although the original design included 1 large map with 5 other miniature maps, the final composition shows the year 2020 at a scale of 1: 4,500,000, while the other years are at a scale of 1: 6,000,000. This decision may be justified by the fact that due to the data density and minimalist presentation, it was necessary to provide 1 larger so-called "reference map". Since the main target audience is not professional people, it was justified to mark the county seats, large geographical regions and larger water areas of the country on the map. In the testing phase, the lack of incomplete city labels and geographical names on other maps was also questioned. All map layouts were made in A3 format and printed on 100 g/m² matte white paper. The choice of physical media reflects one of the central objectives of the research: to examine whether the fact that map users can touch, fold or explore maps in physical form, rather than in digital form, matters in the comparison process. Therefore, the multi-year layout had to be presented in a form that allows for this comparison and allows for the same annual layers to be compared online later. In the printed format, it was important that although similar color palettes were used, each map, due to the experiment with transparency, displayed different intensities and saturations of the same colors. Or a combination of these or a significantly transparent version, which resulted in differences in color and shade in the legends and map layers. This could have had a visual impact on users testing the maps later, as some prefer more intense colors and others prefer more pastel, less loud shades. It should also be noted that special attention was paid to the visual limitations of color-blind and color-deprived individuals when creating the maps, where possible, by selecting the appropriate symbolization and color by highlighting the appropriate contrast differences. After

printing, the desired photorealistic shades resulted in the desired colors, thus the comparability of printed and digital maps proved valid for subsequent testing.

In order to directly compare drought intensity and vegetation response, the corresponding NDVI degradation difference maps were included on the back of each printed map. This allowed both datasets to be examined together within the same physical product.

5.7 NDVI Loss Mapping

The preprocessing workflow resulted in six annual NDVI difference datasets covering the period between 2020 and 2025. These raster layers represented the spatial distribution of vegetation degradation between the spring and late-summer observation periods. The design planning of the *Vegetation degradation maps* followed the same minimalist visual philosophy adopted for the drought intensity maps, ensuring a consistent appearance throughout the visuals. Several alternative visualization methods, including grid-based representations, Wurman Dot maps, and choropleth maps, were considered during the design process. However, because these techniques had already been applied to the drought indicator data, they were not adopted for the vegetation analysis to preserve visual diversity between the different map series. In order to support cartographic representation and facilitate comparison with the drought datasets, the NDVI difference rasters were transformed into vector polygons through a raster-to-polygon conversion. Following the conversion, the datasets could be classified, symbolized, and integrated into the map design workflow. The resulting vector layers formed the basis of the NDVI degradation maps presented in this chapter. In addition to drought intensity mapping based on the CDI, a separate cartographic approach was desired to visualize and support the potential impact of drought conditions on vegetation. Although raster-based visualization may appear less visually refined than generalized vector representations, it more faithfully preserves the spatial characteristics and resolution of the original remote sensing data. Retaining the pixel structure also provides a direct visual connection to the source imagery from which the NDVI values were calculated, making the processing workflow more transparent for the more experienced eye. While CDI represents meteorological and agricultural drought risk through the integration of precipitation, soil moisture, and vegetation anomalies, the NDVI Difference maps focus directly on observed vegetation responses derived from satellite imagery.

The visualization was based on seasonal NDVI difference calculations derived from Sentinel-2 satellite imagery, as described detailed the I. Research chapter. Sentinel-2 was selected due to its high spatial resolution and multispectral capabilities, particularly its near-infrared bands designed for vegetation monitoring applications (Addabbo et al., 2016). For each year between 2020 and 2025, a spring mosaic representing peak vegetation development (May–early June) and a late-summer mosaic representing the end of the growing season (August–early September) were generated. The spring NDVI values were subsequently subtracted from the corresponding late-summer values in order to identify areas where vegetation condition declined during the summer period. This approach was selected because drought impacts on vegetation are often expressed through reduced greenness, biomass loss, and early senescence, particularly in grasslands, agricultural areas, and drought-sensitive vegetation coverages. Following preprocessing and masking procedures, only pixels representing vegetated surfaces were retained for mapping, while water bodies, urban areas, and other non-vegetated surfaces were excluded. The resulting NDVI difference raster was classified into three categories representing the relative intensity of vegetation degradation:

- Moderate vegetation loss
- High vegetation loss
- Very high vegetation loss

This simplified classification was chosen to improve interpretability and facilitate visual comparison between years. Rather than displaying continuous NDVI values, the categorical representation highlights areas where vegetation experienced the strongest decline relative to spring conditions. Consequently, the maps provide an opportunity to compare drought indicators with observed vegetation responses and to identify regions where drought conditions may have translated into measurable ecological impacts. This design decision intentionally contrasts with the generalized drought maps, illustrating the difference between an interpreted drought indicator and an observed satellite-derived vegetation response. While the drought maps presented in this study required

extensive data processing, aggregation and generalization to improve readability, the NDVI Difference maps were intended to communicate actual vegetation responses with minimal additional cartographic abstraction to still remaining accessible to non-specialist users.

Finally, several limitations should be acknowledged. Although the Sentinel-2 imagery was carefully selected to minimize cloud contamination, complete cloud-free coverage was not always available within the desired seasonal acquisition windows. As a result, the 2025 NDVI Difference map contains anomalously high vegetation loss values in parts of the Kisalföld region of northwestern Hungary. Visual inspection indicated that these values were caused by residual cloud contamination in the late-summer mosaic rather than by actual vegetation degradation. While the masking workflow successfully removed cloud-related artefacts in the remaining years, the same procedure proved insufficient for this particular image. A dedicated cloud-masking workflow would likely reduce such errors; however, suitable cloud-free imagery for the selected period was not available, meaning that alternative acquisition dates would have been required. Consequently, the affected area should be interpreted with caution when evaluating the 2025 results. Despite these limitations, the NDVI Difference maps provide a valuable complementary perspective to drought intensity mapping by visualizing the spatial distribution of vegetation decline and highlighting regions where prolonged summer drought conditions may have had the greatest impact on ecosystem productivity and vegetation health.

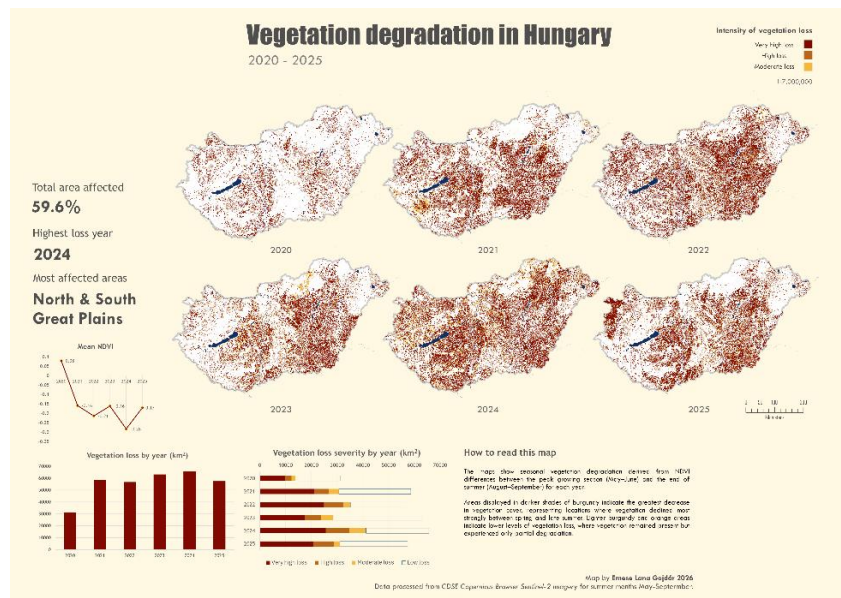


Figure 32. Vegetation degradation map final layout (Own figure)

5.8 Interactive Web Maps

Although the primary goal of the research was to produce printed posters and foldable leporello maps, the development of web maps, which have become increasingly popular and famous in the past decade, also formed the basis for the comparison. These are interactive, web-based versions of the static maps, similar "copies". Web map-based displays have undergone significant development in recent years and have a number of modern tools that static and printed formats cannot reproduce. These include time-lapse displays, switching between transparent layers, Swipe function and interactive measurement or drawing on the map and animation of the movement of anomalies, etc. Beyond the limited toolkit and display maps of Hungarian drought monitoring systems discussed in the *State of the Art* chapter, the goal was to create an improved, more visually engaging map that would leave people with a more memorable and interesting experience and that they would be more willing to return to understand and learn about the drought that affects them. The theoretical foundations of this approach are found in the concept of geovisualization. It was born from the integration of cartography, GIS, scientific visualization,

information visualization and human-computer interaction research. According to Kraak (2003), maps in a geovisualization environment function not only as presentation tools, but also as interfaces for exploring spatial data. With these innovations, users are enabled to examine patterns, relationships and trends through interaction, rather than passive observation. They allow us to examine the same data set from multiple perspectives, which may remain hidden in printed form, while facilitating the understanding of spatial features through interaction. (Krassanakis et al., 2023) In addition to the above, the interactive maps provide additional benefits to users. They can access additional information on demand. This can be done through pop-ups, layer controls, filter options and temporal navigation tools without overwhelming the visual composition of the map. These are the principles of user-centered geovisualization. According to which, effective maps should support both information communication and user discovery, while considering different levels of expertise. (Nakić et al., 2022) The web drought maps for Hungary were created using the web map function available on the ArcGIS Online interface, from which a web application was created using the ESRI Experience Builder add-on. This way, they got a map application accessible from both phones and the web, and with the user-friendly drag-and-drop development, simple but ready-to-use web maps can be easily created. The end result was created on this interface, and programming knowledge was not required for the web map part. It should be noted that web applications with a very wide range of tools can also be created with open source and other online map services, the main aspect of this thesis was not web maps, but the comparison of drought visualizations and methods.

6 USER EVALUATION RESULTS

To assess the readability and practical usability of the developed cartographic products, a qualitative user evaluation was conducted with GIS professionals and non-expert participants, from different professional backgrounds. A total of 15 participants participated in the testing, of which 8 professional participants volunteered to review the maps. The basic idea was to have the maps tested by people from personal circles of acquaintances who were not experienced in map reading, as well as by experts whose profession is remote sensing and GIS, former university classmates and colleagues. Respondents then compared the visualization methods, examined both the printed and web-based interactive outputs, identified the representations they considered most understandable, and commented on elements that could be improved or corrected. The purpose of the evaluation was not to verify the scientific validity of the underlying drought data, but to investigate how effectively the different cartographic approaches communicated spatial and temporal information to users and which map types was the most engaging one for them to have a detailed review and learn more about the drought affected areas with the created maps.

The people reviewing the map had to give a short evaluation report focusing on the following questions:

- Which drought map was the easiest for you to interpret visually?
- Were you able to determine how severely your home area has been affected by drought in recent years?
- What can you tell from the maps? Did you learn any new information about the situation?
- What did you find most useful?
- What did you find incomplete, confusing, or difficult to understand?
- Which did you find more understandable and useful: the static (printed) maps or the web-based (interactive) maps?

- Based on the maps, what can you say about the impacts on vegetation?

6.1 User preferences

A main finding was that no visualization method was regarded as universally superior. When the main research questions of the thesis were formulated, a specific result was expected. However, preferences depended strongly on the intended task, the spatial scale of interest, and the participant's previous experience with maps and data visualization. In the following, the different types of maps are evaluated by type in turn.

Firstly, mentioning the *Statistical Map*, combining choropleth coloring with pie-chart diagrams, was the most frequently preferred representation. Participants generally described it as clean, familiar and easy to interpret. The administrative units provided recognizable spatial references, while the color scheme enabled rapid comparison of drought intensity between regions. Several respondents also valued the combination of spatial overview and quantitative information withing a single layout. However, the pie charts did not function equally well for all users. Some participants found them informative, particularly comparing the composition of drought categories, whereas others could not immediately determine what the diagrams represented. Their relatively small size further reduced readability in the printed version. These reviews indicate that the diagrams can add meaningful information but require clearer explanation and possibly stronger visual emphasis. Overall, the Statistical Map proved to be the easiest to interpret for the reviewers, although it should be mentioned that in relation to the display of drought, the symbolization of city-level administrative zones can be misleading, since the extent of the drought does not change in reality at the "borders" of the cities, yet from a decision-support perspective, and for less experienced map readers - i.e. the inexperienced average person - these were the maps that were most easily used to find and interpret the severity of the drought in their homes and immediate surroundings.

Responses to the *Wurman Dot Map* were more varied. Several participants considered it the most intuitive representation because its regular grid and discrete symbols supported rapid recognition of national-scale patterns. The separation between symbol sizes and colors also reduced overlap and made differences in intensity visually distinct. Some professional users appreciated its equal-area structure and the reduced influence of administrative boundaries, while several non-experts responded positively to its unusual but visually engaging appearance. Other participants ranked the Wurman Dots Map lower, because the gridded pattern appeared less natural than

continuous polygons and was less useful for identifying individual settlements. Its strengths are therefore most apparent at the national overview scale on the printed static maps, whereas zooming into local areas on the interactive maps reduced the benefit of the regular dot structure. Based on this, we can state that the symbolization of the Wurman Dots map only works well if the displayed points on the interactive maps are scaled appropriately even after zooming, so that we obtain adequate visual clarity while maintaining the proportions of the covered area and not only the visualization works on the scale of the entire national coverage.

The *Area Polygon Map* was also evaluated positively, especially by users who preferred a direct representation of drought as a spatially continuous environmental phenomenon. Its uncluttered appearance and smooth regional patterns made the general extent of drought easy to recognize. GIS professionals in particular appreciated that the representation was not constrained by municipal or country boundaries. At the same time, some respondents noted that the blended colors made precise category boundaries more difficult to identify than in the Statistical or Wurman Dot maps. During the testing phase of this type of map, especially for less experienced reviewers, a brief explanation was often needed to explain how to interpret the map and what exactly it showed. It is worth mentioning here that although a description to help interpret the map was included with each map, several participants did not take the instructions into account and tried to interpret it on their own. However, people with more experience and an expert background found this display method more visually appealing and understandable, both in terms of interpretability and ease of use.

The *Outlines Map* was consistently identified as the most demanding representation. Although its appearance was often described as original, aesthetically attractive or visually expressive, the dense accumulation of lines made the underlying drought pattern difficult to interpret, especially in years with extensive drought coverage. Some users understood it only after comparing it with the filled polygons or the Statistical maps, while others remained uncertain about whether the lines represented intensity, frequency or changing boundaries. The method therefore appears more suitable as an experimental cartographic output than as a primary tool for communicating drought conditions to a broad audience. A few respondents nevertheless suggested that combining the outlines with partially transparent polygon fills could improve its interpretability. In practice, this could mean that the Area Polygons and Outlines visualizations together could theoretically prove to be more powerful and effective than either one alone.

6.2 Information extraction and interpretation

The evaluation also examined whether participants were able to extract meaningful information from the maps beyond a mere expression of visual preferences. In general, respondents were able to identify key differences between years and recognized that drought conditions varied significantly both spatially and temporally. For better understanding, the study scored results based on the following criteria.

The severe drought of 2022 was immediately visible to most users, while the comparatively limited drought extent in 2023 was frequently mentioned as unexpected. Several participants had previously confused the conditions of these two years or had not realized how strongly they differed. The more widespread drought conditions that recurred in 2024 and 2025 were also interpreted as evidence of a stable spatial pattern. Meanwhile, participants were particularly surprised by the changing geographical distribution of the most severely affected areas - which is truly surprising and significant differences were also apparent during data processing, but the results displayed are real based on the EDO data. Many initially expected the Great Hungarian Plain to dominate the drought pattern throughout the complete period. The maps instead showed that parts of Transdanubia experienced similarly severe or, in some years, stronger drought intensity. The respondents also identified recurring exposure in southern Hungary, while mountain regions and parts of the western border area appeared comparatively less affected across several years. These observations show that the combined display of all six annual maps successfully proved the simplified assumptions that the drought is almost exclusively limited to the plains of the Great Hungarian Plain, as it is clearly visible that the rest of the country may also be affected periodically, but its effects are mainly concentrated in the Great Hungarian Plain.

The arrangement of the printed layout maps at a consistent scale was repeatedly described as one of the most useful design decisions with its minimalistic visuals. Users could compare the extent, location and severity of

drought directly without changing views or remembering previously displayed layers. The infographic elements (charts and diagrams) further supported this comparison by summarizing annual drought-affected areas and different drought level class distributions. For several respondents, these graphics provided a faster indication of overall differences than the maps alone. When we consider these aspects, it can be concluded that for less experienced map readers or people with more analytical thinking, the statistical additional elements made the understanding of the data visually much more understandable, and the maps only supported an understanding based on spatial placement. It is worth noting that without them, the maps would probably have carried less information for many people, and the maps alone would have been less engaging content in terms of readability.

Among the last considerations in interpreting information, the *NDVI* maps generated substantial discussion because vegetation degradation did not correspond perfectly with the CDI patterns. Participants observed that years with the greatest drought severity did not always contain the most extensive mapped vegetation loss. Some interpreted this as a possible indication of delayed or cumulative vegetation response, while others suggested that additional factors such as land cover, irrigation, fire, local climatic conditions or species composition could influence the results. These experiences while reading the maps are significantly related to the professional level at which the test subjects viewed the map and how much geographical background knowledge they had. For the general public, however, this understanding of the vegetation map provided feedback that suggests that they better understood the impact on the vegetation in Hungary and thus had a deeper understanding of the fact that the condition of the vegetation shows an increasingly deteriorating trend and predicts it for the future. The relatively high degradation displayed for 2023 and the anomalous values in western Hungary in 2025 were questioned several reviewers - I should mention here that the exceptionally high numbers in the Kisalföld region in 2025 are unfortunately the result of an error during data processing, which have been already explained in more detail in the *NDVI* processing chapter. These reactions are important because they show that users did not interpret the *NDVI* maps as a simple copy of the drought indicator. Instead, the joint presentation encouraged them to recognize that vegetation health is influenced by many different processes, and that agricultural crops, our forests, and our grasslands are responding differently and with delays to the drought conditions of the past decade.

6.3 Static and Interactive map use comparison

Although the original research questions included the aspect of wanting to understand whether printed static maps or web interactive maps would perform better in the study, a more comprehensive result was obtained. The printed and interactive products were generally regarded as complementary rather than competing formats. Respondents assigned them different roles according to the scale and purpose of the task. In the total overview, the printed layouts were preferred for national-scale interpretation, presentations, publications and rapid comparison between years. Since all annual maps are displayed simultaneously, users can identify temporal changes without operating controls or switching between layers. The consistent arrangement was especially useful for communicating the overall drought narrative and for identifying outliers. The interactive web application, on the other hand, was considered more effective for examining specific locations. Search, zoom, layer switching, pop-up information and the *NDVI* swipe function helped users locate their home area and inspect local conditions in greater detail. Journalistic and professional respondents emphasized that the web map would be particularly useful when preparing regional analyses, investigating individual settlements or extracting information for local communication. These are very promising results for a potentially further developed and nationally distributed educational, informative drought map for the Hungarian people.

Nevertheless, the interactive environment introduced additional usability challenges for some users. The large number of available layers occasionally made it difficult for non-experts to understand which dataset was active or why different layers returned different drought values. The Contours representation was particularly confusing for many, but when combined with other layers, it provided some clarity in their interpretation, as similar shapes were recognized in terms of drought severity. Some users also encountered unexplained search markers – however, this was a limitation of ESRI Geocoding Search Engines – which navigated the user to the given area after a site search but placed random yellow dots on the map following the searches. They noted the ambiguous default labels on the basemaps and the labels for regions – also a limitation of ArcGIS Online symbolization, as the aesthetic placement of areas was only available in ArcGIS Pro - and the feature selection behavior typical of Wurman Dots

maps, as here the entire square grid was selected during the selection of areas, regardless of the point intensity, for the entire area.

6.4 Usability issues and possible improvements

Several different suggestions appeared in the evaluations and opinions received. The most common was related to geographical orientation, because there were participants who would have requested the names of the main settlements on all my maps. Furthermore, this presentation was intentionally made in this way so that the very first map could also serve as a kind of reference for map users, which could help in interpreting the static maps in subsequent years. Naturally, due to the scale, it was not justified to visually clutter all the maps with city and region names, but if this would have provided significant assistance in interpretation, this improvement could easily be made in the case of all static maps. This was especially important for those users who did not know the exact location of Hungarian cities, or who wanted to quickly determine their own region. A clearer emphasis on the capital, Budapest, and the county seats was preferred over minimalist maps. Larger rivers and bodies of water, especially the Tisza and Lake Fertő close to the Austrian border, were also suggested as stronger reference elements.

Terminology and legend design represented another recurring issue. Some users did not recognize the CDI abbreviation without consulting the thesis and recommended writing out Combined Drought Indicator within the map or explanatory text, so continued this evaluation this was corrected in the 'How to read this map' section. Participants mentioned that for the better understanding of the pie charts, they requested more simpler and clearer explanations of the legend of the pie charts and, in some cases a numerical threshold for the drought risk levels. However, because CDI is a categorical composite indicator rather than a single continuous score, the latter request reflects a need for a clearer description of class definitions rather than simply adding numerical break values. This definition was mentioned in the map reader's guide which was attached to the printed and interactive version as well. The personally guided user reviews were more effective related to understanding the CDI in the present than it was as if the tester was left on its own to discover the maps.

For the interactive web application, suggested improvements included more advanced transparency controls, and wider selection of base maps, clearer polygon highlighting on the selections, a clearer Swipe function to identify the two years being compared, and short explanations for location search results and randomly generated symbols - these are for the previously mentioned Geolocation search engine's own generated points, which is most likely a limitation of the software used and did not appear to be an issue for all testers.

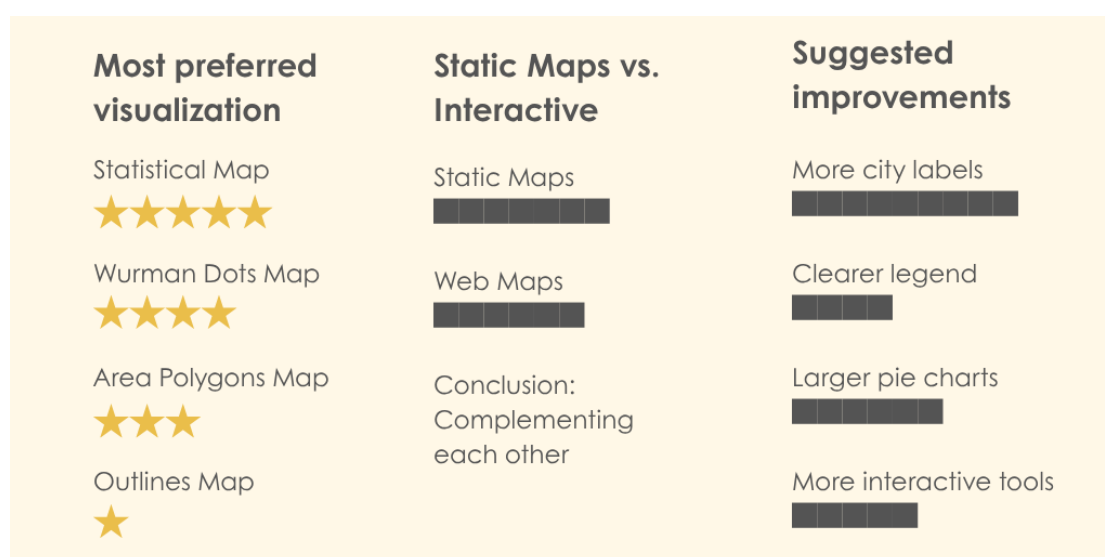


Figure 33. Testing evaluation results (Own figure)

7 DISCUSSION

The evaluation of the testing confirms that the visualization methods can serve different communication purposes. The Statistical Map offers the clearest connection to recognizable administrative areas and supports quick regional comparisons for general understanding, but its diagrams require stronger explanation and understanding. The Area Polygon Map effectively conveys the continuous spatial nature of drought, although the mixed category boundaries may reduce accuracy for some people. The Wurman Dots Map performs well as a generalized national overview and offers a visually distinctive alternative to boundary-based mapping, but is less effective in identifying local drought severity, and this mapping method works mainly in print, losing its data visualization value when zoomed in on an interactive map. The Outlines Map, while providing an interesting and aesthetically pleasing display, has interpretation requirements that limit its value in general communication and are therefore not suitable for educational or informational purposes.

The reviews also show that professional background influenced preferences more than might be expected during the map production. While GIS professionals, environmentalists, journalists, and non-expert users did not always choose the same representation as the best performing and easiest to understand, it can be said that they generally recognized the same major temporal and regional patterns. This suggests that the core information was successfully conveyed across the different cartographic formats, despite differences in ease of interpretation and method. Rather than selecting out a single universally optimal map as preferred over others, the results support the use of multiple mixed representations. No single method can simultaneously maximize national overview, local orientation, visual simplicity, and all-encompassing detail. The original goals were also to produce a more visually desirable graphical map product that people would prefer to hold in their hands or explore and learn from interactive maps, rather than the original professional national drought maps, which are often difficult to interpret and require higher background knowledge in several respects. Ultimately, the printed products proved to be the most effective for comparison and narrative presentation, while the interactive application supports detailed and user-directed individual investigation. This further implies that the combined use of the two outputs is the most effective way to convey information from both an educational and decision-support perspective.

Although web maps are not a new modern form of mapping from the future, the study shows that the online mapping knowledge currently available in Hungary and the meteorological, especially drought monitoring web maps themselves are much more outdated. Throughout Europe and globally, much more complete and advanced visualizations are used to draw attention to the importance of environmental crises, therefore the final result of the thesis provides substantive information mainly for Hungarian people and decision-makers or those working in education. Which can help to better understand in which direction it would be possible to move more modern accessible maps for the population and support more understandable forms of communication with these visualizations that will take their place in the news, social media and even in future textbooks.

Table 2. User testing result of the comparison (Own table)

Map type	Interpretability	National overview	Local identification	Visual complexity
Statistical Map	High	High	High	Moderate
Area Polygon Map	High	High	Moderate	Low
Wurman Dots Map	Moderate–High	High	Moderate–Low	Moderate
Outlines Map	Low	Moderate	Low	High

8 CONCLUSION

The main topic of the thesis was to make drought mapping and visualization more graphically appealing and engaging. Although Hungary has always been in an extreme location exposed to droughts, in recent decades and due to climate change, irreversible processes have begun in the Carpathian Basin. In order to understand these processes, information, education and communication tools that are as factual and scientifically based as possible are needed for current and future strategic and adaptation plans, both at the political decision-making level and for ordinary people. The main intention was to create visualizations and maps that would arouse people's interest, help them understand the cause-and-effect relationships, and provide explanations for possible droughts and current vegetation changes. The current weather forecasting and drought communication tools explored in this thesis, although very powerful and data-rich services, do not take into account aspects intended for public understanding. These are well-known problems and everyday questions in both academic and expert circles, but for the average person, a scientific map service and GIS data service provide little understandable information. At the same time, informing other professional circles would also be an important aspect, be it national parks, urban planners, farmers, livestock breeders or stakeholders.

To achieve this goal, the main starting point was the datasets provided by Copernicus Services that are freely available throughout Europe, such as the CDI provided by Copernicus Emergency Services via the European Drought Observatory web application. A lot of information can be extracted from the raw data downloaded here and the desired mapping techniques were also possible. After obtaining the data, by running automated models, it was possible to generate surfaces such as those shown on the Drought Aware dashboard interactive map covering the American continent. The assumption is that if the maps produced by the thesis provide a similarly interesting visual and interactive experience, they could arouse interest much more than the currently available data services. In addition to displaying drought, it was important to somehow link the state of vegetation, which has been increasingly spectacularly withering in the past decade, to the frequency of dry summers. Therefore, this parallel could be illustrated by mapping the degradation of vegetation at the end of the summer season. This decision is also justified by the fact that although headlines and news about drought appear frequently in social media and public media, the state of vegetation and its damage are not mentioned enough. It should be mentioned here that it would be worthwhile to supplement the completed maps from a hydrological perspective, as significant changes have also occurred in the country's water management, but this paper only focuses on the development of vegetation trends in relation to drought. Therefore, during the preprocessing of the drought data and NDVI data, it was also a consideration that the completed ArcGIS Model and Jupyter Notebooks should create a processing system that provides a reproducible workflow for anyone. This allows anyone who wants to conduct cartographic experiments from the raw EDO data to generate similar visualizations and data. Therefore, detailed instructions and descriptions were prepared for the codes and the model, supplemented with a flowchart.

After the data was prepared, the mapping experiments aimed to produce several cartographic representations, highlighting drought from different visual perspectives. Four complementary map types were developed, ranging from more artistic visualizations like the Area Polygons Map and the Outlines Map, intended to attract attention and raise awareness. And more data-oriented representations such as the Wurman Dots Map and the Statistical Map. Alongside the drought maps, an NDVI based Vegetation Degradation Map was also created using the original pixel-based Sentinel-2 raster data, providing an additional basis for comparison between drought intensity and vegetation response. The final products were prepared both as printed posters and foldable double-sided maps – with drought maps on the front and the corresponding NDVI maps on the reverse side. Interactive web applications was also developed using ArcGIS Online and Experience Builder, allowing users to explore the same datasets through additional functions such as layer switching, alternative basemaps, zooming and location search.

The testing was mainly conducted by GIS professionals, but a few non-professionals also evaluated the outputs according to the given criteria. The main question was focused on the usability of the maps and whether map readers learn any new information based on what they see. Professional opinions were mainly important in this comparison because the validity of the functionality of the maps was of interest. Possible details for improvement and errors were noticed earlier by professional colleagues and university professors, they were able to give their opinions in a targeted manner in their feedback, and most of these were corrected when evaluating the results. It

is important to mention that among the testing participants there were several applicants who were unable to give a substantive opinion because the interpretation of maps was completely foreign to them. There were also those for whom interactive maps were a challenge because they did not know how they worked or had never used digital maps before, perhaps only on their phones. Because of these factors, it was important to strive for a generalized and minimalist presentation when designing the maps, as a map with multiple components and multiple data, with many layers and graphic elements, can be overstimulating for people who may have difficulty reading maps. The final comparison testing involved 15 people, of whom 8 were GIS or remote sensing specialists, data visualization experts, environmental engineers or university professors. The final evaluation yielded unexpected results, according to which it emerged that no mapping method showed outstanding preferences over the other. There are drought maps with more effective and stronger communication properties among the tested products, but based on the feedback, people liked both static and printed maps and enjoyed turning them in their hands just as much as they enjoyed exploring regions on interactive maps and playing with the layers and interchangeable views. Individual preferences naturally emerged and the aforementioned prior experience and background knowledge were significantly important for the test subjects, but an overall and general ranking of the maps nevertheless emerged. The most frequently chosen and preferred map type was the Statistical map, with the simple explanation that the symbolism and colors of the map type guided the map user's eye to their own studied areas in a much more understandable and representative way. It was easier to navigate and identify the appropriate drought intensity and provided a more comprehensive picture when comparing annual trends. This was followed by the Wurman Dots intensity map, where, with a similar clear display and logic, people could easily identify the extent of drought in their area of residence or the most endangered regions. It should also be mentioned here that this map could cause problems in some cases in digital form due to spatial coverage and displacements. The Area Polygon map came in third place, this type of map was particularly popular among GIS experts, with several testers highlighting that it was a visually impressive and different form of mapping. The average map reader also liked it, although during several tests it was highlighted that they had trouble understanding the structure of the layers and the nature of their frequency on this map, although they considered it beautiful from an artistic point of view. The least liked and chosen map was Outlines, which several test subjects found to be interpretable only if they tried to read the form of the patterns together with the other maps. At the same time, they found it graphically interesting, but the comparison shows that this type of map is not recommended for educational and science communication purposes. Among the positive results, the majority of respondents found the vegetation degradation map useful and interesting. Several of them successfully discovered on their own that the response of vegetation to drought is delayed by up to 1-2 years in drought years and that the greatest drying does not necessarily occur each year. This confirms that it served as a useful complement to the maps, and from several feedbacks it can be concluded that the maps showing the state of vegetation provided new information to several people based on their previous knowledge, and the information transfer achieved its goal.

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ATTACHMENTS

Structure of digital data

- **Input_Data** Contains all original input datasets used in the research, including Copernicus Emergency Management Service (EDO) data, Sentinel-2 satellite imagery, and basic vector layers for mapping.
- **Output_Data** Contains all processed datasets and final cartographic products.
 - **Data** Contains the processed EDO and NDVI datasets.
 - **Figures** Contains figures and illustrations used in the thesis.
 - **Graphs** Contains statistical charts and tables generated from the processed datasets.
 - **Jupyter_Notebooks** Contains the Python and ArcPy Jupyter Notebooks used for data preprocessing, automation, and analysis.
 - **Maps** Contains the final static map layouts.
- **Poster** Contains the final research poster prepared for printing.
- **Text** Contains the master's thesis manuscript.
- **Web** Contains the webmap scripts with assets.

The Copernicus Emergency Management Service (European Drought Observatory) datasets and Sentinel-2 imagery used in this thesis are publicly available under the Copernicus Programme data policy. Supplementary vector datasets obtained from OpenStreetMap are distributed under the Open Database License (ODbL). The processed datasets, scripts, cartographic layouts, and web application were created by the author solely for the purposes of this master's thesis.