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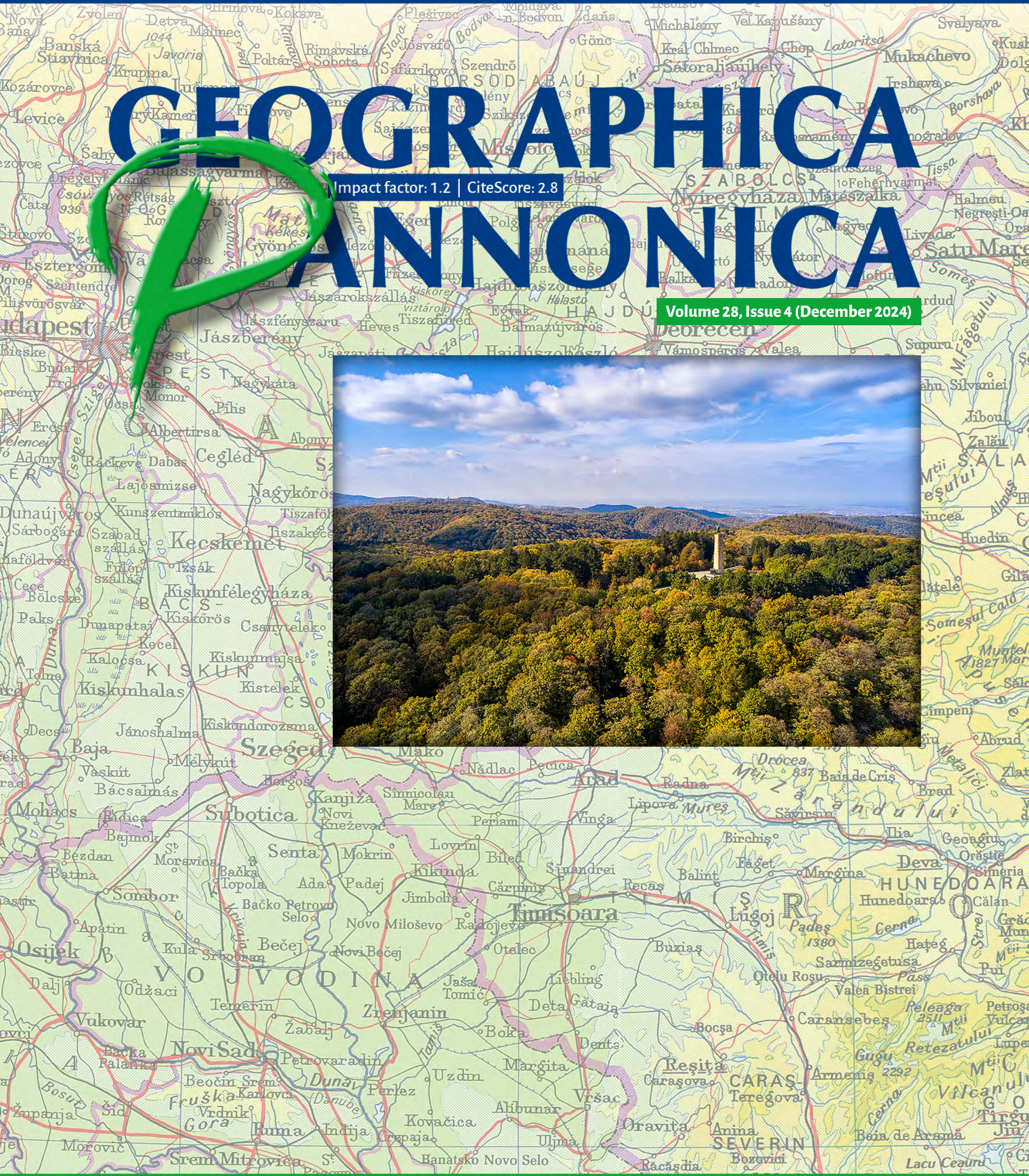

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DEPARTMENT OF GEOGRAPHY, TOURISM AND HOTEL MANAGEMENT

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Phenology Analysis for Detection of Vegetation Changes Based on Landsat 8 Images in Nature Park Kopački rit, Croatia

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KEYWORDS

- vegetation activity
- "npphen" package
- management zones
- phenology analysis
- normalized difference vegetation index (NDVI)
- k-means classification

ABSTRACT

This study proposed a method for detecting vegetation changes and establishing geospatial management zones based on the 10-year phenology analysis using normalized difference vegetation index (NDVI) long-term trends from Landsat 8 multispectral imagery in Nature Park Kopački rit. The main components of the proposed method include phenology analysis and NDVI anomaly detection supported by unsupervised k-means classification of vegetation management zones. The reference monthly NDVI values (2013–2019) with three test years (2020–2022) strongly indicated very high heterogeneity in vegetation activity. A 100 m spatial resolution and a monthly temporal resolution were used. The results of unsupervised k-means classification in five vegetation activity classes indicated that three of these classes have considerably high negative NDVI anomalies, covering 64.1% of the study area. While the proposed method ensures the detection of vegetation changes and vegetation activity zones, a comprehensive field observation is required to determine the potential environmental and/or anthropogenic causes. However, the proposed approach significantly reduces the need for extensive fieldwork, allowing biologists to focus their efforts on areas with detected abnormal vegetation activity.

Introduction

Detecting changes in vegetation within protected natural areas is critical for environmental monitoring, conservation, and management (Slingsby et al., 2020). Vegetation is a key indicator of ecosystem health, biodiversity, and environmental change, which is of special importance in managing protected natural areas (Wang et al., 2020). Changes in vegetation patterns can indicate a variety of ecological disturbances, including wildfires, invasive species, or human-caused impacts such as land use change. Conservationists, land managers, and policymakers can use timely and accurate detection of these changes to develop effective mitigation solutions and maintain the biological integrity of protected areas (Elsen et al., 2023). Monitoring vegetation dynamics also provides significant insights into the effects of climate change, as changes in plant composition and phenology are often associated with changing climate pat-

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terns. The invasive species (ElMasry & Nakauchi, 2016), and human-caused events such as land-use changes (Ntukey et al., 2022) can cause changes in vegetation that can have a major impact on biodiversity and overall ecological balance. The emerging threats can be timely addressed by identifying these changes in real-time using advanced monitoring technologies such as remote sensing (Khanal et al., 2020). This proactive strategy enables the adoption of specific conservation measures, such as habitat restoration, invasive species control, or wildfire management, to reduce the impact of disturbances. In addition, the data provided by vegetation change detection supports evidence-based decision-making for land-use planning and policy-making that promotes the protection of natural areas (Bell et al., 2023).

Remote sensing technologies, especially open data satellite imagery, have greatly improved the ability to detect rapid changes in vegetation over multiple geographic and temporal scales (Radočaj et al., 2020). Such developments allow for early intervention and adaptive management and contribute to the overall sustainable management of protected natural areas, ensuring the survival of various ecosystems and their essential ecological services (Li et al., 2020). This high spatial and spectral resolution enables precise monitoring of plant cover and the detection of small changes that may indicate disturbance (Ustin & Middleton, 2021). In addition, its temporal resolution enables multiple sensing to the same region, allowing the detection of phenological patterns that represent seasonal changes in vegetation over time. Phenology analysis is critical for determining the timing of key life cycle events such as flowering and leaf emergence, which are sensitive markers of environmental change (Dronova & Taddeo, 2022). However, it requires long-term satellite imagery to establish long-term trends in vegetation activities, for which Landsat missions provide stable and historically available data since 1972 (Hemati et al., 2021). Using Landsat multispectral imagery for phenology analysis improves the ability to detect and interpret rapid changes in vegetation, resulting in a more complete understanding of biological changes within protected areas. This knowledge is critical for making informed conservation decisions, as it helps to establish adaptive management methods tailored to the unique biological needs of protected natural areas (Roux et al., 2021).

The use of vegetation indices for ecological studies, including phenological analysis, requires careful evaluation of individual study objectives and environmental factors (Poggi et al., 2021). While indices such as the enhanced vegetation index (EVI), normalized difference red edge vegetation index (NDRE), and soil adjusted vegetation index (SAVI) have distinct advantages, the normalized difference vegetation index (NDVI) remains the preferred option for a phenology analysis due to its standardized [-1,1] value range and well-documented relationship of its values to vegetation health and vigor (Misra et al., 2020; Torgbor et al., 2022). NDVI has proven successful in capturing the many phenological phases of vegetation, such as green-up in spring and senescence in fall (Zeng et al., 2020). Its sensitivity to chlorophyll concentration makes it a reliable indicator of plant photosynthetic activity, and thus an effective proxy for phenological shifts. Moreover, a recent study showed that these indices mutually produce a significant level of multicollinearity, indicating that there are only minor differences in their use for assessing vegetation health (Radočaj et al., 2023). The simplicity and ease of understanding of the NDVI makes it generally relevant across different ecosystems, facilitating comparisons across studies. While previous studies thoroughly evaluated various vegetation indices as a part of phenology analysis (Granero-Belinchon et al., 2020; Hu et al., 2021; Zhou et al., 2020), there has been a research gap in developing the methodology to detect vegetation changes and establish geospatial management zones for effective vegetation monitoring and management.

To address this research gap, the objective of this study is to propose a straightforward and robust method of detecting vegetation changes utilizing Landsat 8 multispectral imagery for phenology analysis during 10 years (2013–2022) for protected Nature Park Kopački rit in eastern Croatia.

Data and methods

The proposed method of detecting vegetation changes utilizing Landsat 8 multispectral imagery for phenology analysisconsists of three major steps: 1) acquiring and preprocessing of Landsat 8 multispectral imagery; 2) phenology analysis and NDVI anomalies detection; and 3) unsupervised classification of vegetation management zones (Figure 1).

Study area

Nature Park Kopački rit covers 177 km^2 of ecologically diverse wetland region situated in eastern Croatia along the Danube River (Figure 2). Dominant vegetation includes forests of white willow in the floodplain, while slightly elevated areas support forests of black poplar and pedunculate oak (Šag et al., 2016). Aquatic vegetation thrives in the park's numerous water bodies, with communities of duckweed, water lilies, and bulrushes prevalent. The park is crucial for preserving the ecological balance of the area, maintaining migrating bird populations, and providing nesting habitats for various species (Bjedov et al., 2023). Identifying changes in vegetation is crucial for monitoring ecosystem health and detecting potential dangers such as

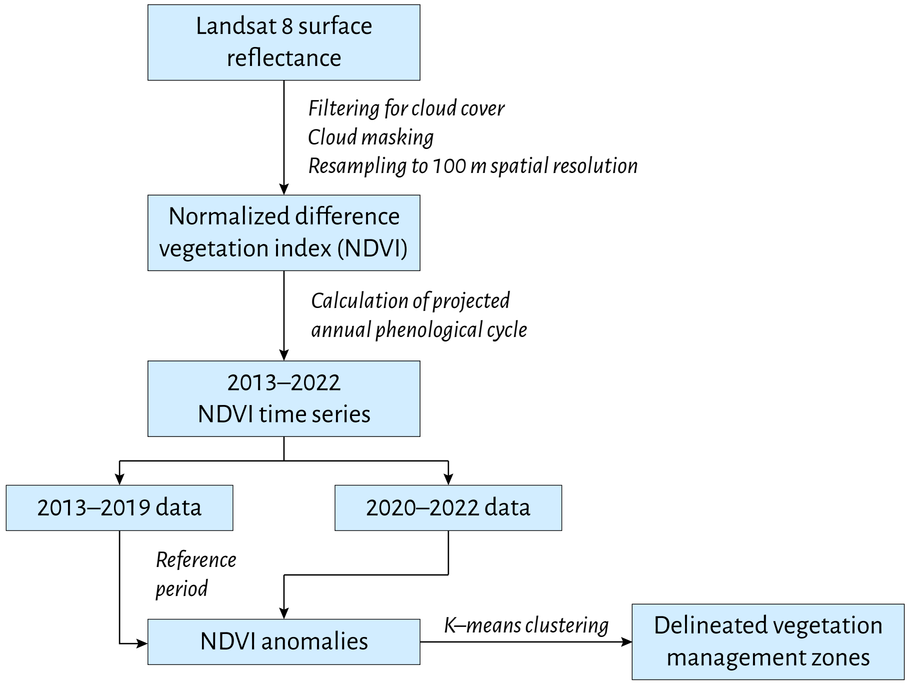

Figure 1. Flowchart of the study

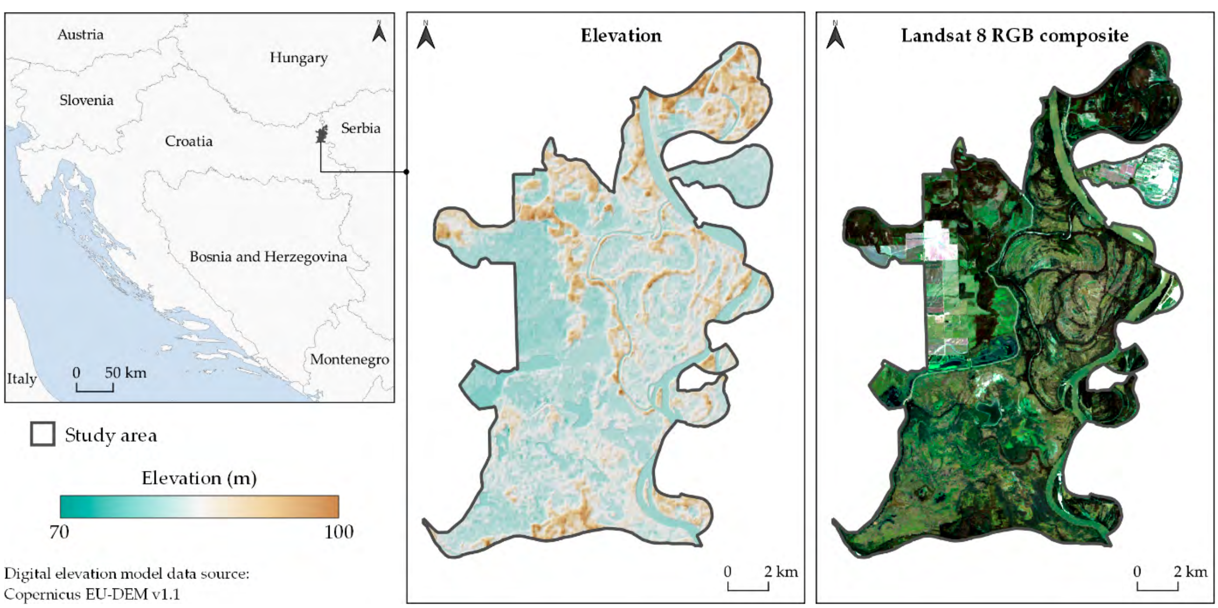

Figure 2. Study area of the Nature Park Kopački rit

invasive species, habitat loss, or water quality deterioration. Early identification of these changes enables timely implementation of adaptive management strategies and interventions to minimize negative effects and preserve the ecological integrity of Nature Park Kopački rit.

Landsat 8 multispectral imagery and preprocessing

The Landsat 8 Surface Reflectance (SR) imagery underwent preprocessing using a cloud masking approach after obtaining the Landsat 8 satellite imagery from Google Earth Engine (Gorelick et al., 2017). The time frame for filtering available imagery was set from 1 January 2013 to 31 December 2022, leaving only satellite scences with less than 75% overall cloud cover. The cloud masking function utilized various masking approaches to filter out unreliable pixels affected by cloud cover or sensor saturation, such as Quality Assessment (QA) and Radiometric Saturation (RADSAT) values (Pereira et al., 2020). The spatial resolution of calibrated Landsat 8 bands was resampled to the 100 m spatial resolution in the Croatian Terrestrial Reference System (HTRS96/TM) prior to the phenology analysis. The NDVI was calculated using red (band 4) and near-infrared (band 5) Landsat 8 bands, using a normalized difference formula (Zeng et al., 2020). It was selected as a vegetation index for phenology analysis, as its formulation increases the sensitivity of the index to changes in chlorophyll content, canopy structure, and overall vegetation vigor using the scale range from -1 to 1 (Eisfelder et al., 2023; Garroutte et al., 2016). In addition, NDVI's widespread use in ecological studies and its compatibility with historical satellite data make it an excellent choice for long-term phenology monitoring, allowing researchers to evaluate vegetation trends and changes over extended periods of time (Granero-Belinchon et al., 2020).

Table 1. provides a comprehensive overview of the number of Landsat 8 images utilized in the study per month and year from 2013 to 2022. The data reveal variations in the number of Landsat 8 images acquired over the study period, reflecting factors such as satellite availability, cloud cover, and operational considerations. Overall, the number of Landsat 8 images used in the study ranges from 25 to 33 per year, with slight fluctuations observed across different years. Months with higher counts of Landsat 8 images, such as July and August, indicate periods of more frequent satellite acquisitions, influenced by favorable weather conditions and lower cloud cover. Conversely,

Table 1. The number of valid preprocessed Landsat 8 images per month during the study period of 2013–2022

Month	Study year									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
January	0	3	0	1	4	2	2	2	2	4
February	0	1	1	2	2	1	2	3	2	1
March	0	2	4	3	3	1	4	3	2	2
April	1	2	3	2	2	2	2	3	3	3
May	3	2	2	2	3	4	1	3	4	3
June	3	2	4	3	3	3	4	2	4	4
July	5	4	3	4	4	3	3	3	4	3
August	4	4	3	4	4	4	4	4	3	2
September	4	1	3	2	1	2	3	4	2	1
October	3	2	1	0	3	1	3	1	2	3
November	1	2	2	1	1	1	2	2	3	1
December	4	1	3	3	3	1	3	1	2	0
Overall	28	26	29	27	33	25	33	31	33	27

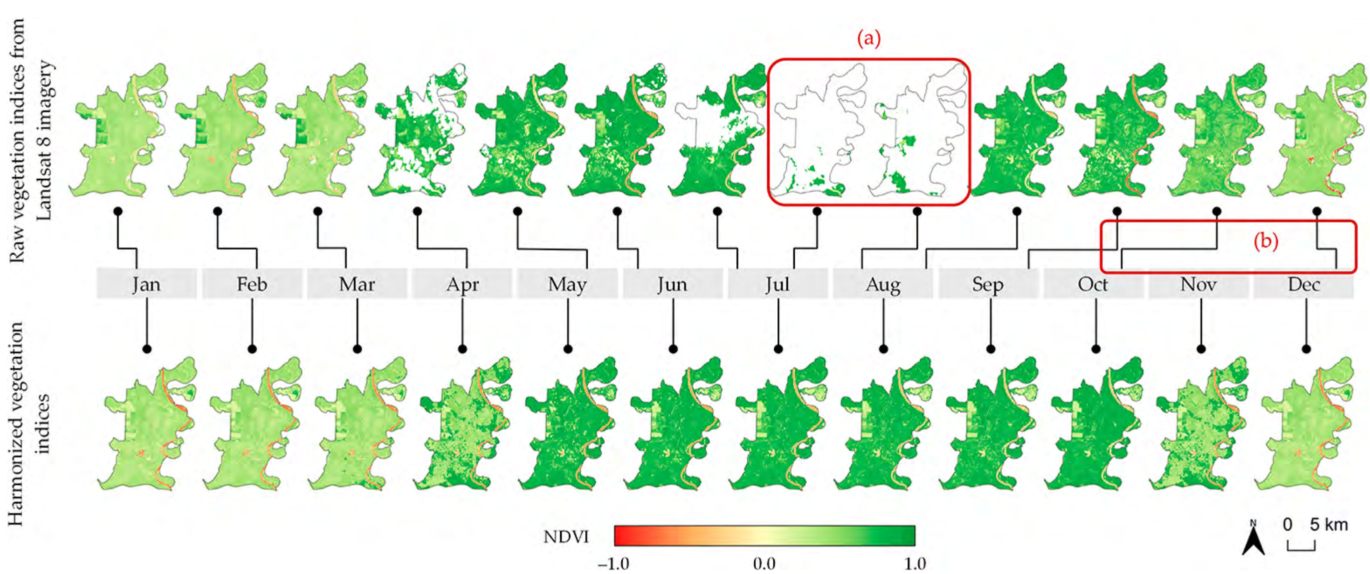

Figure 3. The representation of Landsat 8 images before and after harmonization using "npphen" package, having the issues of: a) dominant cloud cover, and b) missing images with less than 75% overall cloud cover across large intervals. Harmonized vegetation indices displayed on the bottom represent resulting rasters from phenology analysis

months with lower counts, such as January and October, suggest periods of reduced satellite availability or higher cloud cover, limiting the number of usable images.

However, since the availability of cloud-free Landsat 8 images varies across the long-term periods, the phenology analysis for the creation of harmonized monthly NDVI rasters was required (Figure 3). The harmonization process within the "npphen" package involved aligning NDVI values across different images to account for seasonal changes and resampling them to the uniform grid system due to presence of multiple Landsat 8 tile grids.

Phenology analysis and ndvi anomalies detection

The "npphen" R package was used for phenology analysis and detecting anomalies that indicate vegetation changes (Chávez et al., 2023). Designed to maximize the potential of satellite-derived vegetation indices, "npphen" facilitated the extraction of phenological metrics such as season start, season end, and season peak, which are crucial for understanding vegetation dynamics. It also included anomaly detection techniques that allowed finding deviations from predicted phenological patterns from the reference seven-year period that indicate rapid changes in plant activity. However, since it was released very recently, there is very restricted documented research on "npphen" application in research studies. The "npphen" time series analysis capabilities allowed a systematic evaluation of temporal patterns in vegetation indicators, revealing changes in phenological cycles caused by disturbances such as wildfires, disease outbreaks, or anthropogenic impacts (Estay et al., 2023). The ability to detect anomalies using "npphen" enhanced the ability to quickly detect and respond to ecological disturbances, which helps in the development of targeted conservation and management plans for protected natural areas. As a comprehensive and user-friendly tool, "npphen" made a significant contribution to phenology research and monitoring by providing essential insights into ecosystem health and resilience (Chávez et al., 2023). Using Landsat 8 long-term imagery, the approach was based on calculating the projected annual phenological cycle using raster stacks of vegetation indices or time series. The method efficiently captured the distribution of NDVI values over time by utilizing a bivariate kernel density estimator (Wand & Jones, 1994). From the 10-year study period, seven years during 2013–2019 were selected as the reference period for the phenology analysis, providing a basis for the anomaly detection for each year in the remaining three-year test period during 2020–2022.

Unsupervised classification of vegetation management zones

The final delineation of vegetation management zones within the Kopački rit Nature Park was based on the sum of NDVI anomalies between 2020 and 2022, using the R package "terra" (Hijmans et al., 2024). K-means clustering, a data-driven approach that divided the study area into discrete groups based on similarities in NDVI anomaly patterns, was utilized without the requirement for pre-defined training samples. K-means clustering is an effective geospatial approach to identify spatially coherent zones that display similar vegetation dynamics and anomalies based on NDVI anomaly data collected over the long term (Ahmed et al., 2020). This method also distinguished locations that consistently face vegetative stress or are resilient to environmental changes from other sites with unique phenological features (Silveira et al., 2022). The accuracy and dependability of vegetation management zone delineation were improved by adding NDVI anomalies over a multi-year period, which provided a strong foundation for capturing long-term trends and variability in vegetation dynamics.

Results

The boxplots in Figure 4 after outlier removal using the interquartile range approach present that the reference study period produced comparatively lower median NDVI values for the majority of months in comparison to each of the test years. Most notably, NDVI value ranges during January–April 2020 were notably lower than both the reference period and the other two years in the test period. However, it also produced the highest median NDVI values during August–December, which reinforces the necessity of observing multiple years in the phenology analysis, as diverse environmental and anthropogenic effects might affect the long-term trends in vegetation activity.

Figure 5 displays representative NDVI anomalies for each of the test years, indicating diverse vegetation change cases. While their occurrence in the western part of the study area is justified by the presence of arable cropland and the effect of crop rotation systems, there is a necessity for extensive field monitoring to detect the causes of vegetation anomalies without an apparent cause. Moreover, since high anomalies for arable cropland are expected due to crop rotation systems, the cause for vegetation anomalies at those areas is known. All three representative NDVI anomalies also produced distinctively lower NDVI values for most of their respective test years, following a more normalized trend according to the long-term NDVI trend based on the reference period.

Table 2. presents an interpretation of NDVI anomalies across five classes produced by k-means unsupervised

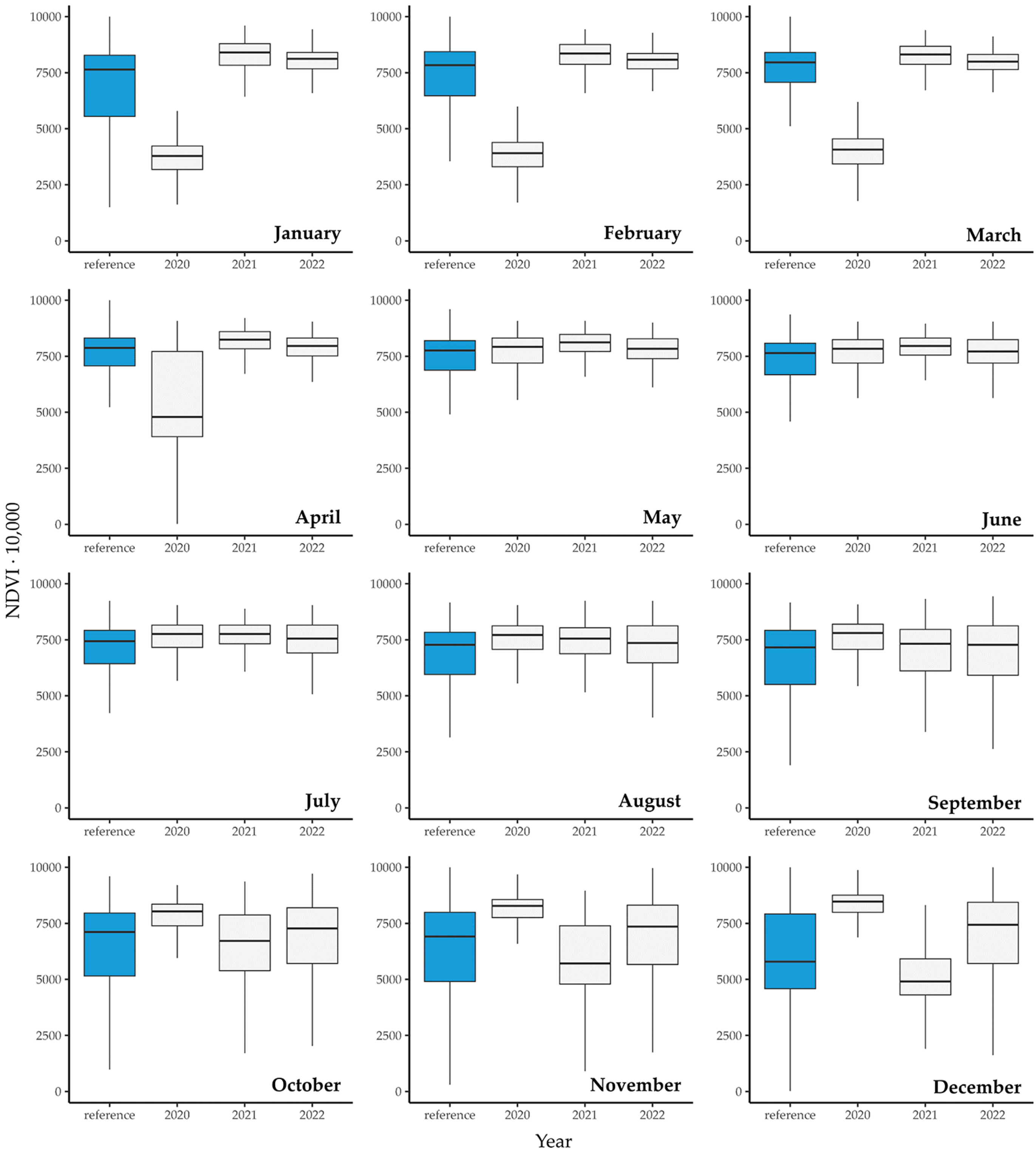

Figure 4. The boxplots of monthly NDVI values for the reference period (2013–2019) and three test years (2020–2022) with removed outliers

classification and their respective areas within the study area over the years 2020, 2021, and 2022, along with their average values. The NDVI anomalies provided in the table represent class centers from k-means classification results from test years. NDVI anomalies were categorized into five classes based on their magnitude: extremely negative, moderately negative, slightly negative, neutral, and positive NDVI anomalies. The negative NDVI anomalies, including extremely, moderately, and slightly negative categories, exhibit decreases in vegetation greenness compared to the reference period, with extremely negative anomalies indicating the most severe declines. Converse-

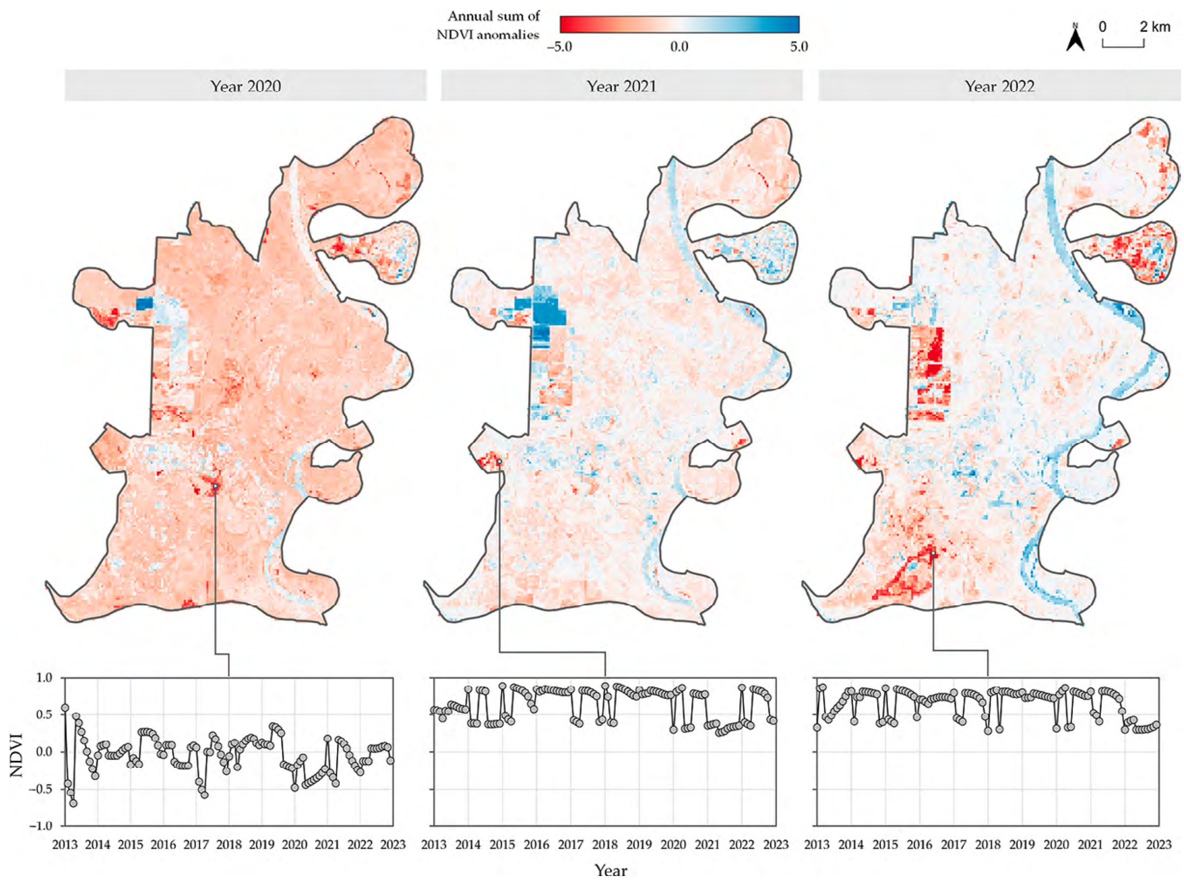

Figure 5. The example NDVI anomalies for each of test years based on their monthly sum, indicating vegetation changes

ly, positive NDVI anomalies denote increases in vegetation greenness and primarily contain arable cropland and water bodies. The table illustrates notable variations in the magnitude and distribution of NDVI anomalies across the study period. For instance, the area affected by extremely negative NDVI anomalies experienced a substantial increase from 2020 to 2022, reaching its peak in 2022. Conversely, moderately negative NDVI anomalies displayed fluctuations over the years, with a significant decrease observed in 2022 compared to the previous two years. Slightly negative NDVI anomalies exhibited a decreasing trend over the study period, with the area affected declining sharply from 2020 to 2021 and almost disappearing in 2022. Neutral NDVI anomalies showed fluctuations over the years, with a notable increase in 2021 compared to 2020 and a subsequent decrease in 2022. Positive NDVI anomalies demonstrated an overall increasing trend, particularly notable in 2021, indicating improvements in vegetation greenness compared to the baseline. The resulting five vegetation activity classes based on the sum of monthly NDVI anomalies during test period are displayed in Figure 6.

Table 2. The results k-means unsupervised classification of NDVI anomalies during test years and corresponding statistics in five vegetation activity classes

Classes	NDVI anomalies				Area (%)
	Annual sum (2020)	Annual sum (2021)	Annual sum (2022)	Average	
Extremely negative NDVI	–13598	–8770	–34921	–19097	4.9%
Moderately negative NDVI	–17768	–7965	–10917	–12217	15.2%
Slightly negative NDVI	–14916	–4606	–77	–6533	44.0%
Neutral NDVI	–8599	1355	–687	–2643	28.3%
Positive NDVI	3273	15527	15908	11569	7.5%

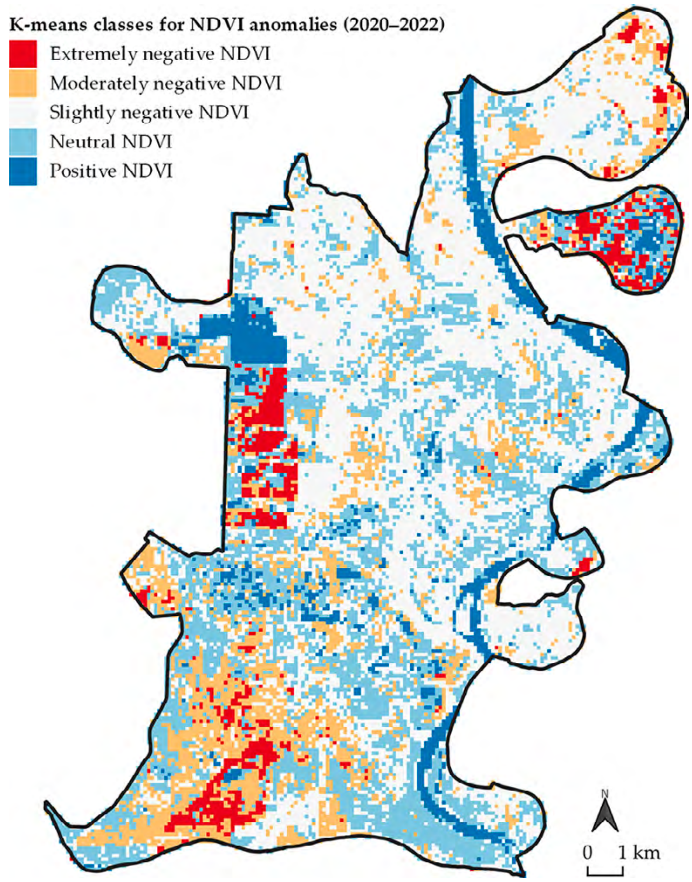

Figure 6. The five vegetation activity classes produced by k-means unsupervised classification based on the sum of monthly NDVI anomalies during test period

Discussion

The results from this study proved that the combination of Landsat 8 data with the NDVI allows for phenology analysis to identify anomalies and track vegetative dynamics in protected areas. The vegetation anomalies were determined individually for years 2020, 2021 and 2022 based on the reference period between 2013 and 2019. The long-term phenology studies provide insights into ecosystem health, resilience, and responses to environmental stresses, particularly in protected regions where conservation efforts are paramount (Cumming et al., 2015). Understanding these dynamics can guide management strategies aimed at preserving biodiversity and mitigating the impacts of climate change. Since NDVI obtained from satellite imaging is sensitive to both chlorophyll content and canopy structure, it was a reliable indicator of plant health and vitality (Garroutte et al., 2016). The notable application of the proposed approach is that it significantly reduces the need for extensive fieldwork in phenological studies, allowing biologists to focus their efforts on areas with detected abnormal vegetation activity. This allows monitoring large areas consistently and efficiently, capturing spatiotemporal patterns of vegetation without the logistical challenges associated with ground surveys (Zeng et al., 2020). This allows biologists to prioritize field investigations in specific locations that show significant anomalies, thus optimizing resource allocation and enhancing the effectiveness of conservation efforts. This targeted approach not only streamlines research processes but also improves data quality by focusing on areas where ground truthing is most needed to validate satellite observations and refine ecological models (Azizan et al., 2021). However, in diverse landscapes or smaller-scale land use areas, the spatial resolution of Landsat 8 imagery may not be sufficient to detect minor changes in plant dynamics. To enhance the detection capabilities of vegetation phenology anomalies, additional multispectral datasets with higher spatial resolutions, such as Sentinel-2 with spatial resolutions up to 10 m (Phiri et al., 2020), or commercial high-resolution imagery like PlanetScope with resolutions as fine as 3 meters, can be integrated (Panđa et al., 2024). Moreover, the creation of continuous time series records over several decades aids in identifying long-term environmental changes in these protected areas. The integration of Landsat 7 and Landsat 5 data ensures consistency and reliability in the long-term monitoring of vegetative changes, allowing for improved continuity in phenology analysis. By enabling more comprehensive evaluations of vegetation dynamics at smaller spatial scales, these higher-resolution datasets allow for the identification of changes in smaller land cover features or fragmented landscapes. Furthermore, the inclusion of supplementary data, such as meteorological characteristics obtained from weather stations or reanalysis datasets, strengthens the analysis by providing insights into the environmental forces that impact vegetation dynamics (Pardela et al., 2020). The phenology of vegetation is influenced by variables such as temperature, precipitation, and soil moisture, which can be used to explain abnormalities identified through multisensory analysis (Radočaj et al., 2024). To ensure effective anomaly identification in multisensory phenology analysis, the temporal resolution of accessible multispectral images is just as important as their spatial resolution (Sedona et al., 2021). Sentinel-2's frequent revisit time allows for more frequent observations than Landsat 8, which is particularly useful for monitoring vegetation dynamics at finer temporal scales. To comprehend the intricate relationships between climatic variability and ecosystem responses, it is promising to establish a link between monthly anomalies in vegetation dynamics and climate data rasters for the years 2020-2022. However, this attempt faces difficulties when climate data rasters are regularly provided with a time buffer (Fick & Hijmans, 2017; Karger et al., 2017), resulting in temporal misalignment between the two datasets. To align climatic data with vegetation observations, several techniques can be used, such as statistical modeling to account for temporal misalignment, time lag analyses to identify delays between climatic events and vegetation responses, temporal aggregation or interpolation of climate data to match the temporal resolution of vegetation anomalies, and long-term trend analyses to find consistent patterns over several years (Zhao et al., 2020). Resolving the temporal discrepancy between vegetation anomalies and climate data has the potential to clarify the complex connections between ecosystem dynamics and climate variability (Jiao et al., 2021). This can ultimately improve comprehension of how ecosystems adapt to environmental change, despite the difficulties involved.

For phenology analysis in protected areas, using multispectral satellite images that cover periods longer than ten years can likely be beneficial, providing more complete insights into long-term vegetation dynamics and ecosystem changes (Li et al., 2017). This allows for more detailed identification of trends, patterns, and anomalies in vegetation phenology by tracking phenological variations over extended periods of time and establishing thorough baseline information by utilizing historical satellite data. Long-term phenology studies can enhance the understanding of ecosystem health, resilience, and responses to environmental stresses as well, particularly in protected regions where conservation efforts are crucial (Cumming et al., 2015). Continuous time series records can be created for several decades, aiding in the identification of long-term patterns and changes in the environment in protected regions. The integration of Landsat 7 and Landsat 5 data ensures consistency and dependability in the long-term monitoring of vegetative changes, allowing for an improved continuity in phenology analysis.

The classified maps produced from the NDVI analysis can be utilized by Nature Park management for monitoring vegetation health, ecologists for research purposes and policymakers for informed decision-making. The maps indicate that significant positive and negative NDVI anomalies may be influenced by natural events such as droughts and flooding, as well as human activities like deforestation and urbanization, which should be further explored in the field. However, this research relies on statistical outputs without adequately exploring the ecological implications of these anomalies. The study acknowledges several limitations that could affect the results. First, months with little or no data can introduce biases in NDVI calculations, leading to inaccurate assessments of vegetation health. Second, challenges in collecting ground truthing data due to accessibility issues may impact the validation of remote sensing accuracy. Third, the lack of integration of climate data is a significant gap, as NDVI changes can result from natural variability rather than abrupt disturbances; incorporating data from nearby meteorological stations could clarify how climatic factors influence vegetation dynamics. These limitations should be addressed in future studies, which should include ground truth data collected in the field.

Conclusion

This study proposed the method of detecting vegetation changes based on phenology analysis using Landsat 8 multispectral images, utilizing phenology analysis for NDVI anomalies detection and unsupervised k-means classification for the determination of vegetation management zones. Overall, the multispectral imagery acquired during the 10-year study period in Nature Park Kopački rit in eastern Croatia, divided into seven-year reference (2013–2019) and three-year test periods (2020–2022) produced the following observations and conclusions:

- the zones based on NDVI anomalied can be utilized by Nature Park management to monitor vegetation health and changes over time, enabling better conservation strategies;
- the areas which produced highest and lowest NDVI anomalies are recommended to be analyzed comprehensively during fieldwork to determine the cause of abnormal vegetation activity;
- the phenology analysis based on the long-term Landsat 8 multispectral imagery using "npphen" R package successfully harmonized temporally uneven images into systematized monthly NDVI rasters without spatial gaps;
- high heterogeneity was observed for both monthly NDVI values and NDVI anomalies after the phenology analysis;
- the results of unsupervised k-means classification ensured the determination of five vegetation activity classes, with three of these classes having considerably high negative NDVI anomalies as class centers;
- a comprehensive field observation is required to determine the potential environmental and/or anthropogenic causes of vegetation changes on areas with extremely negative and moderately negative NDVI anomalies;
- longer study periods using the proposed methodology and combining earlier Landsat images with Landsat 8 would likely produce additional and more complete information on the vegetation activity and anomalies indicating vegetation changes to produce more informed land management plants of protected areas.

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The Water-Energy-Food Nexus Index for Bulgaria – Overview and Comments

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KEYWORDS

- Water–Energy–Food (WEF)
- WEF Nexus Index
- Bulgaria

ABSTRACT

The 'Water–Energy–Food' (WEF) Nexus concept is evolving and expanding, as it is essential for finding synergies and compromises between these three sectors under climate change and for building a green economy. This work aims to present and analyse some indicators of the WEF Nexus Index for Bulgaria, according to which the country ranked 66th in the world in 2022. The data sources were the publications of the National Statistical Institute, the Ministry of Environment and Water, etc. The current study found that most indicators in the three pillars objectively assess the country's water resources, energy, and food sectors. The findings reveal a lack of information about the 'Food' pillar, resulting in an inability to assess this pillar objectively. Additionally, the evaluation of several sub-pillars based on the official data shows inaccuracies in the final WEF Index result for the country. This work represents the first presentation of the WEF Nexus Index for Bulgaria and continues the authors' study on the dynamics of the water, energy, and food sectors.

Introduction

Although discussions and criticism (Williams et al., 2019) about the meaning of the Food-Energy-Water (WEF) nexus framework continue (Wichelns, 2017; Pandey & Shrestha, 2017), the concept is developing and broadening because it is crucial for achieving Sustainable Development Goals water-, energy-, and food-related (Yue et al., 2021; Cansino-Loeza et al., 2021; Proctor et al., 2021; Senzanje et al., 2022; Segovia-Hernández et al., 2023), for the transition toward a green economy (Brears, 2023), and to promote sustainability (Cansino-Loeza et al., 2022). The WEF is a systems-based approach for objectively analysing the synergies, conflicts, and trade-offs between these critical linkages (Albrecht et al., 2018). This framework is also significant because the link between vital water, energy, and food systems is essential for efficient governance and securitisation of resources (Leese & Meisch, 2015) to guide cross-sectoral policies (Albrecht et al., 2018) for poverty reduction. Understanding the links among water, energy, and food systems can improve climate change adaptation strategies (Herrera-Franco et al., 2023) and sustainable development of the socio-ecological systems (Jahel et al., 2023). The WEF Nexus aligns with the Stockholm Environment Institute's (SEI) concepts for societal development, which focus on integrating the lower socioeconomic classes, enhancing economic efficiency by "creating more with less," and maintaining ecosystem services (SEI,

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2011). The essence of the water, energy, and food framework is the interconnectedness of the three systems, and a change in one sector will have consequences for the others. By maintaining an ecologically sustainable balance among these critical sectors, the WEF framework can significantly shape future development strategies, particularly in regions where resource security is at risk.

Bulgaria's available renewable freshwater resources in 2022 are 15-16 m, less than the reference period 1961-1990. The freshwater abstraction for the economic sectors in the same year is 5.5 billion m^3 cubic meters. Most water is abstracted for cooling processes in the energy sector, 66.4%. The water abstracted for water supply (from the water supply and sewerage) is 14.7%, and for irrigation in agriculture, it is 14.3% of all water used for the economy. More than 50% of abstracted freshwater in Bulgaria for cooling processes in energy production comes from the Danube River. Water reserves decrease significantly during the summer-autumn period, accounting for 12% and 18% of the annual river runoff. Over 200 settlements in the country experienced interrupted water supply. The water levels in the reservoirs are decreasing, hindering vegetable producers and hydropower generation in run-of-river hydropower plants. The described situation creates a need for compromises between available water reserves, water supply, hydropower generation, and irrigation. The state of the link between the water, energy, and food sectors in Bulgaria under climate change is described by Hristova & Nikolova (2024). The current study aims to present and comment on the "water-energy-food" index for Bulgaria in the last five years.

Data and Methods

The sources of the data for Bulgaria in the current study are the Ministry of Environmental and Water (MOEW), the Ministry of Health, the Ministry of Agriculture and Food, the National Statistical Institute (NSI), the Executive Environment Agency (ExEA), Strategy for Sustainable Energy Development of the Republic of Bulgaria until 2030 with a horizon until 2050, Strategic plan for the development of agriculture and rural areas 2023–2027, General strategy for the management and development of hydro melioration and protection from the harmful effects of water, River Basin Management Plans 2022–2027, Annual Report and Comparative Analysis of the State of the Water Supply Sector in the Republic of Bulgaria for 2021, Integrated plan in the field of energy and climate of the Republic of Bulgaria 2021–2030. There is no data in these sources for the following indicators: renewable energy consumption and renewable electricity outputs for 2022. There is no direct data on sub-pillar "Food Availability" indicators, except for cereal yield. The current study does not calculate WEF Nexus Index indicators because there is no statistical data for most indicators in pillar "Food". The NSI gives data for cereal yield in 2021 and CO2 emissions in the same year. The lack of information makes it impossible for the open-access COIN Tool to be used (Excel-based), and this study does not comment on these indicators.

Simpson et al. (2019) developed the WEF Nexus (for the countries in the South Africa region), a composite index with three pillars: water, energy, and food: pillar "water" measures access to water resources, availability, and quality; pillar "energy" assesses energy access, efficiency, and renewable energy use; and pillar "food" evaluates food availability, food security, and agricultural productivity. Each pillar has two sub-pillars: "access" (for the population's ability to access resources) and "availability" (for the quantity and quality of resources available in the country) (Fig. 1). Simpson et al. (2019) developed the WEF Nexus (for the countries in the South Africa region), a composite index with three pillars: water, energy, and food: pillar "water" measures access to water resources, availability, and quality; pillar "energy" assesses energy access, efficiency, and renewable energy use; and pillar "food" evaluates food availability, food security, and agricultural productivity. Each pillar has two sub-pillars: "access" (for the population's ability to access resources) and "availability" (for the quantity and quality of resources available in the country).

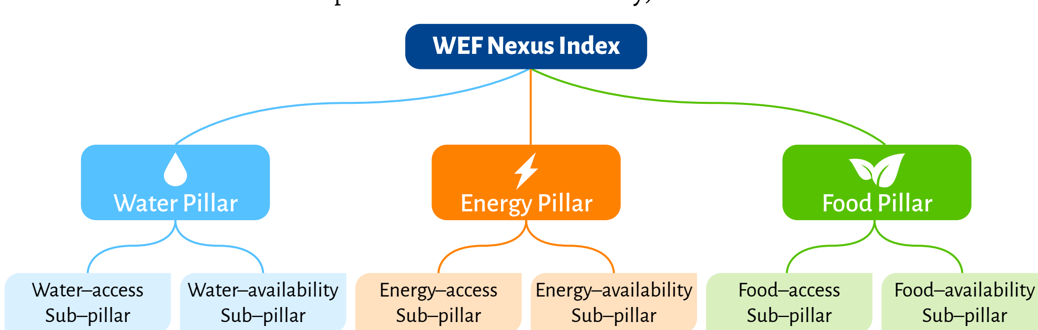

Figure 1. Pillars and sub-pillars of the WEF Nexus Index

Source: Simpson et al., 2023.

Results and discussions

The WEF Nexus Index value for Bulgaria varies between 58.3 for 2020 and 60 for 2022, placing the country in the 66th position among the other countries (Table 1). In comparison, the highest index was 83.9 for Iceland in 2020.

Table 1. WEF Nexus Index for Bulgaria during 2019–2022

Year	2019	2020	2021	2022	2023
WEF Nexus Index	58.5	58.3	60.0	60	59.2
Rank	72	78	70	66	69

Source: https://wefnexusindex.org

Table 2. Score and rank of Bulgaria by pillars of the WEF Nexus index, 2019–2023

Pillar	2019		2020		2021		2022		2023	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Water	60.5	89	59.9	92	62.2	84	61.7	73	60.1	70
Energy	55.9	67	55.0	68	57.5	66	57.5	68	55.6	75
Food	59.0	53	60.0	60	60.4	62	60.8	66	62.0	61

Source: https://wefnexusindex.org

Bulgaria's scores by pillars do not vary significantly for 2019–2023 (Table 2). The numeric index for the water pillar alters between 59.9 (92nd worldwide rank) in 2020 and 60.1 (70th worldwide rank) in 2023, showing progress towards achieving goals 6, 7 and 12 of the Sustainable Development Goals. The energy and food pillars data for 2023 put Bulgaria in a lower position than in previous years (Table 2).

Pillar "Water"

Sub-pillar: Water Access. The analysis of the first two indicators (01 and 02) in the sub-pillar "Water Access" shows that they are objectively evaluated (Table 3). Bulgaria has no settlements without a water supply and sanitation system (WSS). According to the "Annual Report and Comparative Analysis of the State of the Water Supply Sector in the Republic of Bulgaria for 2021," this indicator's score must be 99.7% (99% in the WEF Index). The same number of points must be assigned to the second indicator. The third indicator, the degree of integrated water resources management implementation, was calculated at 77 points. This estimate needs to be revised because Bulgaria implemented the Water Framework Directive according to all its requirements: develop the River Basin Management and Flood Risk Management Plans, and conduct studies and assessments. We agree that the score cannot also be 100 points because there is no National Real Time Water Management System, coordination between land use and flood management, and centers on increasing the population's preparedness for an adequate response to floods (for now so far). The last facts confirm the need to implement the Food–Energy–Water Nexus framework: only the coordination and policy coherence across the several ministries can effectively implement these activities.

Sub-pillar: Water Availability. The score of the annual water extraction is 26.9 (indicator 04), and renewable do-

Table 3. Score by indicators for pillar Water, 2019–2023

Sub-pillars	2019	2020	2021	2022	2023
Water Access					
01. Percentage of people using at least basic drinking water services (%)	99.3	99.1	99	99	99
02. Percentage of people using at least basic sanitation services (%)	86	86	86	72.2	72.2
03. Degree of integrated water resources management implementation (1–100)	60.2	60.9	69	77	69
Water Availability					
04. Annual freshwater withdrawals	27.2	26.6	26.9	26.9	24.2
05. Renewable internal freshwater resource per capita.	2.91	2.94	2.98	2.98	3.03
06. Environmental flow requirements (106 m3/annum)	7.8	7.8	7.8	7.8	7.8
07. Average precipitation (mm/year)	608	608	608	608	608

Source: https://wefnexusindex.org

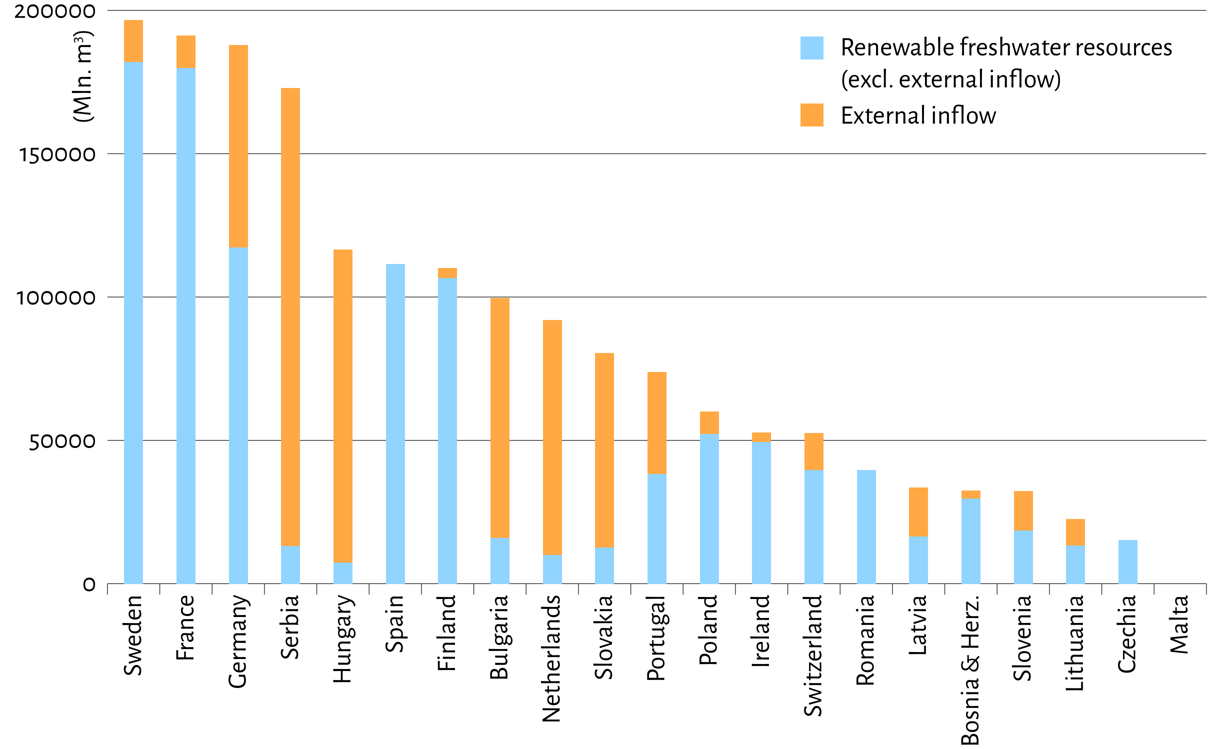

Figure 2. Available renewable freshwater resources in European countries

Source: Eurostat

mestic freshwater resources per capita were at 2.98 (indicator 05). Indicator 04 is objectively estimated. Available renewable freshwater resources in Bulgaria, excluding external inflow for 1981–2020, is 15,789 million m^3 (National Statistical Institute, 2022). The renewable internal freshwater resource per capita in 2021 is 14,452 m^3 with the Danube River and 2,936 m^3 without the Danube River. Furthermore, is that there is no "water stress" in the country (annual water resources are above 1,700 m^3 per capita, 5.1% for 2021, close to the average for 2000–2019, 6.0%) (Fig. 2). These two facts raise (or must raise) the score of the 05 indicator from the WEF Nexus point of view.

The indicator environmental flow requirements score of 7.8 (106 m^3/annum) for 2021 is wrong. The ecological flow in 2019 is 51 106 m^3/annum (10% by annual streamflow of 20,195.1 × 10^6 m^3 in the same year). The indicator for the average precipitation (mm/year) has to rise. The average precipitation for 1997–2022 in Bulgaria is 632 mm (between 377.0 and 963.0 mm). The difference with published data of 603 mm is insignificant, but it will be better to calculate this indicator for the equal study period in different countries.

Pillar "Energy"

Sub-pillar: Energy Access. The score for the first two indicators ((% of the population, % of the population) in the sub-pillar for energy access is constant in 2019, 2020, and 2021 (Table 4). There is no reason for the decrease in the numeric index from 100 to 99.7 points in 2021 and 2021 because there has been no change in access to electricity. The

Table 4. Score by indicators for pillar "Energy", 2019–2023

Sub-pillars	2019	2020	2021	2022	2023
Energy Access					
08. Access to electricity (% of the population)	100	100	100	99.7	99.7
09. Renewable energy consumption (% of total energy consumption)	17.7	17.7	17.7	19.3	21.1
10. Renewable electricity outputs (% of electricity output)	18	18	18	18	18
11. CO_2 emission (metric tons per capita)	5.9	5.9	5.9	5.6	4.9
Energy Availability					
12. Electric power consumption (kWh per capita)	4.71	4.71	4.71	4.71	4.71
13. Energy imports (net % of energy use).	36.6	36.6	36.6	36.6	36.6

Source: https://wefnexusindex.org

following indicator, “renewable energy consumption (% of total energy consumption), takes into account the country’s electricity production structure changes. Renewable energy consumption (% of total energy consumption) rose from 2017 to 2021, except in 2021, renewable energy represented 17.0% of the energy consumed in the country, down from 23.3% in 2020 (Table 5). The same trend is in the EU for these two years (22.1% in 2020 and 21.8% in 2021). This indicator was close to the average for European countries during the first three years of this period (Fig. 3) CO_2 per capita. This indicator varies substantially, but the trend in the last few years has been negative (Republic of Bulgaria Ministry of Environment and Water, 2021). The study by Harizanova-Metodieva and Harizanova-Bartos (2020) shows a positive relation between energy consumption and emitted carbon dioxide in the short run. Stoyanova-Asenova et al. (2024) did not find a correlation between government regulation and emission levels.

Sub-pillar: Energy Availability. According to the National Statistical Institute, Bulgaria, the gross electricity production in Bulgaria for 2023 is 40246 GWh, which is lower than in the previous year (2022 the production was 50385 GWh). The energy use shows a strong decrease in the period 1988–1991. In 1991 energy use decreased by approximately 20% in comparison to 1990. The difference in the values for the period 1999–2020 is not very big (Fig. 5). And the decrease in energy use in 2023 compared to 2022 is about 13%.

Table 5. Renewable energy consumption in Bulgaria (% of total energy consumption)

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
13.9	14.2	15.8	18.9	18.1	18.3	18.8	18.7	20.6	21.6	23.3	17.0

Source: National Statistical Institute

Renewable energy production capacity in Bulgaria is 4,532 megawatts in 2021 and 5,205 megawatts in 2022. The largest share of renewable energy capacity at the end of last year was hydropower capacity (2505 megawatts). Solar capacity has strong growth; their capacity increased to 1,948 megawatts in 2022 from 1,275 megawatts in 2021 (or by almost 53%). The share of renewable energy in the total electrical capacity in Bulgaria increased to 43.8% from 40.4% a year earlier and 35.3% ten years ago. Hence, the score of the indicator of renewable electricity outputs (% of electricity output) has to rise.

CO_2 emission (metric tons per capita) for 2020 is 4.9 and this is the lowest value for the period 1990–2020 (Fig. 4). In 2021, Bulgaria’s carbon dioxide emissions were 6.33 tons of

The country’s energy dependence in the period 2018–2022 varies between 36 and 39% (Table 6). Energy dependence on imports as of in 2021 was 36.1%, lower than the European Union average of 57.5%, less than Germany, Greece, Belgium, Ireland, etc. Bulgaria is a net exporter of electricity (Ministry of Energy of Bulgaria, 2021). Bulgaria is

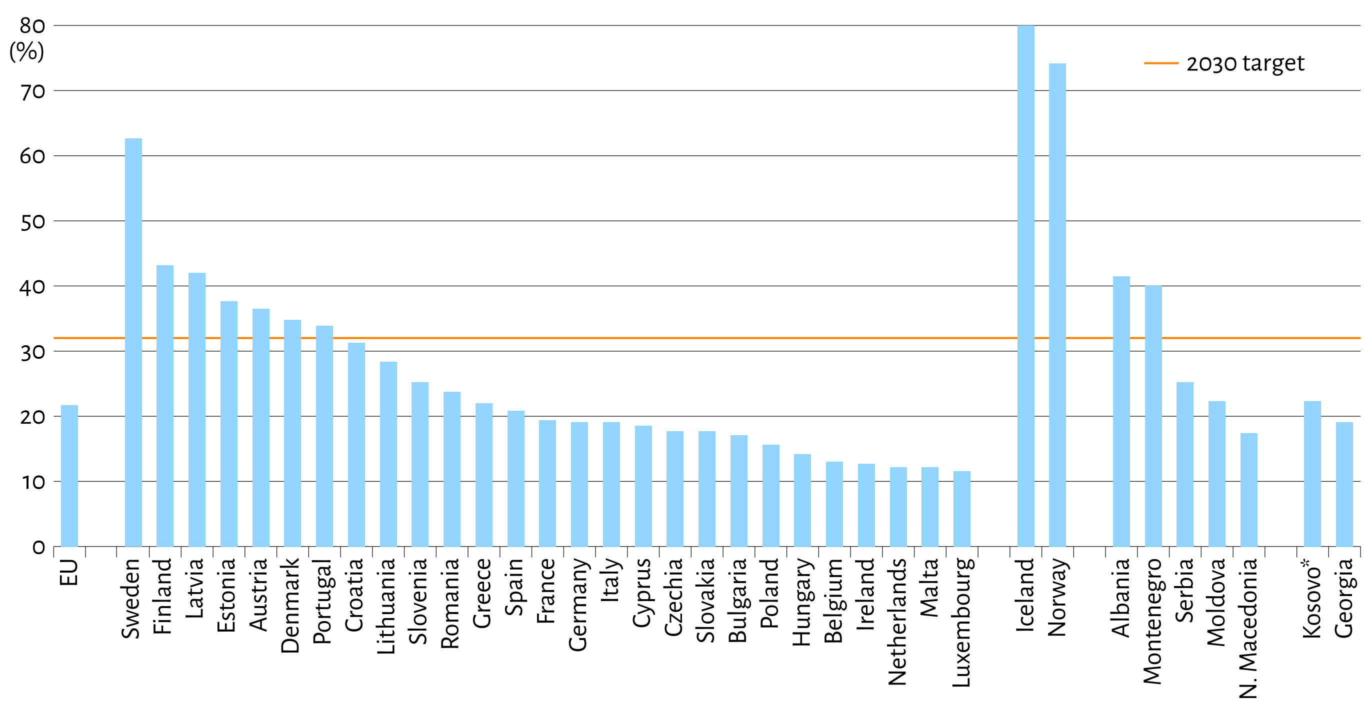

Figure 3. Share of energy from renewable sources, 2021 (% of gross final energy consumption)

Source: Eurostat

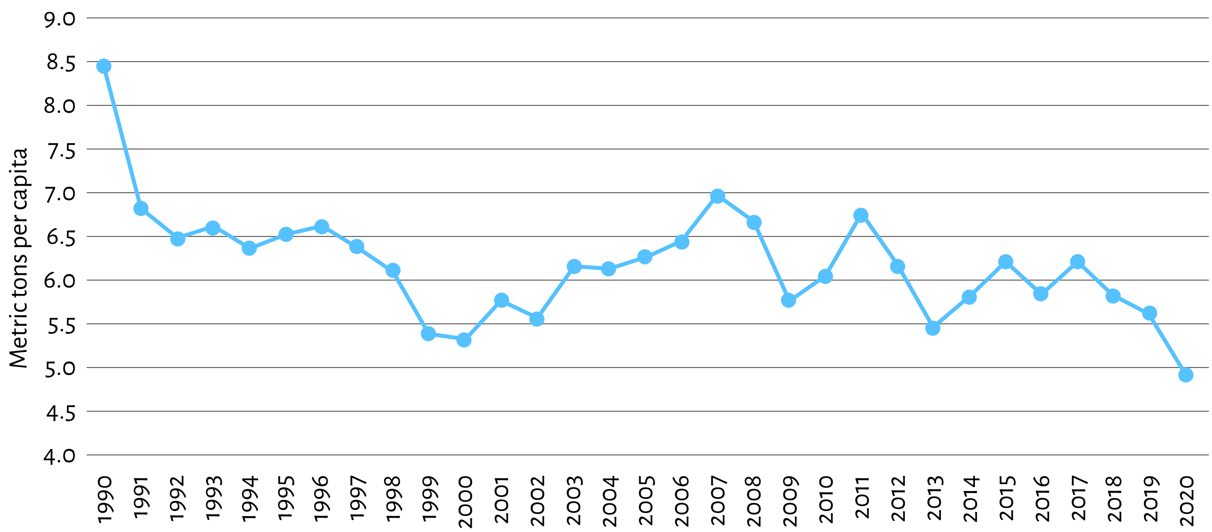

Figure 4. CO_2 emission in Bulgaria (metric tons per capita)

Source: World Resources Institute, 2023

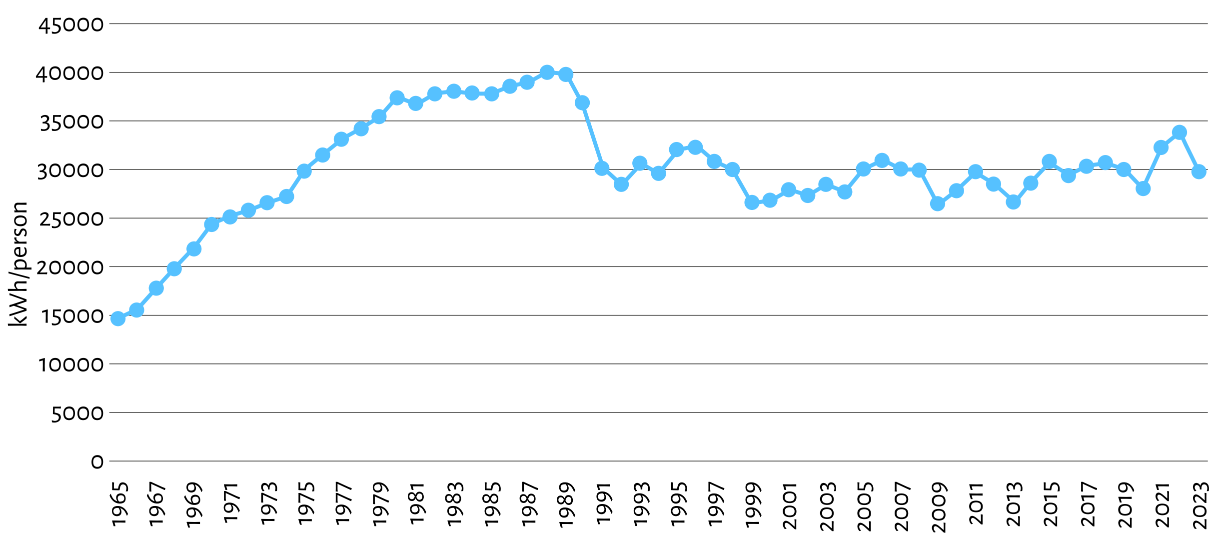

Figure 5. Energy use per person in Bulgaria

Source: ourworldindata.org/

among the five countries best dealing with energy vulnerability in Eastern Europe in the Euromonitor International index (on data on energy efficiency, energy import dependence, energy mix and electricity generation capacity). According to these indicators, Bulgaria is around the average level globally, and it is among the leaders in the region of Eastern Europe. The reason is the large share of nuclear energy, which provides an alternative to fossil fuels. The country has excellent access to the energy grid and one of the region's highest electricity generation levels per capita.

Table 6. The energy dependence of Bulgaria (%)

2017	2018	2019	2020	2021	2022
39.4	36.6	38.5	38.2	36.1	37.1

Source: National Statistical Institute

Pillar "Food"

Sub-pillar: Food Access. The first three indicators in this sub-pillar are prevalence of undernourishment, children under five years old affected by wasting, and children under five years old who are stunted are challenging to assess due to the lack of publicly available data (Table 7). Therefore, we can only comment on the last indicator: the prevalence of obesity in the adult population (aged 18 and older).

The indicator "prevalence of obesity in the adult population" was calculated in the WEF Nexus Index for Bulgaria at 25. This calculation was based on data related to body mass index (BMI), underweight, overweight, and obesity from 1975 to 2016. However, more recent data from 2022 show that this indicator is 23.2% (https://renewbariatrics.com, 2023). The prevalence of obesity in the adult popu-

Table 7. Score by indicators for pillar "Food", 2019–2023

Sub-pillars	2019	2020	2021	2022	2023
Food Access					
14. Prevalence of undernourishment (%)	3	3	3	3	3
15. Percentage of children under 5 affected by wasting (%)	3.2	6.3	6.3		
16. Percentage of children under 5 who are stunted (%)	8.8	7.0	6.4	6.4	5.6
17. Prevalence of obesity in the adult population	27.4	25	25	25	25
Food Availability					
18. Average protein supply (gr/caput/day)	94	82.7	84.3	83.3	80.7
19. Cereal yield (kg/ha)	4817.8	5479.7	5463.8	5463.8	5949.6
20. Average dietary energy supply adequacy	117	113	115	116	119
21. Average value of food production ($/capita).	457	456	157	157	157

Source: https://wefnexusindex.org

lation in Bulgaria by body mass index above 30 kg/m^2 for 2022 is 14.8% (Table 8). This data indicates that adult obesity in Bulgaria is lower than the average in the European Region, which is 59% (WHO European Regional Obesity Report 2022). Therefore, this indicator in the WEF Nexus Index should be corrected. According to the World Obesity Federation (2022), the percentage of the adult population with obesity in Bulgaria is projected to rise to 31.4% by 2030.

Table 8. Prevalence of obesity in the adult population (18 years and older) in Bulgaria in 2022 (%)

Body mass index	Total	Men	Women
Overweight (25.00–29.99)	39.2	46.7	32.6
Obesity (30.00+)	14.8	15.5	14.2

Source: National Statistical Institute, 2023

Sub-pillar: Food Availability. There is only data for this sub-pillar for cereal yield (indicator 19). According to the World Bank, the cereal yield (kg per hectare) in the European Union was 5,666 kg/ha in 2021, and in Bulgaria, it was 5,666 kg/ha for the same year (Ministry of Agriculture and Food, 2023), but without rice, millet, buckwheat, and mixed grains (Table 9). The cereal yield (kg per hectare) in the world was 4,153 kg/ha in 2021.

Table 9. Cereals in Bulgaria in 2021 (Source: Ministry of Agriculture and Food, 2023)

Cereals	ha	kg/ha
Wheat	1 208 457	5902
Rye	8088	2170
Barley	126 957	5411
Oats	10 335	2373
Maize	579 613	5892
Sorghum	2405	2784

Conclusions

The WEF Nexus Index for 2019-2023 places Bulgaria in a mid-range position among 164 countries. The water pillar numeric indexes increase and show at the same time that further action is needed to enhance water management: Bulgaria is gradually growing renewable energy production, but water consumption in the energy sector is still high; the water resources in the summer are not enough for irrigation. Nevertheless, the database by Nexus index indicates the need for a more aggressive strategy to transition towards sustainable energy practices. The food pillar presents the most significant challenge in the WEF Nexus assessment for Bulgaria due to insufficient information.

The current study proves that the WEF Nexus Index provides valuable insights into Bulgaria's water, energy, and food sectors, but its objectivity depends heavily on the quality and availability of data. The results also show that the index methodology needs refinement regarding some indicators and the database used.

In relation to the achievement of the Sustainable Development Goals (SDGs), this study contributes to advancing adaptation strategies for climate change, particularly at the local scale, where microclimate conditions are further altered by anthropogenic activities (SDG 13).

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Direct Contact with Nature and Online Perspective: Does it Make a Difference in Environmental Attitudes Regarding the Nature Conservation Challenges in Serbia?

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KEYWORDS

- environmental attitudes
- local communities
- visitors
- stakeholders
- direct contact
- online

ABSTRACT

Attitudes towards environment are important for organizing nature protection, especially in countries undergoing political and economic transition. In this paper, attitudes of visitors, local communities and stakeholders towards the environment and nature protection are researched online and within the Special Nature Reserve and surroundings settlements. Data were obtained on the basis of the survey research as part of the 'LIFE WILDisland' project. Additionally, this paper was focused on comparing the attitudes of respondents between those who were in direct contact with nature and those who responded online. Gained results showed that respondents who were in direct contact with nature have more intensive interactions with it and have a good understanding of conservation-restoration measures. Both groups of respondents support nature protection activities.

Introduction

The conventional approach to nature protection emphasises the identification and conservation of important natural 'goods', particularly species and ecosystems (Bennett et al., 2009). Protected areas are one of the most effective tools for conducting nature conservation activities (Baldi, 2020). In the management of protected areas, it is essential to consider their ecological (He & Wei, 2023; Prato & Fagre, 2005), social (Jones et al., 2020; Prato & Fagre, 2005) and economic functions (Pisani et al., 2021; Prato & Fagre, 2005). Nature conservation activities are often hindered by conflicts between conservation interests and the social interests of local populations, as well as political and national economic interests that impede a progress in conservation (Freudenberger et al., 2013). A considerable number of studies on the social relations of protected areas are primarily or solely designed to measure the attitudes of local people towards protected areas (Holmes, 2013).

Environmental attitudes are important because they often, but not always, determine behaviour that either increases or decreases environmental quality (Gifford & Sussman, 2012). Activities aimed at preserving the environment reflect people's attitudes towards it. Besides other factors, environmental attitudes are important in nature conservation (Baierl & Bogner, 2023). Research on attitudes and opinions is conducted to better understand why someone behaves in a particular way. Attitudes also

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play a vital role in the acceptance of environmental policies (Karanth et al., 2008). Effective actions to protect global biodiversity must consider the attitudes of individuals and local communities. Since attitudes are rooted in complex value orientations, the conservation of environmental resources relies on a comprehensive understanding of these orientations (Ihemezie et al., 2021).

Since protected areas reproduce numerous ecological, social and economic functions through sustainable development policies (Gatiso et al., 2022; Rodríguez-Darias & Díaz-Rodríguez, 2023), the management process of these areas must consider the attitudes of different stakeholders (Brankov et al., 2022). The existence of multiple perspectives and representations of different stakeholders poses critical challenges to conservation initiatives. Thus, to foster more just and sustainable agendas in protected areas, this diversity of perspectives must be better understood, acknowledged and tackled (Fromont et al., 2022). To promote pro-environmental attitudes and mitigate conflicts between protected areas and stakeholders, improving environmental education and establishing joint management of protected areas is recommended (Liu et al., 2010).

The task of this paper is to highlight environmental attitudes in the Republic of Serbia, a less developed European country and society in transition facing environmental and nature protection challenges (Stojanović et al., 2022). The results derived from the research published in this paper are part of the international project 'LIFE WILDisland' which, besides the restoration and protection of the Danube islands, aims to assess public support for nature, wildlife and forest conservation actions in Central and South-eastern Europe. The project task 'Socio-economic effect of wilderness protection along the Danube' focuses on: (1) assessing public awareness in support of natural habitat protection along rivers and restoration actions for degraded habitats; (2) comparing public opinion in settlements closer to and further from protected areas along the Danube and (3) the socio-economic impact on the lives of local communities (residents and other stakeholders). Accordingly, the main goal of this paper is to assess environmental attitudes and highlight potential differences in attitudes between visitors, residents and other stakeholders (who were in direct contact with nature) compared to those online opinions of citizens who are geographically distant from the Danube and nature protection in protected areas along this river.

Literature Review

Visitors' Attitudes Regarding Nature Conservation

The attractiveness of the natural environment has deep roots in the history of modern tourism, where such environments are seen as a reason for a development of nature-based tourism forms, such as ecotourism or adventure tourism (Williams & Lew, 2015). Areas of exceptional natural value and rich biodiversity can be subject to strong ecological impacts precisely because they attract many visitors (Wolf et al., 2019). Research has shown that the greatest success in influencing visitors' actions comes from understanding what they think about a particular behaviour. Therefore, it is necessary to influence visitors' attitudes through organized visitor management (Brown et al., 2010; Cheung & Fok, 2013). Positive attitudes towards natural environment are reportedly associated with higher levels of satisfaction when visiting a protected area (de Oliveira et al., 2021). Visitors with pro-environmental attitudes are more willing to support management's conservation efforts (Thapa et al., 2024). A lack of concern for environmental issues among visitors may be due to a lack of ecological awareness, for example, due to omissions in the school system where they were previously educated (Ghazvini et al., 2020). Education and interpretation are key goals of many protected areas, which are also places where visitors can learn about nature and develop positive attitudes towards nature conservation (Hornoiu et al., 2014; Leung et al., 2018).

Local Communities' Attitudes Regarding Nature Conservation

The relationship between nature conservation and local communities is vital for biodiversity conservation (Dawson et al., 2021; Ma et al., 2022), so a better understanding of this issue can help in protecting the biodiversity, while maximizing benefits for local populations at the same time (Holmes, 2013). Contemporary biodiversity conservation trends increasingly view the ecological and social dimensions of this process as inseparable (Guerrero et al., 2018). However, the essence of the relationship between nature conservation and local communities is still not sufficiently and precisely clear (Guo et al., 2024). The role of managers in nature conservation and protected areas is particularly important for local communities (IUCN, 2004; Wells et al., 1992). Managerial understanding of local communities' perspectives on protected area management is paramount for sustainable development of such areas and the establishment of harmonious working relationships within them (Angwenyi et al., 2021). Raising awareness and educating local populations about the importance of biodiversity and nature conservation are recognized as a valuable tool in managing protected areas in a nature-friendly manner (Fotsing et al., 2024; Macharia et al., 2010). The economic perspective and well-being can play a significant role in shaping the attitudes of local communities toward nature conservation (Abukari, 2020).

Stakeholders' Attitudes Regarding Nature Conservation

Attitudes and perceptions of stakeholders towards a conservation area, nature protection and the policy being implemented are essential elements for sustainable conservation (Weladji et al., 2003). The integration of protected areas and their surrounding space relies on the interaction of various stakeholders, including policymakers, practitioners, local communities and visitors (Brankov et al., 2022; Rodríguez-Rodríguez et al., 2019). Effective stakeholder engagement requires a broader strategic view of the social environment and without it, support for nature conservation may be lacking (Mannetti et al., 2019). The link between threats to natural values, priority management actions and trust in protected area management must align with the stakeholders' preferred approach (Engen et al., 2019).

Importance of peoples' direct contact with nature

According to Soga and Gaston (2016), increasing number of people are becoming distanced from nature and they do not have a lot of direct contact with natural resources in their everyday activities. Possible reasons of such situation might be reflected in an increased number of people inhabited within urban areas (Zhang et al., 2014), technological innovations together with activities related to intensive usage of technology (Ballouard et al., 2011) and overscheduled everyday activities (Hofferth, 2009). Nowadays, direct contact with nature is therefore decreasing and it is usually replaced by online alternatives (Ballouard et al., 2011; Hofferth, 2009). Soga and Gaston (2016) indicated that decreased interactions of people with nature also decreases their positive emotions, perceptions and behaviour towards the environment and they highlighted that researchers and policy makers need to focus their efforts towards reconnecting the people with nature, in order to overcome a wide range of environmental issues. In respect to that, this paper is focused on researching the direct contact with nature and online perspective among two separate samples, in order to identify potential differences and similarities in environmental attitudes regarding the nature conservation challenges in Serbia.

Background of the research

The research results on environmental attitudes presented in this paper are also a part of the outcomes of the 'Danube Wild Island Habitat Corridor' project (acronym: 'LIFE WILDisland'), which is being implemented from 2021 to 2027 and aims to protect and restore river islands on the Danube. The project involves 15 partners from eight Danube countries (Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria and Romania).

The Danube is an ecological corridor of exceptional significance for Europe, connecting more biogeographical regions than any other European river. Accordingly, the Danube's course is followed by extraordinarily rich biodiversity. The Danube islands represent unique locations with untouched nature and valuable habitats for both plant and animal life. The Danube islands are simultaneously endangered biodiversity hotspots, indicators of dynamic river activity and ecological cornerstones for the development of green infrastructure. Owing to the analysis of the significance of the Danube islands, the 'WILDisland' initiative was formed and launched through the 'DANUBEparksCONNECTED' project. Within the framework of realized activities, it was established that the Danube's course is followed by an eco-corridor composed of 912 river islands (Sidó Öllös, 2019).

The 'LIFE WILDisland' project task 'Socio-economic effect of wilderness protection along the Danube' relates to assessing the public perception of the undertaken nature restoration measures. The first perception survey in all the countries involved in the Project was conducted in 2022, with a follow-up planned for 2027.

An integral part of this work is the results of the environmental attitudes survey conducted in 2022 by the Serbian participant in the 'LIFE WILDisland' project, which is the Public Enterprise 'Vojvodina šume' (responsible for the revitalization of the islands in the Special Nature Reserve 'Gornje Podunavlje', at the cross-border area of Serbia, Croatia and Hungary). Respondents who were in direct contact with nature were surveyed in the area of the Special Nature Reserve and its immediate surroundings. Online respondents were from various parts of Serbia. The research results exclusively reflect the views of the researchers involved in the 'LIFE WILDisland' project from the Faculty of Sciences at the University of Novi Sad and their associates, who were engaged as subcontractors on the Project.

Methodology

Instrument

The research was conducted on the basis of the questionnaire formed for the purpose of previously mentioned 'LIFE WILDisland' international Project focused on a protection of small islands along the flow of the Danube River. More precisely, questions are in line with the main idea of the Project to contribute to a preservation of nature and biodiversity within the islands that are identified as the most natural and valuable in eight Danube countries. The 'LIFE WILDIslands Project' is implemented in a cooperation with different sectors, starting from the managers of protected areas, over representatives of navigation, forestry, hydropower to tourism, which resulted in questions related to all aforementioned sectors. Questions are also in line with main task of the 'LIFE WILDIslands' Project focused on gaining the basic information from visitors, local community members and stakeholders that would contribute to a better design and communication of activities for river and island conservation in the Danube region. The starting point of the research was the previously mentioned project. However, the wider goal of the research is aimed at improving the nature protection in Serbia and other countries on the flow of the Danube River Based on abovementioned facts, the questionnaire could be divided in two sessions. The first group of questions is focused on the respondents' basic socio-demographic characteristics, while the second group of questions represents the main part of this research and it is focused on the respondents' perception regarding the nature conservation challenges along the flow of the Danube River. This study will present the main findings of the LIFE WILDIslands project gained within the territory of Serbia.

Data collecting procedure

Questionnaires were distributed in two ways, online, as well as a part of the field research. Online sample was gathered from January to May of 2023 and it was distributed by various contacts that live within the researched territory (next to the banks of the Danube river in Serbia), as well as by sharing the online questionnaire (previously prepared on the basis of the Google Drive option) via the social media (mainly thematic groups related to nature preservation, recreation and similar topics). When it comes to the sample obtained in the field, it started slightly earlier (in December of 2022) and it also lasts until May of 2023. This part of the research started by collecting the stakeholders' answers during the official meeting which gathered the stakeholders of the Special Nature Reserve 'Gornje Podunavlje' during the regular annual meeting. Later, these stakeholders significantly contributed a distribution of the questionnaires to the visitors and the local community members. Gained answers are analysed separately, in order to compare the answers of those who participated in the study in the field and thus were in direct interaction with nature, with answers of those who provided their answers on the basis of the online platforms, distanced from the researched territory.

Sample

Online sample that was collected on the basis of a distribution of e-questionnaires included 310 respondents, while the ***sample gathered in the field*** included 10 stakeholders (NGOs that are cooperating with the Special Nature Reserve 'Gornje Podunavlje', representatives of the local tourism organizations, managers of protected areas), 50 members of the local community and 100 visitors. Their socio-demographic characteristics are represented within the Table 1.

The research is based on a descriptive statistics. Distribution of the respondents' answers are represented in the form of frequencies and the mean values. Descriptive statistics is also used in order to represent the main characteristics of the respondents.

Table 1. Socio-demographic characteristics of the respondents

	Online sample N = 310	Sample gathered in the field		
		Stakeholders N = 10	Local community N = 50	Visitors N = 100
Gender				
Males	34.2%	50%	36%	40,8%
Females	65.5%	50%	64%	59.2%
Age				
Up to 20	3.5%	/	/	19.4%
20-29	46.5%	/	6%	22.4%
30-39	24.8%	40%	18%	9.2%
40-49	9.7%	40%	38%	31.6%
50-59	11.9%	10%	26%	12.2%
60-69	2.9%	/	10%	4.1%
70 and more	0.6%	10%	2%	1.0%
Education degree				
Primary school or less	0.6%	/	6%	1%
High-school	31.7%	/	50%	45.9%
University	67.7%	100%	44%	53.1%

Results

When they think about the Danube River, online respondents pointed out that the following issues spontaneously come to their minds: protected areas Gornje Podunavlje and Đerdap, larger and smaller cities along the flow of the Danube River through Serbia, historical fortifications, weekend settlements, bridges, but also the sense of peace and silence. When it comes to the broader concepts, online respondents indicated Europe, in the context of the European Amazon (Mura-Drava-Danube Transboundary Biosphere Reserve) and the river that connects countries and peoples. All three groups of respondents from the sample gathered in the field, or more precisely stakeholders, local community and visitors, also expressed the awareness of the fact that Danube is a river which connects countries in its course. It is interesting to notice that Gornje Podunavlje is not mentioned only in the group of respondents from the local community. Representatives of this group mentioned general concepts related to nature and protected areas. Also, it is noticeable that representatives of the local community and visitors, unlike the group of stakeholders, also mentioned the aspects related to the waste in the immediate vicinity. All three groups mentioned concrete activities, with the fact that they are numerous in the group of respondents from the local community and visitors, while in the group of stakeholders only fishing is mentioned.

Based on the research results represented within the Table 2, it can be noted that majority of online respondents (41.3%) is visiting the Danube River and/or the floodplains of this river several times per year. When it comes to the stakeholders group, 50% of representatives among this group are visiting the mentioned areas at least once a week. Representatives of the local community (38%) are visiting these areas several times per year in the largest percentage. When it comes to the visitors, 35.4% of these respondents are visiting the Danube and/or the floodplains of this river at least once a week.

Regarding the functions of the Danube River are represented within the Figure 1. Online respondents consider that habitat of protected species and ecosystem of rich biodiversity are among the most important facts. Slightly lower mean values were recorded regarding online respondents' perception of the importance of other functions of the Danube River, such as source of (drinking) water, fishing and forestry (wood production and hunting). In the field, respondents from all three groups consider that ecosystem of rich biodiversity is the most important fact. When it comes to the function of the Danube River, which can be said to have lower importance, respondents from the group of stakeholders and representatives of the local community agreed on the fact that it is a source of a drinking water. On the other hand, visitors believe that forestry (wood production) and hunting have the least importance of the abovementioned functions.

Respondents were further asked to choose up to three answers related to the elements of importance when visiting the Danube River, results are represented within the Table 3. It can be seen that minimal differences are repre-

Table 2. Frequency of visiting the Danube River and/or its flood habitats

	Online sample	Sample gathered in the field		
		Stakeholders	Local community	Visitors
a. Every day	3.9%	10%	4%	11%
b. At least once a week	22.9%	50%	28%	35.4%
c. At least once a month	25.8%	30%	24%	25.3%
d. Several times per year	41.3%	10%	38%	26.3%
e. Never or almost never	6.1%	/	6%	2%

Table 3. The most important aspects of visiting the Danube River

	Online sample	Sample gathered in the field		
		Stakeholders	Local community	Visitors
▸ Clean water	58.4%	40%	65.3%	51.1%
▸ Pleasant roads	38.7%	30%	36%	36.9%
▸ Pleasant river shores and beaches	69.7%	60%	74%	71.3%
▸ Nature to research, flora and fauna to watch	58.4%	70%	50%	63.2%
▸ Combination of culture and good food	23.8%	30%	22%	31.8%
▸ Offer for visitors and infrastructure	22.9%	20%	16%	19.5%
▸ Distanced places	11.9%	10%	10%	16.3%
▸ I am never visiting the Danube and therefore I am not involved in such activities	/	/	/	4.9%
▸ Other (protection of flood habitats, fishing access)	1%	/	/	2.5%

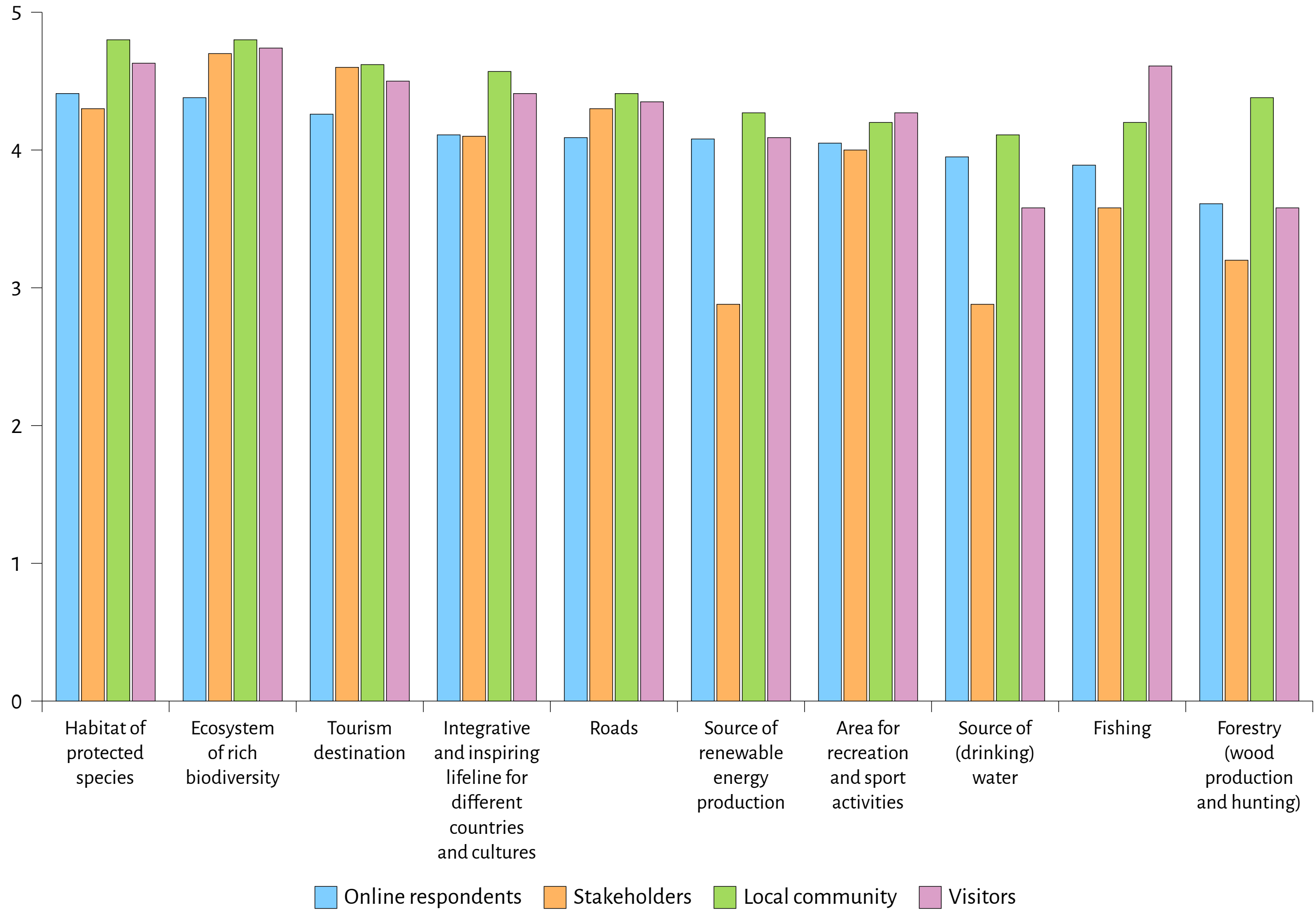

Figure 1. Functions of the Danube River – respondents' perception of their importance

sented when ranking the mentioned elements among different groups of respondents.

In terms of ecology, it can be said that numerous sections of the Danube River are not in an optimal condition. There are many types of threats and pressures and online respondents believe that it is mostly about pollution (for example, from industry, pesticides from agriculture, waste water) (93.2%), as it could be seen in the Table 4. In the field, all three groups of respondents, more precisely 90% of stakeholders, 94% of the local community representatives and 94% of visitors also agreed with this statement.

Table 4. The main types of threats and pressures on the Danube River (in ecological terms)

	Online sample	Sample gathered in the field		
		Stakeholders	Local community	Visitors
▸ Pollution (e.g. from industry, pesticides from agriculture, waste water)	93.2%	90%	94%	94%
▸ Waste and garbage	87.4%	50%	88%	78.6%
▸ River regulation (such as embankments)	2.3%	40%	10%	26.8%
▸ Hydro power plants	29.4%	50%	6%	28.2%
▸ Intensive usage by people for recreation and sport	6.5%	10%	10%	2.8%
▸ Land use, spreading of cities, (traffic) infrastructure	54.8%	20%	44%	67.8%
▸ Intensive forestry	13.5%	10%	20%	19.7%
▸ Other (the quantity of water is decreasing rapidly, exploitation of sand and pebble, degradation of the shore habitats, negligence of humans)	/	10%	/	6.9%

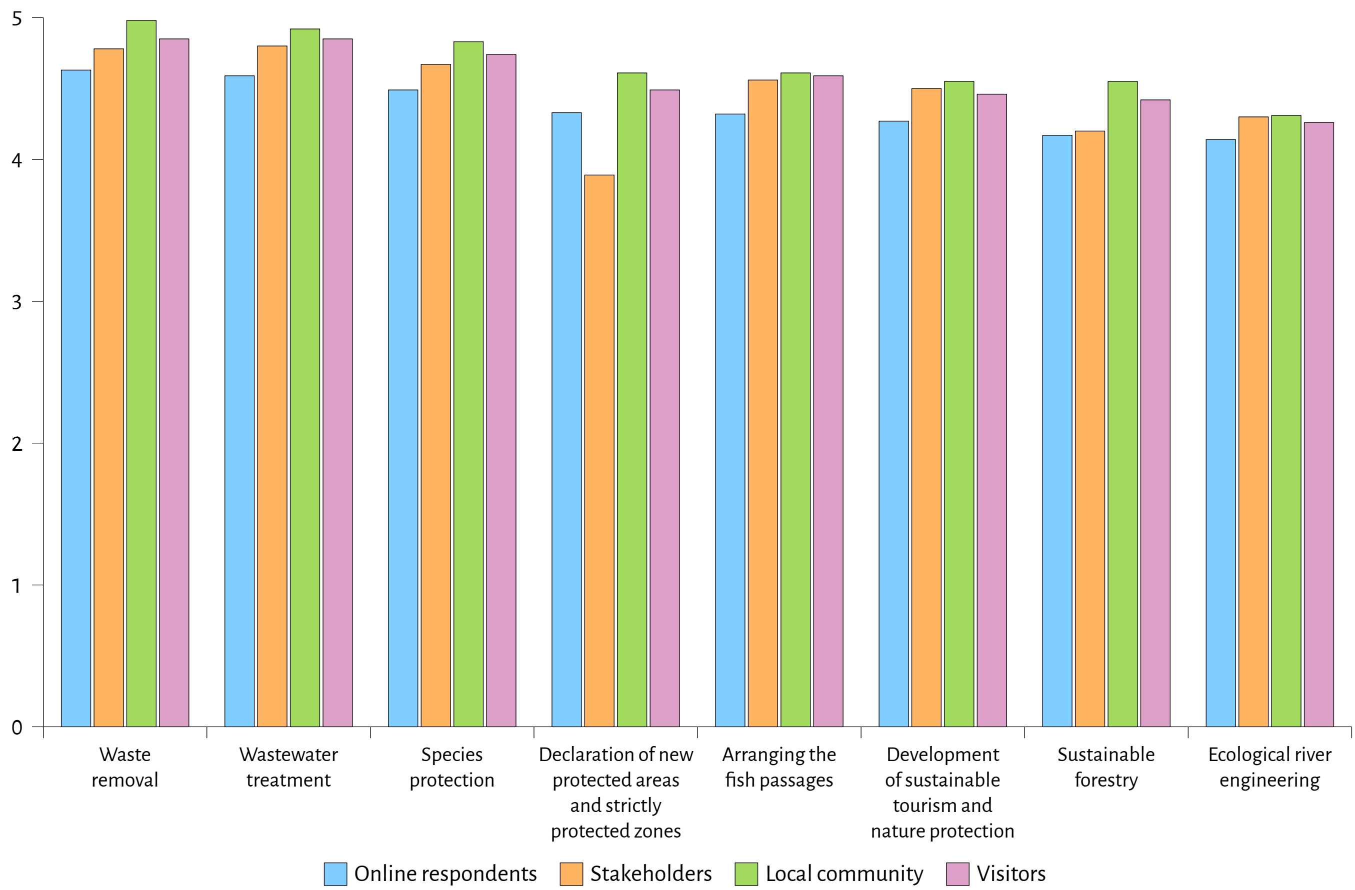

Figure 2. Conservation-restoration measures along the flow of the Danube River – respondents' perception

Online respondents showed a high degree of understanding of conservation-restoration measures along the flow of the Danube River, such as the waste removal, wastewater treatment, species protection. In the field, stakeholders believe that wastewater treatment is the most important. On the other hand, representatives of the local community emphasize the importance of the waste removal. Visitors value both conservation and restoration measures mentioned above equally. The measure for which the lowest mean value was recorded in all three groups of respondents, refers to the formation of new protected areas and strictly protected zones. Details are represented within the Figure 2.

The Danube islands (900 in total) are the habitats of the last remnants of wilderness, 80% of the population of certain species of birds and they also represent places where people can find forest habitats. Encouraging results of this research are indicating that even 83.5% of online respondents would support strict protection and non-interventionist management of 147 most natural islands along the flow of the Danube River. In the field, gained results of the survey also indicated the major interest of respondents to support the strict protection and non-interventional management of the 147 most natural islands along the Danube River flow. In the case of the stakeholders and the local community representatives, this percentage exceeds 90%. The research results also indicated the major understanding of the field respondents about the fact that access to the strictly protected islands is prohibited in order to better preserve their sensitive nature. The percentage of respondents who showed the understanding of this important item exceeds 80% in the case of all three groups of respondents.

Results of the online survey also indicated that 41.3% of respondents stated that they know some protected area along the flow of the Danube River, such as Gornje Podunavlje, Bačko Podunavlje, Djerdap. However, they also stated that they found themselves only somewhat informed (40.6%) or uninformed (39.7%) about protected areas along the flow of the Danube River in Serbia. More precisely, 11.6% of the online respondents feel completely uninformed, while only 1.3% of online respondents stated that they found themselves very informed about this topic. It is an encouraging fact that 47.7% of respondents support the activities focused on preservation of the Danube and its nature, such as natural islands. Besides that, even 36.5% of online respondents would be absolutely willing and interested in supporting the conservation work. As expected, all stakeholders who participated in the survey in the field pointed out that they are informed about protected areas along the flow of the Danube River. A significant percentage responded positively in the group of the local community representatives (75%) and visitors (81.6%). It is important to indicate that Gornje Podunavlje represents the protected area that is mentioned by respondents in all three groups. When it comes to the respondents' awareness of protected areas along the Danube flow in Serbia, 50% of stakeholders stated that they are very informed. On the other hand, 75.5% of the local community representatives believe that they are somewhat informed about the mentioned topic, while 42.4% of the visitors think the same. Furthermore, the research results indicated that majority of the field respondents are interested in supporting the activities to preserve the Danube and its nature, including the natural islands. More precisely, 60% of stakeholders, 72% of the local community representatives and 46.5% of the visitors would support conservation work.

When asked about the manner in which they could contribute to the preservation of the Danube, its islands and surrounding nature, online respondents firstly stated the attempt to influence the opinion and behaviour of others (65.2%). Finally, respondents from the sample gathered in the field also see their contribution to the preservation of the Danube and its nature on the basis of attempting to influence the opinion and behaviour of others. A detailed presentation of other responses is provided within the Table 5.

Table 5. Contribution to protection of the Danube River, its islands and surrounding nature

	Online sample	Sample gathered in the field		
		Stakeholders	Local community	Visitors
a. By changing the personal behavior in nature	57.7%	40%	46.9%	59.5%
b. By intention to change the attitudes and behavior of others	65.2%	70%	59.2%	71.6%
c. By volunteering	38.7%	30%	28.6%	53.8%
d. By financial contribution	11.9%	/	4.1%	23.3%
e. By sharing the informative campaigns	29.7%	40%	8.2%	33.3%
f. By gathering the waste	46.5%	20%	44.9%	58.4%
g. Other (by promoting the teambuilding (with eco-content), as well as by active promotion of staying in nature among younger generations, participation in projects, nature research)	26.1%	/	2%	8.5%

Discussion

The success of nature protection highly depends on a number of factors of this demanding process in environmental preservation and especially on the participation of the local community members, visitors and other stakeholders, such as managers of protected areas, forest holdings, tourist organizations (Baierl & Bogner, 2023; Brankov et al., 2022; Fromont et al., 2022; Gifford & Sussman, 2012; Holmes, 2013; Ihemezie et al., 2021; Karanth et al., 2008; Liu et al., 2010; Rodríguez-Rodríguez et al., 2019). Broad participation is even more important in societies in transition with lower level of economic development (Freudenberger et al., 2013; Stojanović et al., 2022). Therefore, the main focus of this paper is on the perception of a wide group of respondents regarding the issues of nature protection importance, which later might be used in practical nature protection activities. Previous papers put the visitors, local community members stakeholders and their general perceptions in the focus (Abukari, 2020; Angwenyi et al., 2021; Brown et al., 2010; Cheung & Fok, 2013; Engen et al., 2019; Holmes, 2013; Mannetti et al., 2019; Rodríguez-Rodríguez et al., 2019; Thapa et al., 2024), while this paper is additionally pointing to the importance of comparing the perception of respondents who were in direct contact with specific protected area and those who completed the questionnaire online, distanced from nature. This issue is becoming important topic nowadays, due to the evident decreased interaction of people with nature (Ballouard et al., 2011; Hofferth 2009; Zhang et al., 2014), which also decreases the positive emotions, attitudes and behavior towards the environment (Soga & Gaston, 2016).

First identified difference between online respondents and those who were surveyed in the field for the purpose of our study is reflected in the frequency of their visits to the Danube River and its vicinity. Majority of the online respondents highlighted that they are visiting the Danube River and/or the floodplains of this river only several times per year, while majority of the sample gathered in the field (predominantly stakeholders and visitors) are visiting the mentioned areas at least once a week. Such frequency might be a reason of different first associations on the Danube River, when speaking about online and the sample gathered in the field. More precisely, representatives of the local community and visitors mentioned the aspects related to the waste in the immediate vicinity, while online visitors did not cite the issues related to the waste in the open-ended questions as their firs association to the researched area. It seems that visitors who were in direct contact with nature have different perspective in terms of indicating the problems related to the nature conservation, while first association of online respondents was primarily related to a positive aspects of visiting the protected area. However, online respondents later expressed a high degree of understanding the issues related to the waste management, when speaking about the understanding of conservation-restoration measures along the flow of the Danube River, which still might be encouraging. Besides that, opposite to the online respondents, representatives of all three groups of the sample gathered in the field, underestimated the importance of formation of new protected areas and strictly protected zones, which might be a consequence of better understanding of the terrain, icluding its strenghts and threats and the following problems that might be caused based on such activities.

When citing the important functions of the Danube River, both online and respondents who were in direct contact with nature highlighted those functions that are important for enjoying within the protected area, while other practical ones are neglected, or more precisely those related to fishing activities, forestry, as well as considering the Danube as a source of a drinking water. It is interesting to notice that online respondents and those who were in direct contact with nature have similar perception of the current state considering the fact that numerous sections of the Danube River are not in an optimal condition. It is also encouraging that majority of online respondents, the same as those surveyed in the field, support the activities focused on a preservation of the Danube and its nature, including its natural islands. This issue is very important to be considered in the future and it is in line with the findings of the study conducted by Wolf et al. (2019), who highlighted the fact that preserved nature is important aspect for attracting the visitors in a concrete protected area, which might shape the higher levels of satisfaction when visiting protected area, as stated in the study of de Oliveira et al. (2021). Back to the findings of our paper, both groups also indicated that they could contribute to the preservation of the Danube River, its islands and surrounding nature, based on the attempt to influence the opinion and behavior of others. However, online respondents found themselves only somewhat informed or uninformed about protected areas along the flow of the Danube River, which is opposite to the respondents who were in direct contact with nature.

Therefore, it could be said that, based on the main aim of this paper, to assess the environmental attitudes between visitors, residents and other stakeholders compared to those online opinions of citizens who are geographically distant from the Danube and nature in protected areas along this river, differences and similarities certainly exists. Besides these theoretical contributions, practical implications of the main results are reflected in the fact that these findings might serve as guidelines for various stakeholders in charge for further development of tourism and nature protection. In such manner, managers of protected areas and tourism organizations might further increase their marketing activities focused on raising the awareness on various problems when it comes to the nature protection, especially when speaking about the human negative influence. Brown et al. (2010) and Cheung and Fok (2013) highlighted in their studies that it is important to shape the visitors' attitudes through organized visitor management, while the main findings of our paper might be used in that purpose, too. Basic findings of our paper could also contribute in preparing the informal education for visitors (and future visitors), based on the interpretation and developing positive attitudes towards nature conservation, which is another important aspect that protected areas should implement in their offer, according to the findings of Ghazvini et al. (2020), Leung et al. (2018) and Hornoiu et al. (2014). Developing positive attitudes of stakeholders and the local community members is also important, according to the findings of Engen et al. (2019), Fotsing et al. (2024), Macharia et al. (2010) and Weladji et al. (2003) while findings of our study provides detailed insight into their perspective. On the other hand, Wells et al. (1992), Angwenyi et al. (2021) and IUCN (2004) highlighted the role of managers in protected areas in nature conservation for the local communities, which additionally raises the importance of our study.

Limitations of the paper are primary reflected in the fact that it obtained only one river as a ecological corridor, while further research might be focused on the other rivers ecocorridors in Serbia, like Sava River, Tisa, Velika Morava, etc. Besides that, this paper is also reflecting the results for only one country in the flow of the Danube as the international river. However, this limitation would be surpassed on the basis of the Danube-wide project 'LIFE WILDislands' funded by the European Union established with the intention to contribute to the preservation of nature and biodiversity within the islands that are identified as the most natural and valuable in eight Danube countries.

Conclusion

This research is focused on attitudes towards the environment and nature protection, with a particular emphasis on comparing the attitudes between respondents who had direct contact with nature and those who participated online. While it is encouraging that both groups of respondents are generally supporting the nature protection activities, there are also differences between them. Respondents who had direct contact with nature have more intense interactions with it, take a different approach to issues in protected areas and have a good understanding of conservation-restoration measures. However, this group of respondents (visitors, local communities and stakeholders) does not emphasize the need for a designation of new protected areas and strict protection zones, which can be justified by their knowledge of the terrain or the fact that they are already sufficiently connected to the protected area covered by this research (Gornje Podunavlje Special Nature Reserve).

The data in this paper could also have practical implications for nature protection or tourism development, allowing protected area managers or local tourist organizations to improve their marketing activities aimed at promoting 'environmentally' and 'socially' responsible marketing. Finally, future research could be even more interesting if it compares attitudes across all the countries along the flow of the Danube River. Perhaps the most important finding is related to the fact that both groups of respondents, those in direct contact with nature and online respondents, confirmed that they support the protection of islands on this great River. In the future, it should contribute to better and detailed results on the way to realize this important task.

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Exploring the Contemporary Spatial and Temporary Dynamics of the Settlement Hierarchy and System in Serbia's Srem Region

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KEYWORDS

- settlement hierarchy
- settlement network
- primacy
- rank-size rule
- Srem
- Serbia

ABSTRACT

Newer trends of balanced regional development emphasize the development of functional integrational areas and strong spatial and functional relations based on the nodal concept and a functional process approach. Therefore, it is essential to determine the hierarchy of settlements in the network, which defines their demographic and functional capacity. This paper identifies the nature and characteristics of urban primacy in the Srem region in Serbia, using the rank-size rule and urban primacy index, as well as the hierarchy of settlements in the network, by calculating the importance of secondary activities and the centralization of the settlements. The results confirmed that while urban primacy is not expressed, the hierarchy of the settlements remains dominated by urban and suburban centres.

Introduction

In the modern world, no autonomous settlements or towns are independent of others. Some functions have become so important that they have outgrown the needs of the local population and have begun attracting residents of neighbouring settlements. Such settlements overtake their neighbours in development, size, importance, and standing in certain hierarchical relationships (Kaplan et al., 2014).

The settlement hierarchy means that influential spheres of functions in various cities do not have the same importance and reach and that the area they affect is called a gravitational sphere (Krugman, 1996). Settlement hierarchy and gravitational spheres are two main elements in the settlement system. The settlement system implies that all the settlements in a region, regardless of politics or natural criteria, are in some interdependent relationships (Ćurčić et al., 2021).

When studying the system of settlements in an area, a number of fundamental questions about the relationships between the individual towns and cities and their hinterlands need to be considered. Human settlements today are characterized by a complex structural and functional stratification reflected at many levels – from the typology of the built structures to the relationships and connections they form with each other. Contemporary settlement relations are marked by multi-layered spatial overlapping of urban and rural characteristics in particular areas and equal and reciprocal functional flows of people, capital, goods, information, and technological processes. Growing interdependencies between cities and other surround-

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ing settlements have been significantly transformed from traditional and straightforward one-way relationships to complex dynamic networks dominating various activities (Schaefer, 1977; Sennett, 1994).

Among the first significant theoretical and methodological papers addressing the interaction between urban and rural settlements is Kohl's (1841) model. Additional significant contributions to the further development of this idea were made by Auerbach (1913), Weber (1929), von Thünen (1930), Christaller (1933) and Lösch (1954). A significant contribution was made by Christaller (1933) with his much-respected theory of central places, where he connects the spatial distribution of centres with their essential functions, which supply the population with central goods and services. He assumed that the connections between the settlements are established in an idealized hexagonal pattern, on the principle that a small number of centres of higher rank supply a large number of centres of lower rank in close distances, ignoring the industry and the production function.

In his general theory, Friedmann (1972) points to urban systems as spatially organized unities. On the local and regional level, differences can be made between daily, weekly, and monthly urban systems (Berry, 1967; Friedmann, 1972). At higher levels of spatial aggregation, the urban systems can be considered national, sub-continental, continental, world or global in scope (Geyer, 2002). Castells (1993) distinguishes the difference between global networks and world systems – global networks cover the entire world, while world systems cover the subsets of global networks.

Furthermore, Castells (1994) writes about global cities as hubs and centres, hierarchically organized according to their relative importance in the network. Soja (2000) speaks about the urban revolution that brings many changes in the industry, such as flexible specialized industry, globalized urban regions, post-urban exopolises and "crumbled cities", which Giddens attributed to the westernization of the world and the western conditionality of globalization and its urban indicators (Giddens, 1995, 2002). Saskia Sassen (2001), the most profound analyst of the city's networks from a sociological point of view, also stands side by side with the aforementioned authors. She makes a difference between global and world cities, of which the former are in a network, while the latter do not have to be, but can be. World cities are the focal points of all their functions, while global cities belong to a group in which they must be in order to be global, that is, independent from the place.

According to the theory of the central places, the hierarchy of central places is developed as a result of the wide distribution of people who need goods and services. The term hierarchy of urban centres (Christaller, 1933; Lösch, 1954) is associated with the concept of an urban system and appears in much of the literature and is collectively referred to as the theory of location. This theory deals with factors that determine the location of social and economic activities in an area and the economies of agglomerations (Fujita et al., 1999; Parr, 2002a, 2002b; Malmberg & Maskell, 2002; Richardson, 1973) and which are one of the crucial factors in the manifestation of urban hierarchy. The individual nodes of the cities and their hinterlands are examples of nodal regions, which are the simplest features of the functional, social, and economic space.

Besides all the limitations mentioned above, the classical urban theories have served as spatial models for the planning of settlement networks and the development of areas that are under an immediate impact, as was the case in the south of Germany. They remain a part of planning practice, especially in environments where the hierarchical relationships in the spatial organization are clearly expressed and the interactions between the settlements in the system are less complex.

Recent research in settlement hierarchy explores various approaches to understanding how settlements are structured and categorized based on factors such as population density, economic activity, and geographic distribution (Lee, 2017; Budde & Neumann, 2019; Dobis et al., 2020; Bergs, 2021). In his recent study, Griffith (2022) updates the United States urban hierarchy by using spatial autocorrelation and other geospatial metrics to reveal patterns in settlement structures and their implications on regional development. He finds that geographic proximity and regional factors create coherent settlement groupings, which help define urban-rural distinctions and hierarchical layers within urban networks.

Moreover, Altaweel (2015) employs agent-based modelling to examine settlement dynamics, particularly how interactions between individual agents (people, goods, services) shape hierarchical settlement patterns over time. This modelling approach, grounded in entropy maximization, allows researchers to simulate and analyze changes in settlement hierarchies as influenced by migration and resource distribution patterns, offering a dynamic view of urbanization processes. Similarly, Chun and Kim (2022) investigate South Korea's urban structure evolution from the 1950s to the present, focusing on urban primacy and spatial interactions. They use population data and commuting patterns to assess urban connectivity and hierarchy, applying primacy and spatial interaction indices to analyze how urban areas interact.

Meanwhile, Sat (2018) examines whether Turkey's urban regions have shifted from monocentric to polycentric spatial structures using the Primacy Index and Rank-Size Rule. Recent studies on settlement hierarchy in Hungary concentrate on regional dynamics, particularly challenges in rural and urban development, economic disparities, and the effects of policy reforms on settlement networks. Bagyura (2020) analyzes the effects of suburbanization on power dynamics in municipal councils within Budapest's suburban areas, highlighting shifts in governance influenced by regional growth.

Additionally, recent research on settlement hierarchy in Romania addresses several key areas, including urbanization trends, regional development, and socio-spatial changes due to migration and economic shifts. A significant area of study is the transformation of settlement structures since Romania's post-socialist transition (Benedek, 2006; Mitrică et al., 2014), which altered urban-rural dynamics and population distribution (Lung, 2019). These studies reveal that cities with strong secondary and tertiary sectors, particularly those along major transport corridors, have remained economically resilient (Benedek, 2016). Furthermore, Horeczki et al. (2023) explore Romania's urban development, highlighting challenges and opportunities in its spatial planning and metropolitan growth. The authors argue for a balanced, polycentric urban development model that supports regional centres in fostering growth across the country rather than concentrating resources in Bucharest.

Lastly, Jošić and Žmuk (2020) adopt a novel approach, investigating whether Croatia's urban hierarchy can be approximated using the Fibonacci sequence, analyzing historical population data from 1857 to 2011. They apply two methods: one divides the largest city's population by the golden ratio, and the other applies the golden ratio iteratively to each successive city. Findings show that Croatia's urban hierarchy aligns well with the Fibonacci sequence, particularly when Zagreb is excluded due to its disproportionately large size. This study suggests that the Fibonacci sequence may be valuable for analyzing urban population systems, complementing existing urban economics theories like Zipf's and Gibrat's laws.

Partial approaches, both in territorial and thematic terms, are generally dominant in previous studies that have examined the networks and urban systems of Serbia. On the one hand, there are many studies of geographical networks and settlement systems in some parts of Serbia at a regional or administrative district/municipality level. Some research includes only network and settlement system segments, such as demographic features and functional characteristics. On the other hand, there are fewer territorial and thematically comprehensive studies of the network and the system of settlements. More recent studies of the hierarchy of settlements in Serbia are focused on urban settlements. Filipović et al. (2022) examine the functional dependence and demographic changes in the daily urban system of Belgrade during its post-socialist transition. They redefine commuting zones, observing shifts in functional dependence on the city core due to demographic changes, increased mobility, and shifts in economic centres, which call for strategic planning to manage this growth and dependency.

Meanwhile, Živanović et al. (2020) evaluate urban regions in Serbia, focusing on their functional polycentricity, or the presence and distribution of multiple urban centres within regions. The study assesses factors such as population concentration, employment distribution, and activity sectors across primary and secondary centres. Findings indicate that nearly half of Serbia's urban regions are monocentric, relying primarily on a single central hub, while a few, such as Novi Sad, exhibit greater polycentric characteristics. These polycentric regions benefit from multiple secondary centres that help disperse economic activity, promoting balanced regional development. Furthermore, the authors suggest that policies fostering decentralized growth and re-industrialization could strengthen secondary centres, ultimately achieving a more balanced national urban system.

In this regard, the purpose of this study is to evaluate the hierarchy and characteristics of the settlement network in the Srem settlement system, that is, a cross-section that exists at the beginning of the 21st century, in order to achieve a better understanding of the spatial and functional organization of this region.

The main question examined is what types of connections exist between settlements of all hierarchical levels and how these relationships affect the survival and future of the settlements in the Srem region in Serbia.

Methods

The research was conducted on the territory of the Srem region, which includes the municipalities of Inđija, Irig, Pećinci, Ruma, Sremska Mitrovica, Stara Pazova, and Šid (Figure 1). These municipalities encompass a total area of 3,671 km^2 and are inhabited by 312,278 people, distributed in 109 settlements (Krajić, 2013; Lukić et al., 2014; Đerčan et al., 2017a; Đerčan et al., 2022). The population data used are from the 2011 Census (Statistical Office of the Republic of Serbia, 2014) and the data on the population's activities from the Statistical Office of the Republic of Serbia.

There are different ways to determine the ranking of a settlement in the settlement hierarchy. Christaller (1960) opted for the "telephone method", where the degree of centrality was determined based on the number of telephone connections. Schmook (1968) took into account the population employed in some tertiary activities. Davies (1967) based thinking on a location coefficient and Preston (1975) based his on the value of retail sales, average earnings and share of household income spent on the purchase of goods and services. The Rank-size rule is also often used. It is

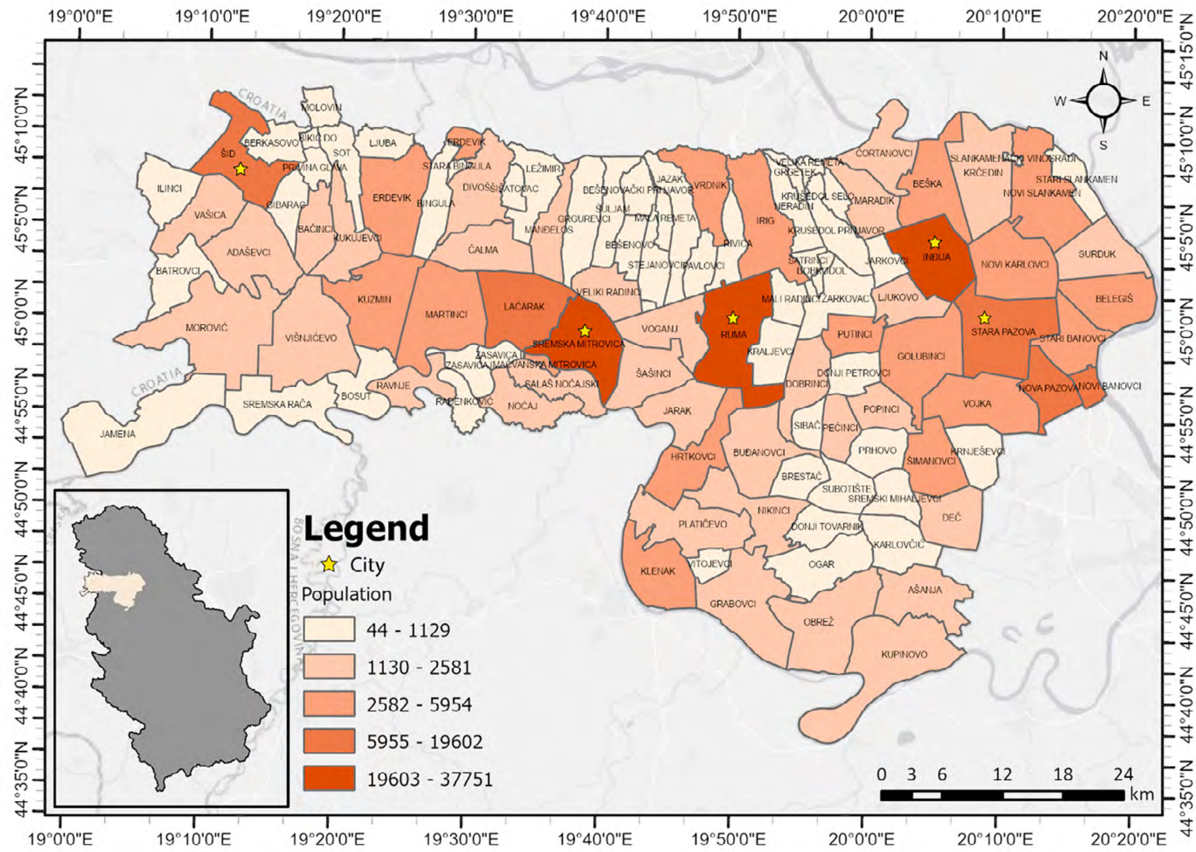

Figure 1. Study area

based on the assumption that the rank of the settlement in the hierarchy complies with its size compared to other places (Vresk, 2002).

Auerbach (1913) noted a specific correlation between the size and the number of cities and a tendency in the number and magnitude of towns in an area. This interdependence theory is formulated as a Rank-size rule, also known as the Zipf law, widely used in this kind of research (Alperovich, 1984, 1993; Guerin-Pace, 1995; Brakman et al., 1999; Gabaix, 1999; Ioannides & Overman, 2003, Soo, 2005; Córdoba, 2008). According to the Rank-size rule, it can be expected that one of the cities in a number of cities of a country or region, ordered by size, will have as many inhabitants as there are in the largest city divided by the number assigned (or ranked) to this city in a number of cities. Thus, the second largest settlement in the series will have half the largest population; the third will have a third and so on. Mathematically, this can be expressed as a formula:

$$Sn = \frac{S_1}{r}$$

Where S_n is the expected number of city inhabitants in the series, S_1 – is the population of the largest city and r – is the number of the city in the series.

Jefferson (1939) noted that urban systems often exhibit irregularities, especially regarding city sizes and ranks. He noted that in some countries, the capital, the primate city, stands out because of its size, while the other cities are much smaller. He called this phenomenon the “law of the primate city,” explaining it by pointing out the capital city’s exceptional political, economic, and social importance.

A simple formula calculates the Urban primacy index of a country or region:

$$I = \frac{G_1}{G_2}$$

Where I is the urban primacy index, G_1 is the largest city’s population, and G_2 is the population of the second largest city. Urban primacy is more significant if the resulting index value exceeds 2. The urban primacy may be expressed by the ratio of the population of the largest city and the population of the following few largest cities in the series:

$$I = \frac{G_1}{G_2 + G_3 + G_4}$$

In practice the following three largest cities are most commonly used to calculate it as follows: $G_2 + G_3 + G_4$.

Quantitative methods determined the importance of secondary activities in the network of settlements. For this purpose, a modified Schmook's (1968) method applied to secondary activities has been used (Vresk, 2002). The results were obtained using this form:

$$ISA_1 = An\left(\frac{SCn}{An} - \frac{SCr}{Ar}\right)$$

Where: *An* –active population in the settlement, *SCn* –active population in the secondary sector of the settlement, *SCr* – active population in the secondary sector in the region, *Ar* – active population in the region.

In order to present the results of the importance of secondary activities graphically, a model derived from Rochefort's method for secondary activities was used (Rochefort 1957, 1959). The hierarchy of settlements using this method is obtained according to the following formulas:

$$X = \frac{SCn}{An}$$

$$Y = \frac{SCn}{SCr}$$

The meaning of the marks is the same as in the previous formula. *X* represents the abscissa, and *Y* is the ordinate in Figure 3.

The hierarchy of settlements by this method is obtained according to the following formula:

$$ISA_2 = \sqrt{X^2 + Y^2} \cdot 100 \cdot tg\frac{Y}{X}$$

Quantitative methods based on the active population in the tertiary–quaternary sector of the settlements were used to determine the centrality of the settlements.

One of the research methods for determining the level of development, location, and importance of the settlement in the network is Schmook's method. According to this method, centrality is calculated as the deviation of the share of the tertiary–quaternary sector in the active population in the settlement compared to the same average for the region. Centrality is calculated according to the following model:

$$C1 = An\left(\frac{TQn}{An} - \frac{TQr}{Ar}\right)$$

Where: *An* – active population in the settlement, *TQn* – active population in tertiary – quaternary sector of the settlement, *TQr* – active population in tertiary – quaternary sector in the region, and *Ar* – active population in the region.

Rochefort's method also provides a graphical representation of settlement centrality in the form of:

$$X = \frac{TQn}{Ar}$$

$$Y = \frac{TQn}{TQr}$$

Form markings have the same meanings as in Schmook's model, where *X* and *Y* are the abscissae, or ordinate, of the coordinate system.

The centrality of the settlement using Rochefort's model was obtained according to the formula:

$$C2 = \sqrt{X^2 + Y^2} \cdot 100 \cdot tg\frac{Y}{X}$$

For this study, ArcGIS Pro software was used to generate maps. The data used for the visualization and geospatial interpretation is derived from the Census of Population, Households and Dwellings in the Republic of Serbia.

Results and discussion

Over time, cities in a country develop a hierarchy. The expression of this hierarchy is the distribution of the size of a city's population that can easily be constructed for any urban system (Dimitrova & Ausloos, 2015). According to the Rank-size rule, the distribution of settlements is most commonly displayed by a graph with an arithmetic scale, so the function is in the form of a curve. If the sizes are expressed with a logarithm, then the graphic form of the order of magnitude will have a straight line. Rightness is clearly visible: There is always a small number of settlements with a larger population and a much larger number of settlements with a small population. The size increases as the size reduces the frequency of settlements with the same population. The distribution of settlements is shown in Figure 2.

However, Pearson's correlation coefficient ($r=.984$, $p=.000$ ($p<0.01$)) indicates that there is a robust positive correlation between the distribution of settlements according to the population size and the distribution of settlements according to the Rank-size rule.

The index of urban primacy was calculated by applying the Rank-size rule according to the aforementioned formulas. Based on the first statement (the ratio of Sremska Mitrovica and Ruma), the urban primacy index is 1.26. Based on the second statement (the ratio of Sremska Mitrovica on one side and settlements Ruma, Inđija and

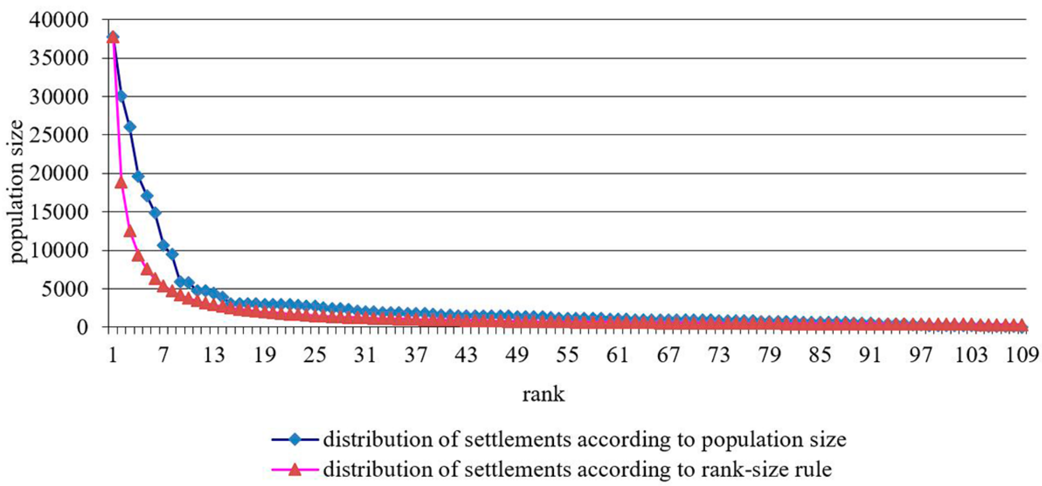

Figure 2. Comparative review of the distribution of settlements according to the population size and the rank-size rule in the Srem region

Stara Pazova on the other side), the urban primacy index is 0.50. In both cases, the value is less than 2, which means that the urban primacy of only one city is not prominent in the Srem region. Although it is the region's administrative centre, Sremska Mitrovica has only 7,000 more inhabitants than Ruma. In the same period, at the Republic of Serbia level, the urban primacy index (Belgrade-Novi Sad) was 4.86 (Đerčan et al., 2017b). The urban primacy phenomenon is even more pronounced in many developing countries. For example, the urban primacy index in Jammu and Kashmir (India) in 2011 was 7.9 (Yousuf & Shah, 2014).

Polèse and Denis-Jacob (2010) analyzed the evolution of city ranking at the top of national urban hierarchies in 74 countries during the 20th century. They found that European city ranking shows significantly fewer variations over time than in North and South America and developing countries. This finding aligns with the view that urban hierarchies become more stable and robust over time as the rural-urban transition is completed and settlement patterns mature. Changes in ranking at the top are rare, and where they do appear, they can be linked to political events that alter the direction of trade or the role of the city as a central place. The urban system of the Srem region is composed of small and medium-sized cities whose population sizes and ranking have not significantly varied over recent years, which is in line with the research carried out by Dimou and Schaffar (2009). They acknowledge that medium-sized cities are more resistant to external shocks caused by conflict, change of national borders and institutional turmoil than those with large agglomerations.

Secondary and tertiary quaternary activities are essential factors in determining the hierarchy in the network of settlements and generally give importance to settlements throughout the Srem region.

Secondary activities, primarily industry, contributed significantly to the growth and development of settlements and strengthened the differentiation in the network of settlements regarding influence. Industry attracts the population; it is the most important factor of urbanization and the driving factor of the polarizing effect of cities and centres in the area.

According to the derived Schmook's model, the importance of secondary activities is shown in Figure 4 (ISA 1). The highest level in the hierarchy of settlements according to the relative importance of secondary activities is Inđija, followed by Stara Pazova, Sremska Mitrovica, Ruma and Šid, all of which are municipal centres. Higher levels have suburbs like Nova Pazova, Laćarak, Vojka, Stari Banovci, Putinci and Mačvanska Mitrovica. It can be concluded that the settlements with relatively high importance of secondary activities are either municipal centres or suburban areas with a high share of daily commuters; together, they form some conurbation. Some previous studies have come to similar conclusions (Bole, 2004, 2011; Nared & Razpotnik Visković, 2016; Popović, 2020). Slovenian authors found that conurbations in Slovenia, defined basically on daily migrations, are more extensive and numerous than conurbations defined by complementary central functions. By adding daily migrants, these authors supported the established approach using complementary central functions, which set the definition of conurbations in broader contexts and point to possibly new directions in spatial development. The importance of secondary activities is shown graphically in Figure 3.

According to the results of this method, settlements with the highest importance are presented with the dots at a greater distance from the coordinate beginning and away from the abscissa and ordinate.

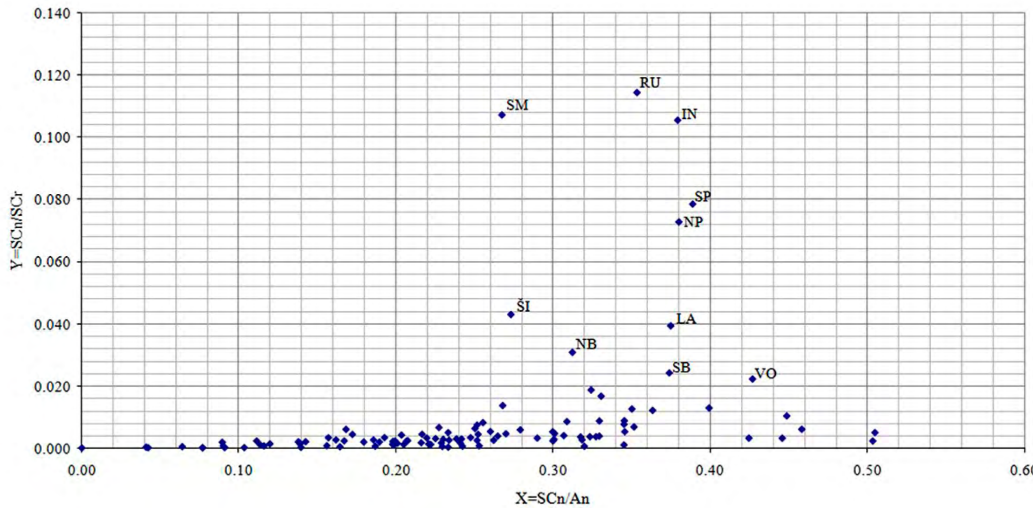

Figure 3. Secondary activities in settlements using the Rochefort'smethod
Legend: RU- Ruma, SM – Sremska Mitrovica, IN – Inđija, SP – Stara Pazova, NP – Nova Pazova, ŠI – Šid, LA – Laćarak, NB – Novi Banovci, SB – Stari Banovci, VO – Vojka

Figure 4 (ISA 2) shows the settlements with the most significant importance of secondary activities in the settlement network of the Srem region according to the modified Rochefort's model.

According to the second model, the changes in the hierarchy within the network of settlements are insignificant. According to Schmook's modified model, the settlements with a higher share of the secondary sector have a relative-

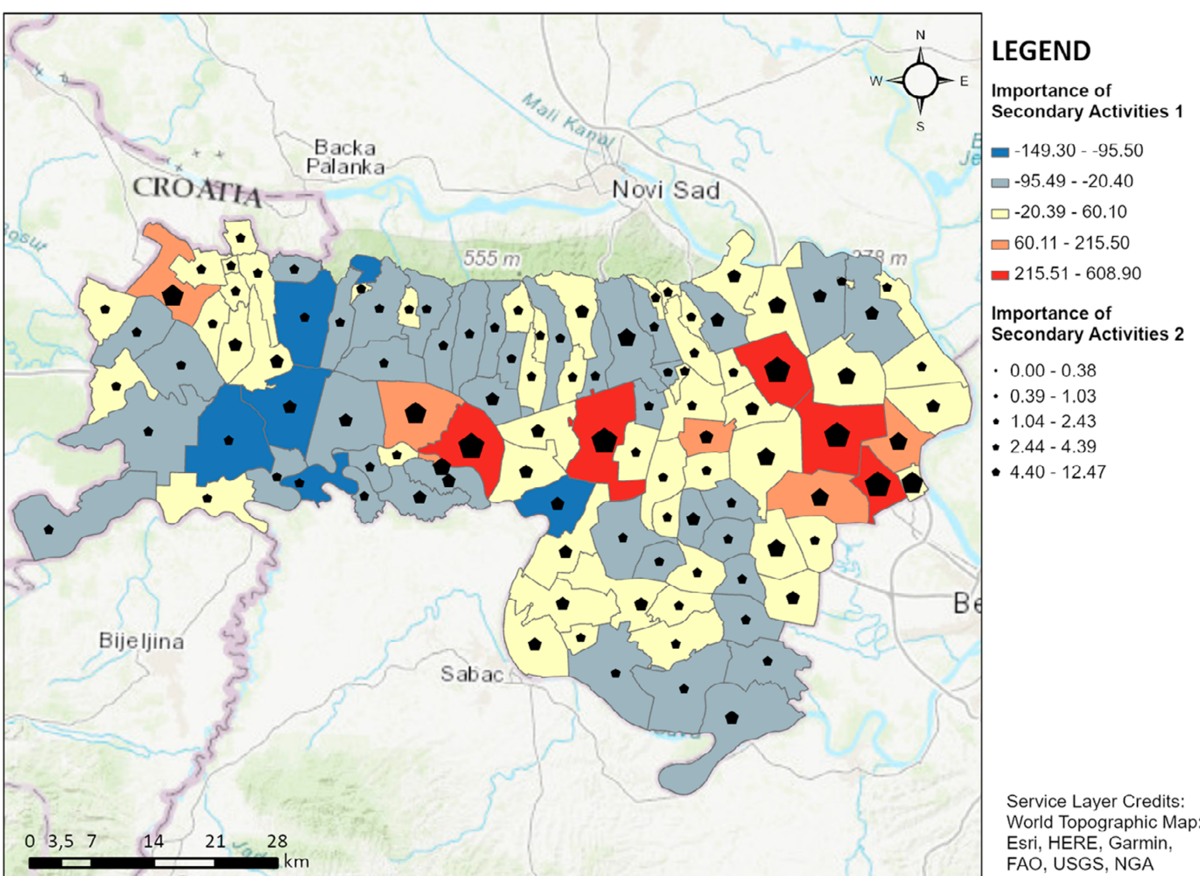

Figure 4. Comparative display of the importance of secondary activities according to the derived Schmook's and Rochefort's models

ly higher significance. In contrast, according to Rochefort's model, settlements with larger active populations in secondary activities have a higher significance.

The position of the settlement in the system or hierarchy is determined by the degree of its centrality. In this system, the higher-ranking cities are those that have a greater gravitational sphere, that has a more significant number of basic functions and those where the functions have more power. They also gather the lower-ranking cities with central importance because the population of smaller towns and their gravitational zones meet a part of their needs in large centres. The Slovenian authors make similar conclusions cited above using the combined index of the degree of centrality (Nared et al., 2017). If the centrality based on functions is greater than the centrality based on the number of inhabitants, the settlement is oversupplied, and if the opposite exists, the system is undersupplied. Undersupply is characteristic of settlements near major cities, which is a consequence of suburbanization. The conclusion is drawn that the competitiveness of the central settlements is moderately correlated with their population size and supply functions.

Sremska Mitrovica has the highest centrality, followed by Ruma, Šid, and Inđija. Among the 15 settlements with the highest centrality are all the municipal centres except Irig. Other settlements with high centrality are mainly suburban areas in the municipalities of Stara Pazova, Inđija, Pećinci and Sremska Mitrovica. According to Schmook's model, the centrality of settlements is shown in Figure 5 (C1).

Graphically presented values of settlements centrality are shown in Figure 6. Settlements at a greater distance from the coordinate system have a greater centrality. It is noted that this is Sremska Mitrovica, the seat of the region and the largest city in the Srem region. It is followed by municipal centres Ruma, Inđija, Stara Pazova and Šid. The municipal centresIrigand Pećinci are not among the settlements with greater centrality. Other settlements are the suburban towns Nova Pazova, Novi Banovci and Laćarak.

The results of Rochefort's model (Figure 5, C2) show that larger settlements have a higher place in the hierarchy of settlements in relation to Schmook's model, where the share of the tertiary–quaternary sector in the active population of the settlement had relatively high importance. However, these two models do not show any significant discrepancies. From this research, Sremska Mitrovica, Ruma, Inđija, Stara and Nova Pazova and Šid are the settlements with the highest centrality.

The results of the hierarchy of settlements in the Srem region according to the importance of secondary activities and centrality showed no significant differences. Municipal centres and their suburban areas are high in the hi-

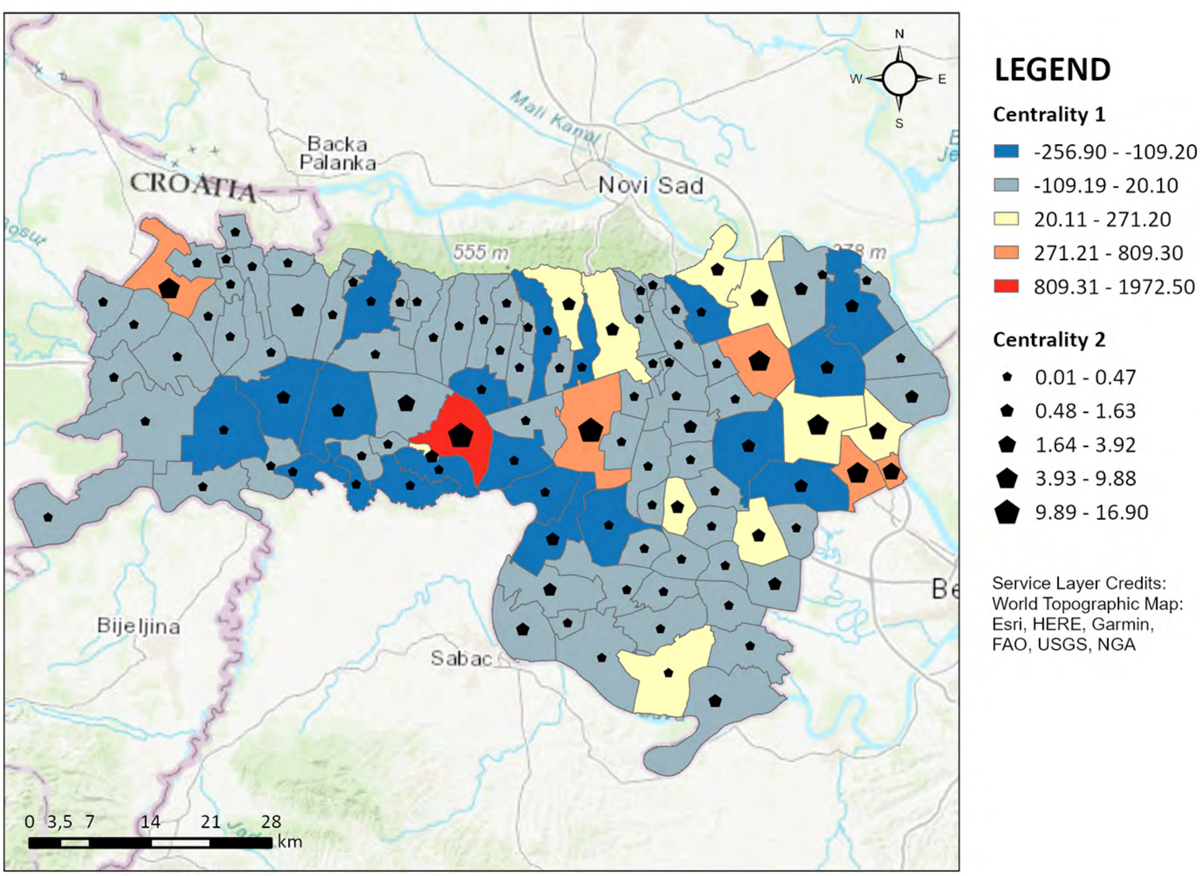

Figure 5. Comparative display of centrality according to the derived Schmook's and Rochefort's models

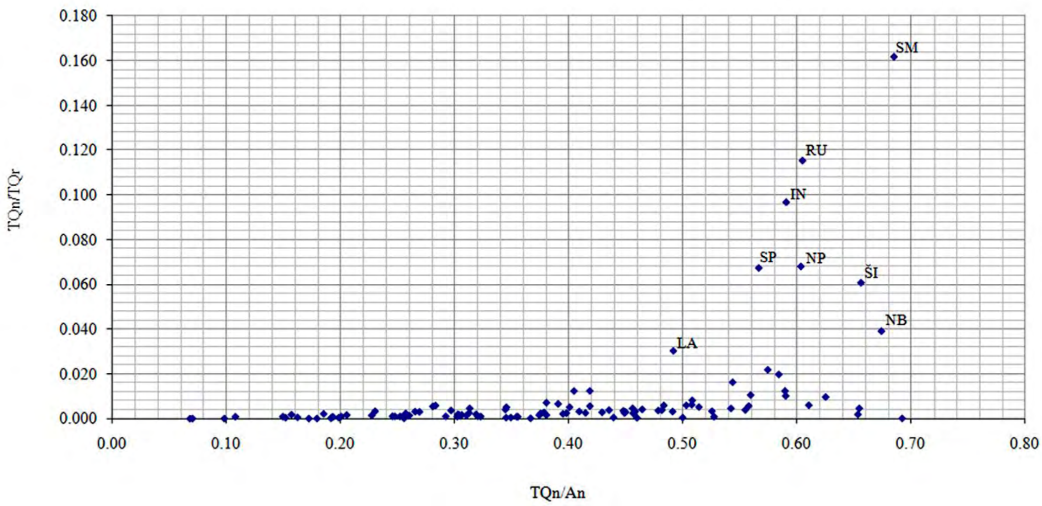

Figure 6. Settlement centrality according to Rochefort's method
Legend: SM – Sremska Mitrovica, RU- Ruma, IN – Inđija, SP – Stara Pazova, NP – Nova Pazova, ŠI – Šid, LA – Laćarak, NB – Novi Banovci.

erarchy sequence. Small, rural settlements, often peripherally located on Fruška Gora, occupy the bottom of the hierarchy of the settlements of the Srem region.

Based on previous research, the organization of the settlement network in the Srem region was defined using five levels:

1. Regional centre,
2. Sub-regional centre,
3. The municipal centre,
4. Local centre,
5. Village.

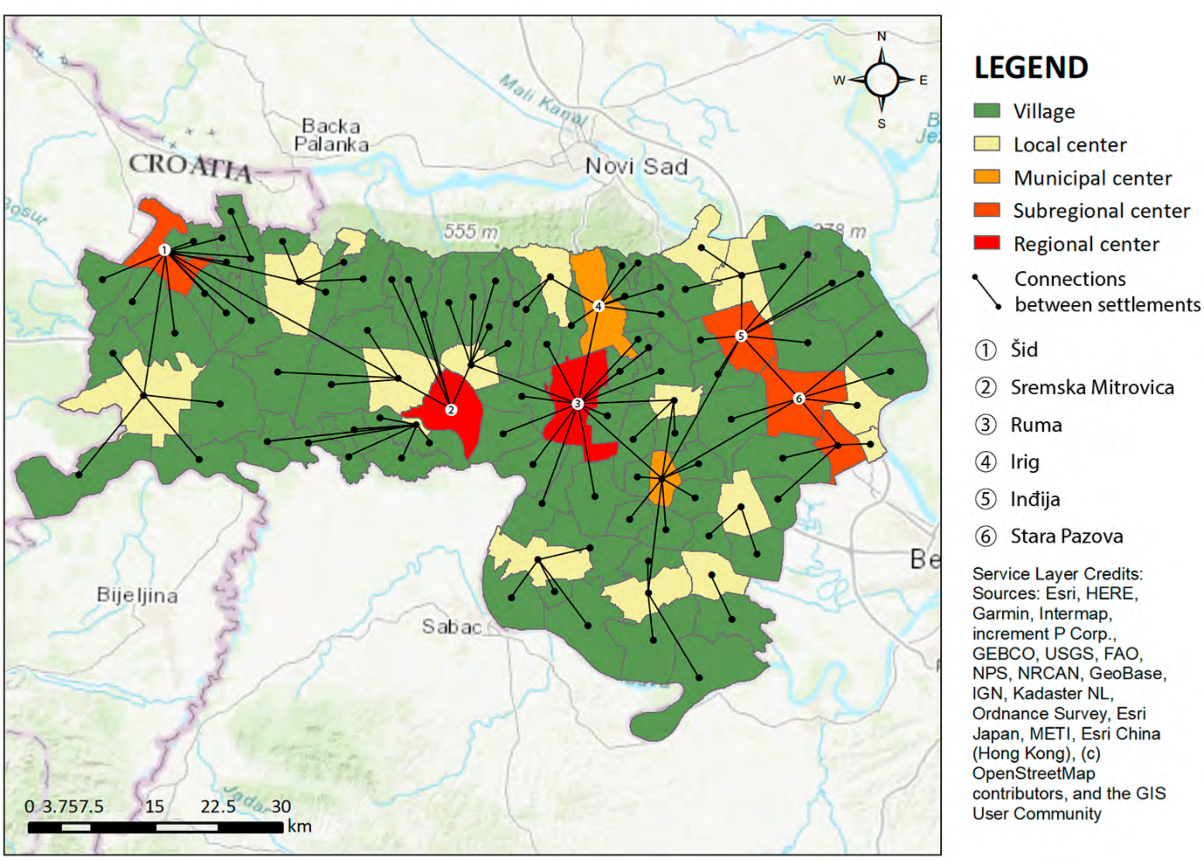

Figure 7. Organization of the settlements network in the Srem region

The criteria used to separate a regional from a sub-regional centre were the number of inhabitants, the value of centrality, the importance of secondary activities and the influential zone of the centre. The sub-regional centre has a smaller population and a lower zone of influence than the regional centre; also, it is linked to the regional centre by some tertiary–quaternary functions. Municipal centres have been identified based on already existing administrative divisions. The local centre is defined based on population, traffic position of the settlement on the municipal level and the type of the settlement according to the structure of activities. The village is one level that failed to meet the previous criteria. The organization of the settlement network is represented in Figure 7.

One of the processes expressed in this system of settlements is concentration. It is an expression of the polarizing effect of the centre and, therefore, is more prominent if the centre is more significant. In the Srem region, the concentration of activities, especially industry and population, is mainly in the eastern part. These are also the municipalities of StaraPazova and Inđija, which have the largest concentrations of economic activities and population; Sremska Mitrovica follows them as the region's centre and the largest city. The population is agglomerated alongside roads throughout the entire region. Congregating alongside the roads provides an opportunity for the development of small businesses and more accessible communication. On the other hand, in the northern and western parts of the region, there are areas where the number of inhabitants and functions in settlements decreases (Đerčan et al., 2017a). Previous regional policy ignored the development of a polycentric settlement system. The only way to avoid further concentration in spatial development is through some dispersion. As previous examples of good practice have shown, the resulting dispersion can have many positive effects on regional development (Kušar, 2013).

Conclusion

By applying the Law of the urban primary and calculating the index of urban primacy, this research has confirmed that urban primacy is not expressed in the Srem region. Sremska Mitrovica is the largest settlement in the Srem region, the administrative seat of the region, and the centre of educational and medical functions. However, the other settlements, primarily Ruma and Inđija, do not fall behind Sremska Mitrovica in population or number of functions. The proximity and relatively good connections with Belgrade and Novi Sad, which have a strong gravitational power, especially to the eastern part of the Srem region, should be considered. These results are in accord with contemporary development concepts, especially in EU countries where areas and regions should be considered and organized by principles that consider the temporal and spatial dynamic links based on the specific and active role of each settlement, not solely on the hierarchical relationship of dependency on the central city.

By analyzing the hierarchy of settlements in the network and calculating the importance of secondary activities and settlement centrality, it was confirmed that Sremska Mitrovica, Ruma, Inđija, Šid, Stara Pazova and Nova Pazova are the settlements that are at the top of the hierarchical ladder.

The analysis also confirms the flow of socio-geographic processes and structural changes in the settlement system, implying simultaneously the temporal and spatial dimensions. When considered as a whole, the Srem region's settlement system contains all forms of feedback effects and correlations of multiple relationships of interdependence.

The demographic, social and spatially functional relationships discussed in this study provide a framework for understanding a complex analysis, planning and directing system in a contemporary context and discussing system-wide development processes in a given space and time. The results represent a solid scientific framework that can be applied to all relevant state institutions and organizations at the local, regional, and national scales, as well as for adopting operational plans for developing strategies in a settlement system and network. Multiple connections between the settlements of all hierarchical levels provide opportunities for more effective use of the existing resources of the Srem region, both in the urban communities and rural areas. This would improve the living conditions for all and reduce the depopulation trends. Similar studies using the same methodology can be applied elsewhere.

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Mortality Risk during Heatwaves: an Evaluation of Effects by Heatwaves Characteristics in Serbia

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KEYWORDS

- heat
- heat-health risk
- DLNM
- mortality
- Serbia

ABSTRACT

Extreme temperatures and heatwaves are recognized as one of the deadliest weather-related hazards. The first of its kind in the Balkans region, this study explores the effects of heatwave timing, duration, and intensity on mortality in Serbia. Using daily all-cause mortality data and mean temperature, a distributed lag non-linear model (DLNM) evaluates the heat-mortality response for each city during the warm season (May to September) for the period 2000-2015 for Belgrade, Novi Sad and Niš. Results indicate that longer heatwaves generally have a greater impact on mortality, regardless of when they occur in the warm season. When comparing warm and extremely warm days, relative risk (RR) increases with intensity, and RRs are higher for earlier season heatwaves Extremely warm, early season heatwaves show significantly high RR in all three cities, respectively, for Belgrade 1.37 (95% CI: 125, 1.5), for Novi Sad 1.27 (95% CI: 1.08, 1.5), and for Niš 1.47 (95% CI: 1.15, 1.87). The findings draw attention to how different heat events modify the health response in Serbia. Stakeholders who work to improve resilience to heat hazards may consider the development of an early warning heat system and a strengthening of local and regional outreach efforts designed to reduce adverse health outcomes.

Introduction

The World Health Organization (WHO) recognizes climate change as one of the greatest challenges of the 21st century and an important public health threat (WHO, 2023; van Daalen et al., 2024). Adverse health outcomes such as mortality and hospitalization are impacted by a variety of complex environmental factors, but thermal exposure is one of the most pronounced (Ballester et al., 2023; IPCC, 2022). Due to anthropogenic climate change, heatwaves have increased in frequency, intensity, and duration (Russo et al., 2014; Mitchell et al., 2019; Perkins-Kirkpatrick & Lewis, 2020; IPCC, 2022). Since the begining of 21st century, Europe has experienced several intense heatwaves, including in 2003 when over 70,000 heat-related deaths occurred (Watts et al., 2018). Studies also report an increase in mortality during the 2015 and 2019 summers (Vicedo-Cabrera et al., 2016; Urban et al., 2017; Arsenović et al., 2019; Mitchell et al., 2019; Blazejczyk et al., 2022). Characterized by record-breaking high temperatures (May – September), Bal-

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lester et al. (2023) estimated more than 60,000 heat-related deaths in Europe during the 2022 warm season.

When analyzing the impact on human health, various heatwaves defintions exist, characterized by duration, intensity, and thermal or atmospheric metric (Anderson & Bell, 2011; D'Ippoliti et al., 2010; Xu et al., 2016; Royé et al., 2020; Awasthi et al., 2022; Yadav et al., 2023). Some studies consider the role of seasonality and heatwave timing (Andreson & Bell, 2010; Sheridan & Lin, 2014; Sun et al., 2020; Alari et al., 2023). Both heatwave length and duration influence health response. A systematic review showed that in heat-related mortality heatwave intensity played a more significant role compared to heatwave duration (Xu et al., 2018; Xu et al., 2016). Results for nine European cities indicate that mortality increases during the heatwaves ranged from 7.6% to 33.6%, depending on geographic location, and this increase was up to three times more pronounced during periods of long lasting and high intensity heatwaves (D'Ippoliti et al., 2010). In Brazil, Silveira et al. (2023) found heatwave intensity to be a greater risk factor than duration.

Evaluating 43 U.S. cities, elevated mortality risk was found for more intense or longer-lasting heatwaves, and mortality risk was higher for early-season events (Anderson & Bell, 2011). In a study of the four largest cities in Spain (1990-2015), Royé et al. (2020) showed a non-linear, J-shaped curve between heateave intensity and mortality. Various studies indicate an acute relationship between human response and heat, lagging heatwave impacts 1-3 days following a heat event (Donaldson et al., 2003; Arbuthnott & Hajat, 2017; Royé et al., 2020). Alarie et al. (2023) found a relationship between seasonal timing and cardiovascular and respiratory mortality in France. While the results indicate a larger influence of later-seasonal events, the results were heavily influenced by the 2003 event. By removing the outlier, early summer heat events showed a greater impact on mortality.

Overall, a lack of studies exist evaluating heatwave characteristics and the relationship to human health outcomes in Central and Eastern Europe, including Serbia (Zaninović & Matzarakis, 2014; Výberči et al., 2015; Petkova et al., 2021; Winklmayr et al., 2022; Ascione et al., 2022; Arsenović et al. 2019; Arsenović et al., 2023; Antonescu et al., 2023). Until now, limited number of studies examined heatwave and high temperature impact on health outcomes in Serbia (Bogdanović et al., 2013; Stanojević et al., 2014; Bijelović et al., 2017; Savić et al., 2018; Arsenović et al., 2019; Arsenović et al., 2022; Savić et al., 2023). Using the three largest cities in Serbia (Belgrade, Novi Sad, and Niš), this research is the first to comprehensively evaluate how mortality risk changes based on different heatwave characteristics in Serbia. By considering how heatwave duration, intensity, and seasonal timing influences mortality outcomes, the results of this research may also be used to better inform stakeholders who aim to reduce adverse health outcomes and improve resilience to future heat events in Serbia.

Data and Methods

Study Area

The study region includes three administrative units in Serbia: the Belgrade area, the Novi Sad City and the Niš City (Figure 1). Belgrade, Novi Sad and Niš are the most populated cities in country, and in 2015, these locations represented 32.0% of Serbia's total population. Total population in Belgrade exceeds 1.5 million people, and the other two cities (Novi Sad and Niš) range between 250,000 to 350,000 residents (Table 1).

Table 1. Descriptive data about administrative organization and total number of urban and rural population in censuses 2002 and 2011, and estimation for 2015, in three cities, Serbia

Area	Administrative organization[A]	Area[A] (in km^2)	2002[B]		2011[B]		2015[C]	
			Urban	Rural	Urban	Rural	Urban	Rural
Belgrade area	17 municipalities	3226	1281801	294323	1344844	314596	1369401	310494
City of Novi Sad	2 municipalities	699	235165	64129	277522	64103	286546	64384
City of Niš	5 municipalities	596	178161	72357	187544	72693	186222	71661

Source: Republički zavod za statistiku, 2003; Republički zavod za statistiku, 2012a; Republički zavod za statistiku, 2012b; Online database[D]

[A] *According to the data in 2011*

[B] *Census data*

[C] *Estimation by Statistical Office of the Republic of Serbia*

[D] *https://data.stat.gov.rs/?caller=SDDB*

Figure 1. Map of study area with marked location of Belgrade, Novi Sad and Niš

Mortality and Meteorological Data

All-cause daily mortality data (ICD-10, code A00-U85) were provided by the Statistical Office of the Republic of Serbia (SORS) from 2000 to 2015. Researchers compiled the data for the three largest areas (cities) in Serbia: Belgrade, Novi Sad and Niš. Temperature data (°C) were provided by the Official Meteorological Yearbooks, available on the Republic Hydrometeorological Service of Serbia (RHMSS) website (https://www.hidmet.gov.rs). The data includes air temperature observations at 0700 (morning), 1400 (midday), and 2100 (evening) time periods. Aggregating these data, average daily air temperatures were calculated for each of the three cities for the warm season (May – September) for the period 2000–2015.

While various heatwave definitions exist (Robinson, 2001; McCarthy et al., 2019; Faye et al., 2021; Ventura et al., 2023), the RHMSS delineates two heatwave thresholds (RHMZS 2023). *Warm days* are defined as days where the daily air temperature exceeds the 91st annual percentile; *Extremely Warm days* are based on the 98th percentile. Using daily air temperature data, percentiles were calculated for each city and used to define warm and extremely warm days over the 16-year period (Table 2). Since the metrics are based on local climatology, the heatwaves incorporate a spatial variability rather than a nation-wide absolute threshold. A heatwave metrics in Belgrade is not the same as Novi Sad.

To compare the impact of heatwaves on mortality, heatwaves (HW) are subdivided to account for duration (short and long) and seasonal (early and late) events taking place from May - September. Short heatwaves (HW_{Short}) were periods where the daily mean air temperature exceeded the 91st or 98th percentile for one or two days. Long events (HW_{Long}) include days when the temperature threshold exceeded these thresholds but persisted for more than 2 days. This study included a 5-month warm season to account for early and late season heat events that may occur outside of the traditional meteorological summer. Early summer events (HW_{early}) occurred between 1 May - 14 July while 15 July to 30 September represented late summer (HW_{Late}). Similar methodological approaches have been used in the past (Allen & Sheridan, 2018).

Table 2. Percentile thresholds used to define *Warm* and *Extremely Warm* Heatwave (HW) days (°C)

Area	91^{st}	98^{th}
Belgrade	25.4	29.2
Nis	24.5	28.2
Novi Sad	23.8	27.2

Statistical analysis

To assess the heat-health effects, researchers employed a distributed lag non-linear model (DLNM). Common in public health research (Gasparrini et al., 2011; Armstrong, 2006; Gasparrini & Armstrong, 2011; Silveira et al., 2023; Boudreault et al., 2024), the DLNM is available as a package in R and evaluates both the non-linear exposure-response and delayed effects with time.

The model uses a quasi-Poisson regression to model the daily counts of deaths as a function of
(Equation 1):

$HW = 1$ *if heatwave exists*

$Y_{subset} \sim quasi\ poisson(HW)$

$Log(HW) = \alpha + S\,(Time_{Year},\ var.df = 4) + S\,(Time_{JulianDay};\ 7\times15) + DOW$

Where *HW* is a binary representation of a heatwave day, Y_{subset} is the observed daily mortality, α is the intercept, $Time_{Year}$ represents the long-term trend, $Time_{JulianDay}$ represents seasonal trends, and *DOW* was a dummy variable representing day of week (Equation 1). Confounders accounted for the seasonal variability in daily mortality, year, and day of week. *S* is the natural cubic spline function whereby *var.df* is the degree of freedom (df) for each variable. Four degrees of freedom were assigned to the long-term trend line while 7 df/year were used to identify the seasonality curve. These metrics are consistent with prior work (Allen & Sheridan, 2018).

The study used a 7-day lag model to account for the acute response of heat. Various lags were considered (3-, 5-, 7-, 10-, 14-day), yet the differences in results were generally minimal. Mean, maximum, and minimum relative risk were assessed. Statistical significance was based upon the 95% confidence intervals whereby if the minimum relative risk value was greater than 1.0, significance was assigned to the value. DLNM computed relative risk values for each category, and each HW category was independently analyzed: HW_{Early}, HW_{Late}, HW_{Shor}t, HW_{Long}, and all HW days. For example, all HW_{Early} days were compared against all non-HW days. The model used quasi-Poisson regression to determine the daily counts of deaths as a function of HW. Relative risk (RR) values were computed based upon DLNM iterations for each of the classifications.

Results

Summary statistics show differential HW characteristics across each of the three cities (Table 3). On average, at least 33 heatwave days occurred in each city, with the largest number of warm days (537) occurring in Niš. Across the 16-years, each city experienced averaged at least 7 extremely warm days per year. With 51 total, Belgrade recorded the most extremely warm days. Across the three cities, heatwaves varied in terms of intensity, duration, and seasonal timing. Anaysis in this study shows that longer and more intense HW were more frequent in Belgrade and Novi Sad.

Given the city's geographic location, it is no surprise the highest T_{avg} took place in Belgrade. Niš is situated in the southeast mountainous region while Novi Sad is further north and not as sprawling, thus perhaps not as influenced by the urban heat island as Belgrade. On average, locations experienced approximately 35 warm days per year- and 8 extremely warm days per year.

Average mortality was higher during extremely warm days when compared with warm days. For example, four additional people died on average in Belgrade during higher-threshold heatwave events. Statistical relationships are limited by the population size, but this result of warmer events is supported by previous research (Alarie et al., 2023; Anderson & Bell, 2011; Allen & Sheridan, 2018).

Table 4 shows the relative risk (RR) between different HW characteristics. All three cities showed significant, elevated risk associated with HW_{early}, regardless of the intensity metric. The highest RR was found in Niš and associated with early season, extremely warm days (RR: 1.47; 95% CI: 1.15, 1.87). While elevated risk was still found for late-season events, only Belgrade and Novi Sad showed significant results. Generally, mortality risk was higher under extremely warm days when compared to warm days or non-heatwave days. Comparing all heatwave iterations, higher RR was found for Belgrade and Novi Sad; both cit-

Table 3. HW characteristics, with average daily temperature (T_{avg}, in °C), average daily mortality (M_{avg}), and total heatwave days for Belgrade, Novi Sad, and Niš, 2000 - 2015.

HW timing/duration	HW intensity	Belgrade			Novi Sad			Niš		
		T_{avg}	M_{avg}	Total HW Days	T_{avg}	M_{avg}	Total Days	T_{avg}	M_{avg}	Total Days
HW_{early}	Warm	27.60	48	234	26.04	11	233	26.71	6	209
	Extremely Warm	30.20	52	45	28.25	12	56	29.15	6	45
HW_{late}	Warm	28.03	46	297	26.02	10	300	26.73	5	328
	Extremely Warm	30.50	51	83	28.32	12	70	29.38	6	73
HW_{short}	Warm	27.04	44	265	25.34	10	265	25.90	5	245
	Extremely Warm	30.18	50	91	28.07	11	87	29.13	6	84
HW_{long}	Warm	28.61	49	268	26.69	11	269	27.40	5	294
	Extremely Warm	30.94	54	37	28.77	14	39	29.70	6	34
All	Warm	27.84	47	531	26.03	11	533	26.72	5	537
	Extremely Warm	30.40	51	128	28.29	12	126	29.29	6	118

Table 4. Effects of heatwaves on mortality for different heatwave characteristics (mean RR using a 7-day lag) in Belgrade, Novi Sad and Niš, 2000-2015.

Timing/Duration	Intensity	Belgrade	Novi Sad	Niš
HW_{early}	Warm	1.21 (1.16, 1.26)	1.21 (1.12, 1.31)	1.19 (1.06, 1.34)
	Extremely Warm	1.37 (1.25, 1.5)	1.27 (1.08, 1.5)	1.47 (1.15, 1.87)
HW_{late}	Warm	1.16 (1.11, 1.2)	1.15 (1.07, 1.24)	1.01 (0.91, 1.11)
	Extremely Warm	1.27 (1.19, 1.37)	1.33 (1.15, 1.55)	1.01 (0.81, 1.25)
HW_{short}	Warm	1.02 (0.96, 1.08)	0.94 (0.83, 1.06)	1.07 (0.89, 1.29)
	Extremely Warm	1.19 (1.08, 1.31)	1.03 (0.84, 1.26)	1.04 (0.8, 1.36)
HW_{long}	Warm	1.22 (1.18, 1.27)	1.30 (1.21, 1.4)	1.09 (0.98, 1.21)
	Extremely Warm	1.43 (1.29, 1.59)	1.57 (1.29, 1.93)	1.31 (0.97, 1.76)
All	Warm	1.18 (1.14, 1.22)	1.18 (1.11, 1.25)	1.08 (0.99, 1.17)
	Extremely Warm	1.31 (1.24, 1.39)	1.31 (1.16, 1.47)	1.17(0.99, 1.39)

ies are located more north and likely impacted by population size available for robust statistical analysis. Different methodological approaches are needed to explore non-urban heat-health relationships (Allen et al. 2024).

When exploring the role of HW duration, HW_{long} showed greater RR compared to HW_{short}. Results in Belgrade and Novi Sad were significant, suggesting longer-lasting HW had a greater impact on mortality risk. A greater RR associated with long-lasting, extremely warm days was found compared to warm days or non-heatwave days. When comparing all HW days, extremely warm days showed a higher risk than the lower threshold of warm days.

Discussion

This is the first study to explore how HW duration, intensity, and seasonal timing modifies the mortality relationship in Serbia. Results indicate a few important findings. First, long-lasting heatwaves typically have a greater impact on mortality, regardless of when they occur in the warm season. Longer-lasting heatwaves show elevated RRs when compared to both shorter and non-heatwave days. HW duration has important role in mortality risk (Borrell et al., 2006; Sheridan & Lin, 2014; Steul et al., 2018; Allen & Sheridan, 2018), and according to some research, duration of HW is better signal for excess mortality than temperature alone (Steul et al., 2018). Variations do exist, however, as Guo et al. (2017) showed intensity to have a more significant role that duration.

This research found early season HW to have a greater impact on mortality that later-season HW. Studies show heatwaves occurring earlier in the warm season result in greater mortality risk (Díaz et al., 2002; Anderson & Bell, 2011; Sheridan & Linn, 2014; Smith et al., 2014; Xu et al., 2018). Various factors including seasonal acclimation play a role in such results. Throughout the warm season, heat-related risk may decrease because of seasonal acclimation or mortality harvesting, although prolonged heat days still had a greater influence on mortality (IPCC, 2022; Allen & Sheridan, 2018). Sun et al. (2020) found that mortality risk during the first heatwave of the season increased by 16.3%, while during the each subsequent heatwave, risk decreased. While other studies indicate mixed results (Alarie et al., 2023), results of this study indicate higher mortality risk during early-season HW.

Finally, this study identified association between HW intensity and mortality, suggesting that population vulnerability is particularly pronounced during the extremely warm days. Intensity modified the temperature-mortality relationship with extremely warm days generally showing higher RR when compared to warm HW days. In Spain, Roye et al. (2020) found a strong relationship between mortality and the effects of heatwave intensity, with particularly high impact on the same day and 1-3 days following heatwave. Acute mortality response is well-documented within heat-health literature (Meade et al., 2020; Liu et al., 2022), and short-term mortality harvesting may explain some of the results.

While variability exists across the 3 Serbian cities, the results are generally consistent in that longer-lasting, earlier occurring, and more extreme heatwave show the greatest mortality response. Heatwave characteristics matter in the context of heat-health response and how communities may prepare for future heatwaves. As heatwaves become more frequent and extreme (Perkins-Kirkpatrick & Lewis, 2020; IPCC, 2022), how communities prepare for 21st century heatwaves must consider changes in HW characteristics. A heatwave in 2024 is not the same as a heatwave in 2003, nor are Belgrade heatwaves the same as those in Novi Sad. Geography matters. Population demographics vary. Community networks designed to reduce heat-related mortality differ across scales. The strengthening of local and national multi-sectoral partnerships (public health, emergency response, weather forecasting, governance and policy) is needed to reduce the heat-health burden. Improved heat communication, policies designed to protect human health, the creation of new and protection of old green space, and various other strategies are noted elsewhere (Stanojević et al., 2014; Bijelović et al., 2017; Tong & Ebi, 2019; Muccione et al., 2024; Turner et al., 2022; Keith & Meerow, 2022).

Regional variations in RR were founded as important issue, since results shows a higher mortality risk in northern part of country. These differences might result from several factors, including different levels of exposure, demographic characteristics, or geographical, meteorological, or pollution factors (Anderson & Bell 2011). Physiological and behavioural adaptations of the local population also play a role in heat vulnerability (McGeehin & Mirabelli, 2001; Anderson & Bell, 2011; Sun et al., 2020). Belgrade and Novi Sad are more urbanized and effects of the urban heat island may modify risk. Cleland et al. (2023) showed that high urban heat island intensity areas account for 35% of the total heat-related cardiovascular burden, while low urban heat island intensity account for 4%. While urban communtiies cope with thermal comfort (Yin et al., 2023), it is important to note that adverse heat-related health outcomes are not merely an urban phenomenon. Rural residents are often more at risk during heat events than those in urban areas even after considering the urban heat island effect, built environmental factors, and population density (Fechter-Leggett et al., 2016; Jagai et al., 2017; Li et al., 2017). Mitigating the impact of heat on human health requires an all-hands-on approach to reduce vulnerability, particularly in the face of anthropogenic climate change which has already modified the duration, intensity, and spatial extent of heatwaves.

Limitations and Future Research

This study includes limitations and outlines potential areas for future research. Given the avaibility of data, the study only assesses heatwaves over a 16-year period, up through 2015. Thus, more recent heat events, which were characterized as more severe and intense (Ballester et al., 2023), were not included. Temperature data was based on a single location in each city, thus the results do not consider the small-scale variations in the urban heat island that are necessary to target intervention strategies. Other studies have showed temperatures within a community may differ substantially based on where one resides (Reid et al., 2009; Kim et al., 2017; Savić et al., 2018; Milošević et al., 2022). The results of this study are based on three cities in Serbia. In part, these locations were selected due to their large populations; the methodological approaches employed in this research rely on large population sizes for statistical testing. Heat is not merely an urban issue, however, and continued research as to how communiites, populations, and indiviuduals prepare, adapt, and respond to current and future heatwaves is needed, particularly in the face of anthropogenic climate change (Brown et al., 2020; Guardaro et al., 2022). Diverse approaches are needed to better contextualize heat impacts beyond the urban core (Tuholske et al., 2021; Mashhoodi & Kasraian, 2024). This is particularly important as communities around the world provide healthcare services to rural communities in spite of growing, urbanizing cores. Future research may build upon these results and assess the relationship with hospital admission data or evalaute heat perceptions within the community. Fewer studies explore morbidity data, in part due to the avaiability and ease of obtaining of such data.

Conclusion

This study shows that heatwaves increase the mortality risk, and heatwave characteristics, such as duration, seasonal timing, and intensity play important role in heat-related mortality. On average, early season, longer lasting, and more extreme heatwaves had a greater impact on mortality. Findings in this study could be useful and contribute to the development of a heat-watch warning system and improved communication as to the health hazard of heat may be future outcomes of this research, interlacing the government and non-government sectors who are interested in reducing heat-health disparities across Serbia.

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Analyzing Precipitation Trends in the Cholistan Desert, Pakistan: A Statistical and GIS-Based Study

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KEYWORDS

- desert precipitation variability
- Mann–Kendall trend test
- Sen Slope Estimator
- arid environment
- Cholistan Desert

ABSTRACT

Climate change is driving significant shifts in temperature and precipitation patterns globally, with far-reaching socio-economic and environmental impacts, especially in arid regions. This study examines precipitation variability and long-term trends from 1980 to 2020 in Pakistan's Cholistan Desert, a region where water scarcity poses critical challenges for local communities and ecosystems. Using data from five meteorological stations, we applied a combination of Geographic Information System (GIS) techniques and statistical analyses to assess both seasonal fluctuations and annual trends in precipitation. The results reveal notable spatial variability in precipitation trends across the Cholistan Desert. Positive trends, indicating increased precipitation over time, were observed in the northwestern areas, particularly at the Bhagla, Khanpur, and Fort Abbas stations. In contrast, significant negative trends were detected in the southwestern areas, represented by the DinGarh and MaujGarh stations, where precipitation has steadily decreased over the study period. These contrasting trends reveal the diverse impacts of climate change within the desert pointing out the areas that may face heightened water scarcity. The ongoing shifts in precipitation necessitate targeted water management and climate adaptation strategies to address the challenges posed by these shifting precipitation patterns. For areas with declining trends, strategies focused on rainwater harvesting and conservation will be critical. Regions experiencing increased precipitation may require infrastructure improvements to manage and store water more effectively.

Introduction

Climate change is a pressing global issue that is driving unprecedented shifts in temperature and precipitation patterns, with profound impacts on ecosystems, agriculture, water resources, and human livelihoods. Since the industrial era, global average temperatures have risen significantly, with the Intergovernmental Panel on Climate Change (IPCC) reporting an increase of approximately 1.1°C above pre-industrial levels, mainly due to human activities (IPCC, 2021). This warming trend is accompanied by more frequent and intense extreme weather events, including droughts, floods, and storms, which affect billions of people worldwide and strain resources, particularly in vulnerable regions (Amouzay et al., 2023). Precipitation patterns have also been notably altered, with

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regions such as Africa, South America, and parts of Asia experiencing significant increases or decreases in rainfall, leading to both flood risks and severe drought conditions (Nordhaus, 2018; Wagesho et al., 2013).

In South Asia, climate variability has become more pronounced over the past few decades, marked by erratic monsoon patterns, longer dry spells, and more intense rainfall events. The region is experiencing an increase in the frequency of extreme weather events, driven by changes in atmospheric circulation and the influence of warming oceans. Recent studies have shown that South Asia's annual monsoon season has become less predictable, with some areas receiving above-average precipitation and others suffering from prolonged droughts (Deng et al., 2019; Ghorbani et al., 2021). These shifts in precipitation not only affect agricultural productivity but also increase the risk of water scarcity in arid and semi-arid areas where communities rely on seasonal rains for survival (Singh & AchutaRao, 2019). South Asia is particularly vulnerable due to its dense population, high dependence on agriculture, and limited resources for climate adaptation (Balogun et al., 2023).

Pakistan, as part of this climate-sensitive region, faces severe consequences from these shifts in climate. The country has witnessed a rise in extreme weather events, including both intense monsoonal flooding and prolonged droughts (Abbas et al., 2023). In its Sixth Assessment Report, the IPCC highlighted that Pakistan is among the countries most vulnerable to climate impacts due to its diverse geography, reliance on agriculture, and already stressed water resources (IPCC, 2021). Research indicates that Pakistan's annual mean temperature has increased by approximately 0.6°C in recent decades, accompanied by variable rainfall patterns, resulting in increased aridity in some areas and unexpected flooding in others (Baig et al., 2022; Hussain & Abbas, 2019). The impact on water resources has been particularly acute in arid and semi-arid zones, where even small reductions in rainfall can lead to severe water shortages, affecting both human and ecological systems (Arshad et al., 2022; Xu et al., 2011).

The Cholistan Desert in South Punjab, Pakistan, is an arid region that relies heavily on seasonal precipitation for water resources. Covering an area of approximately 26,000 square kilometers, it forms part of the larger Thar Desert ecosystem and is characterized by extremely low and erratic rainfall. Local communities in this region depend on rainwater harvesting techniques, such as using natural depressions and artificial ponds, or *tobas*, to capture and store rainfall for use during dry periods. However, as precipitation patterns continue to shift, the desert's limited water resources are increasingly at risk. The region's population, livestock, and limited agricultural activities are highly vulnerable to the impacts of climate change, as changes in precipitation can exacerbate already challenging conditions (Rahman & Dawood, 2017; Dawood et al., 2018).

Despite the pressing need to understand precipitation trends in the Cholistan Desert, few studies have focused specifically on this region. Research on climate variability in Pakistan has generally concentrated on major river basins and highland areas, such as the Indus Basin and northern mountains, where water resources play a vital role in national agriculture and hydropower. To address this gap, this study investigates long-term precipitation trends in the Cholistan Desert over a 40-year period (1980–2020), using data from five meteorological stations. By employing GIS techniques and statistical analyses – including the Mann-Kendall Trend (MKT) test and Theil-Sen's Slope (TSS) estimator – this study aims to detect seasonal and annual precipitation trends across different parts of the desert. Understanding these trends is crucial for designing effective water resource management strategies and informing policy decisions aimed at increasing the resilience of local communities to climate variability. The findings from this study contribute insights for managing water resources in arid regions and enhance our understanding of climate variability within the Cholistan Desert. These results can assist policymakers, resource managers, and the scientific community in developing adaptive strategies to address water scarcity and ensure sustainable water availability in the face of changing climate patterns. By shedding light on the effects of climate change in one of Pakistan's most water-stressed regions, this research adds to the broader scientific literature on arid-zone climate dynamics and provides a foundation for future studies on climate adaptation in vulnerable ecosystems.

Characteristics of the Study Area

The Cholistan Desert, situated in Southern Punjab, Bahawalpur Pakistan (Figure 1), encompasses a vast expanse of arid landscape, extending between latitudes 27° 42´ to 29° 45´ North and longitudes 69° 52´ 30 to 75° 24´ East. Spanning an estimated 2.6 million hectares (26,000 km^2), it comprises two distinct regions: Greater Cholistan spans approximately 18,130 km^2, while Lesser Cholistan covers roughly 7,770 km^2 (Rafique & Hassan, 2015). The desert stretches an impressive 481 km in length and 193 km in width, dominating two-thirds of the Bahawalpur Division's landmass. A predominantly sandy terrain, the Cholistan Desert bears resemblance to Great India's Rajputana Desert, extending to the Indian border and lying southwest of the now-dry course of the Hakra River. Lesser Cholistan, on the other hand, extends from the termination point of the Sutlej River northeastward to the Hakra River (Akram et al., 2008; Hassan et al., 2021).

Beyond its geographical features, the Cholistan Desert exhibits unique human and natural aspects. Human settlements in the desert primarily consist of nomadic tribes, such as the Cholistanis (Malik et al., 2017), who rely on traditional livelihoods like animal husbandry, particularly camel rearing, to sustain their communities. These nomads traverse the desert landscape in search of water and pasture for their livestock, forming an integral part of the desert's cultural fabric (Haider et al., 2021). Rainwater is primarily collected in naturally low-lying areas or in man-made small pools, such as depressions locally known as *tobas* (Rasheed et al., 2018). In the arid landscape of the Cholistan Desert, rainfall serves as the sole source of drinking water for both humans and livestock. However, these water bodies, or *tobas*, typically retain water for only a maximum of four to five months before evaporating or being absorbed into the ground. Moreover, the salinity of underground water sources in the region tends to be high (Mumtaz, 1982). There are approximately 2000 small and large *tobas* scattered across the desert (Figure 1) (Rasheed et al., 2018). However, only around half of these *tobas*, roughly 1000, remain functional, while the others have become filled with silt and sand, reaching the land surface (Hussain & Abbas, 2019).

The size and storage capacity of each toba vary based on its dimensions, including length, width, and depth. Additionally, the amount of rainwater collected in these tobas fluctuates depending on the size of their catchment areas. On average, the water storage capacity of these tobas ranges between 500 and 1000 cubic meters (equivalent to 0.1 to 0.2 million gallons) (Malik et al., 2017). Therefore, the total water storage capacity of approximately 1000 tobas in the Cholistan Desert is estimated to be around 0.5 million cubic meters (or 80 million gallons) according to the Capital Development Authority (CDA) in 2022 (Imran et al., 2023).

According to the Köppen climate classification, the Cholistan Desert (Arid, Semi-arid) falls under the **"BWh"** climate type, which denotes a **hot desert climate**. Characterized by extremely low and erratic annual rainfall and high temperatures, especially during summer. Climate-wise, the Cholistan Desert experiences distinct

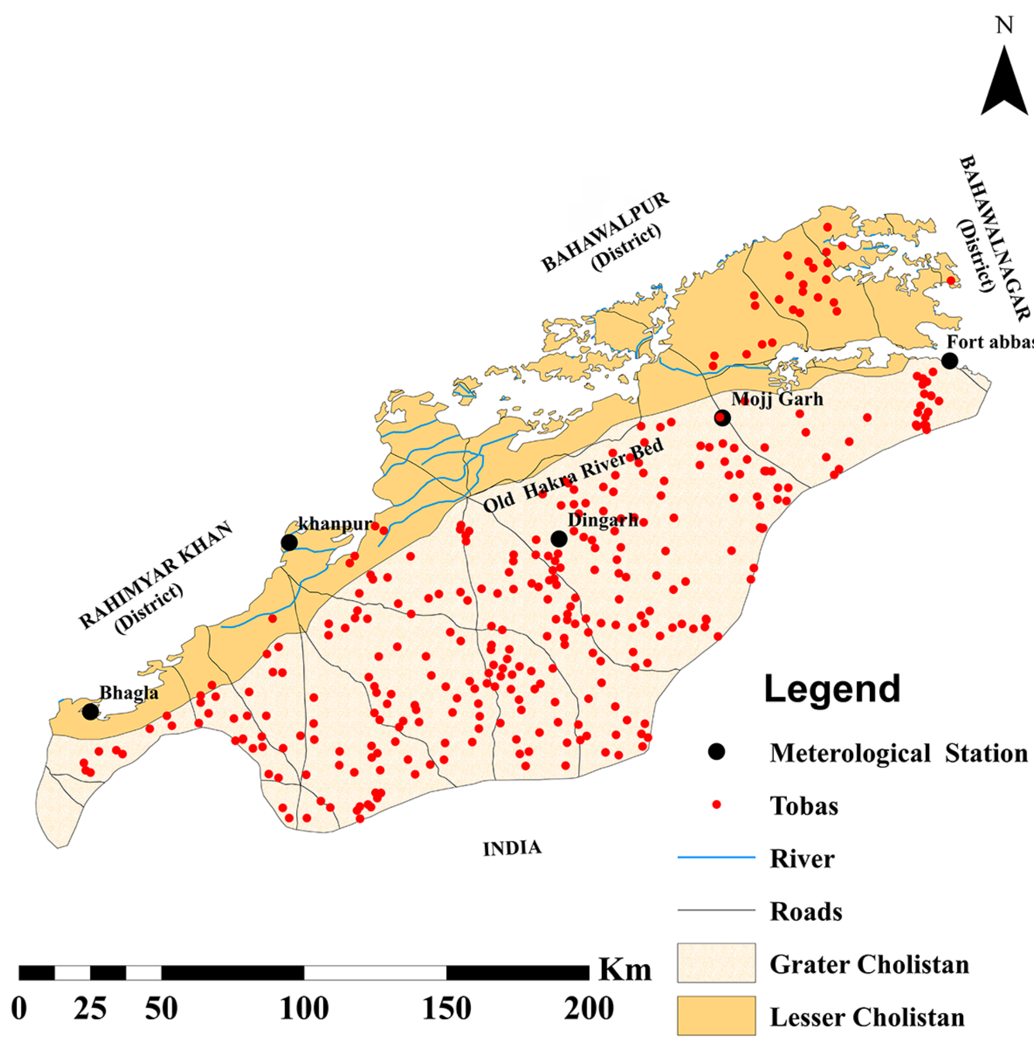

Figure 1. Location Map of the Cholistan Desert, South Punjab, Pakistan.
The shapefiles used in this map were downloaded from DIVAGIS.COM.

seasonal variations, with the summer monsoon season typically receiving more rainfall compared to the winter months. This wet season brings relief to the parched landscape, rejuvenating water sources and fostering temporary vegetation growth. Relative humidity levels fluctuate between 50% and 58%, influencing local climatic conditions and ecosystem dynamics (Haider et al., 2021). Understanding the climatic factors in the Cholistan Desert is vital for sustainable development and environmental conservation efforts in the region. As such, this study aims to delve into the complex interactions shaping the desert's hydrological patterns and their implications for water resource management and community livelihoods.

Material and Methods

Data Collection

This study utilized precipitation data spanning a 40-year period (1981–2020), obtained from the Pakistan Meteorological Department (PMD), including its main office in Lahore and regional office in Bahawalpur. Five meteorological stations were selected for data collection: Din Garh, Mauj Garh, Bhagla, Khanpur, and Fort Abbas (Figure 1). These stations were chosen based on key criteria to ensure comprehensive spatial coverage and representative data for the Cholistan Desert (Khan et al., 2020).

The selected stations provide broad spatial coverage across the desert, capturing precipitation variability influenced by local climatic conditions. Each station is positioned near areas with significant human and livestock populations, making them essential for monitoring precipitation trends and assessing water resource availability in this water-scarce region. The 40-year dataset enables a robust analysis of long-term precipitation trends, critical for understanding the impacts of climate change on water resources in the Cholistan Desert.

Data Processing and Analysis

Before conducting statistical analyses, the collected rainfall data underwent thorough preprocessing steps. This involved data cleaning to remove any inconsistencies or outliers, as well as data aggregation to calculate yearly mean rainfall values for each meteorological station.

Mann-Kendall Trend Test

The Mann-Kendall test, a robust non-parametric method, was applied to assess long-term trends in the rainfall time series data (Mann, 1945; Kendall, 1948). This widely used test is particularly suited for climatological and hydrological studies, as it does not rely on assumptions about the underlying distribution of the data. The MKT was applied to detect monotonic trends in precipitation, providing statistical outputs such as the Kendall (Tau) value, p-value (at 95% confidence), and z-statistics. A positive z-score indicates an increasing trend in the time series, while a negative z-score suggests a decreasing trend. Eq. (i) gives (Dawood & Shirazi, 2022) a simplified expression of the Mann Kendall Test.

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n-1} Sign(T_j-Ti) \tag{i}$$

$$Sign\left(t_j-t_i\right)=\begin{Bmatrix} 1 & T_i-T_i & >0 \\ 0 & T_j-T_i & =0 \\ -1 & T_j-T_i & <0 \end{Bmatrix} \tag{ii}$$

The variance can be expressed as follow:

$$Var(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{n} t_i(t_i-1)(2t_i+5)}{18} \tag{iii}$$

Initially, the precipitation data was calculated using Addinsoft XLSTAT 2014 and were analyzed using MKTM and SSE against null hypothesis (H_o) to a 95% significance level. The application of the MKT in climate studies has been well-documented in the literature. Previous research by Bannayan et al. (2020), Wang et al. (2020), and Yu et al. (2024) utilized the MKT to analyze precipitation trends, highlighting its effectiveness in detecting significant trends without requiring data to conform to specific distributions.

Theil Sen's Slope (TSS) Method

The Theil Sen's slope method, another robust technique, was utilized to further analyze the temporal changes in rainfall patterns (Sen, 1968; Yu et al., 2024). This method calculates the slope or direction of change in the time series data, providing insights into the magnitude and direction of trends. The TSS method is particularly valuable for its ability to handle outliers and non-linear data, making it well-suited for climate data analysis.

The magnitude of the temporal precipitation data's slope (T_i) is expressed (Dawood et al., 2024) as Eq (iv):

$$F(t)=Q_t+B \tag{iv}$$

- where Q represents the slope's magnitude, and B denotes a constant. However, the magnitude of the slope is calculated differently (v), to assess the slope for the temporal rainfall data:

$$Qi = \frac{X_i + X_j}{j - k} \quad \text{(v)}$$

- here, X_i and X_j represent pairs of precipitation data, respectively, with i=1,2,3,4,5,6, 7,...,N, and among time, denoted by j and k (where $j>k$). The median of the N values of Ti is calculated as Eq. (vi),

$$Q_{med} = \begin{cases} \frac{Q_{\left[\frac{N+1}{2}\right]}}{} & (if\ N\ is\ odd) \\ \frac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}}{2} & (If\ N\ is\ even) \end{cases} \quad \text{(vi)}$$

Consequently, if N is odd, the Theil Sen's slope (TSS) is computed as: $Q_{med} = T\ (N + 1)/2$. On the other hand, if N is even, TSS is calculated as: $Q_{med} = T(N+2) + T(N+2)/2$. Finally, Q_{med} is determined using the non-parametric model (MKT) to ascertain magnitude. In the context of Theil Sen's slope (TSS), Q_{med} represents the median of the calculated slopes (Qi). It serves as a measure of central tendency for the set of slopes derived from the pairwise differences in precipitation data over time. This median slope (Q_{med}) is then used to characterize the overall trend or direction of change in the rainfall data. If Qi is positive, it suggests an increasing trend in precipitation, whereas a negative Qi indicates a decreasing trend. Geographic Information System (GIS) technology was used for the spatial interpolation and finally expressing the slope of the detected trend as different maps.

Spatial Interpolation Technique GIS

All spatial maps of precipitation were prepared using the widely adopted Inverse Distance Weighted (IDW) technique in ARCGIS software. IDW is a common spatial interpolation method for creating rainfall maps and is straightforward to implement within a GIS environment (Nath et al., 2024). In GIS, spatial interpolation estimates unknown values at specific geographic locations based on known values from surrounding areas (Hu et al., 2019). Precipitation data were first computed in Microsoft Excel and then interpolated in ArcGIS, using various tones and shades to illustrate precipitation variability across the region. This color-coded approach effectively presents climate data and highlights geographic differences. Temporal rainfall data were interpolated into a raster format, enabling the analysis of geostatistical relationships among sites (Ozturk & Kilic, 2016). GIS was utilized to develop spatial databases and prepare result maps, ensuring accurate representation of precipitation trends.

Results

Analysis of the Annual Precipitation

The Mann-Kendall Trend test was employed to analyze the mean annual rainfall data collected from meteorological stations including Din Garh, Mauj Garh, Bhagla, Khanpur, and Fortabbas. For Din Garh station, encompassing the years 1980 to 2020, the mean annual rainfall was recorded at 2.196 mm, with a standard deviation (SD) of 1.582 mm. Notably, the year 1984 witnessed the highest annual rainfall of 5.477 mm, while the lowest was observed in 2009 at 0.196 mm (Table 1). Applying the MKT test to 40 years of rainfall data from the Din Garh station revealed a significant declining trend, with Kendall's Tau (τ) computed as -0.410 at a significance level of 0.05. The associated p-value (< 0.0001) indicates statistical significance, leading to the acceptance of the null hypothesis (Ho) and suggesting a significant negative trend. Additionally, Sen's slope for Din Garh was calculated as -0.088, further indicating a negative downward trend (Figure 2).

Similarly, at Mauj Garh station, the standard deviation was found to be 1.245 mm, with minimum, maximum, and mean rainfall values of 0.321 mm, 4.555 mm, and 1.900 mm, respectively. The calculated Kendall's tau (τ) of -0.4410 suggests a slight negative trend in rainfall data, with a p-value (< 0.0001) indicating statistical significance and the acceptance of Ho, implying a significant decreasing trend. Sen's slope for Mauj Garh was determined as -0.059, corroborating the negative downward trend observed. In contrast, Bhagla station recorded a comparatively lower annual mean rainfall of 0.9841 mm, with 2017 witnessing the highest recorded rainfall of 3.568 mm and 1983 experiencing the lowest at 0.186 mm. Interestingly, the MKT test results for Bhagla station revealed no discernible pattern in rainfall, with a calculated Kendall's tau of 0.5154 indicating a positive trend (p-value = 0.000637) at a significance level of 0.05. This rejection of the null hypothesis suggests a statistically significant positive trend in rainfall data.

The dataset from the Khanpur meteorological station exhibits considerable variability in precipitation levels, characterized by a mean of 3.1063 mm and a standard deviation of 3.6069 mm. Rainfall measurements range from a minimum recorded value of 0.114 mm to a maximum of 15.073 mm. For Khanpur station, the estimated Kendall's tau was found to be 0.4615, suggesting a slightly positive temporal rainfall trend with a corresponding p-value of 0.000144. Additionally, Sen's slope was calculated as

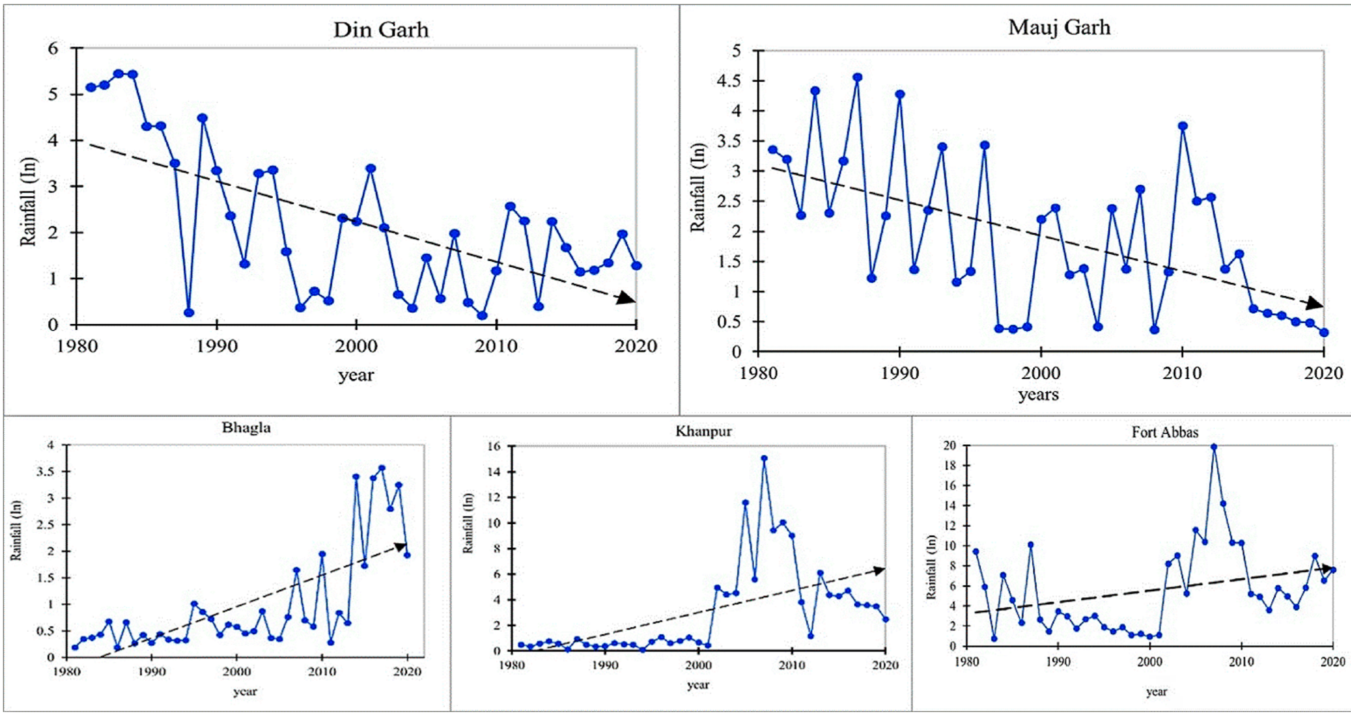

Figure 2. Mean annual rainfall trend (1980-2020) across the selected meteorological stations

0.1102 for the Khanpur station, indicating a positive slope and signaling a visible rising trend in rainfall over the past 40 years. This positive Sen's slope, reflecting an anticipated increase in rainfall intensity per unit of time, corroborates the findings of Kendall's Tau. Furthermore, employing the Mann-Kendall test, analysis of 40-year rainfall data from the Fort Abbas meteorological station reveals a notable and statistically significant increasing trend in rainfall. The dataset, characterized by a mean of 5.597 mm and a standard deviation of 4.202 mm, exhibits significant variability in rainfall amounts, ranging from 0.740 mm to 19.850 mm. The MKT results indicate a strong statistical trend of increasing rainfall, supported by a low p-value of 0.015 and a positive Kendall's tau of 0.196, indicating rejection of the null hypothesis (Table 1).

SSTD (Statistically Significant Trend Detected)

The application of Theil-Sen's slope (TSS) estimator to the annual time series data of rainfall revealed distinct trends across meteorological stations. Din Garh and Mauj Garh stations exhibited a negative slope magnitude (Figure 2), indicating a decreasing pattern in rainfall. Specifically, for Din Garh, the Sen's slope was calculated as Q = -0.088, illustrating a negative downward trend in precipitation (Figure 3). Similarly, Mauj Garh station displayed a negative SSTD (Statistically Significant Trend Detected) slope with Q = -0.059, indicating a downward trend in rainfall. Conversely, Bhagla, Khanpur, and Fort Abbas stations demonstrated positive slope magnitudes, signifying an increase in rainfall pattern. The Sen's slope for Bhagla station was Q = 0.0318, indicating a visible rising trend in rainfall over the past 40 years (Figure 2). Similarly, Khanpur station exhibited a positive slope with Q = 0.1102, suggesting a notable upward trend in rainfall intensity. These positive Sen's slopes align with Kendall's Tau's findings and provide further support for the observed trends.

Furthermore, Fort Abbas station displayed a positive Sen's slope of Q = 0.098, indicating an estimated increase in rainfall intensity over the four-decade period. This quantifies the size of the trend, corroborating the over-

Table 1. Results of Mann Kendall trend test on mean annual rainfall (1980-2020)

Met station	Mean rainfall (mm)	SD	Kendall's tau	P-value	alpha	Sen's slope	TSS remarks	MK test remarks	Model Interpretation
Din Garh	2.196	1.58	-0.410	0.0001	0.05	-0.088	Decreasing trend	Accept H_0	SSTD
Mauj Garh	1.900	1.24	-0.4410	0.0001	0.05	-0.059	Decreasing trend	Accept H_0	SSTD
Bhagla	0.9841	0.98	0.5154	0.0006	0.05	0.0318	Rising trend	Reject H_0	SSTD
Khanpur	3.1063	3.606	0.4615	0.0001	0.05	0.1102	Rising trend	Reject H_0	SSTD
Fort Abbas	5.597	4.202	0.196	0.015	0.05	0.098	Rising trend	Reject H_0	SSTD

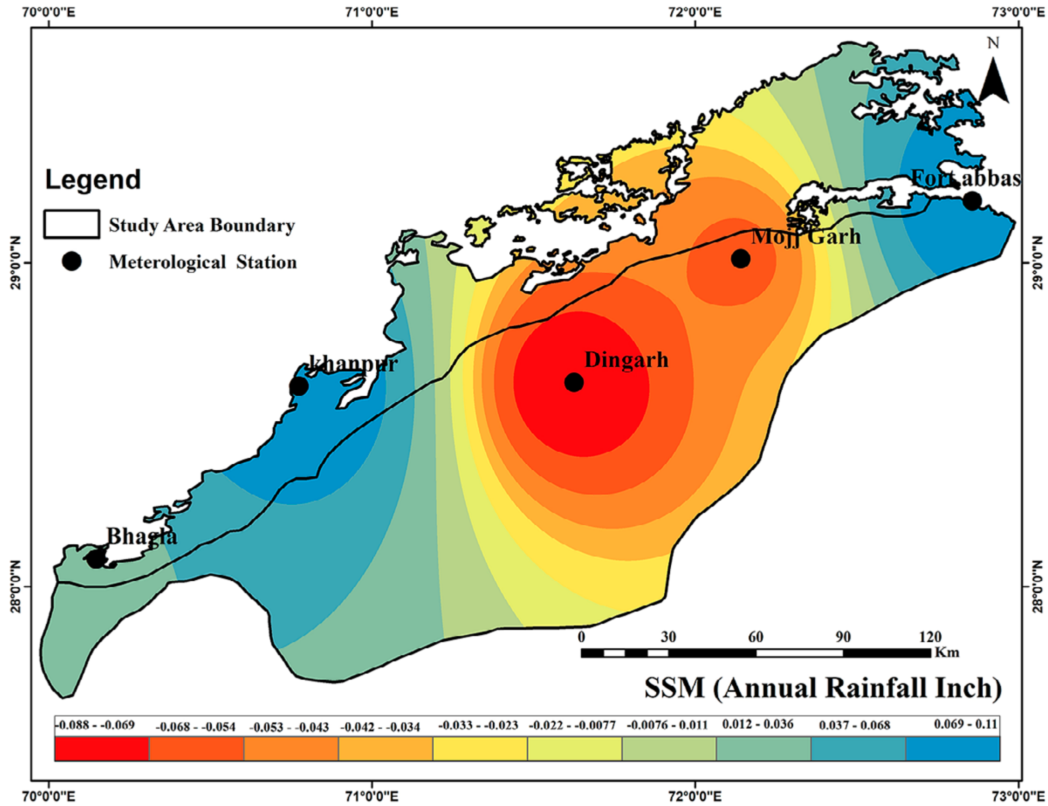

Figure 3. Cholistan Desert, slope magnitude for annual precipitation (Inches).

all findings. Moreover, the subsequent analysis highlights the relationship between precipitation patterns and slope magnitude at an annual scale. It indicates that changes in precipitation trends are associated with variations in slope magnitude, reflecting the dynamic nature of rainfall pattern over time (Table 1).

Analysis of Mean Monthly Precipitation

The analysis revealed significant variations in mean monthly precipitation across different meteorological stations (Figure 4). Bhagla meteorological station recorded the highest mean monthly precipitation of 11 mm in June, closely followed by 43 mm in July. Conversely, October and November witnessed the lowest monthly rainfall. Similarly, Din Garh station experienced substantial precipitation in January (5.5 mm) and July (43 mm) throughout the period 1980–2020. Conversely, Fort Abbas station reported the highest mean monthly rainfall of 54 mm, 58 mm, and 86 mm in July, August, and September, respectively, while January recorded 22 mm during the same period.

In contrast, Khanpur station registered the lowest mean monthly rainfall of 2.9 mm in June, 18 mm in July, and a minimum recorded rainfall of 0.7 mm in October, with December recording 5.1 mm betweenn1980-2020. Mauj Garh station data revealed 6.2 mm of rainfall in June, 45 mm in July, and 60 mm in September, with a significant drop to 1.3 mm in October, indicating considerable variation compared to other stations. Similarly, Bhagla station experienced the highest mean monthly rainfall of 60 mm in September and the lowest of 1.1 mm in October (1980–2020). Furthermore, both Mauj Garh and Fort Abbas stations recorded the lowest mean monthly rainfall of 3.5 mm in December and the highest of 72 mm in September. These findings underscore the presence of substantial variations in rainfall patterns among meteorological stations, attributed to factors such as geographical location, altitude, and temporal intervals.

Precipitation Seasonality in the Cholistan Desert

The Cholistan Desert exhibits marked seasonality in precipitation, with extended dry periods interrupted by infrequent rainfall, predominantly during the summer monsoon season (July to September). Over the study period from 1981 to 2020, this seasonal precipitation pattern has shown considerable variability, influencing the region's water availability and environmental conditions. Analysis of precipitation data using the Standardized Precipitation Index (SPI) at DinGarh and MaujGarh meteorological stations indicates a gradual increase in drought severity (Figure 5). Severe drought events were documented in the years 1981, 1988, 1997, 1999, 2002, 2007, 2018, and 2019, with prolonged dry spells particularly common during the early spring and summer months. These dry periods, exceeding several consecutive months in some years,

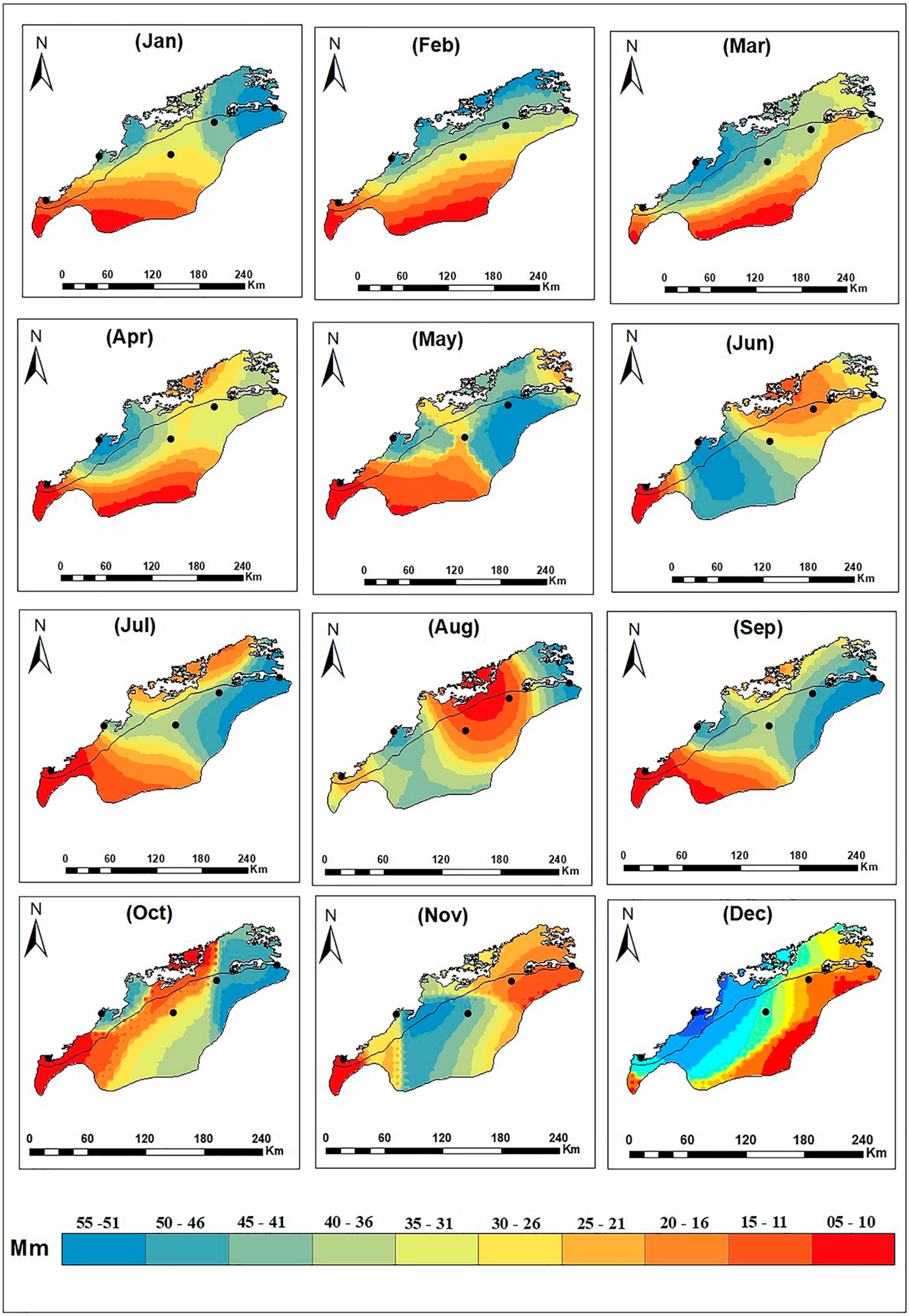

Figure 4. Spatial distribution of mean monthly rainfall (mm) for 12 months marked as Jan to Dec

reveal the challenges of sustaining adequate water levels in surface storage structures like *tobas* and *kunds*, which rely heavily on the limited monsoon rains.

Precipitation seasonality also varies across different parts of the Cholistan Desert, as illustrated by differences among the selected meteorological stations. DinGarh, generally dry year-round, experienced brief wet periods in years like 1982, 1993, and 2007, which temporarily improved water storage and vegetation conditions. Conversely, MaujGarh encountered more severe dry spells in years such as 1983, 1990, and 2020, with near-total precipitation deficits contributing to extreme aridity. Bhagla and Khanpur stations similarly recorded prolonged dry spells in 1981, 1983, 1986, 1994, and 2002, punctuated by occasional wet years like 2005 and 2007, which offered temporary relief.

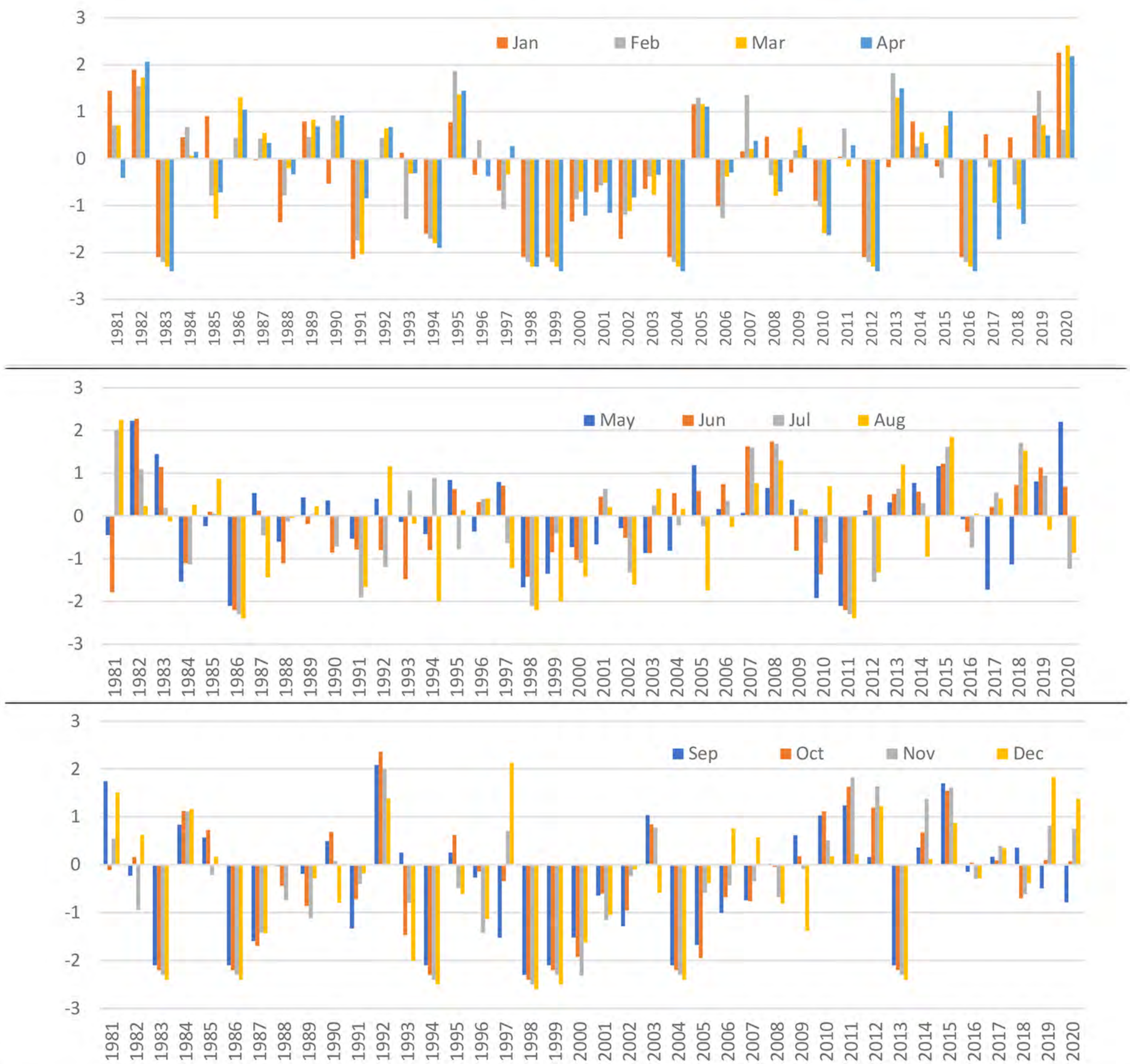

Figure 5(a). Seasonality and drought analysis of the Cholistan Desert using SPI. *Fort Abbas precipitation seasonality*

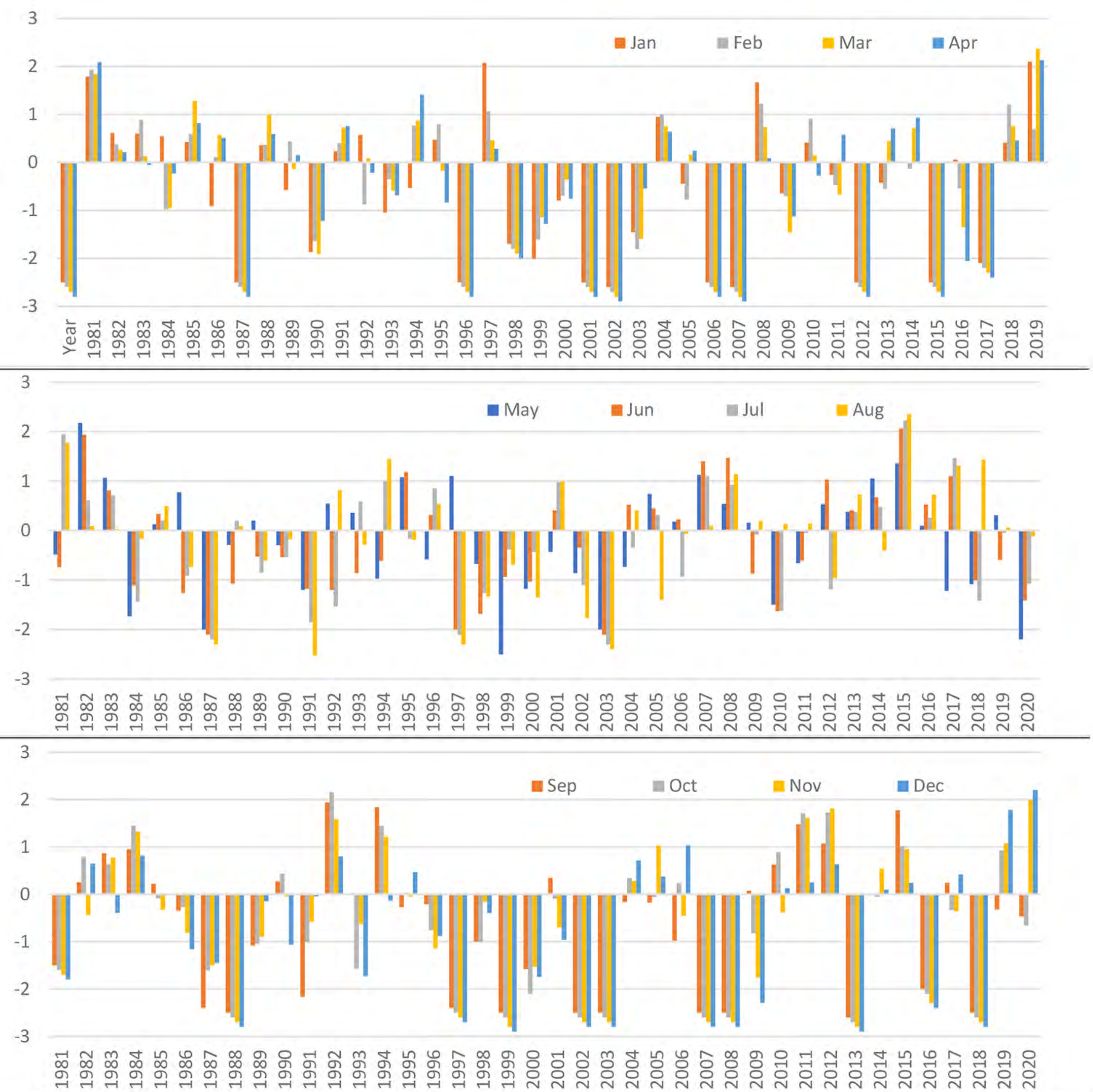

Figure 5(b). Seasonality and drought analysis of the Cholistan Desert using SPI. *DinGhar precipitation seasonality*

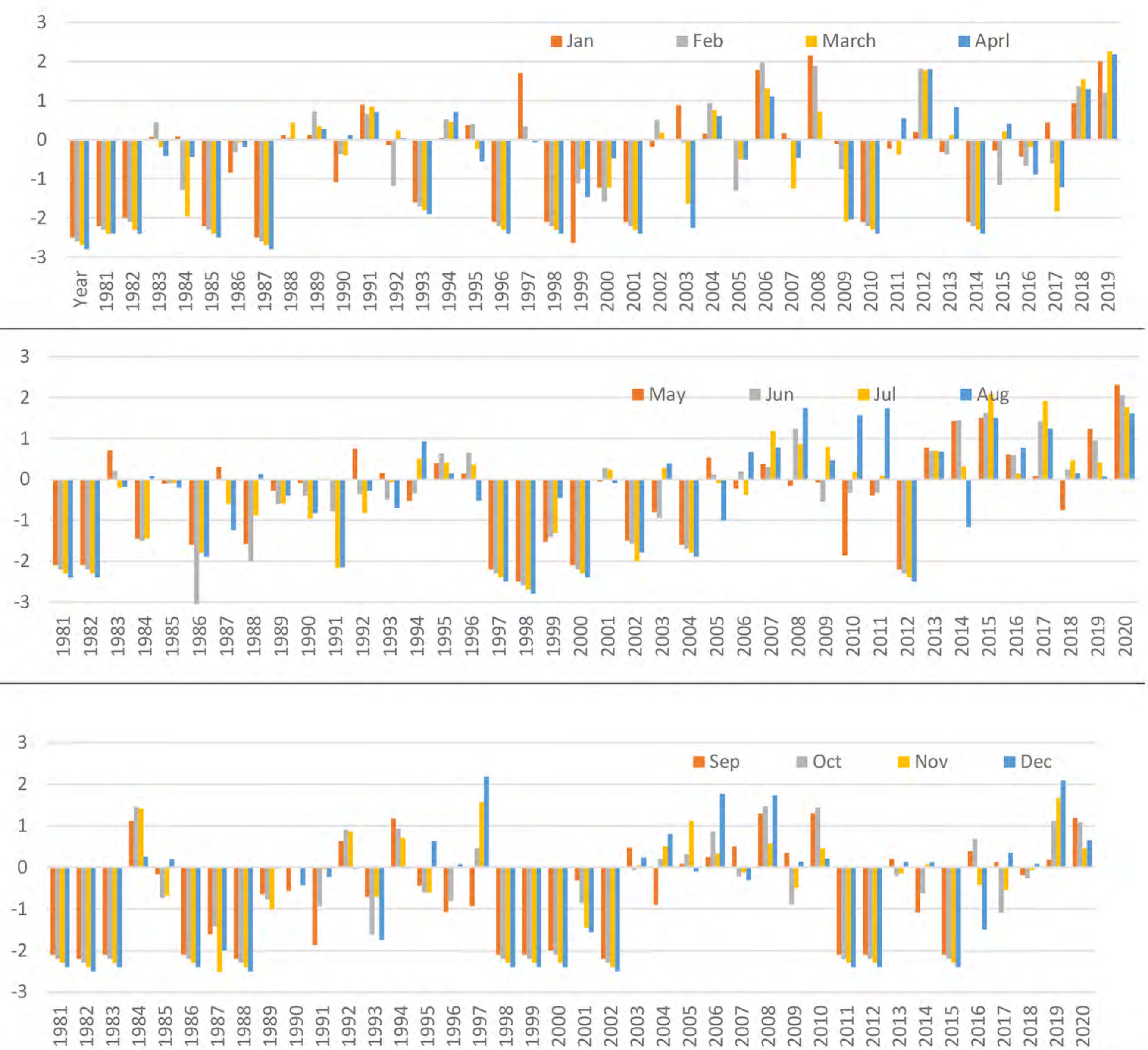

Figure 5(c). Seasonality and drought analysis of the Cholistan Desert using SPI. *Bhagla precipitation seasonality*

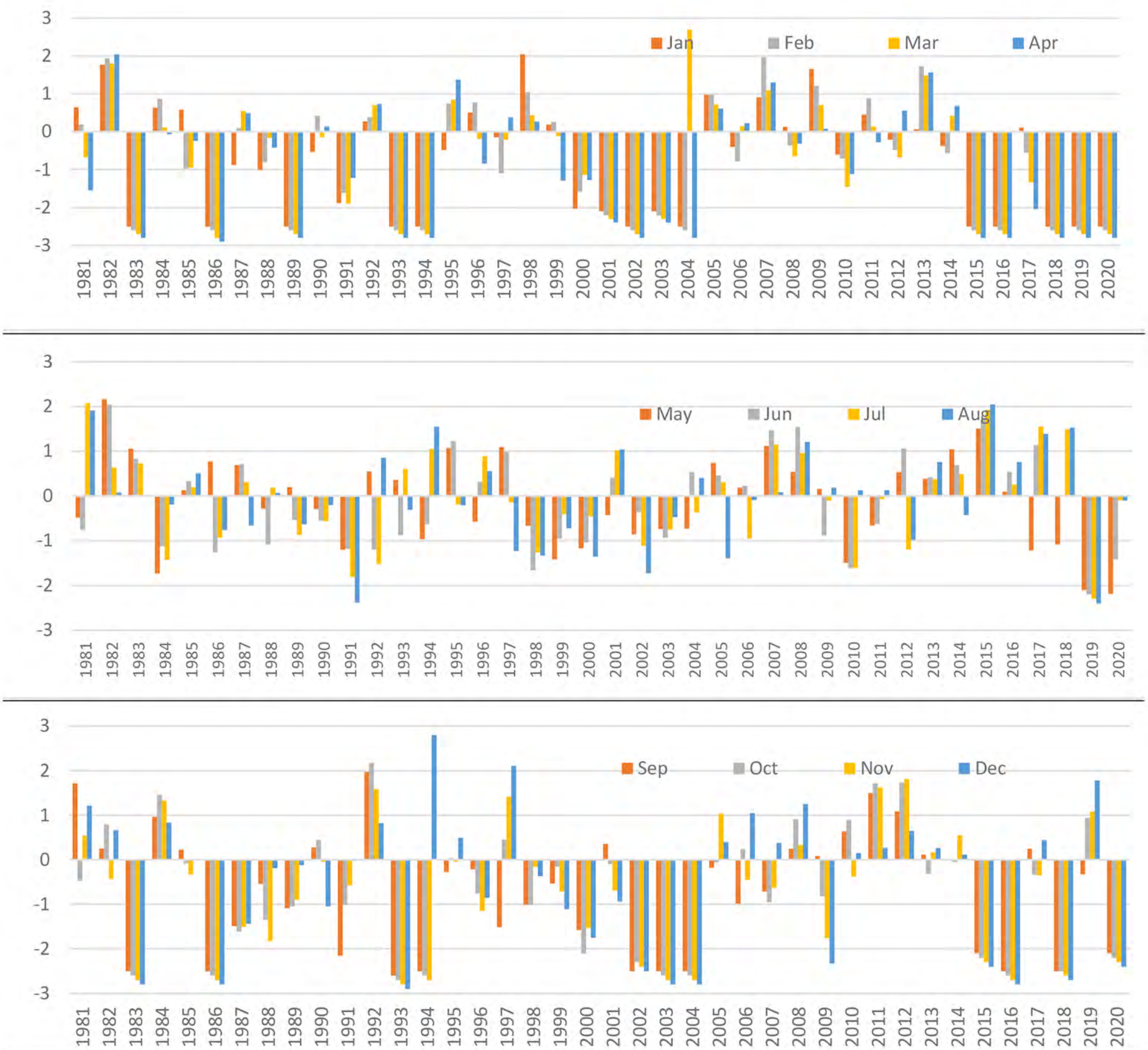

Figure 5(d). Seasonality and drought analysis of the Cholistan Desert using SPI. *MoujGarh precipitation seasonality*

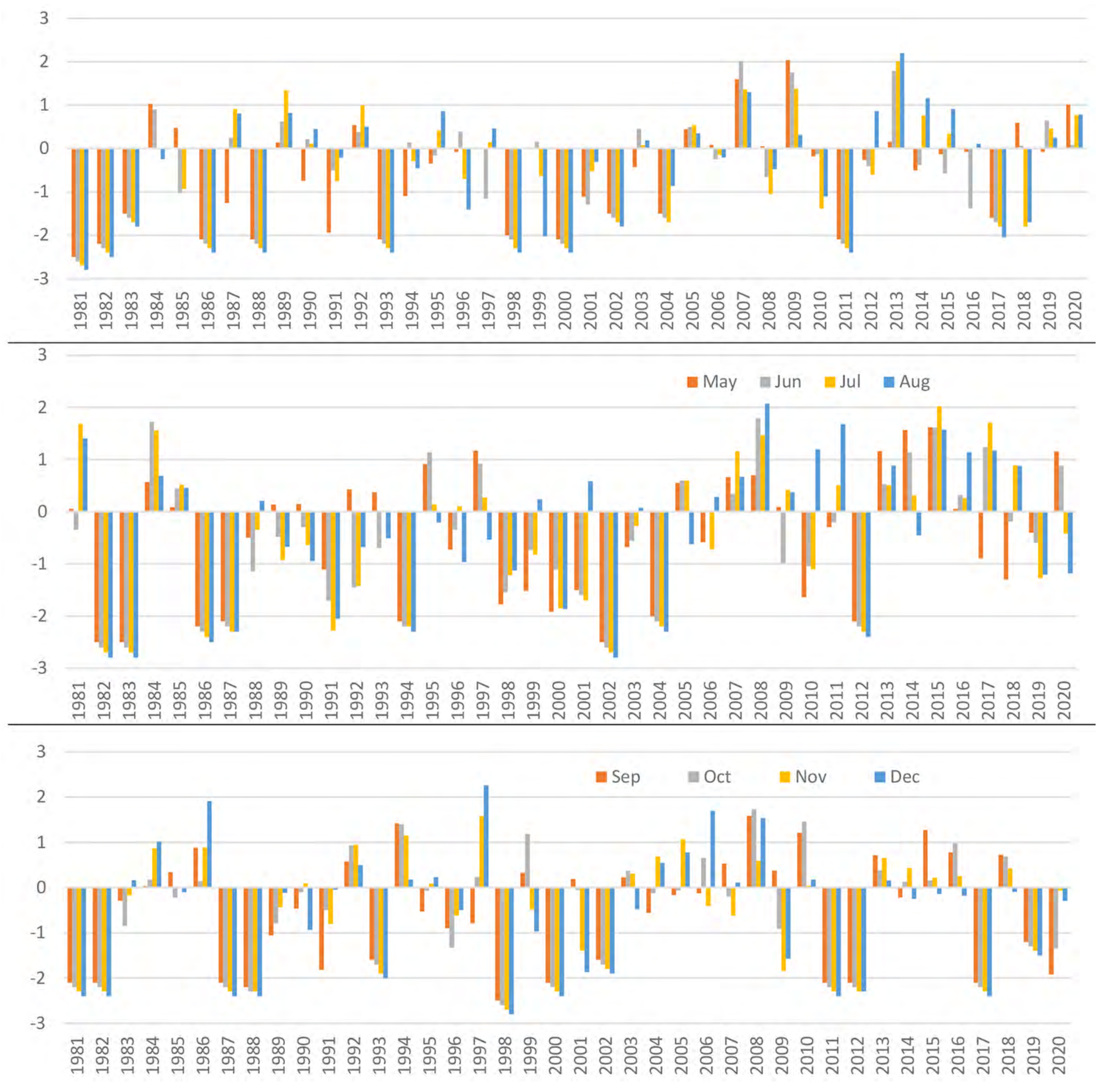

Figure 5(e). Seasonality and drought analysis of the Cholistan Desert using SPI. *Khanpur precipitation seasonality*

Discussion

The results indicate that Din Garh and Mauj Garh stations exhibit significant declining trends in annual rainfall, as evidenced by negative Kendall's Tau values and negative Sen's slopes. Specifically, Din Garh showed a Kendall's Tau of -0.410 (p-value < 0.0001) and a Sen's slope of -0.088, while MaujGarh displayed a Kendall's Tau of -0.441 (p-value < 0.0001) and a Sen's slope of -0.059. Conversely, Bhagla, Khanpur, and Fort Abbas stations demonstrated significant increasing trends in annual rainfall. Bhagla's Kendall's Tau was 0.5154 (p-value = 0.000637) with a Sen's slope of 0.0318, Khanpur's Kendall's Tau was 0.4615 (p-value = 0.000144) with a Sen's slope of 0.1102, and Fort Abbas's Kendall's Tau was 0.196 (p-value = 0.015) with a Sen's slope of 0.098. Hussain and Abbas (2029) also reported similar trends with rainfall variability ranging from 100 mm to 200 mm, while occasionally reaching to 300 mm. The analysis of mean monthly rainfall patterns also revealed significant seasonal variability across the stations. For instance, Bhagla and Fort Abbas stations recorded the highest mean monthly rainfall during the monsoon months (June to September), with Bhagla peaking at 11 mm in June and 43 mm in July, and Fort Abbas recording 54 mm, 58 mm, and 86 mm in July, August, and September, respectively. In contrast, the lowest rainfall was observed in the dry months of October and November.

The hypothesis of this study postulated that there are significant spatial and temporal variations in annual and monthly rainfall patterns across the study area driven by a combination of climatic and geographical factors. This hypothesis was tested using the Mann-Kendall (MK) trend test and Theil-Sen's Slope (TSS) estimator applied to rainfall data from five meteorological stations. The results support the hypothesis, confirming significant spatial and temporal variations in rainfall patterns. The observed trends in annual and monthly rainfall, along with the varying slope magnitudes, explain the influence microclimate factors. The spatial variability also reveals the complex interplay of local and regional climatic influences.

The declining trends observed at Din Garh and Mauj Garh stations indicate a worrying reduction in annual rainfall. These trends suggest an increasing aridity in the proximal areas, potentially exacerbating desertification processes. This is consistent with broader climate change predictions that arid regions will become drier due to altered atmospheric circulation patterns and reduced moisture availability (Haider et al., 2021). The significant negative trends at these stations highlight the urgent need for enhanced water conservation strategies. The reduction in rainfall at these locations poses severe risks for both local agriculture and the availability of potable water, directly impacting the livelihoods of communities dependent on these water sources (Wahla & Kazmi, 2022).

The spatial variability in precipitation trends observed in the Cholistan Desert reflects similar patterns seen in other arid regions around the world, where climate change often drives complex patterns of both increasing and decreasing rainfall across short distances. For instance, studies in the Sahara Desert and the adjacent Sahel region reveal a heterogeneous rainfall distribution, with some areas experiencing intensified dryness while others exhibit a "greening" effect due to seasonal increases in precipitation (Badr et al., 2016; Biasutti, 2019). In India's Thar Desert, research has documented both spatial and temporal variations in rainfall, influenced by shifts in monsoon intensity and direction, which are shaped by microclimatic and atmospheric factors similar to those impacting the Cholistan Desert (Saini et al., 2022; Singh & Choudhary, 2023). The Rub' al Khali region in the Arabian Desert also shows variable precipitation trends, with slight increases in some areas attributed to the influence of the Indian Ocean Dipole (IOD). However, the overall trend in the region leans toward reduced precipitation, which further exacerbates water scarcity (Almazroui et al., 2012). In contrast, the Atacama Desert in South America predominantly exhibits declining rainfall patterns, largely influenced by the Pacific Decadal Oscillation (PDO) and El Niño events, resulting in intensified aridity (Houston & Hartley, 2003).

Conversely, the increasing rainfall trends at Bhagla, Khanpur, and Fort Abbas stations suggest a different microclimatic influence. These areas show positive slopes in their annual rainfall patterns, indicating a trend towards wetter conditions. This spatial variability within the Cholistan Desert can be attributed to localized climatic factors and possibly the influence of the Indian monsoon as also suggested by (Wariss et al., 2013), while similar localized trends can be observed in other surrounding deserts such as Nara Desert in Sindh as reported by (Qureshi & Bhatti 2008).

The significant seasonal variability in monthly rainfall further suggests the challenges of water resource management in the Cholistan Desert. The pronounced peaks during the monsoon months (June to September) contrast sharply with the dry periods experienced throughout the rest of the year. This variability necessitates effective rainwater harvesting and storage systems to capture and utilize the monsoon rains efficiently. The existing rainwater harvesting practices, as mentioned in Hussain and Abbas (2019), including the use of tobas and kunds, are vital but require significant improvements to address seepage, evaporation, and contamination issues. Climate change impacts in the Cholistan Desert are evident through the observed trends in rainfall. The increasing temperature and changing precipitation patterns align with global climate change models predicting more extreme weather events, including both severe droughts and intense rainfall periods (Bashir and Hanif 2018). These changes necessitate adaptive strategies that enhance resilience to climate variability. Improved meteorological monitoring, coupled with advanced modeling techniques, can provide better predictions, and inform more effective water management policies.

Water scarcity remains a critical issue in the Cholistan Desert, directly linked to the observed rainfall trends (Afzal & Rizwan 2017). The areas experiencing declining rainfall trends are likely to face heightened water scarcity, exacerbating the challenges of sustaining local populations and their agricultural activities. The results from this study unveil the vulnerability of the region to prolonged dry spells, with the majority of rainfall occurring during the monsoon season (July to September). However, this monsoon rainfall is often inconsistent, leading to extended periods of drought, especially in early spring and summer, which poses significant challenges for maintaining water levels in traditional storage systems such as tobas and kunds. The gradual increase in drought severity observed at DinGarh and MaujGarh stations, as indicated by the Standardized Precipitation Index (SPI), underscores the pressing issue of water scarcity, which is exacerbated by climate variability.

The spatial variation in precipitation seasonality across different parts of the desert further complicates water resource management. For instance, DinGarh experienced sporadic wet years, providing brief but essential relief for water storage, whereas MaujGarh encountered more frequent and severe droughts, leading to greater environmental stress. Similarly, stations like Bhagla and Khanpur, which experienced prolonged dry spells interrupted by only occasional wet years, reveal the uneven distribution of precipitation across the desert. This variability emphasizes the need for tailored water management practices in different regions of Cholistan. Improving and expanding rainwater harvesting infrastructure, as well as enhancing drought resilience through sustainable water storage and conservation practices, would be essential for adapting to the area's increasingly unpredictable precipitation patterns.

Conclusion and Research Prospects

This study delved into the analysis of rainfall patterns in the Cholistan Desert, located in South Punjab, Pakistan, utilizing temporal rainfall data collected from meteorological stations including DinGarh, MaujGarh, Bhagla, Khanpur, and Fort Abbas. Through advanced GIS technology and statistical modeling, trends and fluctuations in rainfall were examined, shedding light on the changing precipitation dynamics in the region. The analysis revealed notable trends in annual rainfall across various meteorological stations. Particularly, a significant upward trend in precipitation was observed at Fort Abbas, Bhagla, and Khanpur stations, indicating an increase in rainfall over the study period. Conversely, DinGarh and MaujGarh stations showed less significant trends, suggesting a more stable or declining rainfall pattern. Furthermore, the application of Theil-Sen's Slope (TSS) method provided deeper insights into the temporal trends of precipitation. Positive Sen's slopes were identified at Bhagla, Khanpur, and Fort Abbas stations, indicating an increasing trend in rainfall intensity over the past four decades. Conversely, Din Garh and Mauj Garh stations exhibited negative Sen's slopes, signifying a decreasing trend in precipitation. The analysis of mean monthly rainfall patterns highlighted significant variations across different months and meteorological stations. While certain months like July and September experienced substantial rainfall, others such as October and November recorded minimal precipitation. These variations underscore the complex interplay of seasonal and geographical factors influencing rainfall distribution in the Cholistan Desert.

This study provides insights into the spatio-temporal trends of rainfall variability in the Cholistan Desert. The observed trends indicate a shift in precipitation patterns, with some areas experiencing an increase while others show a decline in rainfall intensity over time. These findings have significant implications for water resource management and agricultural practices in the region. Climate change-induced fluctuations in precipitation pose a substantial challenge to the already scarce water resources in the Cholistan Desert. The occurrence of extreme weather events like droughts and heatwaves further exacerbates the vulnerability of local communities, threatening their livelihoods and well-being. Moving forward, it is imperative to conduct further research to better understand the underlying drivers of rainfall variability in the Cholistan Desert and its broader implications for climate change adaptation and mitigation strategies. The integration of remote sensing technology and advanced modeling techniques can enhance our ability to monitor and predict changes in precipitation patterns, thereby informing more effective decision-making processes and resource allocation efforts. Addressing the challenges posed by climate change and water scarcity requires a multi-disciplinary approach, involving collaboration between scientists, policymakers, and local communities. By fostering greater awareness and understanding of climate-related risks and vulnerabilities, we can work towards building resilience and sustainable development in the Cholistan Desert and beyond.

The Cholistan Desert, with its harsh arid-to-semi-arid climate and remote location, presents several limitations for this study. The availability of meteorological data is limited, as there are few stations in the region, many of which lack long-term, continuous records and modern monitoring technologies. These stations cover only a portion of the vast desert, which restricts the spatial comprehensiveness of the data.

To improve future investigations of precipitation trends in the Cholistan Desert, efforts should focus on enhancing data quality and spatial coverage. Expanding the network of meteorological stations and upgrading existing ones with advanced technologies would enable more accurate and frequent data collection. Additionally, integrating high-resolution satellite imagery with ground-based data can provide a broader view of precipitation patterns. Employing advanced techniques, such as machine learning models, could also help capture complex precipitation variations that may be missed by traditional methods.

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