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# Hydro-ecological trends of the Chepelarska River (Western Rhodope Mountains, Bulgaria)

Krasya KOLCHEVA[1], Kalin SEYMENOV[1,*], Kristina GARTSIYANOVA[1], Emilia TCHERKEZOVA[2]

[1] Hydrology and Water Management Research Center, National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, "Academic Georgi Bonchev" Str., 1113, Sofia, Bulgaria
[2] Applied Geoinformatics Division, Department of Geography, National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, "Academic Georgi Bonchev" Str., 1113, Sofia, Bulgaria
* *Corresponding author*: kalin.seimenov@abv.bg

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**Abstract**

Significant anthropogenic impacts and climate change are putting the hydro-ecological conditions in river systems at risk of deterioration. It is crucial to record long-term trends for both an objective assessment during the planning process and the development of a methodological basis for further scientific investigations. This article analyzes human pressure and changes in the hydro-ecological status of the Chepelarska River (Southern Bulgaria), making recommendations for its improvement. The study relies on long-term hydrological data about registered runoff for 74 years from 1950 to 2023, information regarding hydro-morphological changes (regulated river sections and constructed hydropower plants), and dataset from monitoring of biological (phytobenthos, phytoplankton, fish fauna, macrophytes, and macrozoobenthos), physicochemical (pH, $DO_2$, $BOD_5$, Total N, Total P, $NH_4$, $NO_3$, $NO_2$, and $PO_4$), and specific chemical (Al, Cd, Cu, Pb, Mn, and Zn) water quality elements collected for 14 years between 2010 and 2023. The resulting information show a rising variability of runoff and a statistically significant tendency toward a flow volume decline, increasing morphological pressure from hydropower construction and aquaculture farming, and despite the overall positive hydro-ecological trend – constant deviations in some biological (macrozoobenthos), physicochemical (Total N, Total P, $NH_4$, $NO_2$, $PO_4$), and specific chemical (Cd, Mn, Pb, Zn) water quality elements. The achievement of better hydro-ecological conditions requires the application of a complex of environmental, engineering, and legislative measures.
**Keywords:** *anthropogenic pressure, hydrological trend, hydro-ecological status, surface water quality, Chepelarska River*

## Introduction

River water plays a key role in ecosystems' protection and development, offering vital services, such as potable freshwater provision, biodiversity maintenance, and regulation of local climatic conditions and processes (Watson, 2017). However, under the existing circumstances of dynamically changing natural and anthropogenic factors, the hydro-ecological state of river systems worsens (Rose et al., 2023; Tang, 2020). This is due, on the one hand, to water pollution from industry, agriculture, and expanding urbanization, and, on the other hand, to changes in the river runoff regime, including as a result of the influence of extreme phenomena, related to climate change, such as floods and droughts (Asadieh & Krakauer, 2017; Blöschl et al., 2019; Vigiak et al., 2018).

The transition of the Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive – WFD) into an integrated river basin management paradigm requires a comprehensive approach when assessing the state of surface water, which includes a wide range of criteria and indicators (Giakoumis et al., 2018; Howarth, 2018).

Performed during the process of river basin planning, the assessment of the waters' hydro-ecological state using biological, physicochemical, and hydro-morphological, including hydrological parameters, based on an established anthropogenic pressure, data from conducted monitoring and on an adopted for individual elements classification scale (Kolcheva et al., 2023), presents the general trends in the time and the possible effects on aquatic ecosystems (Karr, 2020). The variations in the hydro-ecological conditions enable the definition of recurring causes of pollution or shortage of water and reassessment of the planned measures.

In the spirit of the implementation of the WFD 2000/60/EC, numerous studies were being conducted in European countries, including Bulgaria, aimed at analyzing the adverse effects of changing natural and anthropogenic factors on hydro-ecological conditions in river systems. Catianis et al. (2012) assesed the hydro-ecological conditions in the region of the Danube Delta (Eastern Romania), using physicochemical parameters (pH, dissolved oxygen, electrical conductivity, total

dissolved solids, sulfates, etc.), litological samples of sediments (total organic matter, carbonates and siliciclastic fraction), and biological assay (identification of benthic communities), and reported that due to the upstream anthropogenic activities, delta water is subjected to susceptible chemical loading and traces of metalloids and heavy metals are found in bottom fauna, taking into account that the Danube River is receiving large amounts of industrial, agricultural, and urban wastewater. Štefunková et al. (2020), using the River Basin Habitat Simulation System (RHABSIM), investigated the hydro-ecological impact of a cascade of dams and hydroelectric power plants built on the Váh River (Western Slovakia) and established a significant reduction in ichthyofauna due to failure to ensure the minimum ecological flow. Ligorini et al. (2023) estimated the influence of multiple and increasing threats (demographic pressures, eutrophication, climate change) on the hydro-ecological status of 95 Mediterranean coastal lagoons and their adjacent connected drainage basins in the Corsica Island (France) and founded that increasing air temperatures and anthtopogenic pollution due to urbanization negatively affected seasonal biogeochemical cycles, disrupted photosynthetic efficiency, produced higher phytoplankton biomass, and provoked blooms of potentially harmful dinoflagellates. Malovanyy et al. (2025), using methods of mathematical modelling, the Spearman's and the Pearson's rank correlation coefficients, as well as the Macrophyte Index of Rivers (MIR), focused on the ecological sustainability of landscapes on the formation of the hydro-ecological state of water in the upper part of the Prypiat River Basin (Southern Belarus and Northern Ukraine) under conditions of climate change and human activities, and concluded that the areas with a higher coefficient of ecological sustainability of landscapes have better water quality indicators, which implies a lower rate of erosion, a weaker anthropogenic impact, and a stronger hydro-ecological potential. These complex relationships between climate change, human pressure, and hydro-ecological processes in rivers were also demonstrated by Radeva & Seymenov (2019) for the Lom River Basin (Northwest Bulgaria). Using information about registered river flow, hydro-morphological parameters, physicochemical (pH, dissolved oxygen, biochemical oxygen demand, ammonia, nitrates, and phosphates) and biological (macrophytes, macrozoobenthos, and phytobenthos) water quality elements, the authors found significant deviations from the reference conditions. The flow regime is altered, and the hydro-morphological status is graded as "poor" due to the effect of hydropower plants and water abstraction facilities. The physicochemical state is "moderate", resulting from constant exceedances in values of key biogenic components, while the biological quality elements showed a relatively "good" state with periodic deviations (Radeva & Seymenov, 2019). The authors summarized that the overall hydro-ecological status could be assessed as "moderate", resulting from organic and biogenic water pollution by agriculture and domestic sources, as well as the various types of hydro-morphological pressures.

The Chepelarska River is another example of a river in the Republic of Bulgaria, subjected to diverse human impacts, disrupting the natural hydro-ecological status and hindering the implementation of the objective ‘all water bodies to achieve good status’ following the guidelines of WFD 2000/60/EC. The selected river basin is characterized by a lot of settlements without urban sewage systems, dozens of unregulated landfills for solid household wastes, an increasing number of hydropower facilities, as well as developed industrial production associated with two of the largest lead-zinc ore mines in the country. As a result of uncontrolled discharge of untreated industrial and domestic wastewater, water is polluted with substances of various origins and compositions like heavy metals, metalloids, and nutrient components (Dospatliev et al., 2015; Gartsiyanova, 2022; Gartsiyanova et al., 2023; Pencheva et al., 2002; Radeva & Seymenov, 2021). T

he deteriorated physicochemical state of river water and the constructed hydroelectric plants negatively affected aquatic ecosystems, disrupting fish migration and reducing biodiversity (Gecheva et al., 2023; Patronov & Kirin, 2024). Parasites and parasite communities have also been established (Zaharieva, 2023).

In this context, the present study aims to analyse the anthropogenic impact on the surface water quality, as well as the hydro-ecological trends of the Chepelarska River, based on statistical data about specific periods, provided by the National Institute of Meteorology and Hydrology (NIMH) and the Eastern Aegean Basin Directorate (EABD). In the spirit of sustainable development, the implementation of this task is important for achieving the good-water-state aim and expanding the research activities to increase the level of objectivity during the planning process.

## Study area

The Chepelarska River has a length of 85.9 km. Its catchment drains an area of 1051.39 km$^2$ with a mean altitude of 1143 m a.s.l. (River Basin Management Plans – RBMP, 2022–2027; Tcherkezova et al., 2023) (Fig. 1).

The source of the river is on the western foothills of the Rozhen Peak at an altitude of 1550 m a.s.l. Farther, the river flows north and northeast in a deep narrow gorge valley between the ridges of Chernatitsa, Dobrostan, and Radyuva Mountain: constituent units within the Western Rhodopes. Downstream the river leaves the mountainous environment, enters the Upper Thracian Lowland, and flows from the right into the Maritsa River after the village of Katunitsa at an altitude of 148 m a.s.l. (Hristova, 2012).

The climate is transitional continental with mountainous influences. The mean annual air

temperature increases from 7.3°C for the city of Chepelare up to 12.3°C by the town of Sadovo. July is the hottest month with mean air temperatures between 16°C and 24°C, while January is the coldest one with -2.5°C and 1.0°C, respectively (Plan for Integrated Municipal Development, 2021–2027). The annual amount of precipitation rises from 550–650 mm (in the lowland) up to 750–1100 mm (in the mountain) with two maximums in May/June and November/December, and two minimums during February/March and August/September (Velev, 2010). The climate scenarios Representative Concentration Pathways (RCP) for the territory of the EABD predict a rise in the mean annual air temperatures by 2.79°C (RCP 4.5) and 3.76°C (RCP 8.5) for 2071–2100 compared to the reference period 1976–2005. Warming is expected for all seasons. The mean annual sum of precipitation is also predicted to increase – by 1.17% (RCP 4.5) and 3.31% (RCP 8.5), especially in autumn by 24.8%, but to decrease in summer by 9.1% (RBMP, 2022–2027).

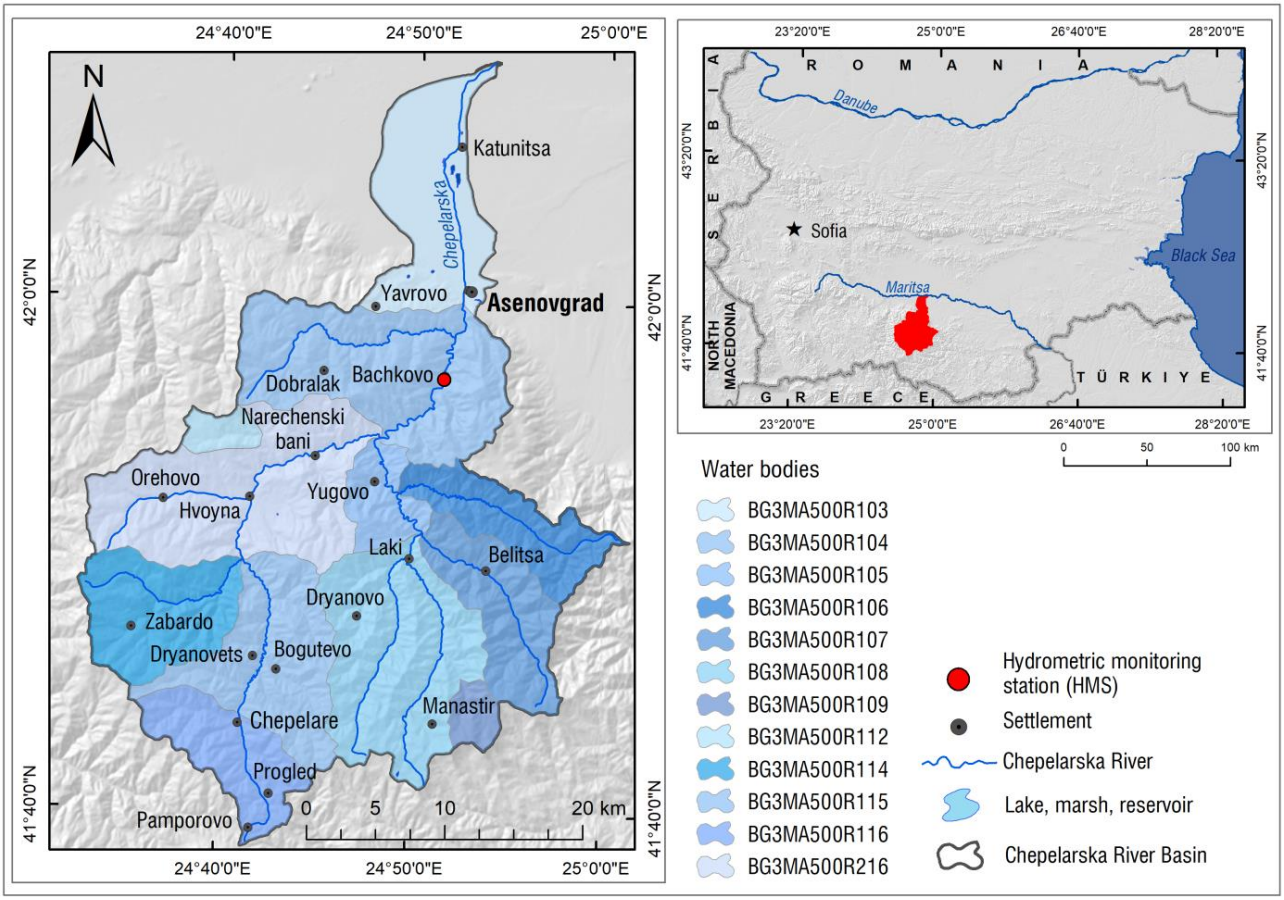


**Figure 1. Study area**

The Chepelarska River Basin is divided into 12 surface water bodies (SWBs) of types R3 (Mountainous rivers in an Ecoregion 7: Eastern Balkans) and R5 (Semi-mountainous rivers in an Ecoregion 7: Eastern Balkans) (Table 1). Most of these SWBs are classified as ''natural'', excluding a water body BG3MA500R103, which belongs to category ''highly modified'', and another two are "drinking water bodies" (DWB).

Based on the List of complex and significant reservoirs under Appendix No 1 to the Water Act (2000), published by the Ministry of Environment and Water (MOEW), no dams are of national importance in the studied river basin. The anthropogenic impact on the drainage system is presented by water intakes for electro-production, aquaculture farming, drinking, household, and industrial needs, as well as by flood protection dykes and irrigation channels near the mouth (RBMP, 2022–2027).

Following the administrative division of the Republic of Bulgaria, the Chepelarska River Basin includes parts of nine municipalities (Asenovgrad, Banite, Chepelare, Devin, Kuklen, Laki, Rodopi, Sadovo, and Smolyan), which are distributed over two districts (Plovdiv and Smolyan). The main economic branches include wood-processing and ore-mining industries, ski- and spa-tourism for the municipalities in the Western Rhodopes, while crop cultivation and livestock farming are among the crucial activities for the municipalities in the Upper Thracian Lowland (Plans for Integrated Municipal Development, 2021–2027).

**Table 1. Surface water bodies in the Chepelarska River Basin (RBMP, 2022–2027)**

| Number | Name | Type | Length of river (km) | Catchment area (km$^2$) |
|---|---|---|---|---|
| BG3MA500R103 | The Chepelarska River from the town of Asenovgrad to its mouth | R5 | 19.31 | 109.84 |
| BG3MA500R104 | The Chepelarska River from the Yugovska River to the town of Asenovgrad | R3 | 16.54 | 165.69 |
| BG3MA500R105 | The Yugovska River from the Sushitsa River to its mouth | R3 | 10.91 | 33.79 |
| BG3MA500R106 | The Sushitsa River | R3 | 20.80 | 62.25 |
| BG3MA500R107 | The Belishka River | R3 | 17.75 | 74.49 |
| BG3MA500R108 | The Manastirska River and the Dzhurkovska River | R3 | 22.81 | 148.64 |
| BG3MA500R109 | The Krushovska River – DWB | R3 | 4.76 | 14.71 |
| BG3MA500R216 | The Chepelarska River from the Zabardovska River to the confluence of the Yugovska River and the Oreshitsa River | R3 | 18.20 | 171.66 |
| BG3MA500R112 | The Ledenitsa River – DWB | R3 | 5.48 | 14.53 |
| BG3MA500R114 | The Zabardovska River | R3 | 15.14 | 85.37 |
| BG3MA500R115 | The Chepelarska River from the town of Chepelare to the Zabardovska River | R3 | 14.61 | 107.29 |
| BG3MA500R116 | The Chepelarska River from its source to the town of Chepelare | R3 | 11.03 | 63.14 |

## Methodology

In each river basin planning period (the first one for the Republic of Bulgaria being 2010–2015) relationships analysis between anthropogenic pressure and impact and assessment the degree of the impact on waters through the conceptual model "Driving Force–Pressure–Impact–Answer" (DFPIA), according to Guide No. 3 - Analysis of pressures and impacts of the General strategy for the implementation of the WFD. The updated assessment of the pressures in the RBMP for the planning period 2022–2027, the following categories of pressure on surface water bodies has been identified: from point and diffuse sources of pollution and from hydro-morphological changes. And if the impact determines the negative changes of individual quantitative and qualitative parameters of the water body, then the monitoring (hydrobiological, physicochemical, and chemical) data is the basis for assessing the degree of impact of the pressure and the general ecological and chemical state of the surface water bodies.

Monitoring (control, operational, and research) of surface waters is implemented with the necessary scope and frequency using standardized methods, in accordance with current European and national standards. The NIMH maintains the national hydrometric network and provides operational information about river runoff since the beginning of the 20$^{th}$ century, and the Executive Environment Agency (ExEA) administers the surface water quality monitoring networks.

The frequency of the operative monitoring for biological elements of water quality (BEQ) is once a year, with the exception of phytoplankton, monitored twice a year, and for the physicochemical ones, incl. specific pollutants is four times a year (once every three months). River morphology and continuity are surveyed once every six years.

The classification for the assessment of quality elements, according to Annex V of the WFD and Guideline No. 6 in five, three, and two classes, respectively, is presented in Table 2.

**Table 2. Classification and designations of ecological status (Ordinance No H-4 of September 14 2012)**

| Ecological status - water quality elements | | |
|---|---|---|
| **Biological** | **Physicochemical** | **Hydro-morphological** |
| Excellent | Excellent | Excellent |
| Good | Good | Good |
| Moderate | Moderate | |
| Poor | | |
| Bad | | |

An updated "General approach to evaluating the environmental status and potential of surface water bodies in the Republic of Bulgaria" has been attached to the RBMP (2022–2027), considering the general patterns in the state changes and the specifics of interpretation of the monitoring data. The final evaluation is determined by the water quality element in the worst status, according to the "one out–all out" rule (Annex V of the WFD). All requirements regarding the classification and presentation of the studied status are enshrined in Ordinance No H-4 of September 14 2012 for surface water characterization.

*Hydro-morphological elements of water quality (HMEQ)* – these elements, in support of Biological elements of water quality (BEQ), are studied in two directions: hydrological, related to quantitative changes in the hydrological regime (e.g. after a dam or due to water intakes), changes in the speed of the river velocity, level, and continuity (number and types of barriers and ensuring the passage of aquatic organisms), and *morphological*, related to physical changes in the

riverbed, including in its profile, in the transport of sediments, and in erosion processes.

*Hydrological parameters* – Statistical information provided by the NIMH, responsible for conducting the quantitative monitoring of surface water, according to the letter No. OD-03-994-1/09.01.2025 is used to assess the hydrological characteristics of the Chepelarska River. The study includes 74 years from 1949/1950 to 2022/2023. The hydrometric observations are conducted at the stream gauging station No. 72460 (latitude 41.9498° N; longitude 24.8580° E), located in the village of Bachkovo. The mean elevation of the drainage basin to the station is 1241 m a.s.l., and its area is 824.9 $km^2$ (78.4% of the total catchment area) (Hydrological Reference Book, 1981). Flow variabilities are evaluated at three time-scales: annual, monthly, and seasonal. The analysis is conducted for hydrological years, lasting from November of the previous calendar year to October of the following calendar year, and including three seasons: winter (XI–II), spring (III–VI), and summer-autumn (VII–X) (Panayotov, 1972).

Initially, the data set is checked for homogeneity through double mass curves. Then, descriptive statistical characteristics, such as minima, maxima, and mean values, and a coefficient of variation (Cv) are calculated.

*Water withdrawal* from surface water bodies with an annual limit ≥ $150x10^3$ $m^3/y$ is significant, and the pressure from it on the available resource is distinguished as: weak (0–15%), moderate (15–30%), and significant (>30%).

*River continuity and morphology* – Standardized field protocols and concepts are used to assess the morphological conditions under the WFD 2000/60/EC, in accordance with the guidelines of the Guidance standard for assessing the hydro-morphological features and Ordinance No H-4 of September 14 2012 for surface water characterization. Significant hydro-morphological changes (corrected and affected by the extracting of inert materials river sections) are those that change the ecological status of water from "good" to "poor" based on BEC data and the relationship between BEC and hydro-morphological quality elements. For example, the River Habitats Survey Protocol used in Europe aims to provide reliable information on hydro-morphological quality elements in a standard section of 500 m in length. The morphological pressure in the second planning cycle is expertly accepted as significant, when the length of the affected river section compared to that of research is as follows: corrected or with extraction of inert materials and bank protection facilities more than 70%, with migration barriers over 50%, and regulated over 30%.

*Biological elements of water quality (BEQ)* – In the RBMP all mandatory are covered five BEQs (phytoplankton, macrophyte flora, phytobenthos, benthic macroinvertebrate fauna, and fish fauna) required for the determination of the ecological status and potential of rivers/lakes. The methods for BEQ assessment in Bulgaria are based on the requirements of WFD 2000/60/EC and Ordinance No H-4 of September 14 2012 for surface water characterization. The comparative assessment of observed biological data with reference conditions is presented by the Ecological Quality Ratio (EQR).

The estimation of phytoplankton (for lakes/dams), considered the most important biological quality element in assessing the ecological status or potential of lakes and reservoirs, is based on one-time sampling and subsequent analysis, carried out in accordance with the following guidance documents for water quality: Guidance on the design of sampling programmes and sampling techniques ISO 5667-1:2006/AC:2007, Guidance on the preservation and handling of water samples ISO 5667-3:2003/AC:2007, Guidance standard on the enumeration of phytoplankton using inverted microscopy (Utermöhl technique) EN 15204:2006 by the Utermöhl method and calculation of the biovolume by taxon-specific cell volumes of planktonic algae, and Spectrometric determination of the chlorophyll-a concentration ISO 10260:1992. Phytoplankton is the most sensitive element to nutrient pollution (eutrophication).

The assessment of macrophytes is based primarily on careful selection of a "macrophyte" river section (up to 100 m long) or "macrophyte" lake belt transects, as initially using the results of the Reference Index (RI), successfully applied in Germany (Bavaria). For the analysis, the following international standards for surface water quality are also applied: Guidance standard for the surveying of macrophytes in lakes EN 15460:2007 and Guidance standard for the surveying of aquatic macrophytes in running waters EN 14184:2003. Macrophytes are an indicator of water pollution with biogenic components and some specific pollutants.

Phytobenthos (rivers) assessment is related to estimation of periphyton diatoms (diatoms) in accordance with two standards from 2003 and 2004 for water quality: Guidance standard for the routine sampling and pretreatment of benthic diatoms from rivers and Guidance standard for identification, enumeration and interpretation of benthic diatom samples from rivers.

About macrozoobenthos at the national level only benthic (bottom-dwelling) invertebrates (for rivers), assessed according to an adapted Irish Biotic Index (IBI), are studied. Both elements are indicators of organic and toxic water pollution. For the fish fauna, the European Fish Index EFI+ method, developed at the European level, is applied.

*Physicochemical elements of water quality (PCEQ)* – This type of assessment includes three groups of indicators – general, biogenic, and specific chemical pollutants. In this study, the following elements with statistically confirmed representativeness of the "pressure-impact" relationship are used: hydrogen indicator (pH), dissolved oxygen ($DO_2$), biochemical oxygen demand ($BOD_5$), total nitrogen (TN), total

phosphorus (TP), ammonia ($NH_4$), nitrates ($NO_3$), nitrites ($NO_2$), and phosphates ($PO_4$), as well as the elements: aluminium (Al), cadmium (Cd), copper (Cu), lead (Pb), manganese (Mn), and zinc (Zn) from the third group. The assessment of each one of the physicochemical elements is based on the available monitoring data and the rules specified in Annex No. 6 to Article 12, paragraph 4, part B. Physicochemical quality elements in Ordinance No H-4/September 14 2012 for surface water characterization.

In the planning process, the assessment of ecological status/potential of surface water bodies by the specified quality elements is improved with the implementation of research projects. For example, in the current RBMP, the assessment is based on an updated "General approach for assessment of the ecological status/ecological potential of surface water bodies in the Republic of Bulgaria", aiming the greatest possible objectivity, taking into account both the general patterns in changes in the ecological status and the specifics in the interpretation of monitoring data.

Summarized data from annual reports on the surface water status on the territory of the EABD region for the period 2010÷2023 have been used to assessing the BEQ and PCEQ, and the parameters with an exceedance, defining state, different from the "good" hydro-ecological state, have been considered.

To find tendencies, a linear trend is applied. The statistical significance of the regression line is estimated by the Mann-Kendall Test. If the *p-value* is less than the critical level of 0.05, the non-parametric estimator determines the trend as monotonic.

Additionally, the following spatial data were also used: Digital Terrain Model (DTM) for Continental Europe with a grid size of 30 m (Hengl et al., 2020) and Open Street Map Project (OSM): settlements, roads, railroads (2025).

## Results and discussion

Changes in the general hydro-ecological state are determined by an analysis of the information collected for two main periods: the first – hydrological (1949/1950–2022/2023) and the second for assessing the ecological state (2010–2023), according to the planning periods.

*Hydro-morphological elements of water quality (HMEQ)* – The following parameters are considered in this study: hydrological, including water withdrawal, and river continuity and morphology.

*Hydrological parameters* – The initial statistical analysis shows that the time-series data are not homogeneous. The double-mass curve demonstrates a break in the slope of the cumulative function in the mid-1980s (Fig. 2). Then, due to rising air temperatures and scanty precipitation, the Chepelarska River Basin experienced a severe hydro-meteorological drought, which was especially pronounced from 1982/1983 until 1993/1994 (Gerasimov et al., 2001).

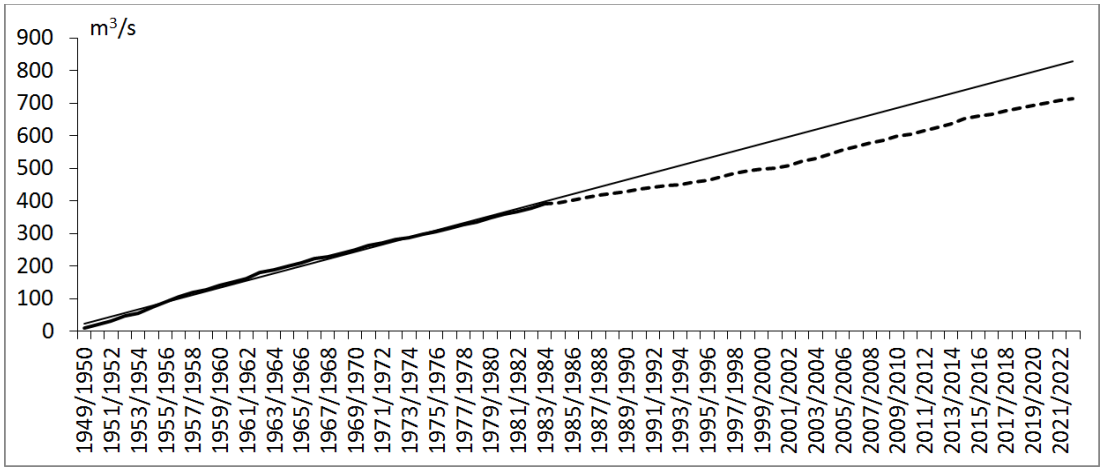


**Figure 2. Double mass curve of the annual streamflow in the Chepelarska River Basin at Bachkovo**

The obtained result gives a reason to divide the observation period into two sub-periods with a homogeneous data set and an approximately equal length. The 1984/1985 hydrological year is taken as the boundary. Henceforth, the descriptive statistical measures of river flow for the two sub-periods will be calculated and presented.

The average annual streamflow of the Chepelarska River at the gauging station of Bachkovo for 1984/1985–2022/2023 is 8.33 $m^3/s$ (from 3.71 $m^3/s$ in 1993/1994 to 16.97 $m^3/s$ in 2014/2015) or less than the mean annual flow for 1949/1950–1983/1984: 11.15 $m^3/s$ (between 5.38 $m^3/s$ in 1967/1968 and 18.99 $m^3/s$ in 1962/1963) (Fig. 3). The annual streamflow increases its fluctuations around the norm during the last four decades: Cv is 0.37 (1984/1985–2022/2023) compared to 0.28 (1949/1950–1983/1984). The decrease in the annual streamflow volumes is confirmed by the linear hydrological trend. The slope of the regression line is statistically significant (Fig. 3, Table 3).

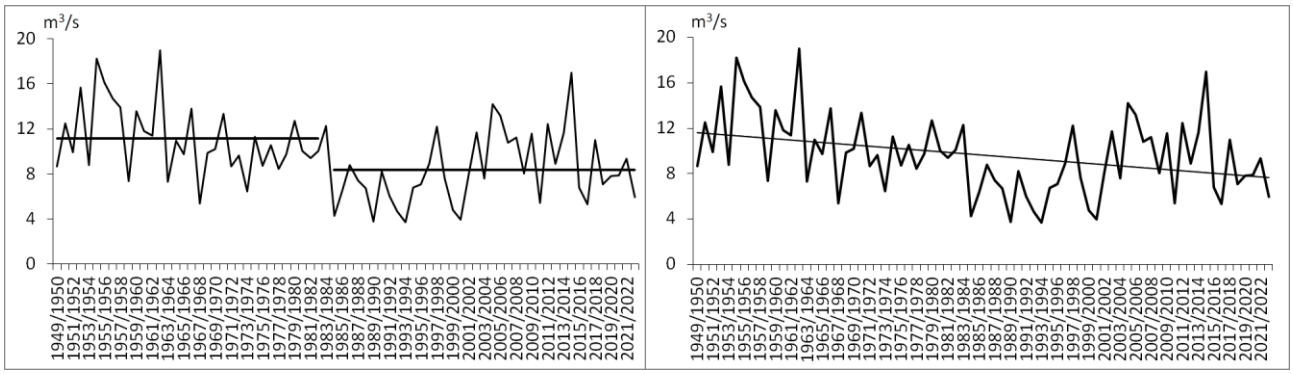


**Figure 3. Long-term fluctuations with average values (on the left) and linear trend (on the right) of the annual streamflow in the Chepelarska River Basin at Bachkovo**

**Table 3. Flow trends in the Chepelarska River Basin at Bachkovo according to the Mann-Kendall test**

| Time scales | | Mann-Kendall's test parameters | | |
|---|---|---|---|---|
| | | *p-value* | *Kendall's tau* | *Sen's slope* |
| Annual | | 0.004 | -0.246 | -0.018 |
| Seasonal | Winter | 0.001 | -0.332 | -0.015 |
| | Spring | 0.007 | -0.241 | -0.013 |
| | Summer-autumn | 0.084 | -0.067 | -0.001 |

The intra-annual runoff distribution of the Chepelarska River belongs to the moderate-continental type: the period of high-water levels is during the spring months, while the low-flow phase occurs in the summer-autumn months (Fig. 4, Table 4). In general terms, the monthly runoff increases from October to April and decreases from May to September. The highest streamflow is observed in April, while the lowest flow is measured in September. There is no change in the configuration of the monthly and seasonal maxima and minima for the studied two sub-periods, which indicates a relatively stable runoff regime.

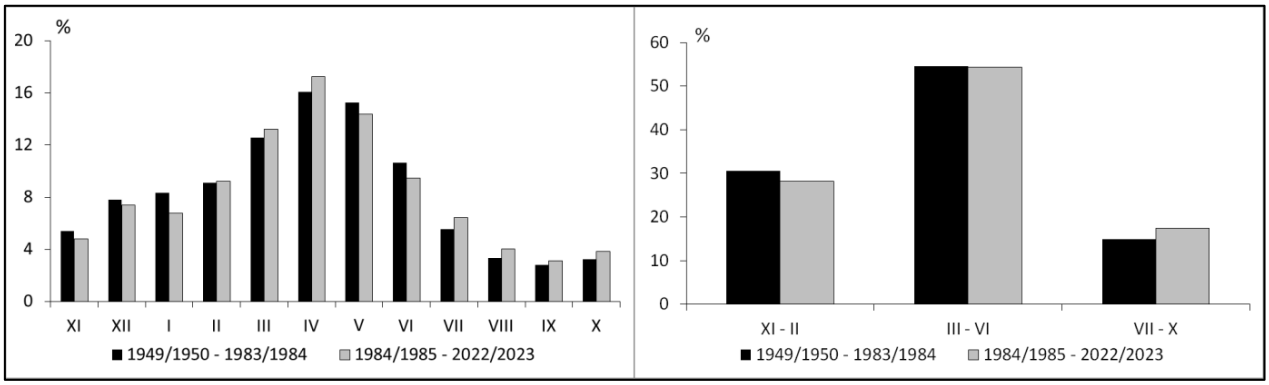


**Figure 4. Monthly and seasonal streamflow distribution (% of the annual volume) in the Chepelarska River Basin at Bachkovo**

**Table 4. Descriptive statistics of the monthly streamflow in the Chepelarska River Basin at Bachkovo**

| Period | Indicators | Months | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | XI | XII | I | II | III | IV | V | VI | VII | VIII | IX | X |
| 1949/1950–1983/1984 | $Q_{min.}$, m³/s | 1.49 | 1.78 | 2.97 | 2.64 | 4.37 | 6.54 | 5.90 | 3.49 | 2.15 | 1.49 | 1.02 | 1.30 |
| | $Q_{av.}$, m³/s | 7.20 | 10.43 | 11.14 | 12.15 | 16.84 | 21.49 | 20.39 | 14.22 | 7.39 | 4.43 | 3.78 | 4.32 |
| | $Q_{max.}$, m³/s | 24.10 | 30.30 | 36.40 | 44.40 | 42.00 | 44.00 | 40.70 | 43.80 | 20.00 | 24.60 | 13.10 | 17.00 |
| | $C_v$ | 0.73 | 0.69 | 0.76 | 0.68 | 0.52 | 0.45 | 0.46 | 0.63 | 0.61 | 0.93 | 0.74 | 0.85 |
| 1984/1985–2022/2023 | $Q_{min.}$, m³/s | 1.37 | 1.39 | 1.81 | 1.66 | 3.87 | 4.48 | 5.42 | 2.86 | 1.46 | 1.13 | 0.96 | 1.11 |
| | $Q_{av.}$, m³/s | 4.76 | 7.33 | 6.80 | 9.22 | 13.21 | 17.28 | 14.36 | 9.50 | 6.45 | 4.05 | 3.14 | 3.86 |
| | $Q_{max.}$, m³/s | 29.45 | 25.17 | 16.03 | 26.78 | 34.59 | 33.53 | 50.83 | 23.42 | 21.85 | 18.08 | 23.41 | 22.10 |
| | $C_v$ | 1.18 | 0.80 | 0.61 | 0.63 | 0.58 | 0.43 | 0.67 | 0.50 | 0.75 | 0.93 | 1.14 | 1.02 |

The average monthly flow decreases during the 1984/1985–2022/2023 period compared to the earlier one (Table 4). This decrease is larger (exceeding 20%) from November to June, especially in January (39%), November (34%), and June (33%) and closely correlates with the significant air temperature increase, whereas it is barely influenced by precipitation, which has slightly changed. In other months, the decrease is less than 20%.

The seasonal flow distribution (%) is 30.6/54.5/14.9 (1949/1950–1983/84) and 28.2/54.3/17.5 (1984/1985–2022/2023) for a winter, spring, and summer-autumn hydrological season, respectively. The declining share of winter runoff is probably due to the lower snow cover height. On the other side, the rising relative share of summer-autumn river flow reflects the increasing autumn precipitation.

The average seasonal flow also declines for 1984/1985–2022/2023 compared to 1949/1950–1983/1984. This change is expressed for winter (31%), followed by spring (25%), and summer-autumn (12%) hydrological seasons (Table 5). There is a statistically significant negative trend for all hydrological seasons, excepting summer-autumn (Fig. 5, Table 3). Torrential and intense summer-autumn precipitation caused sharp peaks in hydrographs and increased flow variability in last years, especially during the summers of 2005 and 2014. That to some extent explains the lack of a significant decrease in runoff for the summer-autumn hydrological season, regardless of rising air temperatures.

**Table 5. Descriptive statistics of the seasonal streamflow in the Chepelarska River Basin at Bachkovo**

| Period | Indicators | Hydrological seasons | | |
|---|---|---|---|---|
| | | Winter | Spring | Summer-autumn |
| 1949/1950–1983/1984 | $Q_{min.}$, m³/s | 2.66 | 7.37 | 1.79 |
| | $Q_{av.}$, m³/s | 10.23 | 18.24 | 4.98 |
| | $Q_{max.}$, m³/s | 23.50 | 29.78 | 11.51 |
| | $C_v$ | 0.53 | 0.29 | 0.55 |
| 1984/1985–2022/2023 | $Q_{min.}$, m³/s | 2.04 | 5.60 | 1.26 |
| | $Q_{av.}$, m³/s | 7.03 | 13.58 | 4.38 |
| | $Q_{max.}$, m³/s | 22.01 | 29.19 | 16.50 |
| | $C_v$ | 0.60 | 0.38 | 0.74 |

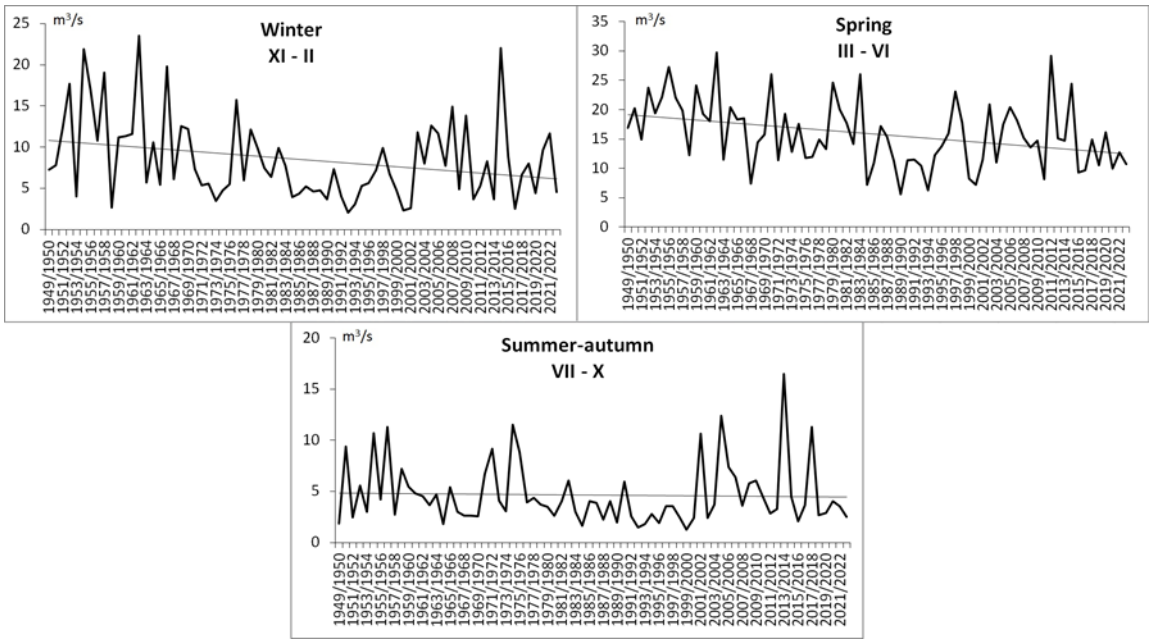


**Figure 5. Linear trend of the seasonal streamflow in the Chepelarska River Basin at Bachkovo**

The ratio between winter and spring streamflow ranges from 0.21 to 1.32 (1949/1950–1983/1984) and from 0.18 to 0.97 (1984/1985–2022/2023). The mean annual values are 0.57 and 0.52, respectively. The ratio exceeds the critical value of 1.00 only for two hydrological years (1966/1967 and 1976/1977), which confirms the moderate-continental type of the seasonal flow distribution. The variability in ratio values over the past decades is evidence of changing seasonal patterns of streamflow.

*Water withdrawal, river continuity and morphology* – The main activities generating hydro-morphological

pressure on SWBs in the Chepelarska River Basin are: water withdrawal (including the constructed water intake facilities), electricity production through small hydropower plants (SHPPs), flood protection dykes, migration barriers, and the extraction of inert materials (sands and gravels).

The general structure of water use by 2025, without intakes for electricity production, is presented in Figure 6.

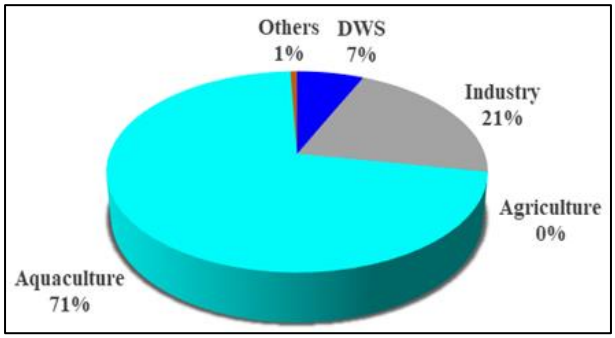


**Figure 6. Structure of water use without electricity production in the Chepelarska River Basin**

Considering the overall water use in the studied river basin, the leading sector is the hydropower, presented by multiple operating and under construction SHPPs (Figure 7). Two SHPPs – "Asenitsa" 1 and "Asenitsa" 2 with a derivation channel (L = 5.0 km, Q average = 12 $m^3/s$) for electricity production and irrigation have been built along the stream of the Chepelarska River from the town of Asenovgrad to the village of Bachkovo. Two more SHPPs – "Tunela" and "Lukovitsa" (along the Lukovitsa River) are under construction. In the river section from the village of Bachkovo to the village of Narechen, the SHPP "Narechen" is operating, and five more ("Asenitsa 3", "Bukov dol", "Konsort", "Hana", and "Laki") are under construction. From the village of Narechen to the town of Chepelare, the SHPPs "Hvoyna", "Pavelsko", "Chaya", "Desislava", and "Persenk" are in operation (Fig. 7 ). On the feeder of the Zabardovska River, the SHPP "Niki 60" operates, and three more are under construction: "Hlapach", "Zabardo", and "Chudnite Mostove". Four SHPPs are in operation in the catchment of the Yugovska River, and six more are being constructed. The total permitted water volume for electricity production by February 2025 is 5380.661*$10^6 m^3$. Water intake facilities for SHPPs are barriers that disrupt the continuity of the river and impede the free migration of fish and their reproduction. Additionally, most of these SHPPs are derivational and can cause drying of river sections, not ensuring the minimum ecological flow. In the pilot river basin, this pressure is significant along the main river course in the section from the confluence of the Zabardovska River to the mouth of the Chepelarska River.

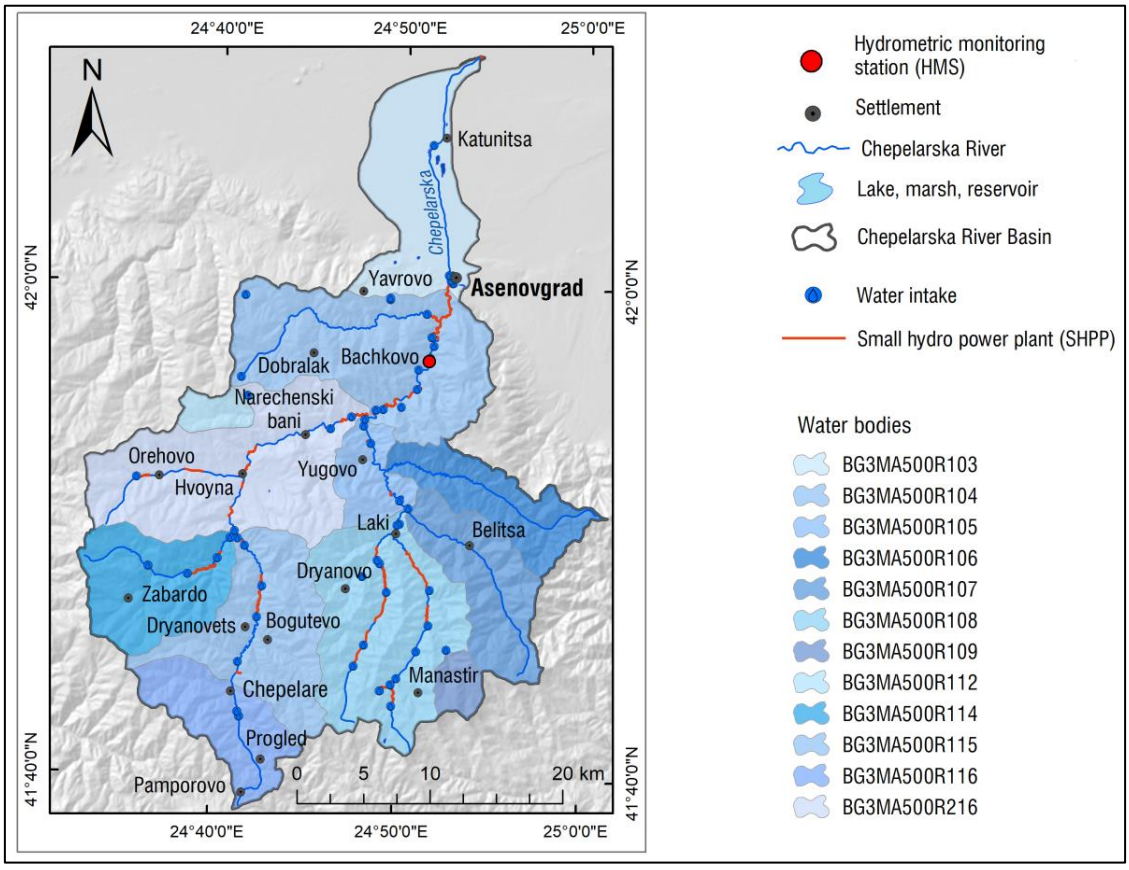


**Figure 7. Map of the Chepelarska River Basin with surface water bodies, water intakes, and small hydro power plants**

The next significant activity in the studied drainage basin is the aquaculture farming in artificially created flow-through basins (fisheries), located near to the town of Asenovgrad and the villages of Hvoyna, Bachkovo, Zabardo, and Dryanovo. The total permitted water volume for aquaculture by February 2025 is estimated at 769.680*$10^3$$m^3$. The permitted annual limit for each of the SWBs with aquaculture farming (BG3MA500R104, BG3MA500R108, and BG3MA500R216) is over 150*$10^3$$m^3$/y.

The industry is mainly represented by water intakes related to the extraction of polymetallic lead-and-zinc ore in the mines of "Dzhurkovo" and "Druzhba", and the "Tailings Pond Laki-2 Complex" with an operator "Laki Invest" AD near to the town of Laki, which is classified as an "enterprise with a high-risk potential". Representatives of other industrial sectors are: Rosa Impex Cosmetic Factory and Production Base in the village of Yagodovo; Fish processing workshop "Sinite hancheta" between the villages of Pavelsko and Hvoyna; a dairy farm in the village of Zabardo; a recreation base within the Resort Complex "Pamporovo", a shopping complex, a car-wash, etc. (RBMP, 2022–2027).

The drinking water supply (DWS), which is represented by local water intakes near to the larger settlements, has a relatively smaller share. The share of agriculture and other economic sectors in the overall structure of water use is negligible (Fig. 6).

The calculations on the degree of hydro-morphological pressure shows that it is moderate from flood protection dykes for one SWB (BG3MA500R103) with a share of the affected river section of 62%, from migration barriers it is significant for two SWBs (BG3MA500R103 and BG3MA500R104), from drying out from the constructed derivational SHPPs it is significant for one SWB (BG3MA500R103) with a share of the affected river section of 56%, and from the extraction of inert materials (sands and gravels) for seven SWBs it is weak, varying from 1.3% (BG3MA500R108) to 20% (BG3MA500R103).

In summary, the assessment of the *HMEQ*, carried out through an analysis of hydrological parameters, including water withdrawal, and river continuity and morphology, establishes: declining annual streamflow volume without significant change in its monthly and seasonal distribution, predominant water use for electricity production and aquaculture farming, absence of hydro-morphological pressure from the targeted water abstraction permitted by 2025, and disturbances in river morphology from barrier facilities, given the construction of derivational SHPPs and flood protection dykes.

*Biological and physicochemical elements of water quality (BEQ and PCEQ)* – Changes in the general hydro-ecological status of the Chepelarska River for the period 2010÷2023, and separately, on the number of SWBs in a "poor" status, are presented in Figures 8 and 9.

The general tendency is toward improving the water quality state, with an increasing number of water bodies in a "good" status and a decreasing number of these reported to have retained a "poor" status.

The observed peak in the number of SWBs in a "good" status in 2020 and 2021 can be explained by: improved monitoring methods, assessment of water bodies that were previously in "unknown" status, improved analysis of the spread of specific chemical pollutants, and possibly lower sampling frequency during the COVID-19 pandemic.

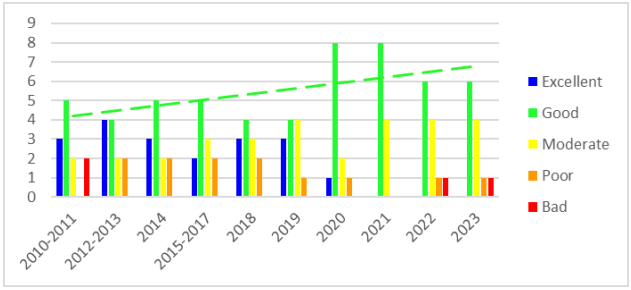


**Figure 8. General hydro-ecological trend in the period 2010-2023**

Despite the observed positive trend, water bodies in a "poor" status continue to be identified, which necessitates a reassessment of measures for water quality protection. In the current edition of the RBMP (2022–2027), six SWBs (BG3MA500R103, BG3MA500R104, BG3MA500R105, BG3MA500R108, BG3MA500R115, and BG3MA500R216) are assessed at risk regarding the general ecological state, and respecting the chemical state three SWBs (BG3MA500R103, BG3MA500R104, and BG3MA500R108) are defined as not achieving a "good" status, with a decline in the number of parameters with deviations compared to previous years.

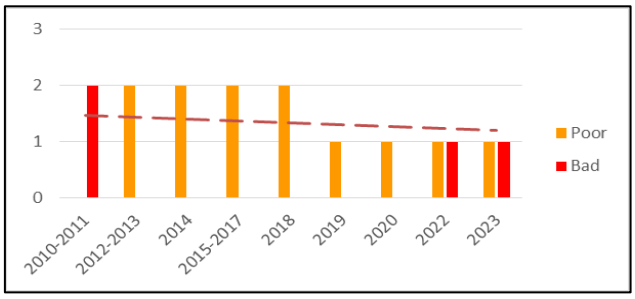


**Figure 9. Poor state change in the period 2010-2023**

Based on the monitoring data, carried out during the period 2012÷2023, exceedances have been found for those parameters shown in Table 6, characterizing the main physicochemical and biological elements of water quality. Regarding physicochemical and specific chemical elements, the most disturbing is heavy metal pollution (Zn, Pb, Cd, Mn, and Cu), typical not only of those SWBs (BG3MA500R105 and BG3MA500R108) that cover the mining-affected areas, but also of downstream SWBs

(BG3MA500R103). Elevated values of metalloids and heavy metals in the lower reaches of the main river were reported in past studies as well (Gartsiyanova, 2022; Gartsiyanova et al., 2023; Radeva & Seymenov, 2021). Unregulated discharges of industrial and mining wastewater from the mines of "Druzhba" and "Dzhurkovo" continue. Water pollution with biogenic components (TN, TP, $NH_4$, $NO_2$, $NO_3$, and $PO_4$) is a widespread problem, which affects both the upper (BG3MA500R115) and lower (BG3MA500R103) reaches of the river. The main reason for this situation is the lack of sewage systems in the settlements and the inflow of untreated domestic and fecal effluents (Radeva & Seymenov, 2021). This requires the implementation of measures related to the construction or modernization of a public sewage network and urban wastewater treatment plants for agglomerations with more than of 2000 population equivalent (p.e.). In the study area, wastewater treatment plants are currently constructed and operated only in the town of Asenovgrad and the village of Progled (Plan for Integrated Municipal Development, 2021–2027).

**Table 6. Parameters with norm exceedances in the period 2012-2023, presented by SWBs**

| Year / SWBs | BG3MA500R103 | BG3MA500R104 | BG3MA500R105 | BG3MA500R108 | BG3MA500R115 |
|---|---|---|---|---|---|
| **2012** | Biotic Index (BI), $NH_4$, $NO_2$, $PO_4$, Zn, Cd, Pb | $NO_3$, $PO_4$, TP, Cd | BI | - | $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP, BI |
| **2013** | $NH_4$, $NO_2$, $PO_4$, Zn, Cd | $PO_4$, TP | - | - | $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2014** | Macrozoobenthos, $NH_4$, $NO_2$, $PO_4$, Cd | $PO_4$, TP | Macrozoobenthos, Zn, Cu | - | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2015** | Chepelarska River after Asenovgrad: $PO_4$; Chepelarska River at the mouth, Kemera station: $PO_4$, Zn, Cd | $PO_4$, TP | Macrozoobenthos | Macrozoobenthos | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2016** | Macrozoobenthos, Chepelarska River after Asenovgrad: $NO_2$, $PO_4$ | TP | Cu | Macrozoobenthos | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2017** | Macrozoobenthos, Chepelarska River after Asenovgrad: $NO_2$, $PO_4$, TP; Chepelarska River at the mouth, Kemera station: $NO_2$, $PO_4$, TN, TP, Mn, Zn, Cd, Pb | TP | Cu, Mn, Pb | Macrozoobenthos, Zn, Pb | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2018** | $NH_4$, $NO_2$, $PO_4$, TN, TP, Mn, Cd, Pb | TP | Zn, Cu, Mn, Cd, Pb | Macrozoobenthos, Zn, Cd | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2019** | Macrozoobenthos, $NH_4$, $NO_2$, $PO_4$, TN, TP, Mn, Cd, Pb | TP | Mn, Cd, Pb | Zn, Cd | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2020** | Macrozoobenthos, electrical conductivity, $NO_3$, $NO_2$, $PO_4$, TN, Mn, Cd, Pb | - | Cd, Pb | Zn, Cd | Macrozoobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2021** | Macrozoobenthos, Phytobenthos, $NO_2$, PO4, TN, TP, Cd, Pb | Fishes, $PO_4$, TP | Cd, Pb | Zn, Cd | Macrozoobenthos, Phytobenthos, $BOD_5$, $NH_4$, $NO_3$, $NO_2$, TN, $PO_4$, TP |
| **2022** | Phytobenthos, Macrozoobenthos, TP | Fishes, TP | Zn, Cu | Al, Zn, Cu | Phytobenthos, Macrozoobenthos, Fishes, TN, TP, $BOD_5$ |
| **2023** | Phytobenthos, Macrozoobenthos, TP, Zn | Fishes, TP | Zn | Zn | Fishes, Phytobenthos, Macroinvertebrates, TN, TP |

Respecting biological elements, the largest and persistent deviations from reference conditions are found for the Macrozoobenthos indicator, especially for two SWBs (BG3MA500R105 and BG3MA500R108), which are exposed to toxic pollution with heavy metals from mining activities (Table 6). Deviations for this element were also established by Patronov & Kirin (2024). After 2021, the Phytobenthos and Fishes indicators also do not meet the requirements. And if for Phytobenthos, deviations are related to organic and biogenic water pollution, for Fishes, the most critical are river sections with built SHPPs (Fig. 7, Table 6). The changes in hydro-morphological conditions negatively affected fish and benthic invertebrates (Gecheva et al., 2023). In this sense, ensuring minimum ecological flow after water abstraction facilities, the construction or reconstruction of fish passes, and the modernization of aquaculture farms by using sensors for real-time monitoring of indicators such as dissolved oxygen are measures that should be taken into account. And last but not least, the objective analysis of the causes of water pollution and the availability of indicators with norm exceedances requires additional research like these carried out by Chunchukova et al. (2020) and Zaharieva & Kirin (2020).

## Conclusion

The results obtained in this study, dedicated to current tendencies in hydro-ecological conditions of a river system facing to climate change and anthropogenic impacts, reported: alternation in hydrological regime with an increasing variability and declining volume of annual runoff, relatively stable monthly and seasonal streamflow distribution, a rising hydro-morphological pressure from hydropower construction, riverbanks correction, and aquaculture farming, and despite the overall positive hydro-ecological trend – water pollution, given the registered deviations in biological and physicochemical quality elements.

The improvement of the general hydro-ecological status and river water protection requires the application of a complex of environmental, engineering, and legislative measures, as well as measures for climate change mitigation. The environmental-friendly measures, that are possible to take, are related to the afforestation of riverside zones to reduce erosion and improve water retention, protection and restoration of wetlands as natural filters for pollution, and biodiversity improvement with exercising control over the invasive species. The measures with an engineering character are: a development and modernization of the water supply, sewerage, and treatment infrastructure with reduction of losses and increase of the purification effect; green infrastructure introduction (green roofs, rain gardens, and special pavements for natural water retention); introduction of energy and water-securing technologies, including water collection and turnover cycles for water reuse; construction of fish passages to maintain the natural migration roads, etc. In the context of sustainable management, the following activities are of great importance: development of integrated water resources management strategies, including for the cases of drought; reassessment of the regulations with stricter control over pollution and water abstraction, environmental standards for the industry and agriculture; introduction of incentives and sanctions such as "the pollutant pays"; optimization and/or expanding the monitoring networks with an introduction of new technologies to improve information security; environmental education and involvement of the local communities; and last but not least, expansion of the methodological and pilot scientific investigations to increase the objectivity of the assessed current and prognostic state, taking into account the dynamic changes, including climate change.

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## Author contribution

Conceptualization, methodology, writing – original draft, MM, GB. All authors have read and agreed to the published.

## Conflicts of interest

The authors declare no conflict of interest.

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# Global trends in watersheds prioritization - a bibliometric analysis

Ioana PASTOR[1,*], Alexandru NEDELEA[2], Sandu BOENGIU[3,*]

[1] University of Bucharest, Faculty of Geography, "Simion Mehedinti" Doctoral School, 1 Nicolae Bălcescu, 010041, Bucharest, Romania
[2] University of Bucharest, Faculty of Geography, Department of Geomorphology-Pedology-Geomatics, 1 Nicolae Bălcescu, 010041, Bucharest, Romania
[3] University of Craiova, Faculty of Sciences, Geography Department, 13 A.I. Cuza Street, 200585, Craiova, Romania
* *Corresponding author*: ioana.pastor@s.unibuc.ro, sboengiu@central.ucv.ro

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**Abstract**

The prioritizing of watersheds is a significant concern for researchers and decision-makers in the context of intensifying hydrological and geomorphological processes. Consequently, implementing territorial management measures has become a priority. The main objective of this paper is to conduct a quantitative analysis of scientific production over time at the global level, through bibliometric methods. A total of 957 scientific and review articles addressing the concept of "prioritization of watersheds" were identified in the Web of Science database. Using the VOSviewer application, trends, co-authorship relationships, country distribution, leading authors, and citation counts were evaluated. The results indicate a steady increase in the number of publications between 1993 and 2025, with 2021 recording the highest number at 114 publications. The most productive countries in terms of publications are India and the USA, with American articles receiving the highest number of citations (8,618) and exhibiting the most extensive collaboration network. Nevertheless, India stands out with two publications each exceeding 400 citations. The involvement of researchers from 55 countries across six habitable continents, each contributing at least three articles, highlights the widespread interest in watershed prioritization. Accordingly, this study suggests future directions for applying the concept and for selecting journals and collaborators to facilitate interventions aimed at sustainable watershed management.
**Keywords:** *watershed prioritization, VosViewer, metadata analysis, research trends, GIS, environmental science, scientific collaboration*

## Introduction

Studies addressing the necessity of watershed prioritization begin with understanding the existence and functioning of a basin itself. The application of the "system" concept to analyze real-world phenomena was introduced by Chorley (1962), who defined the watershed as the "basic geomorphological unit of continents." A watershed is considered to operate as an integrated whole based on laws, models, and mathematical variables (Zăvoianu, 1978); however, the model does not fully coincide with the system concept, being more of an intuitive approach that envisions a behavioral pattern (Ichim et al., 1989). According to Zăvoianu (1978), a watershedis a complex system connected to its geographic environment through an exchange of matter, primarily from precipitation, and a continuous flow of energy supplied by solar radiation. Zaharia (1998) supports the open systems theory, where a watershed can reach a steady-state equilibrium when the inflow and outflow of matter and energy balance each other (this principle underpins the evolution and functioning of all watersheds). Nonetheless, such a system becomes highly susceptible to sudden changes caused by climate warming and human activities (Denissen et al., 2022). Both natural and anthropogenic factors can induce structural and irreversible changes to water and soil resources (Armaș, 1999; Chendeș et al., 2008; Constantin et al., 2011; Ebrahimi Gatgash & Sadeghi, 2024). The expected population growth to approximately 9 billion by 2050 will generate major imbalances in watersheds due to deforestation for urban expansion and irrational resource use (Murătoreanu et al., 2025), threatening food security (Zhang et al., 2024). Therefore, the studies on watershed prioritization can serve as valuable support for authorities in managing natural hazards, guiding decision-makers to focus on basins requiring immediate protection and conservation measures (Chaudhary & Pandey, 2022; Pathare & Pathare, 2021; Shelar et al., 2022; Sarkar et al., 2022).

The aim of this paper is to identify research trends and directions concerning the concept of "prioritization of watersheds" through an analysis of literature indexed in the Web of Science database. Bibliometric analysis provides a clear picture of the international visibility of this research topic. To achieve this, VOSviewer is used to:

- Visualize the temporal evolution of the number of published articles,
- Map the spatial distribution of publications,
- Identify the most influential authors and their co-authorship networks.

This study offers relevant insights into the development and analytical directions of this subject, as well as its scientific impact. Such understanding supports the foundation of research strategies and prioritization of topics based on their prominence, ultimately providing better guidance to decision-makers for effective and timely intervention.

## Theoretical background

The concept of "prioritization of watersheds" has broad applicability at both global and regional scales. Prioritizing anthropogenic interventions (Oli & Pandey, 2024) involves identifying watersheds that require immediate management actions (Halder et al., 2024) and ranking them according to their priority level (Ojha et al., 2023). Previous studies applied watershed prioritization to analyze phenomena, such as flash floods, landslides (Singh et al., 2021), floods (Avand et al., 2021), or pedological droughts (Sousa Estacio et al., 2022), with the aim of conserving both water and soil resources within the analyzed watershed (Pathare & Pathare, 2021). With the advancement of Geographic Information Systems (GIS) and modern techniques for integrating multiple parameters and variables influencing natural hazard occurrence, prioritization studies at the watershed level have become increasingly efficient and practical (Bogale, 2021).

Over time, analyses have incorporated various parameters related to basin area, shape, and length (Meshram & Sharma, 2017); relief configuration aspects such as slope, aspect, and maximum altitude (Chandniha & Kansal, 2017); and geometric factors of the drainage network (Ghosh & Gope, 2021). Basin shape serves as an indicator of the time water is retained and provides information about susceptibility to flash floods, especially in circular basins (Schumm, 1956). Vegetation cover is also relevant due to its capacity to absorb precipitation and reduce soil erosion (Esa et al., 2018). However, the literature reveals multiple approaches, methods, and integrated parameters (Tukura et al., 2021; Odiji et al., 2021; Sankriti et al., 2021), which can sometimes pose limitations. Whether 9, 13, or 18 morphometric parameters are used, the choice of a method that does not weigh the importance of each parameter in assessing hazard susceptibility may lead to the overshadowing of extreme values (Pastor et al., 2024). Therefore, it becomes imperative to identify the most robust model applicable to basins with similar physical properties.

Previous research is divided both methodologically and in terms of applicability. Approaches differ depending on objectives and parameters analyzed: some focus solely on identifying a single hazard type, while others integrate environmental factors with morphometric parameters for multi-hazard assessment. Applied methods range from classical techniques like fuzzy logic and analytic hierarchy process (AHP) (Ahmed et al., 2018) to advanced machine learning methods (ML) (Derakhshani et al., 2023; Darji et al., 2023).

Bibliometric analysis is a branch of scientometrics that quantitatively examines scientific output by applying mathematical and statistical indicators for graphical and cartographic representation of evolution and dynamics research (Donthu et al., 2021).

Bibliometric analysis has a broad range of applications across fields such as medicine (Barrington et al., 2023), education (Lozada et al., 2021), mathematics (Peng et al., 2020), and finance (Nath & Chowdhury, 2021). It can also be applied in environmental science to analyze the interest devoted to watersheds (Beigi et al., 2026). As an objective analytical method, it has the capacity to interrogate large datasets effectively.

Recently, bibliometric analysis has been used to map research evolution in the field of watershed stability, identifying publication trends, institutional collaborations, and spatiotemporal publication patterns (Beigi et al., 2026). However, there is currently no dedicated bibliometric analysis focused exclusively on watershed prioritization, highlighting the relevance and necessity of the present study.

# Methodology

With the increasing emphasis on the concept of sustainable development, the importance of focusing research on territorial planning and watershed management has increasingly attracted the attention of researchers. Scientific production serves as a foundation for policymakers and administrators, with its quality measured by the impact of the studies (Pranckutė, 2021). The aim of this paper is to present the current state of research on watershed prioritization, focusing on the connections established among authors, countries, and institutions, as well as the progression and popularity of publications. Bibliometric analysis achieves these objectives.

The Web of Science Core Collection (WOS) database was selected for this study due to its extensive bibliographic resources and its status as one of the oldest and most widely recognized databases worldwide (Li et al., 2018), attributed to its interdisciplinary character and advanced citation analysis functionalities (Pranckutė, 2021). The keyword "prioritization of watersheds" was used to identify a total of 1001 records containing the term in the title, abstract, or keywords. Filters were applied to improve research efficiency by excluding document types such as proceedings papers, early access articles, and book chapters. The language was restricted to English, covering the entire available time span.

The retrieved results were downloaded in two files using the BibTeX format and the full records function. For data analysis, the VOSviewer software (Van Eck & Waltman, 2010), version 1.6.20, was employed. Within this software, bibliographic maps were created from the

two downloaded files. The following indicators were analyzed: the number of articles published between 1993 and 2025, country distribution, citation counts, and co-authorship patterns. The dataset was subjected to filters including full counting, limiting the maximum number of authors per document to 10, and setting a minimum of 5 documents per author to reduce author redundancy. Country-level values were visualized using the Map Chart feature in Microsoft Excel (version 365), which uses data provided by Bing Maps and its contributors (© Australian Bureau of Statistics, GeoNames, Microsoft, Navinfo, Open Places, OpenStreetMap, Overture Maps Foundation, TomTom, Zenrin).

## Results

### Publication trends

The data were extracted from the Web of Science, providing access to relevant scientific literature. The use of VOSviewer was used to visualize trends by exporting and processing data in Microsoft Excel, which highlighted the increasing research interest during specific periods. Figure 1 presents the evolution of scientific publications on watershed prioritization from 1993 to 2025. A total of 957 scientific articles and review papers were identified in the Web of Science database as of August 2025. The trajectory of the graph shows a rapid increase in the number of publications from 1993 to 2025. This growth can be attributed to a renewed research interest in watershed prioritization in the context of climate change and hazard management.

Moreover, the publication dynamics from 1993 to 2025 were grouped into three phases: slow growth, with an average of 4.71 publications per year (1993-2008); moderate growth, with an average of 29.7 publications per year (2009-2018); and rapid growth, with an average of 84.86 publications per year (2019-2025). The exponential regression coefficient of the graph was 0.75, indicating a positive growth trend in the research field. The highest number of publications (11.91%) was recorded in 2021. Among these, the majority were articles (907), followed by 55 proceeding papers and 16 review articles.

The results reveal that most publications related to watershed prioritization fall under the Environmental Sciences category (463 articles), reflecting a significant interest in environmental impact and land use planning. A considerable number of articles (322) were published in Water Resources, a field known for studies evaluating flood susceptibility and proposing water resource conservation and watershed management measures. Additionally, 85 articles were published in Remote Sensing, predominantly from India, which is also the origin of the "watershed prioritization" concept through a 1993 study titled “Watersheds Prioritization Using Remote-Sensing Techniques: A Case Study of the Mahbubnagar District, Andhra Pradesh, India.”

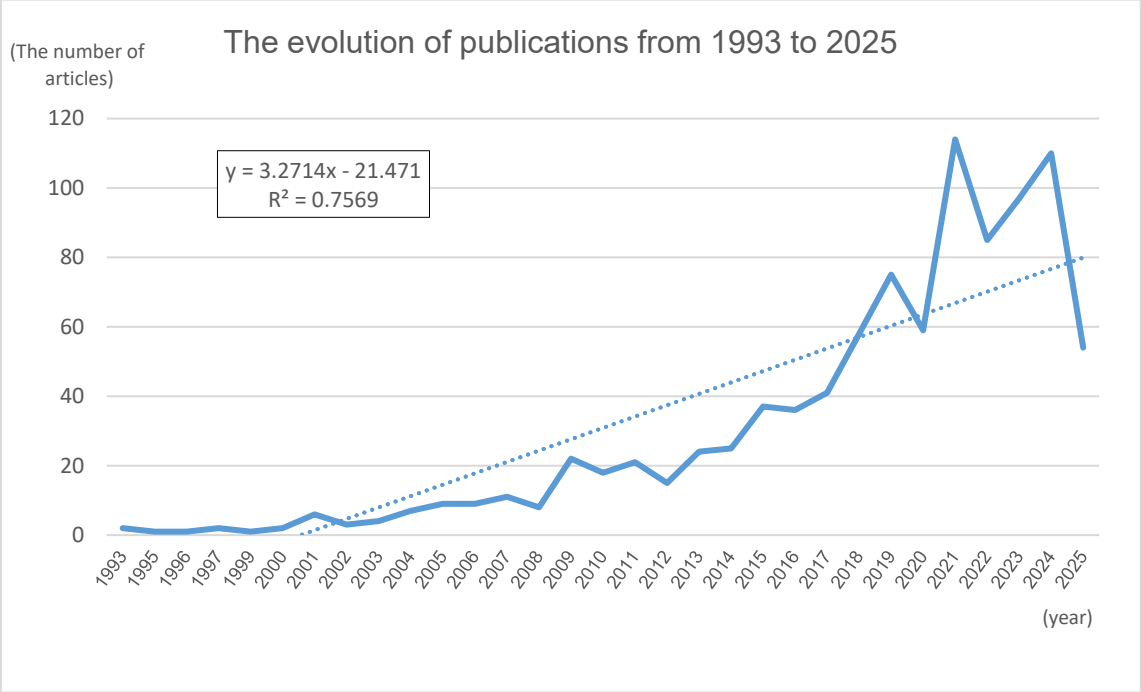


**Figure 1. Evolution of scientific publications on watershed prioritization from 1993 to 2025**

## Spatial distribution of publications

Figure 2 illustrates the distribution of total publications across different countries worldwide. A selection of 55 countries was made, each with a minimum of three articles. To provide an overview of the global level of interest in this topic, the number of publications per country is represented cartographically. It can be observed that, during the period 1993-2025, the highest number of articles on watershed prioritization (23%) were published by India (302) and the USA (295), with the American articles receiving the most citations (8618), followed by the Indian articles (6502).

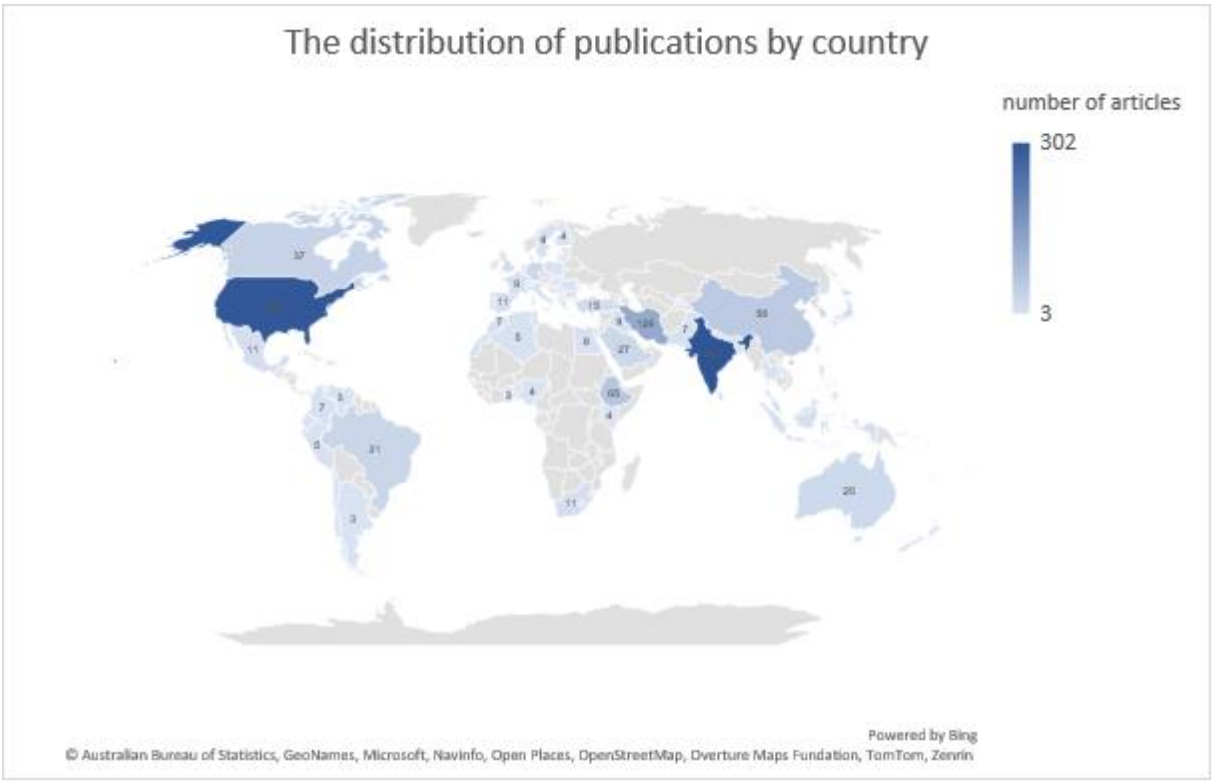


**Figure 2. Distribution of the number of publications by country (*Visualized using Microsoft Excel Map Chart*)**

## Co-authorship networks and influence of publications

Figure 3 presents a visualization map of the co-authorship networks among the 55 selected countries. The scientific production map provides information about the number of co-authored articles published between researchers from two countries. Several trends can be observed. First of all, the size of the nodes indicates that two main countries are the most involved in the collaboration network, especially the USA and India, forming two regional poles.

The small distance between nodes indicates a closer collaboration between researchers and institutions of the two countries. It can be observed that there are frequent collaborations between the two countries. The USA has a total of 87 publications produced in collaboration with 35 other countries, including India, Germany, New Zealand, Australia, and Argentina. India is the second regional hub that stands out, not only by the number of publications but also by its international collaborations. Collaborations with 33 other countries have been identified. According to the TLS (total link strength) indicators, the country is very influential and active in terms of the number of joint articles. On average, India published two articles in collaboration with the same state.

One can observe the subdivision of these countries, grouped by colors based on their geographical position or common interests. A first grouping is made by the states: India, Saudi Arabia, Morocco, and Egypt, highlighted in red. The cluster indicates that they collaborate more with each other, having common interests such as environmental issues related to drought, water stress, or agriculture, given their latitudinal positioning. Moreover, the geopolitical context can facilitate the development of common partnerships between North Africa, the Middle East, and South Asia due to their proximity. Another cluster can be observed among Asian states: China, South Korea, Pakistan, Indonesia, and Thailand, which further supports this pattern based on regional proximity.

Distant clusters can also be observed, such as Bangladesh or Ecuador. For example, Ecuador has limited collaborations with the USA but not few publications, a fact that can be supported by internal collaborations. It is part of the Latin American regional network, while the

USA is grouped in the central cluster, which is why connections have been made between the two states.

In Table 1, we present a list of authors with at least five publications in the field of watershed prioritization research, along with their citation counts and countries of origin. As of September 1, 2025, the most prolific authors are Pourghasemi, with a total of 489 citations, including 20 for the article titled "Prioritization of water erosion-prone subwatersheds using three ensemble methods in Qareaghaj catchment, southern Iran"; and Meshram Sarita, with a total of 448 citations, of which 124 are for the article "Prioritization of watersheds through morphometric parameters: a PCA-based approach" and 89 for "Comparison of AHP and fuzzy AHP models for prioritization of watersheds." Another notable contributor is Pandey, who has a total of 445 citations and holds the highest citation count for a single article on watershed prioritization (249 citations) published in 2007, titled "Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing."

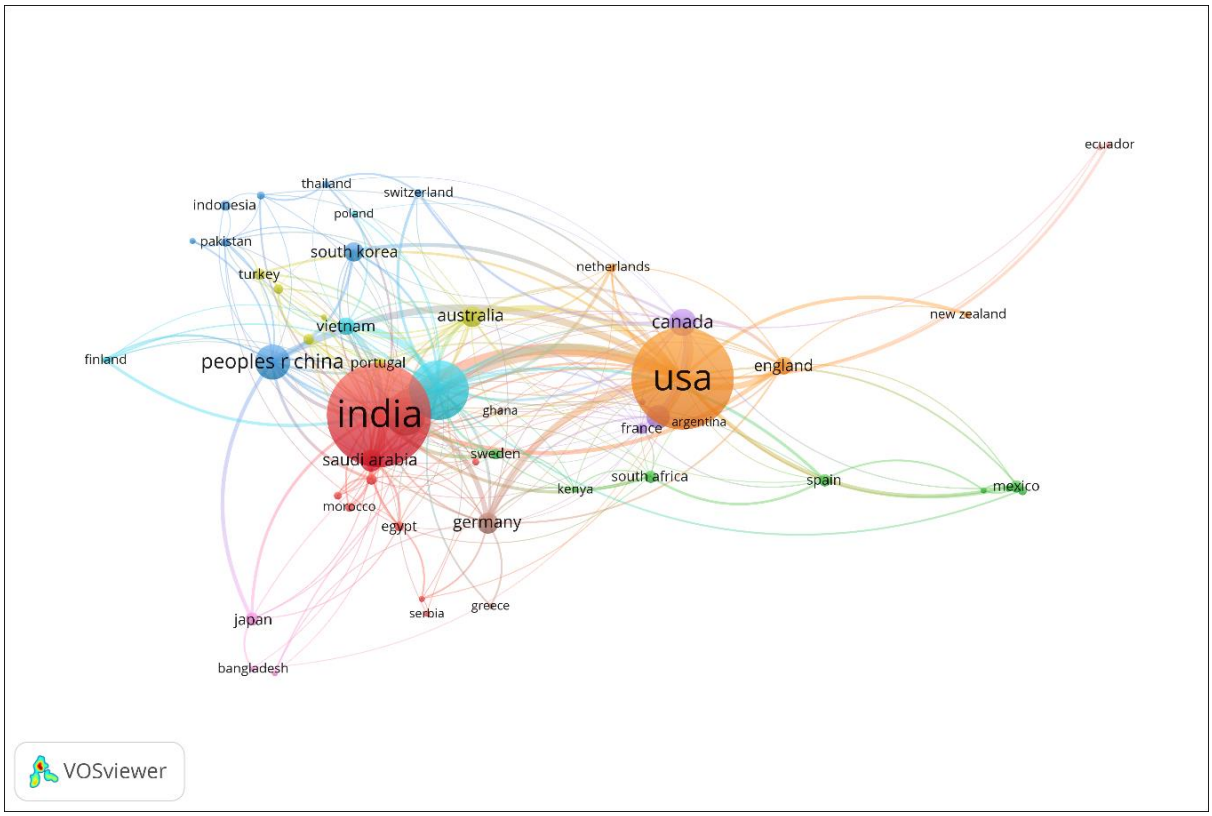


**Figure 3. Bibliometric map of scientific output by country (*Source: Own processing in VOSviewer software*)**

**Table 1. Citation counts for authors with a minimum of 5 articles indexed in the Web of Science database**

| No. | Author (Web of Science) | Number of articles | Number of citations | Country |
|---|---|---|---|---|
| 1 | Alvandi, Ehsan | 6 | 245 | Iran |
| 2 | Chung, Eun-Sung | 7 | 295 | South Korea |
| 3 | Khiavi, Ali Nasiri | 11 | 114 | Iran |
| 4 | Mathew, Aneesh | 5 | 55 | India |
| 5 | Meshram, Chandrashekhar | 8 | 238 | India |
| 6 | Meshram, Sarita Gajbhiye | 12 | 448 | India |
| 7 | Pandey, Ashish | 5 | 445 | India |
| 8 | Patel, Dhruvesh P. | 5 | 298 | India |
| 9 | Pourghasemi, Hamid Reza | 8 | 489 | Iran |
| 10 | Sadeghi, Seyed Hamidreza | 15 | 259 | Iran |
| 11 | Saghafian, Bahram | 6 | 58 | Iran |
| 12 | Shekar, Padala Raja | 5 | 55 | India |
| 13 | Singh, Sudhir Kumar | 7 | 63 | India |

| | | | | |
|---|---|---|---|---|
| 14 | Singh, Vijay P. | 5 | 135 | USA |
| 15 | Srivastava, Prashant K. | 5 | 299 | India |
| 16 | Vafakhah, Mehdi | 9 | 57 | Iran |

The authors were affiliated with 5 countries: India (8 authors), Iran (6 authors), South Korea, and the USA (one author each). Based on what can be observed on the bibliographic map (Fig. 4), Meshram Sarita has the most articles co-authored with other authors (14 collaborators) and a total of 186 articles written in collaboration. This is immediately followed by Meshram Chandrashekhar, with 12 collaborators and 133 articles together, Sadeghi (12 collaborators) and Alvandi (10 collaborators). It has thus been demonstrated that the collaborative relationship is very close, which has led to an increase in the number of articles and the number of citations of these articles.

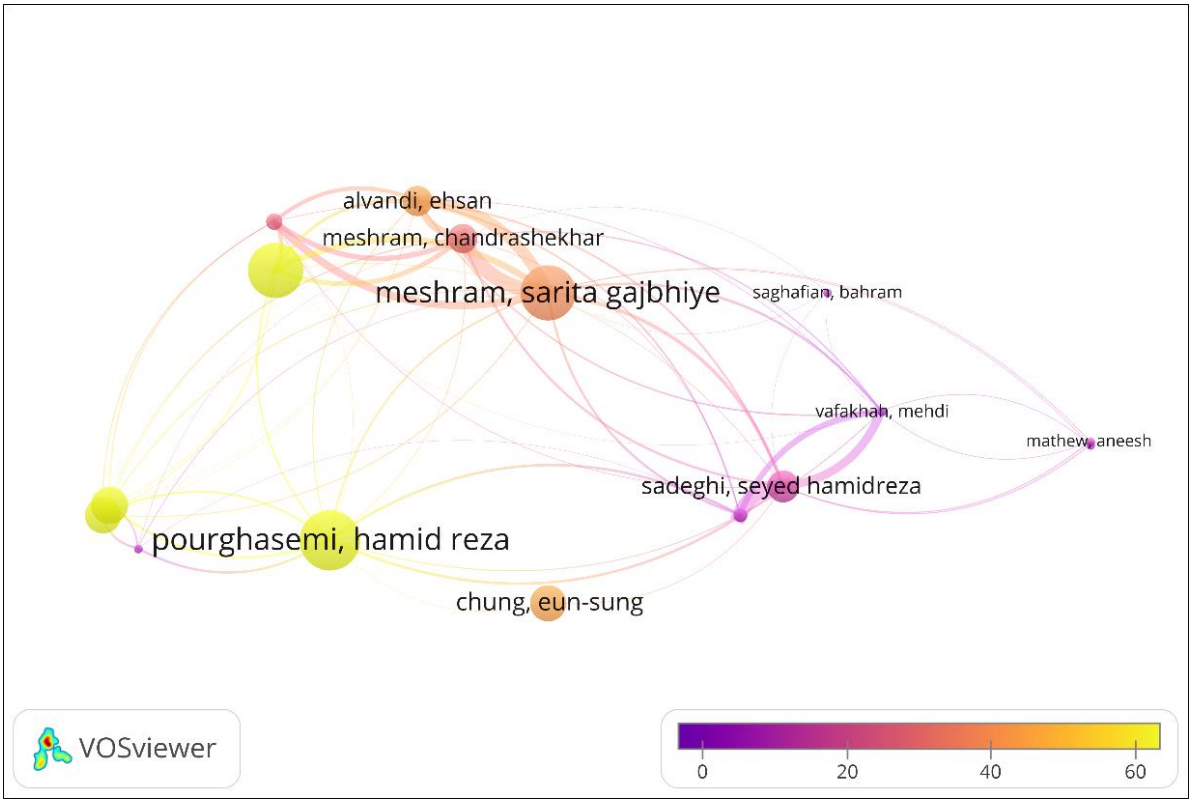


**Figure 4. Bibliometric map of the number of citations per author (*Source: Own processing in VOSviewer software*)**

## Discussion

### Socio-Economic analysis of scientific output in India

India's scientific output has increased from 62.46% during the period 2001-2006 to 72.7% between 2016 and 2020 (Kanaujia et al., 2022). Between 2017 and 2022, India produced approximately 1.3 million scientific articles, significantly exceeding the global average of 22% (https://www.scival.com/landing). In 2023, India ranked among the top 4 countries producing over 100 000 publications, according to the Science and Engineering Indicators report by the National Science Foundation (https://ncses.nsf.gov/pubs/nsb20257/publication-output-by-geography-and-scientific-field#publication-output-by-geography-and-scientific-field). Furthermore, data from the Nature Index reveal a steady increase in output, reaching 1,783 publications in 2024 (https://www.nature.com/nature-index/country-outputs/India).

This upward trend is supported by government funding, which accounts for over 45% of the country's gross expenditure on research and development (Kanaujia et al., 2022).

The advancement of research is closely aligned with socio-economic priorities aimed at fostering innovation, enhancing global competitiveness, and developing a highly skilled workforce (Singh et al., 2020). Inclusion in international databases further enhances the visibility of Indian research, while the large number of universities and research and development centers (exceeding 1,000 universities and numerous government-funded research institutes) provides substantial support for this growth (Garg & Tripathi, 2018).

Investments in the R&D sector represent a model to follow for increasing global publications. For Romania, India's policies can serve as a model in terms of resource management and prioritizing research areas. Moreover, promoting international collaborations, especially with renowned institutes and researchers, can contribute to increasing international visibility and facilitating the exchange of ideas and data (Dua et al., 2023).

To guide researchers, the efficient identification of gaps in the specialized literature becomes necessary. Choosing modern methods for quantifying research history facilitates the quantification of a large dataset, but it can exclude relevant articles indexed in other databases, such as Scopus or regional ones from ScienceDirect, SpringerLink, or Google Scholar.

Recent publications and those from less visible journals may be underrepresented. Thus, in the future, integrating more databases could reduce this limit and improve the result. Recent studies on environmental protection or water resource utilization use traditional visualization methods (CiteSpace) for the purpose of identifying keywords or co-citations (Zhao et al., 2025). Machine learning-based methods can improve these analyzes by more quickly and efficiently identifying the methods or parameters analyzed in watershed management (Mingaleva et al., 2023).

Literature can be fragmented, so the concept of "prioritization of watersheds" may not be mentioned directly in the title or may be expressed differently in another language. In the case of Romania, it can be observed that 3 articles registered in the VosViewer database have been published over time. However, a limitation of this software is that it queries the authors' affiliation, so articles written in teams can be registered multiple times. Analyzing in detail, I observed that as of this moment, there is only one article registered in the aforementioned database that addresses the topic of "prioritization of watersheds" in Romania. This article is published by Pastor et al. (2024) and authored by researchers and professors from 3 universities in the country, which explains its appearance in issue 3 in terms of co-author affiliations. Thus, one of the main limitations of bibliometric analysis is the masking of the actual number of publications, as VosViewer by default applies full counting.

Furthermore, citations do not necessarily reflect the scientific quality or relevance of the article but are influenced by their accessibility or the year of publication. A recent article is receiving a much smaller number of citations compared to a previous one (Preciado Ortiz et al., 2018), and it is not possible to estimate its long-term impact at this time.

## Conclusions

This paper provided a quantitative analysis of the term "watershed prioritization" through Web of Science and bibliometric analysis performed in VOSviewer. The following were analyzed: the evolution of the number of publications, the distribution by country, and the collaboration relationships among researchers.

The results showed a trend of increasing the number of publications during the period 1993-2015, with the most articles published in 2021. Most of them were published in the journals Environmental Sciences and Water Resources, supporting their applicability in water resource management and land-use planning decision-making. The results of the spatial distribution of publications globally indicated that India holds the largest contribution to scientific production (23%), followed by the USA. India has stood out as an important hub of expertise. In the citation ranking, most of the authors affiliated with Indian institutes and universities have positioned themselves, with Pandey Ashish standing out with a total of 249 citations for a single article, followed by Meshram Sarita Gajbhiye, who has the most extensive collaboration network.

Funding policies in the field of Indian research and development represent support in increasing the international visibility of research products and contribute to encouraging collaborations. Thus, decision-makers can adopt policies to stimulate the formation of partnerships between institutions and researchers. This would allow for the exchange of knowledge and access to diverse resources. Funding strategies could strengthen the country's position in global rankings.

However, while bibliometric analysis is applicable in guiding researchers to understand the concept and identify the most relevant publications and methods, it also has some limitations. Firstly, the analysis was conducted exclusively using the Web of Science database; integrating datasets from other platforms such as Scopus or Google Scholar, doctoral theses, and other works from regional databases can improve the quality of the study. Secondly, a qualitative assessment is also necessary, as VOSviewer can multiply the number of publications per country, taking into account the affiliation of each author. Furthermore, the number of citations can be easily quantified, but this indicator does not automatically guarantee quality, relevance, and scientific and methodological validity. The use of machine learning algorithms could improve bibliometric analysis in the future.

However, this paper serves as a starting point for more extensive future research that would include an optimal and representative database: It can also guide researchers in choosing the optimal methods used, bibliographic sources, publishing journals, and collaboration partners. In the long term, analyzing trends and identifying the best advanced analytical methods can facilitate the identification of the most hazard-prone watersheds and help authorities allocate resources efficiently and adopt effective prevention and adaptation measures.

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## Author contribution

Conceptualization, IP, AN and SB; methodology, IP, AN and SB; formal analysis, IP, AN and SB; investigation, IP, AN and SB; writing—original draft preparation, IP; writing—review and editing, AN and SB. All authors have read and agreed to the published version of the manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

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# Spatial prediction of flood hazard susceptibility level in Majene urban area, West Sulawesi, Indonesia

Rahmiyatal MUNAJA[1], Nur Ratika SYAMSIAR[2], Anggit PRIADMODJO[2,*], Ade MULAWARMAN[2], Nur Fitriani MASKUR[1], Adip WAHYUDI[3], Muh. Alfarezi ERWIN[2]

[1] Center for Studies on Disasters and Volunteerism, Universitas Sulawesi Barat, Jl. Prof. Dr. Baharuddin Lopa, S.H., Talumung, Majene, West Sulawesi 91412, Indonesia
[2] Department of Urban and Regional Planning, Universitas Sulawesi Barat, Jl. Prof. Dr. Baharuddin Lopa, S.H., Talumung, Majene, West Sulawesi 91412, Indonesia
[3] Department of Geography, Universitas Negeri Malang, Jl. Semarang 5, Malang, East Java 65145, Indonesia
* *Corresponding author*: anggit.priadmodjo@unsulbar.ac.id

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**Abstract**

This study models flood hazard susceptibility in the Majene urban area, West Sulawesi, Indonesia, for 2029–2049 using a GIS-based framework. It examines how land cover transformation associated with rapid urban growth and educational infrastructure expansion influences flood risk. A coupled Cellular Automata–Artificial Neural Network (CA–ANN) model was applied to simulate land cover change, while Multi-Criteria Decision Analysis (MCDA) was used to assess flood susceptibility. Land cover projections were derived from satellite imagery (2014, 2019, 2024). Validation against observed 2024 land cover produced an overall accuracy of 80.51% and a kappa coefficient of 0.62, indicating substantial predictive performance. Flood susceptibility was evaluated through weighted overlay of six biophysical parameters: land cover, slope, elevation, rainfall, distance to rivers, and soil type. Results indicate continued expansion of built-up and plantation areas, accompanied by reductions in grassland and open land. Susceptibility maps classify the area into low, medium, and high zones. Projections suggest a gradual decline in high-susceptibility areas and expansion of medium-susceptibility zones between 2029 and 2049. This shift is associated with increased vegetation cover from plantation growth, which may enhance infiltration and moderate runoff. The findings demonstrate the dynamic interaction between urban expansion and flood susceptibility, providing spatially explicit evidence to support risk-sensitive spatial planning, disaster risk reduction, and sustainable land management in rapidly developing coastal cities.
**Keywords:** *flood susceptibility, land cover prediction, spatial, GIS, Majene urban area*

## Introduction

Majene Regency is an area in West Sulawesi Province that has experienced rapid development, primarily driven by the determination of Majene Regency to become the center for educational development in West Sulawesi Province, as outlined in West Sulawesi Provincial Regulation Number 1 of 2014 concerning the Spatial Plan of West Sulawesi Province for 2014-2034. Furthermore, in Majene Regency Regulation Number 12 of 2012 concerning the Spatial Plan of Majene Regency for the period 2011-2031, the areas prioritized for the development of education centers are the Banggae and East Banggae Districts. This has encouraged the development of several universities in the urban area of Majene, including West Sulawesi University (UNSULBAR), State Islamic College (STAIN), Open University, and several other private campuses. The presence of multiple university campuses functions as a catalyst for regional development by stimulating diverse socio-economic activities and increasing demand for land and services. Empirical studies consistently show that university-driven development contributes to land-use transformation, population inflow, and intensified built-up expansion in surrounding areas (Rahman et al., 2024; Mohammed et al., 2022; Omollo, 2022; Mohammed & Ukai, 2021; Ambraini et al., 2020). The existence of several campuses can lead to an increase in the area's population (Institute of Economic Development & AtkinsRéalis, 2025; Awang et al., 2025; Wang & Tang, 2020) with the majority of the population comprising students. As student populations increase, supporting commercial and residential activities emerge, reinforcing spatial transformation dynamics.

Land cover change in Majene Regency is significant. Data from the Indonesian Geospatial Information Agency (BIG) show that built-up area coverage in Banggae and East Banggae Districts increased from 10.38% in 2012 to 12.54% in 2018 and 13.74% in 2022. This represents an overall increase of 3.36% in less than a decade. Limited land availability intensifies the conversion of non-built-up land into residential and service-oriented land uses (Adu et al., 2025; Imaduddin et al., 2025; Oktavilia et al., 2022; Ambraini et al., 2020)

Majene's urban expansion occurs predominantly along coastal zones, which are inherently vulnerable to

natural hazards and climate change impacts (Asensio-Montesinos et al., 2024; Zhang et al., 2024; Noor & Abdul Maulud, 2022; Nasution et al., 2020). With its rapidly growing population,concentrated socio-economic activities, and coastal characteristics, Majene faces heightened exposure to flood hazards. According to the Indonesian Disaster Risk Index (Bagaskoro et al., 2025), Majene ranks first among regencies in West Sulawesi Province in terms of disaster risk, with a particularly high flood hazard score of 21.9. Flooding frequently affects the Majene urban area, with significant events recorded in recent years, including a major flood in 2022 that damaged public facilities, schools, markets, and administrative centers (Syukri et al., 2025). The increasing conversion of natural land into built-up areas reduces water infiltration capacity and intensifies surface runoff,exacerbating flood risk.

Disaster mitigation efforts in Majene remain limited, often reactive rather than preventive (Mawan, 2021). Strengthening mitigation requires improved data availability, risk mapping, and predictive modeling (Wang et al., 2025; Khan et al., 2023; Nur et al., 2022; Jayawardene et al., 2021). Flood susceptibility prediction using spatial modeling and GIS-based analysis provides a valuable foundation for proactive disaster risk reduction. Consistent with previous research, GIS and spatial modeling techniques are effective for assessing current and future flood susceptibility (Khodaei et al., 2025; Nkonu & Antwi, 2024).

Therefore, this study aims to analyze how projected land cover dynamics driven by urban expansion influence the spatial–temporal evolution of flood hazard susceptibility in the Majene Urban Area over a 5-year interval period from 2029 to 2049 using integrated CA–ANN and MCDA approaches. The 5-years interval was chosen because, legally, national policy in Indonesia requires that disaster risk assessments in an area be updated every 5 years (BNPB Regulation No. 2 of 2012 on General Guidelines for Disaster Risk Assessment, 2012) and based on previous research (Qiu et al., 2024) indicates that using a five-year interval for hazard-susceptibility prediction effectively captures temporal fluctuations in hazard occurrence, thereby providing a more precise picture of the dynamic character of susceptibility. The findings are expected to support evidence-based planning and decision-making for flood mitigation in coastal urban environments.

## Methodology

This study employs quantitative research approach that, in addressing its research questions, employs the post-positivist paradigm in developing science and utilizes research strategies focused on numerical data. (Emzir, 2019). According to the characteristics of quantitative research in general (Arikunto, 2006). This study employs variables and data expressed in numerical units, which are processed from collection to the presentation of results, utilizing numerical values. The spatial approach employed in achieving the research objectives, using various methods to understand specific symptoms on the earth's surface through spatial media and spatial variables, takes a leading position in each analysis. (Yunus, 2010).

This study combines Cellular Automata – Artificial Neural Network (CA–ANN) and Multi-Criteria Decision Analysis (MCDA) to predict the susceptibility level of flood hazard in Majene. The analytical framework, as proposed in previous study by Nkonu & Antwi (2024), begins with CA–ANN analysis to predict land cover change in the Majene urban area over the coming years. The results will then be used in MCDA to map the spatial distribution of flood susceptibility levels within the area. The collection was carried out through primary and secondary data surveys, where the collected data have a spatial dimension that serves as a parameter in determining the level of susceptibility to flooding (Kusumo & Nursari, 2016). The data include land cover, rainfall, slope, soil type, elevation, and distance to the river. Land cover data is primary data acquired from very high-resolution vertical satellite imagery. To achieve the goal of flood susceptibility prediction, land cover prediction data are needed in the coming years, ensuring that the land cover data used spans different periods (Nuraeni et al., 2017). In this case, the data used are from satellite image recordings in 2014, 2019, and 2024. Slope and elevation data are primary data acquired from the Digital Elevation Model (DEM). Meanwhile, other spatial data are secondary data obtained from related agencies. The data analysis stages consist of three stages, namely:

*a. Spatial Data Preparation*

At this stage, the initial processing of the collected data is carried out. There are three initial processes carried out using ArcMap software, namely

1) On-screen digitization of high-resolution vertical satellite imagery recorded in 2014, 2019, and 2024 to obtain spatial data on land cover for each year. The accuracy of digitized data was analyzed using confusion matrix method (Congalton, 1991) which provides a comprehensive evaluation of the concordance between the sampled reference data and classification outcomes at designated locations, as well as an exhaustive account of misclassifications for each category (Stehman, 1997). Various statistical indices can be derived from the matrix to obtain accuracy metrics tailored to diverse requirements, including overall accuracy, kappa coefficient, user accuracy, and producer accuracy (Congalton, 1991);

2) Derivation of slope and elevation layers from DEM with spatial resolution of 8 m using spatial analyst tools;

3) Processing river network map using Euclidean Distance tools to obtain spatial data of area proximity to river network.

Furthermore, all spatial data were collected in one geodatabase.

*b. Land cover prediction using Cellular Automata - Artificial Neural Network (CA-ANN)*

Land cover prediction was conducted using the MOLUSCE plugin in QGIS. CA–ANN was selected due to its demonstrated effectiveness in simulating land cover dynamics (Sajan et al., 2022). The stages as follows:

• Inputs

The input stage involves entering spatial data on land cover in 2014 and 2019 as basic data, as well as road networks, which serve as driving factors for land cover changes, into the MOLUSCE tool. Land cover in 2014 is entered as initial data, and land cover in 2019 is entered as final data. Furthermore, geometry checks are carried out to ensure that all three datasets have the same geometry.

• Evaluating correlation

This stage involves determining the correlation between the variables that are driving factors.

• Area changes

This stage is conducted to identify changes in each type of land cover. This stage produces a transition matrix that contains information on the area of land cover changes from one type to another.

• Transition potential modeling

At this stage, training of the artificial neural network model is carried out using the following parameters: a neighborhood size of 1 px, a learning rate of 0.1, a maximum of 1000 iterations, a network topology with a multi-perceptron layer and 10 hidden layers, and a momentum of 0.05.

• Cellular automata simulation

Land cover prediction simulation is carried out using cellular automata with one iteration to produce an output in the form of a land cover prediction for 2024.

• Validation

The final step in land cover prediction is to evaluate the accuracy of the predicted land cover in 2024 against the actual land cover in 2024, as determined through digitization, which serves as the reference data. This test requires that the reference/comparator data used be more accurate. (Wiweka, 2014). Then, after the validation test meets the requirements, land cover prediction data for the five years interval from 2029 to 2049 are obtained by carrying out the CA simulation using two to six iterations.

*c. Flood Susceptibility Prediction Analysis*

Flood susceptibility prediction analysis is conducted using the Multi-Criteria Decision Analysis with overlay technique in ArcMAP 10.4. This technique, which involves multiple map datasets containing information with distinct characteristics, aims to gain new insights into the data. The overlay technique used is a weighted overlay in which spatial data that flood susceptibility parameters are given a certain weight that describes the extent of the variable's influence on the measurement object. (Karana & Supriharjo, 2013). Data analysis begins by providing scores and weights to all parameters. Scoring and weighting are based on the principle that the greater the influence of a parameter on flood susceptibility, the higher the score given, with the highest score being nine and vice versa. If the impact on flooding is lower, the score will be lower, with the lowest score being 1 (Matondang et al., 2013). Scoring for each parameter can be presented in the following table:

**Table 1. Flood Susceptibility Parameters**

| No. | Parameter | Weight | Class/grade | Score |
|---|---|---|---|---|
| 1. | Rainfall | 15 | >2500 | 9 |
| | | | 2001 – 2500 | 7 |
| | | | 1501 – 2000 | 5 |
| | | | 1001 – 1500 | 3 |
| | | | ≤1000 | 1 |
| 2. | Slope gradient | 10 | 0 – 8 % | 9 |
| | | | 8 – 15 % | 7 |
| | | | 15 – 25 % | 5 |
| | | | 25 – 40 % | 3 |
| | | | >40 % | 1 |
| 3. | Soil type | 10 | Vertisol, Oxisol | 9 |
| | | | Alfisol, Ultisol, Molysol | 7 |
| | | | Inceptisol | 5 |
| | | | Entisol, Histosol | 3 |
| | | | Spodosol, Andisol | 1 |
| 4. | Land cover | 25 | Open space – Water Bodies – Ponds | 9 |
| | | | Settlements – Rice Fields | 7 |
| | | | Plantation – Fields | 5 |
| | | | Mixed Garden – Shrubs | 3 |
| | | | Forest | 1 |
| 5. | Distance of the area to the river | 20 | 0 – 25 m | 9 |
| | | | 25 – 50 m | 7 |
| | | | 50 – 75 m | 5 |
| | | | 75 – 100 m | 3 |
| | | | >100 m | 1 |
| 6. | Elevation | 20 | 0 – 20 m | 9 |
| | | | 21 – 50 m | 7 |
| | | | 51 – 100 m | 5 |
| | | | 101 – 300 m | 3 |
| | | | >300 m | 1 |

*Source: Kusumo & Nursari, 2016*

Rainfall data used in this study were obtained from official meteorological records and represent long-term average annual precipitation (1501–2000 mm/year). Soil type data were sourced from the national soil database and categorized according to permeability characteristics relevant to runoff generation. The flood susceptibility value is determined by summing the scores of all six parameters that affect flooding (land use, altitude, distance of the area to rivers, rainfall, slope, and soil type), each weighted according to its importance. The analysis was carried out using ArcGIS software with the Weighted Sum Overlay tool. (Wahyuni et al., 2021). The susceptibility value is obtained using the following equation:

$$H = \sum (W_i \, x \, X_i)$$

where,

$H$ = Susceptibility value

$W_i$ =Weight for the parameter

$X_i$ = Class score on the parameter

The stage of the analysis can be presented as follows:

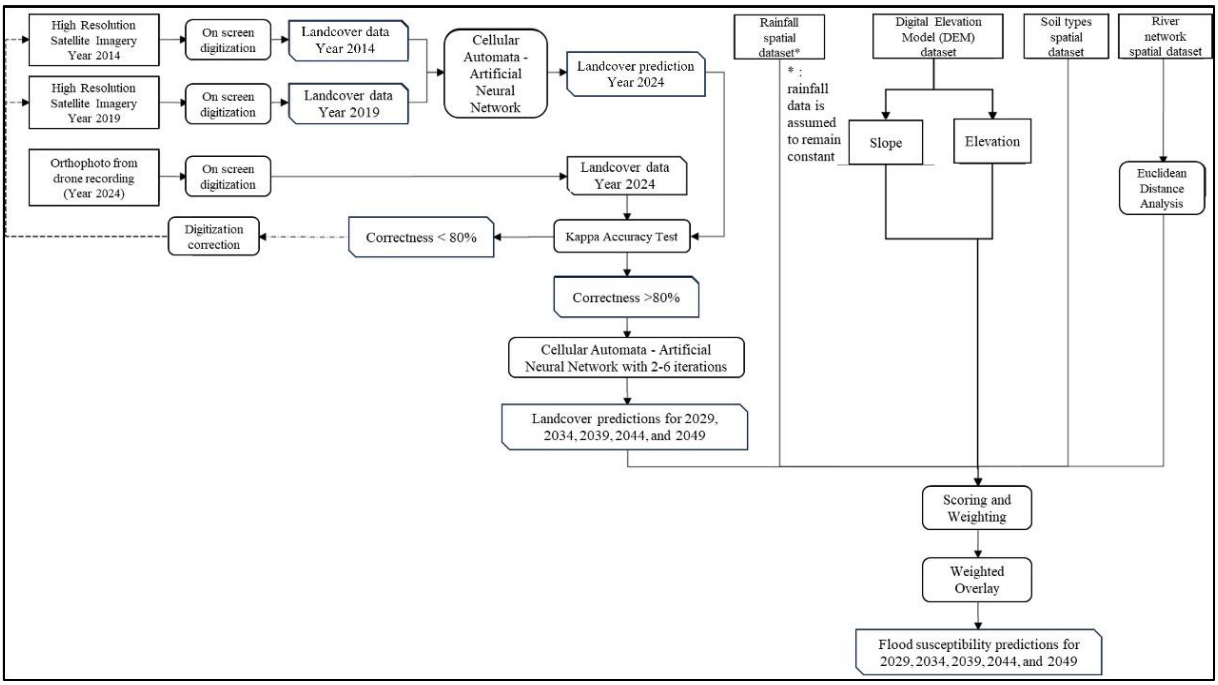


**Figure 1. Data analysis process flow**

## Results and discussion

### Land Cover Development in Majene urban area 2014-2024

The change in land cover from non-built land to built-up land is directly proportional to population growth in an area. With an increasing population in an area, the need for housing and land to support livelihoods will also increase. (Pimentel et al., 1997), which can lead to land conversion. In addition to occurring due to population concentration, land conversion can also result from the development of a new activity center, which can trigger the development of other supporting activities. (Chromicco, 2016). In the Majene urban area, the increase in population was triggered by the determination of the Majene urban areas, namely the Banggae and East Banggae Districts, to be centers of education. The spatial data of land cover of Majene urban area were obtained using on-screen digitation in ArcGIS software. The accuracy assessment of on-screen digitized land cover maps for the Majene Urban Area across 2014, 2019, and 2024 carried out using confusion matrix method and the result as shown in Table 2 demonstrates a consistently robust classification performance. Overall accuracy values of 84%, 79.69%, and 81.31%, respectively, exceed widely accepted thresholds for land cover mapping derived from visual interpretation of remote sensing imagery. Correspondingly, Kappa coefficients ranging from 0.68 to 0.69 indicate a substantial level of agreement between the classified outputs and reference data, confirming the reliability of the digitization process beyond chance effects, in line with contemporary land cover accuracy assessment guidelines (Tyukavina et al., 2025). The marginal decline in accuracy observed in 2019 is attributable to increased urban landscape heterogeneity and the introduction of additional land cover classes, such as bare or open land, which intensified class confusion during interpretation.

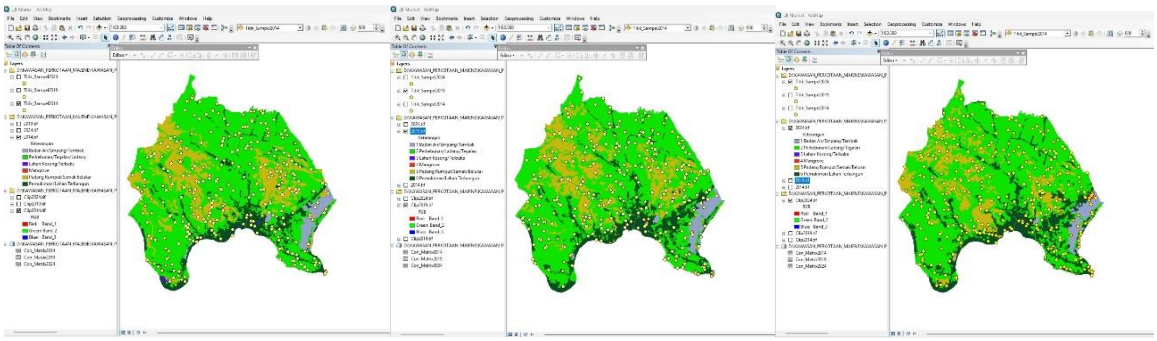

**Figure 2. Accuracy assessment process in ArcGIS for digitized land cover data year 2014, 2019 and 2024**

**Table 2. Confusion matrix of landcover digitized data year 2014, 2019 and 2024**

| Year | Number of Sample | Number of Classes | Overall Accuracy | Producer's Accuracy Range | User's Accuracy Range | Kappa Coefficient |
|---|---|---|---|---|---|---|
| 2014 | 320 | 5 | 0.84 | 0.64 – 1.00 | 0.64 – 1.00 | 0.692 |
| 2019 | 320 | 6 | 0.797 | 0.74 – 1.00 | 0.74 – 1.00 | 0.682 |
| 2024 | 320 | 6 | 0.813 | 0.73 – 1.00 | 0.79 – 1.00 | 0.695 |

Misclassification was predominantly concentrated within non-forest vegetation categories, particularly grassland/shrubland and plantation or dryland agriculture, due to their overlapping visual characteristics and frequent occurrence as spatial mosaics in urban–peri-urban transition zones. This source of uncertainty is consistent with recent land cover classification studies identifying mixed vegetation classes as a principal contributor to classification error, despite overall accuracy and Kappa values remaining within acceptable limits for urban spatial analysis and land-use planning applications (Gülci et al., 2025; Rwanga & Ndambuki, 2017; Congalton et al., 2014)

A comparison of land cover in 2014, 2019 and 2024 in the Majene urban area, which encompasses the Banggae and East Banggae Districts, is presented in Table 3 and Figure 3.

**Table 3. Changes in land cover in the Majene urban area in 2014, 2019 and 2024**

| No | Land cover | Area (ha) | | | Area Difference (ha) | | |
|---|---|---|---|---|---|---|---|
| | | Year 2014 | Year 2019 | Year 2024 | 2014-2019 | 2019-2024 | 2014-2024 |
| 1 | Water Body/ Pond / Fishpond | 158.02 | 160.39 | 153.17 | 2.37 | -7.22 | -4.85 |
| 2 | Plantation/ Dry land / Field | 3,427.9 | 3,325.6 | 3,393.8 | -102.28 | 68.24 | -34.04 |
| 3 | Vacant / Open Land | 7.92 | 0.97 | 2.55 | -6.95 | 1.58 | -5.37 |
| 4 | Mangrove | 2.01 | 3.02 | 10.37 | 1.01 | 7.35 | 8.36 |
| 5 | Grassland / Bushland | 980.02 | 948.11 | 765.25 | -31.91 | -182.86 | -214.77 |
| 6 | Residential / Built-up Land | 565.21 | 702.97 | 815.89 | 137.76 | 112.92 | 250.68 |

*Source: Data analysis, 2024*

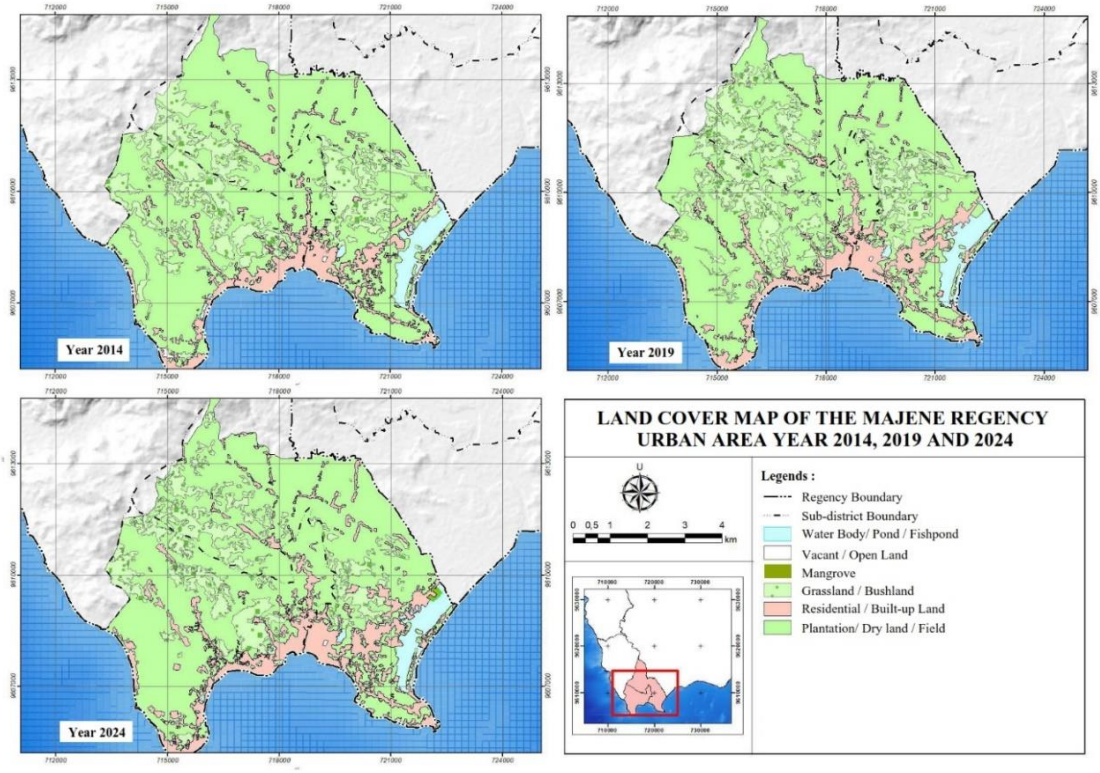


**Figure 3. Land cover map of urban areas in Majene Regency years 2014, 2019 and 2024 (*Source: Data analysis, 2024*)**

In the period 2014-2024, there was a change in non-built land cover to built land of 4.87% or an area of 250.68 ha, whereas in 2014-2019, there was a change in non-built land cover to built land of 137.75 ha and in 2019-2024 there was a change in non-built land cover to built land of 112.92 ha. The change in land cover over the 10 years (2014-2024) was primarily driven by changes in land cover of empty or open land, resulting in a total reduction of open land of 67.79%. The increasingly massive change in non-built land cover to built land in the urban area of Majene Regency is also confirmed by the results of compiling land cover maps in 2014, 2019 and 2024, as presented in Figure 3. Based on the maps in the figure, the area of residential land cover (marked in pink) has increased significantly.

## Land cover prediction model

The change in non-built land cover to built land is influenced by road infrastructure (Liem & Purwanto, 2022; Rusdi, 2013; Moore et al., 2007). A transportation system supported by good infrastructure will increase the movement of goods and services, which will also lead to changes in land cover. Specifically, land located in areas with good accessibility will tend to be more easily converted. Land cover prediction for the Majene urban area is preceded by making a land cover prediction in 2024, which will then be tested against digitized 2024 land cover spatial data as a reference. The probability of changing one land cover type to another between 2014 and 2019 is evident from the Transition Probability Matrix, which was generated using the MOLUSCE plugin in QGIS software and is presented in the following table.

**Table 4. Transition Probability Matrix (TPM) of land cover 2014 – 2019**

| | Water Body/ Pond / Fishpond | Plantation/ Dry land / Field | Vacant / Open Land | Mangrove | Grasslands / Shrubs / Thickets | Settlement / Built-up Land |
|---|---|---|---|---|---|---|
| **Water Body/ Pond / Fish-pond** | 0.9115 | 0.0357 | 0 | 0 | 0.0023 | 0.0504 |
| **Plantation/ Dry land / Field** | 0.0017 | 0.8457 | 0 | 0.0003 | 0.0974 | 0.0548 |
| **Vacant / Open Land** | 0 | 0.5169 | 0.1236 | 0 | 0 | 0.3595 |
| **Mangrove** | 0 | 0 | 0 | 0.9565 | 0 | 0.0435 |
| **Grassland / Bush / Thicket** | 0.0059 | 0.3554 | 0 | 0 | 0.6255 | 0.0132 |
| **Settlement / Built-up Land** | 0.0049 | 0.1169 | 0 | 0 | 0.0044 | 0.8737 |

*Source: Data analysis, 2024*

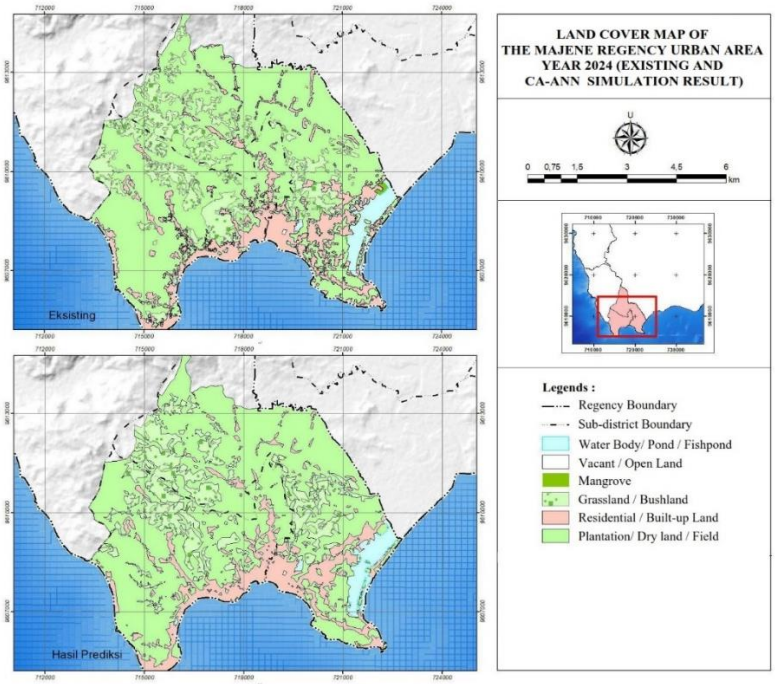


**Figure 4. Land cover map of Majene urban area in 2024, existing and predicted results (*Source: Data analysis, 2024*)**

Several types of land cover tend not to change into other types of land cover, as indicated by a TPM value of zero (0). Land cover that tends to change quite significantly into built-up land is open land with a probability value of

0.3595. The results of land predictions in 2024, obtained through the processing of the Cellular Automata-Artificial Neural Network (CA-ANN) method, and their comparison with the land cover in 2024 from the digitization results are shown in Figure 4.

Based on the comparison of existing land cover in 2024 with the predicted results from CA-ANN processing presented in Table 5, it is evident that the difference in area for each type of land cover between the existing 2024 data and the predicted results is relatively small. This indicates that CA-ANN processing based on land cover data from 2014 and 2019 for the Majene urban area yields fairly accurate land cover predictions. This is also supported by the analysis results' correctness percentage of 80.51% and a kappa value of 0.62, which is classified as good to strong. (Jenness & Wynne, 2005; McCoy, 2005), so that CA-ANN processing can continue to predict land cover development in the coming years, with road data serving as a driving factor.

The predicted results of land cover in the Majene urban area for 2029, 2034, 2039, 2044, and 2049 are presented in Figure 5, and the area of each type of land cover is shown in Table 6.

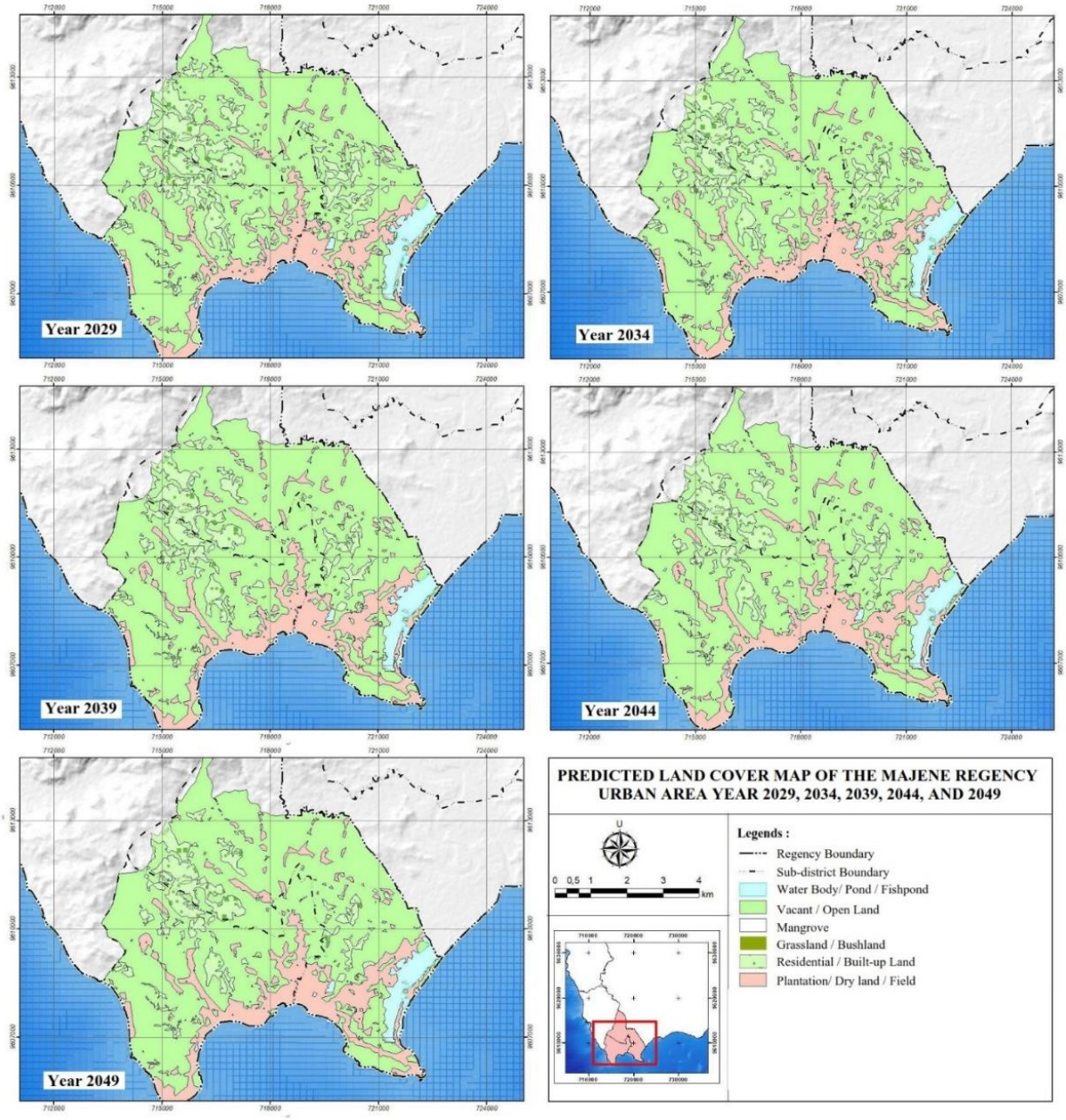


**Figure 5. Predicted land cover map of the Majene urban area in 2029, 2034, 2039, 2044 and 2049 (*Source: Data analysis, 2024*)**

**Table 5. Comparison of existing and predicted land cover in 2024**

| Land cover | Area (ha) | |
|---|---|---|
| | 2024 (existing) | 2024 (prediction) |
| Water Body/ Pond / Fishpond | 153.169 | 159.107 |
| Plantation/Field/ Dry Field | 3,393.808 | 3,407.260 |
| Vacant/Open Land | 2.550 | 0.913 |
| Mangrove | 10.367 | 2.958 |
| Grassland / Bush / Thicket | 765.246 | 804.910 |
| Residential / Built-up Land | 815.889 | 765.641 |

*Source: Data analysis, 2024*

**Table 6. Area of land cover types predicted for 2029, 2034, 2039, 2044 and 2049**

| Land cover | Area (ha) | | | | |
|---|---|---|---|---|---|
| | Year 2029 | Year 2034 | Year 2039 | Year 2044 | Year 2049 |
| Water Body/ Pond / Fishpond | 158.551 | 158.165 | 157.536 | 157.411 | 157.126 |
| Plantation/Field/ Dry Field | 3,471.837 | 3,518.886 | 3,555.747 | 3,583.855 | 3,603.281 |
| Vacant/Open Land | 0.913 | 0.913 | 0.913 | 0.913 | 0.913 |
| Mangrove | 2.958 | 2.958 | 2.958 | 2.958 | 2.958 |
| Grassland / Bush / Thicket | 694.246 | 613.331 | 552.450 | 505.173 | 471.166 |
| Residential / Built-up Land | 812.284 | 846.537 | 871.185 | 890.480 | 905.345 |

*Source: Data analysis, 2024*

The results of this prediction are consistent with the theory and results of previous studies, which state that infrastructure and regional development have a very close and continuous relationship, where infrastructure can be a force that forms regional development (Adisasmita, 2011), where, in terms of the development of the Majene urban area, road infrastructure can serve as a trigger for changes in land cover. Road development will trigger the growth of new economic activities, which can lead to population movement to these new centers of economic activity, ultimately encouraging an increase in the number of requests for residential and other built-up land to meet socio-economic needs. This is what characterizes the development of urban areas, where there is a change in land cover from non-built-up land to built-up land.

## Prediction of flood susceptibility

The flood susceptibility pattern in Majene in this study is modelled based on six variables: rainfall, slope, elevation, soil type, land cover, and proximity to rivers, which are widely recognized as the dominant climatic, morphometric, and land-surface drivers of pluvial and fluvial flooding.

This study emphasizes on modelling of relative flood susceptibility mapping, not physically based hydrodynamic flood depth simulation. While hydrodynamic models require discharge measurements, drainage network density, channel geometry, and boundary conditions, susceptibility mapping aims to identify spatial likelihood patterns under prevailing environmental conditions (Alcântara et al., 2025; Shrestha et al., 2025). Within this framework, the selected six parameters adequately capture the dominant climatic, topographic, pedologic, and land-surface controls of pluvial and fluvial flooding at the urban scale. Tidal influence and groundwater dynamics were also not considered in modelling process due to the absence of long-term tidal gauge and hydrogeological datasets. Consequently, the model primarily captures relative pluvial and fluvial susceptibility rather than compound coastal–tidal flooding. Rainfall acts as the triggering factor, while slope and elevation regulate runoff concentration in low-lying terrain. Soil properties influence infiltration and sediment transport, land cover modifies surface permeability, and river proximity captures floodplain exposure. Similar predictor dominance identified terrain, rainfall, land use, and river distance as statistically robust flood susceptibility determinants across machine-learning and GIS-based frameworks (Jumadi et al., 2024; Farhadi & Najafzadeh, 2021; Khosravi et al., 2019).

The key contribution of this study lies in integrating CA–ANN-based land cover prediction with MCDA flood susceptibility assessment under multi-temporal urban growth scenarios (2029–2049). Unlike static susceptibility analyses, this framework embeds projected land-use transitions into hazard modelling, enabling dynamic evaluation of how urban expansion reshapes flood risk

distribution. Compared with previous CA–ANN applications that primarily focus on static land cover prediction, this study advances the methodological integration by linking multi-temporal land cover projection with future flood susceptibility modelling. Similar studies (Nkonu & Antwi, 2024) demonstrate the effectiveness of CA–ANN for spatial prediction; however, few explicitly connect projected land transformation trajectories with evolving hazard susceptibility classes in a coastal secondary city context.

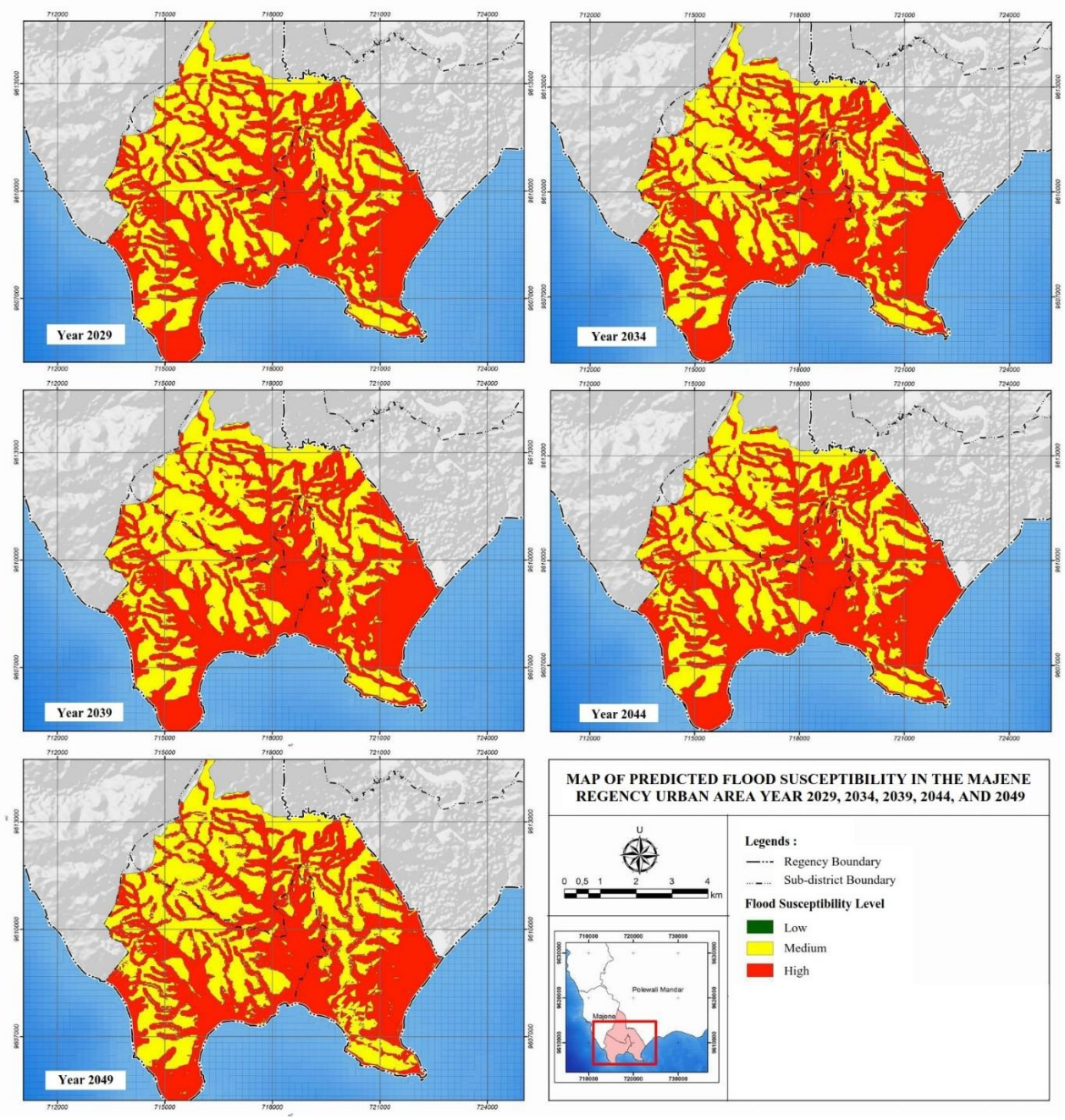


**Figure 6. Map of predicted flood susceptibility in the Majene urban area in 2029, 2034, 2039, 2044 and 2049 (*Source: Data analysis, 2024*)**

The urban area of Majene has an average rainfall classified as moderate, ranging between 1501 and 2000 mm per year. This rainfall can cause flooding if supported by other factors, such as the lack of water catchment areas and river shallowing triggered by sedimentation, either from eroded soil or waste disposal into rivers. Most urban areas in Majene have developed in coastal areas with slopes ranging from 0% to 8%. Flat areas are more prone to flooding than areas with a greater slope. This is related to the nature of water, which tends to accumulate in low-lying and poorly drained flat areas', resulting in most water flow leading to urban areas. In terms of

regional altitude, most urban areas in Majene have areas with varying altitudes. Areas with low altitudes are primarily located in coastal regions, which eventually develop into centers of regional activity. The type of soil that predominates in the urban area of Majene is red-yellow Mediterranean and rendzina, which is found in almost all areas. This type of soil is characterized by further development from the parent material of limestone, with the following characteristics: a soil solum of 1-2 m, a brown to red color, a clay to loamy texture, a lumpy structure, and a loose consistency at the top and a firm consistency at the bottom. The level of sensitivity of this type of soil to erosion is moderate to high, so that if erosion occurs. The eroded soil is transported by surface flow and then deposited in places where the water flow slows down, such as rivers, irrigation channels, reservoirs, lakes, or river mouths. This can cause river shallowing, leading to increased flood intensity during the rainy season. The Majene urban area is traversed by several rivers, which results in some of its areas being within a very close radius of the river. This area should be designated as a local protected area, such as a river boundary area; however, in reality, cultivated land is being used for various purposes, including development, in this area.

Parameters that form flood susceptibility, including land cover predictions, are processed using the Weighted Overlay method with ArcMap software to produce a 5-year flood susceptibility prediction for the period 2029-2049. In this process, each parameter is given a score and weight based on its influence on the level of flood susceptibility. Based on the total number of multiplications of the scores and weights of each parameter, the level of flood susceptibility in Majene urban area determined and mapped as in Figure 6. The level of flood susceptibility is divided into three classes ranging from low to high. Based on the prediction results, most urban areas in Majene are characterized by a high level of flood susceptibility. Most areas with high levels of susceptibility are primarily concentrated in regions dominated by settlement or built-up land cover.

The predicted flood susceptibility map (2029 baseline) was visually compared recent flood susceptibility modelling from previous study (Pratama et al., 2025). Result from previous study as seen in Figure 7 shows that flood inundation is concentrated in low-elevation coastal plains and estuarine areas, which correspond directly to zones classified as high susceptibility in Figure 6. Flood patterns following river corridors align with high-susceptibility areas generated from the river proximity parameter, confirming the model's ability to capture fluvial exposure. Transitional inland areas with moderate inundation in Figure 7 correspond to medium susceptibility classes in Figure 6, reflecting the influence of slope and elevation. Nevertheless, the consistent overlap across coastal lowlands and floodplain corridors indicates that the model effectively reproduces the dominant flood-prone of the study area, strengthening confidence in its 2029–2049 projections.

The prediction results indicate that flood susceptibility in the Majene urban area is expected to decrease from 2029 to 2049 as in Table 7.

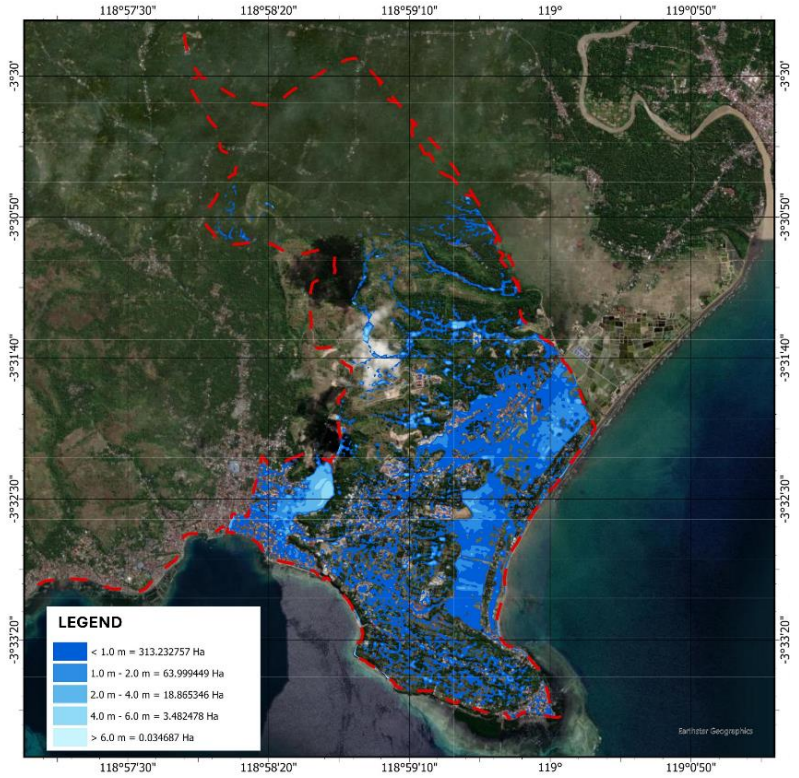


**Figure 7. Flood susceptibility modelling from previous study (Source: Pratama et al., 2025)**

**Table 7. Distribution of flood susceptibility level in Majene urban area**

| Susceptibility level | Area (ha) | | | | |
|---|---|---|---|---|---|
| | Year 2029 | Year 2034 | Year 2039 | Year 2044 | Year 2049 |
| Low | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 |
| Medium | 2098.17 | 2199.06 | 2170.83 | 2150.04 | 2240.27 |
| High | 3040.91 | 2940.02 | 2968.24 | 2989.03 | 2898.81 |

*Source: Data analysis, 2025*

The results indicate a gradual shift from high to moderate susceptibility zones, although the changes are not strictly linear from year to year. Overall, areas with high susceptibility show a net decrease between 2029 and 2049, while areas with moderate susceptibility show a net increase over the same period. This is primarily related to the results of land cover predictions, where, although built-up land has increased, on the other hand, the use of plantation has also increased quite significantly, indicating that there is more vegetation cover that can pass or absorb rainwater into the soil and reduce the amount of rainwater that becomes surface runoff. This coupling of predictive land dynamics and susceptibility mapping strengthens forward-looking spatial planning relevance in medium-sized coastal cities experiencing accelerated development.

The observed reduction in high flood susceptibility despite continued built-up expansion should not be interpreted solely as a direct effect of plantation-driven infiltration. Urban hydrology is influenced by multiple interacting factors. In the Majene urban area, a drainage improvement program implemented in 2025 (Dinas Perumahan dan Permukiman Provinsi Sulawesi Barat, 2025) including channel normalization, culvert enlargement, and localized drainage upgrading in flood-prone corridors likely contributed to improved surface runoff conveyance capacity. However, because hydraulic infrastructure is not explicitly represented in the susceptibility model, these improvements should be understood as a contextual factor rather than a direct driver of the modeled redistribution from high to moderate susceptibility zones.

## Conclusions

Majene's rapid urban development, driven by educational expansion and infrastructure improvement, has significantly transformed land cover patterns over the last decade. Using CA–ANN and MCDA, this study successfully modeled land cover change and flood susceptibility from 2029 to 2049.

Key findings include:

- Built-up and plantation areas will continue to expand through 2049;
- Grassland and open land will continue to decline;
- High flood susceptibility areas will gradually decrease, while medium susceptibility areas will expand;
- Increased vegetation cover contributes to reduced runoff and moderated flood risk.

The integration of GIS-based modeling with spatial multi-criteria analysis provides valuable insights for disaster risk reduction and sustainable spatial planning in coastal urban areas. Policymakers can use these findings to guide land-use regulation, infrastructure development, and flood mitigation strategies.

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## Author contribution

Conceptualization, RM and AP; methodology, NRS; formal analysis, AP, AM and NFM; investigation, MAE; writing—original draft preparation, RM, NRS and AP; writing—review and editing, AM, NFM and AW. All authors have read and agreed to the published version of the manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

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# Geomorphological mapping of steep new vineyard terraces: DJI Mavic 3M vs. Matrice T4 RTK performance with and without GCPs

Jesús GONZÁLEZ-VIVAR[1], Laura CAMBRONERO-RUÍZ[1,2], Maria Teresa GONZÁLEZ-MORENO[1,2], Jesús RODRIGO-COMINO[1,2,*]

[1] Departamento de Análisis Geográfico Regional y Geografía Física, Facultad de Filosofía y Letras, Campus Universitario de Cartuja, University of Granada, 18071 Granada, Spain
[2] Andalusian Research Institute in Data Science and Computational Intelligence, University of Granada, 18016 Granada, Spain
* *Corresponding author*: jesusrc@ugr.es

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**Abstract**

Soil erosion in steep vineyard terraces presents critical environmental challenges that require high-resolution, real-time geomorphological monitoring. Unmanned Aerial Vehicle (UAV) photogrammetry has revolutionized this field; however, an experimental gap persists regarding the operational need for Ground Control Points (GCPs) when utilizing high-precision Real-Time Kinematic (RTK) systems in extreme geometries. This study provides a rigorous comparative analysis between the DJI Mavic 3M and the DJI Matrice T4 (Thermal) platforms under two georeferencing configurations (RTK-only direct georeferencing vs. RTK+GCP workflows). Both drones were operated under identical parameters: flown on the same day at solar noon, with an 80% longitudinal and lateral image overlap, and at a flight altitude of 40 m above ground level. Four key topographic and soil erosion derivatives were extracted in ArcGIS Pro and statistically compared cell-by-cell using raster calculator algebra: Slope Gradient, Topographic Wetness Index (TWI), Convergence Index (CI), and the RUSLE LS-factor. The residual analysis revealed an outstanding structural alignment between workflows, with absolute median discrepancies restricted to 0.7° for slope, 0.4 for TWI, and 0.0 for CI. Absolute coordinate tracking across 10 independent checkpoints unveiled that the non-GCP workflow behaves as a perfectly rigid photogrammetric block, introducing an identical systematic translation vector (Delta X= 0.2 m, Delta Y= 5.4 m, Delta Z= -2.8 m) with near-zero standard deviations (approx. 0.1 m) for both platforms. Because neighborhood-cell algorithms remain unaffected by this rigid displacement, the derivative geomorphological maps are morphologically identical. These findings demonstrate that for high-resolution pedogeomorphological monitoring on steep slopes, the internal positioning stability of the DJI D-RTK 3 system successfully eliminates the operational dependency on physical ground control networks. This methodological shift significantly optimizes fieldwork efficiency, safety, and operational costs without compromising scientific rigor.

**Keywords:** *UAV photogrammetry, RTK direct georeferencing, terraced vineyards, geomorphological mapping, soil erosion modeling*

## Introduction

Soil erosion in vineyards represents one of the most critical environmental challenges in Mediterranean and steep-slope agricultural landscapes (Prosdocimi et al., 2016; Rodrigo-Comino, 2018). The intensive management of these areas to obtain the highest high quality production, combined with continuous tillage with bare soil maintenance, severely accelerates soil erosion and alters hydrological responses (Andrenelli et al., 2025; Gholamahmadi et al., 2025). This acceleration triggers immediate surface runoff, which drives severe associated processes such as the depletion of vital soil nutrients, the mitigation and release of organic carbon into the atmosphere, and a systemic reduction in soil organic matter (Bogunovic et al., 2020; Novara et al., 2011). There is an urgent need to identify, monitor, and implement sustainable management practices capable of mitigating erosion rates, preserving soil structural integrity, and enhancing ecosystem resilience against climate-induced degradation (Caffaro et al., 2024; Gall et al., 2025).

In recent decades, significant advancements in geomorphology, soil geography, and pedogeomorphology have transformed how hillside stability and degradation dynamics are evaluated, primarily driven by developments in remote sensing (Pawlik, 2025; Trevisani & Guth, 2025). Among these technologies, Unmanned Aerial Vehicles (UAVs) have emerged as a revolutionary tool, enabling real-time, ultra-high-resolution monitoring and quantification of active geomorphological processes (Alexiou et al., 2023; Eltner et al., 2013). The integration of modern Real-Time Kinematic (RTK) positioning systems within UAVs, coupled with ground truth validation using Global Positioning Systems (GPS), has exponentially increased the spatial accuracy of digital elevation models (Bertin et al., 2022; Tan et al., 2024). Nevertheless, an

experimental gap persists in international literature: it remains unclear which specific drone platforms and under what precise operational conditions can deliver the most accurate geomorphological maps, especially when balancing technological configurations (Rodrigo-Comino et al., 2026).

In the specific context of viticulture, the construction of terraced systems has historically allowed the cultivation of steep slopes that would otherwise be topographically impracticable (Blavet et al., 2009; Ramos & Porta, 1997). However, numerous authors have demonstrated that these human-modified landforms frequently reach the highest rates of soil erosion (Chen et al., 2017). In the Iberian Peninsula, seminal works by Romero-Díaz et al. (2017a) in the Murcia region, Martínez-Casasnovas et al. (2016) in the Penedès region, and Rodrigo-Comino et al. (2019) in the Málaga province have highlighted how terrace abandonment, structural failure, and lack of vegetative cover trigger catastrophic soil loss. Furthermore, on an international scale, researchers in Italy have successfully started UAV photogrammetry in Italian terraced vine-yards to detect and track the development of severe gully erosion and bank failures, confirming the vulnerability of these agricultural systems (Pijl et al., 2019).

Despite the extensive literature on vineyard erosion, a critical methodological question remains unanswered: What is the optimal workflow to produce highly accurate geomorphological maps in steeply terraced vineyards? Specifically, does the combination of RTK positioning with Ground Control Points (GCPs) significantly outperform a pure RTK direct georeferencing approach without GCPs, or can the latter achieve sufficient accuracy for geomorphological map-ping? Moreover, how does platform choice influence this accuracy? To address this gap, this study provides a rigorous comparative analysis between two distinct UAV platforms supported by a RTK positioning system: the lightweight DJI Mavic 3M and the DJI Matrice T4. Both systems were tested with and without GCPs under strictly controlled experimental conditions: flown on the same day, at identical times to minimize shading varia-tions, using an 80% forward and side overlap, and at a constant flight altitude of 40 meters above ground level.

## Materials and methods

### Study area

The study area (Fig. 1) is located in a recently established vineyard in the municipality of Los Guájares, in the province of Granada (Andalusia, southern Spain). The vineyard belongs to Bodegas Calvente and is located at UTM coordinates ETRS89 Zone 30N (X: 445371; Y: 4075046). The experimental plot ranges in elevation from 1020 m to 1073 m a.s.l., corresponding to the highest terrace.

The study plot covers an area of 2.59 ha and corresponds to a newly planted vineyard established in May 2026 on a recently created agricultural terrace system. These cultivation structures are adapted to an environment of high topographical complexity, characteristic of the mountainous areas in the southern province of Granada, where the transformation of the relief through terraces allows the implementation of woody crops in areas with steep slopes (Durán-Zuazo & Rodriguez, 2008). The terraced configuration of the terrain creates a scenario of interest for the application of remote sensing techniques due to the potential existence of spatial variations associated with factors such as solar exposure, edaphic characteristics, water availability, and microclimatic conditions (Preti & Romano, 2014).

From a physiographic point of view, the study area is located within the setting of the Penibaetic System (Cordillera Penibética), inside a mountainous agricultural landscape characterized by irregular relief and high spatial heterogeneity (García-Ruiz, 1988). The terraced hillslope shows a homogeneous northwestern orientation. While the inner cultivated benches maintain an approximate average slope of 5% to optimize water management, the structural terrace risers and global hillslope topography present steep gradients that aver-age 22°–23° and reach sub-vertical inclinations. These topographical features condition the distribution of incident radiation and the processes related to the sur-face energy balance, factors that can influence the spec-tral and thermal response of the vegetation obtained via remote sensors (Jenerowicz et al., 2023; Farella et al., 2022).

Despite being located at a high altitude, the plot is relatively close to the Mediterranean coast, being approximately 8 km in a straight line from the nearest beach, located in the coastal area of Salobreña (Granada). This geographical position creates a transition between environmental conditions typical of mountainous areas and the maritime influence of the Granadan Costa Tropical. This combination of factors favors conditions characterized by high solar radiation availability, daily thermal amplitude, and a marked Mediterranean character, which are relevant aspects in the development and physiological behavior of the vineyard crop (Costa et al., 2023; Barbera & Cullotta, 2016).

The vineyard is composed of four grapevine varieties, corresponding to three white (Chardonnay, Vigiriego, and Riesling) and one red (Petit Verdot). Due to its recent establishment, the plot is in an initial stage of vegetative development.

At the time of the study, the crop did not have an installed irrigation system, although its incorporation is planned for later stages of the plantation's development, estimated for the coming month. The planting pattern presents a layout of 1.1 m vine spacing and 2.30 m inter-row spacing. At the time of the study, the plot showed a total absence of vegetative cover, characterized by

completely bare soil due to the recent land preparation for planting.

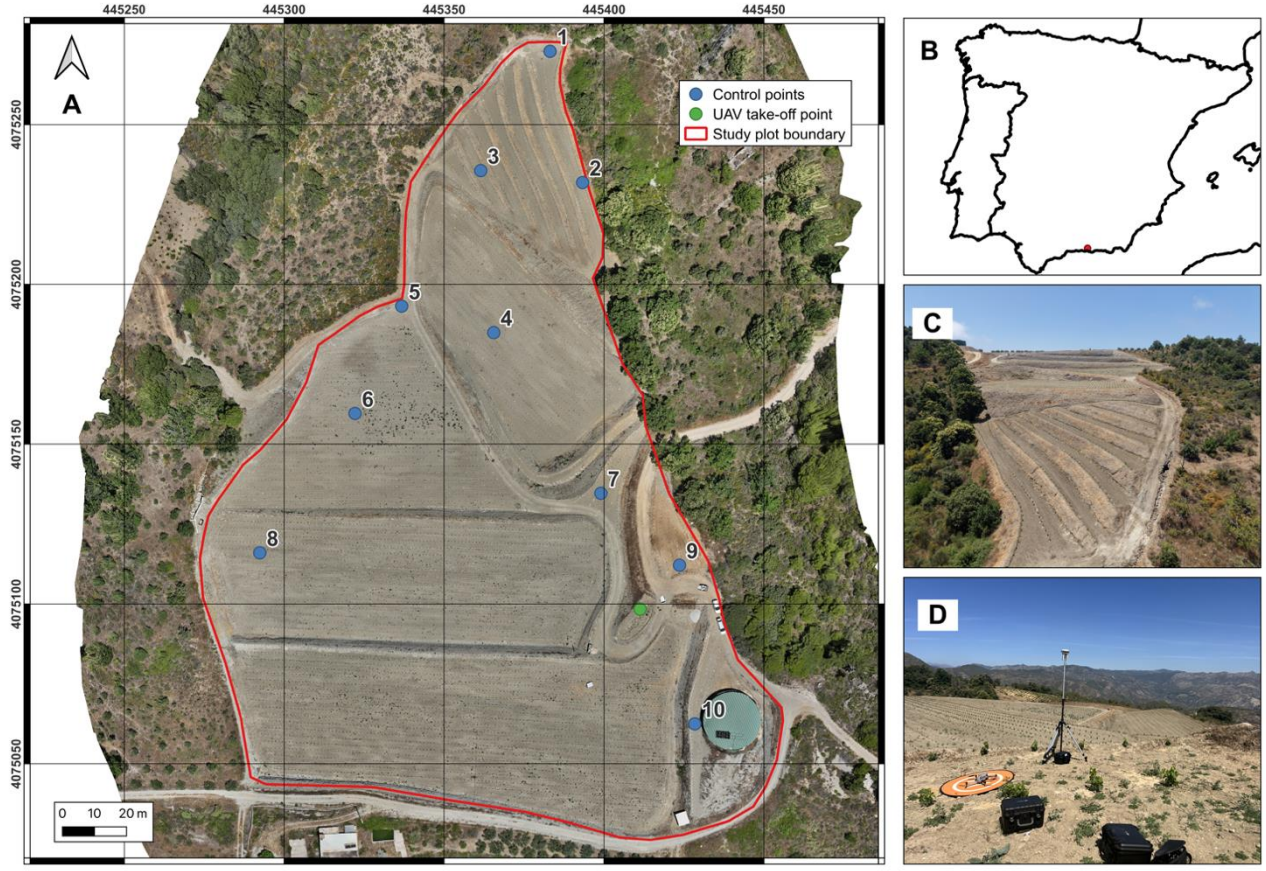


**Figure 1. Localization of the study area: (a) high-resolution orthophoto, including the Ground Control Points (GCPs); (b) location of the study plot in southern Spain; (c) panoramic view of the study plot (DJI MiniPro 5); (d) UAV take-off point, situated at the highest elevation of the study plot and RTK positioning system (1,073 m a.s.l.)**

## Flight campaigns and photogrammetric parameters

To ensure strict experimental consistency and minimize environmental variables, both Unmanned Aerial Vehicle (UAV) flight campaigns were carried out on the same day under identical atmospheric conditions. The missions were synchronized at 12:00 PM (local solar noon) to maximize the solar elevation angle, thereby minimizing shadows cast by the steep terrace risers and ensuring optimal, uniform illumination across the complex topography. Both platforms were operated using automated flight planning software to execute a grid pattern with an 80% frontal (longitudinal) and 80% lateral (transverse) image overlap (DJI Pilot 2). The flight altitude was rigidly maintained at 40 meters above ground level (AGL) relative to the take-off point, balancing high spatial resolution with operational safety in the steep terrain.

Two distinct multi-rotor UAV platforms representing different weight classes and payload configurations were evaluated (Fig. 2):

• DJI Mavic 3 Multispectral (Mavic 3M): A lightweight, compact enterprise drone (take-off weight of 951 g) equipped with an integrated RTK module. For this study, the primary RGB sensor was utilized, featuring a 4/3-inch CMOS sensor with 20 megapixels (MP) and a mechanical shutter to prevent motion blur during high-speed flight.

• DJI Matrice T4 (Thermal): A high-stability industrial enterprise platform equipped with native RTK positioning. For the photogrammetric and geomorphological reconstruction, the primary high-resolution RGB optical sensor integrated into the thermal payload camera system was utilized, operating under identical overlap and altitude constraints.


**Figure 2. UAV platforms used in the study**

## Georeferencing, Base Stations, and Ground Control

To evaluate the absolute and relative spatial accuracy of the geomorphological products under different constraints, a dual-scenario framework (with and without Ground Control Points) was implemented using high-precision Global Navigation Satellite Systems (GNSS).

Real-time kinematic corrections during the flights were provided by a DJI D-RTK 3 High-Precision GNSS Mobile Station, which simultaneously tracks multiple satellite constellations (including GPS, GLONASS, Galileo, and BeiDou). The station was set up over a known local control point to broadcast differential corrections directly to both the Mavic 3M and Matrice T4 via data links, guaranteeing centimeter-level real-time positioning accuracy.

For ground truth validation and the implementation of the GCP-backed scenarios, a network of ten artificial targets was distributed across the new steep terraced vineyard. The precise three-dimensional coordinates (X,Y,Z) were measured using an Emlid Reach RS3 multi-band GNSS receiver equipped with an Inertial Measurement Unit (IMU) for tilt compensation. The receiver tracked GPS/QZSS, GLONASS, BeiDou, and Galileo signals to achieve maximum accuracy. The raw geodetic data collected by the receiver was managed, verified, and post-processed using the Emlid Flow software ecosystem to guarantee maximum coordinate reliability. These points were systematically split into Ground Control Points (GCPs) for block adjustment optimization.

## Data processing and photogrammetric pipeline

The raw digital imagery and embedded EXIF/XMP metadata (including the high-precision RTK geotags) from both drone flights were imported into Esri ArcGIS Drone2Map (Colorado, USA) software for photogrammetric reconstruction. The processing workflow followed a standardized structure divided into two primary georeferencing configurations:

- RTK-Only Scenario: The structural block adjustment was computed relying exclusively on the camera positions georeferenced by the DJI D-RTK 3 station, treating the field-measured targets strictly as independent checkpoints to validate the vertical and horizontal errors.
- RTK + Ten GCP Scenario: The block adjustment was optimized by manually identifying and binding the Emlid-surveyed GCPs within the image matching pipeline, refining the camera calibration parameters and interior orientation.

For both scenarios, the initial tie-point generation, bundle block adjustment, and dense point cloud densification were executed at full resolution. The final outputs generated for geomorphological interpretation and comparative analysis included ultra-high-resolution Digital Surface Models (DSMs), and orthomosaics.

## Geomorphometric maps and geostatistical comparison

To evaluate how platform choice and georeferencing configurations impact the geomorphological characterization of new steep vineyard terraces, a comprehensive geomorphometric and geostatistical pipeline was implemented in Esri ArcGIS Pro following previous works (Cambronero et al., 2025; González-Moreno & Rodrigo-Comino, 2025). Four distinct digital elevation scenarios were analyzed: (1) Mavic 3M RTK-only, (2) Mavic 3M RTK+GCP, (3) Matrice T4 RTK-only, and (4) Matrice T4 RTK+GCP. The raw filtered photogrammetric Digital Surface Models (DSMs) were standardized to a common spatial resolution to ensure spatial compatibility (GSD: 1 cm). Four critical terrain attributes for soil erosion and hydrological modeling were computed using the Spatial Analyst toolbox in ArcGIS Pro:

- Slope Gradient (Degrees): Calculated using the Surface Parameters tool. The algorithm computes the maximum rate of change in elevation from each cell to its neighbors using a bivariate quadratic local surface fitting. This method provides smoother, more realistic derivatives on highly complex, steeply terraced slopes compared to traditional neighborhood methods.
- Topographic Wetness Index (TWI; (Kopecký et al., 2021): It quantifies topographic control on hydrological processes and potential runoff accumulation areas. It was computed via the Raster Calculator using the standard formula:

$$TWI = \ln\left(\frac{\alpha}{\tan(\beta)}\right)$$

where $\alpha$ is is the specific catchment area (local contributing area per unit contour length) derived from a D8 flow accumulation routing algorithm after hydrologically conditioning the DTM (filling sinks), and $\beta$ is the slope gradient in radians.

- Convergence Index (CI): The CI was generated to identify flow convergence (valleys/gullies) and divergence (ridges/terrace risers) structures (Arabameri et al., 2018). The index evaluates the average aspect difference between a central cell and its eight surrounding neighbors. Negative values indicate convergent terrain configurations prone to concentrated runoff, while positive values represent divergent structures.
- LS Factor (RUSLE):The combined slope length (*L*) and slope steepness (*S*) factor from the Revised Universal Soil Loss Equation (RUSLE) was calculated to model topographic susceptibility to soil erosion. The extraction followed an algorithm (Desmet & Govers, 1996), which accounts for complex 3D surfaces and flow convergence:

- $LS = L_{i,j} \cdot S_{i,j}$

where the *L* factor computes the upstream contributing area for each specific pixel (i,j) adjusting for slope changes, and the *S* factor addresses the non-linear acceleration of velocity on steep slopes.

To quantitatively assess the internal consistency and absolute structural deviations between the photogrammetric configurations, a dual-layer statistical comparison was performed. The Raster Calculator tool was utilized to generate cell-by-cell Difference of Elevation maps with 10 known points registering X, Y and Z coordinates. This allowed for the spatial identification of where the largest geometric mismatches occurred (e.g., whether errors clustered on vertical terrace walls, inner channels, or flat vine rows). Spatial structural continuity and spatial dependence of the errors and geomorphometric indices were examined using experimental variograms, transformed into boxplots to graphically observe the differences.

Comparing the variogram parameters (datasets and tables) between the RTK-only and RTK+GCP configurations for both the Mavic 3M and Matrice T4 allowed to identify whether omitting Ground Control Points introduces systemic spatial distortions (tilt or warping) or increases random high-frequency noise across the terraced landscape.

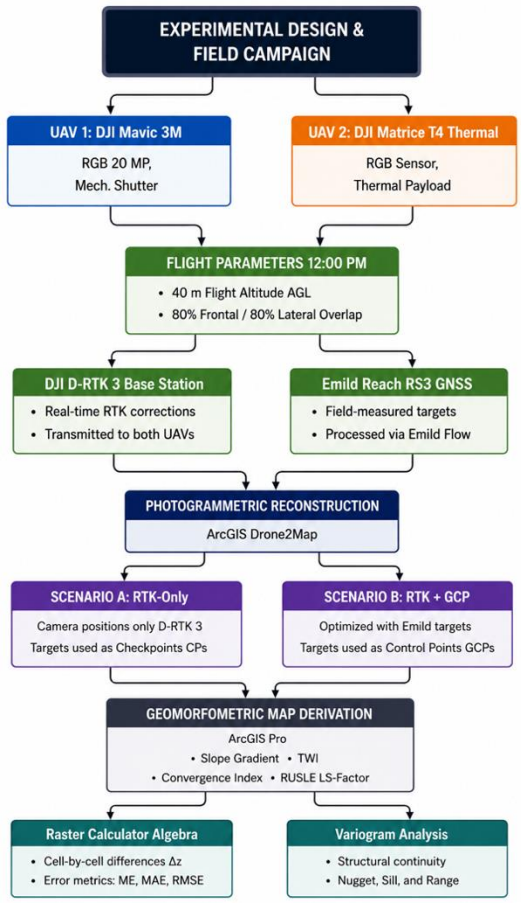


**Figure 3. Methodological workflow**

## Results

### Photogrammetric processing performance

Before evaluating the geomorphological products derived from the digital surface models, the quality of the four photogrammetric reconstructions was assessed to ensure that the resulting datasets were generated under comparable processing conditions (Table 1).

The comparison included the main quality indicators provided by Drone2Map, encompassing project characteristics, image calibration statistics, bundle adjustment performance, camera optimization and image position corrections. These parameters provide an overview of the geometric quality of each photogrammetric block and allow the influence of Ground Control Points (GCPs) on the image adjustment to be evaluated prior to the terrain analysis.

Table 1 summarizes the main processing statistics obtained for the four photogrammetric projects. Complete image calibration was achieved in every case, with all acquired photographs successfully oriented during the bundle adjustment (679 images for the DJI Mavic 3 Multispectral and 2,209 images for the DJI Matrice T4). Likewise, mission size, covered area and mean Ground Sampling Distance (GSD) remained identical between the processing performed with and without GCPs for each UAV platform, confirming that both processing strategies were directly comparable.

The internal quality indicators of the bundle adjustment showed only minor differences between processing strategies. The DJI Mavic 3 Multispectral maintained a Tie Point Mean Reprojection Error (RMSE) of 0.20 pixels irrespective of GCP incorporation, whereas the DJI Matrice T4 exhibited a slight reduction from 0.27 pixels to 0.24 pixels after the inclusion of the ten ground control points.

Similarly, the mean number of tie points per solution point varied only marginally, increasing from 6.56 to 6.63 in the Mavic 3M dataset and from 8.92 to 8.93 in the Matrice T4 dataset. Camera self-calibration remained highly stable for both sensors, with focal length optimization values below 1% in all cases.

The incorporation of GCPs enabled the estimation of absolute positioning residuals during the adjustment. The DJI Mavic 3 Multispectral achieved RMSE values of 0.025 m, 0.022 m and 0.012 m for the X, Y and Z coordinates, respectively, whereas the DJI Matrice T4 recorded corresponding values of 0.045 m, 0.039 m and 0.029 m.

The maximum orientation uncertainties remained below 0.014 m for positional parameters and below 0.006° for angular parameters across all four projects, indicating stable bundle adjustment solutions.

In the RTK-only processing, the differences between the initial and adjusted camera positions were negligible. Conversely, for the projects processed with GCPs, the bundle adjustment resulted in systematic differences between the initial RTK camera positions and the final adjusted positions, with average values of approximately −0.17 m, −5.3 m and +2.8 m along the X, Y and Z components, respectively, for both UAV platforms.

**Table 1. Statistical datasets obtained from each flight and images processing using Drone2map-exported reports**

| Category | Parameter | M3 RTK | M3 RTK + GCPs | MT4 RTK | MT4 RTK + GCPs |
|---|---|---|---|---|---|
| **Project characteristics** | Images calibrated | 679/679 | 679/679 | 2209/2209 | 2209/2209 |
| | Mission size (GPx) | 14.0 | 14.0 | 26.0 | 26.0 |
| | Coverage area (ha) | 9.1 | 9.1 | 8.2 | 8.2 |
| | Mean GSD (m) | 0.013 | 0.013 | 0.017 | 0.017 |
| | Processing time | 2h30m | 1h44m | 2h38m | 4h21m |
| **Bundle adjustment** | Tie Point RMSE (px) | 0.20 | 0.20 | 0.27 | 0.24 |
| | Mean tie points / solution point | 6.56 | 6.63 | 8.92 | 8.93 |
| | Focal length optimization (%) | 0.10 | 0.10 | 0.71 | 0.71 |
| | Maximum orientation uncertainty X (m) | 0.002 | 0.005 | 0.001 | 0.006 |
| | Maximum orientation uncertainty Y (m) | 0.002 | 0.005 | 0.001 | 0.006 |
| | Maximum orientation uncertainty Z (m) | 0.001 | 0.008 | 0.000 | 0.014 |
| | Maximum Ω uncertainty (°) | 0.004 | 0.006 | 0.001 | 0.005 |
| | Maximum Φ uncertainty (°) | 0.003 | 0.006 | 0.001 | 0.005 |
| | Maximum K uncertainty (°) | 0.002 | 0.002 | 0.001 | 0.003 |
| **Image position correction** | Mean ΔX (m) | 0.000 | −0.172 | 0.000 | −0.128 |
| | Mean ΔY (m) | 0.000 | −5.310 | 0.000 | −5.368 |
| | Mean ΔZ (m) | 0.000 | +2.787 | 0.000 | +2.817 |
| **Ground control** | Number of GCPs | 0 | 10 | 0 | 10 |
| | RMSE X (m) | — | 0.025 | — | 0.045 |
| | RMSE Y (m) | — | 0.022 | — | 0.039 |
| | RMSE Z (m) | — | 0.012 | — | 0.029 |

## Geomorphometric products and statistical comparison of the DSMs

**Table 2. Descriptive statistics of cell-by-cell slope dis-crepancies (in degrees) between DJI Mavic 3M and DJI Matrice T4 photogrammetric derivatives under different georeferencing configurations (With GCPs vs. Without GCPs), including abso-lute differences and relative variance changes (%)**

| Parameter | With GCPs | Without GCPs | Difference | Relative change (%) |
|---|---|---|---|---|
| Mean | 1.3 | 1.3 | 0.6 | 2.0 |
| Median | 0.5 | 2.3 | 0.7 | 3.0 |
| Minimum | 0.0 | 0.0 | 0.0 | — |
| Maximum | 89.8 | 89.8 | 0.0 | 0.0 |
| Standard deviation | 21.9 | 22.0 | 0.1 | 0.6 |
| Coefficient of variation (%) | 78.6 | 77.5 | −1.1 | −1.4 |
| Percentile 5 (P5) | 2.9 | 3.0 | 0.1 | 5.1 |
| Percentile 25 (P25) | 8.6 | 9.1 | 0.5 | 5.3 |
| Percentile 75 (P75) | 43.0 | 43.6 | 0.6 | 1.5 |
| Percentile 95 (P95) | 70.6 | 71.5 | 0.9 | 1.3 |

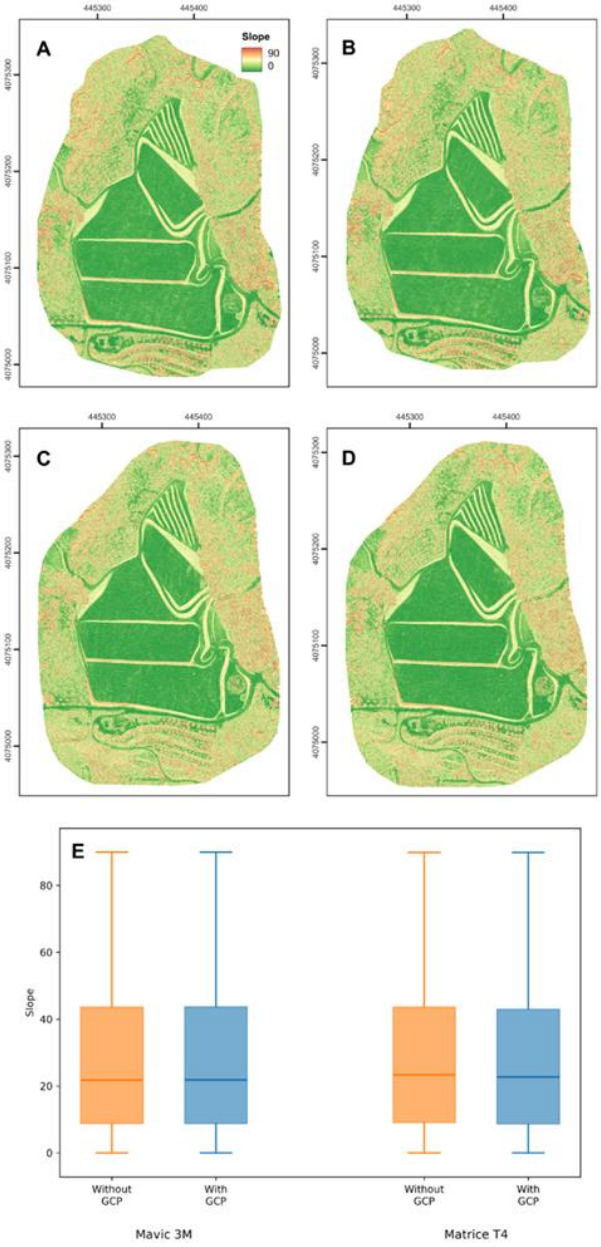


**Figure 4. Comparison of slope maps (degrees) and statistical distributions obtained from the four UAV photogrammetric workflows using RTK direct georeferencing and RTK combined with Ground Control Points (GCPs). (A) DJI Mavic 3 Multispectral (RTK only); (B) DJI Mavic 3 Multispectral (RTK + GCPs); (C) DJI Matrice T4 (RTK only); (D) DJI Matrice T4 (RTK + GCPs); (E) Boxplot comparison of slope distributions**

The spatial and statistical consistency between the geomorphometric layers was evaluated through a cell-by-cell raster subtraction of the slope gradients derived from the DJI Mavic 3M and DJI Matrice T4 platforms. As synthesized in Figure 4 and Table 2, the residual analysis demonstrates an exceptionally high geometric alignment between both UAV systems, confirming that next-generation RTK positioning minimizes structural warping in steep terraced environments. When both platforms were optimized using the Ground Control Point network ("With GCPs"), he mean slope discrepancy was 1.3°, with an absolute difference between configurations of just 0.6° (Table 2).

In the direct georeferencing scenario where ground control targets were omitted ("Without GCPs"), the mean discrepancy remained perfectly stable at 1.3°, while the median variation experienced a subtle increase to 2.3°. This operational shift results in an absolute median difference of 0.7°, which corresponds to a minor relative change of only 3.0% in the internal topographic variance between the two flights. The distribution of the elevation derivatives across the different topographic percentiles further supports the reliability of the non-GCP workflow. In the lower and intermediate slope intervals (P5 to P25), the absolute differences between the workflows do not exceed 0.5°.

Even when evaluating the most complex features of the landscape—such as the sub-vertical terrace risers represented by the upper percentiles—the deviations remain negligible; the 75$^{th}$ percentile (P75) shifts by only 0.6° (from 43.0° to 43.6°) and the 95$^{th}$ percentile (P95) shows a variation of 0.9° (moving from 70.6° to 71.5°). The maximum recorded slope gradient (89.8°) and the overall standard deviation (~22.0°) remained virtually identical across all configurations, displaying a minimal relative change of 0.6%.

**Table 3. Descriptive statistics of cell-by-cell RUSLE LS-factor discrepancies between DJI Mavic 3M and DJI Matrice T4 photogrammetric models under different georeferencing configurations (With GCPs vs. Without GCPs), including absolute differences and relative changes (%)**

| Parameter | With GCPs | Without GCPs | Difference | Relative change (%) |
|---|---|---|---|---|
| Mean | 1.3 | 1.3 | 0.0 | 0.8 |
| Median | 0.5 | 0.5 | 0.0 | −0.3 |
| Minimum | 0.0 | 0.0 | 0.0 | — |
| Maximum | 1636.5 | 1548.0 | −88.5 | −5.4 |
| Standard deviation | 7.1 | 6.9 | −0.1 | −1.9 |
| Coefficient of variation (%) | 553.0 | 538.3 | −14.7 | −2.7 |
| Percentile 5 (P5) | 0.0 | 0.0 | 0.0 | — |
| Percentile 25 (P25) | 0.1 | 0.1 | 0.0 | −3.5 |
| Percentile 75 (P75) | 1.4 | 1.4 | 0.0 | −0.5 |
| Percentile 95 (P95) | 4.0 | 4.0 | 0.0 | 0.9 |

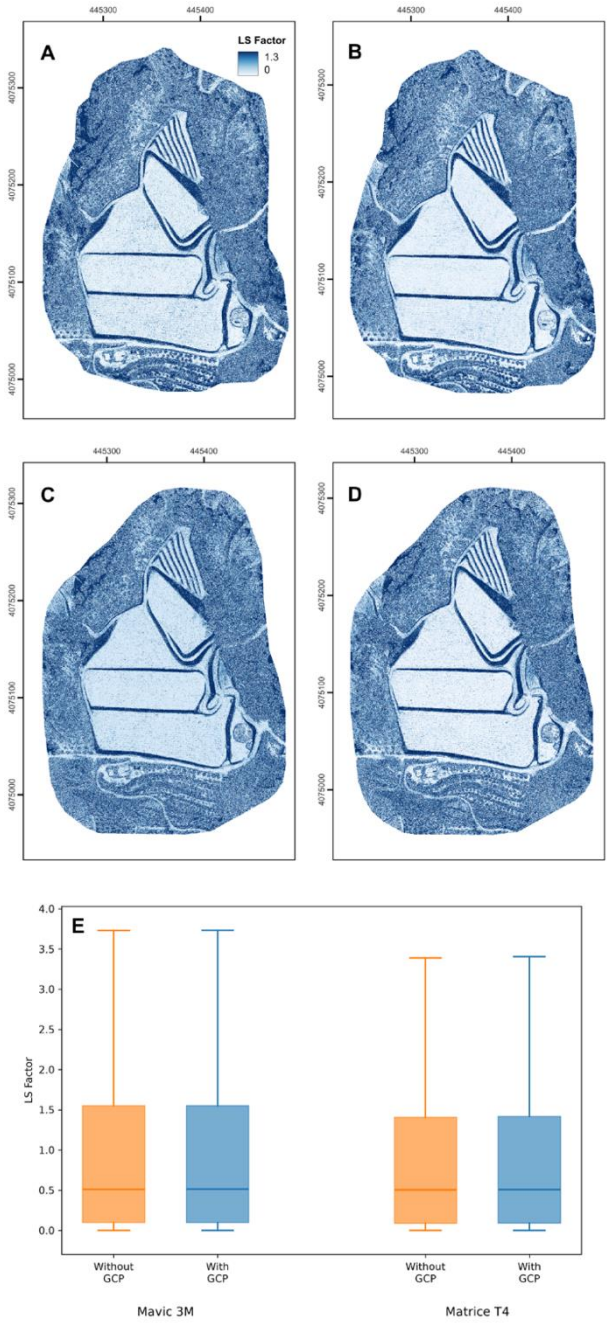


**Figure 5. Comparison of LS factor maps and statistical distributions obtained from the four UAV photogrammetric workflows using RTK direct georeferencing and RTK combined with Ground Control Points (GCPs). (A) DJI Mavic 3 Multispectral (RTK only); (B) DJI Mavic 3 Multispectral (RTK + GCPs); (C) DJI Matrice T4 (RTK only); (D) DJI Matrice T4 (RTK + GCPs); (E) Boxplot comparison of LS factor distributions**

The spatial compliance of the soil erosion modeling parameters was evaluated through a cell-by-cell raster subtraction of the slope length and steepness (*LS*) factor maps generated by the DJI Mavic 3M and DJI Matrice T4 platforms (Fig. 5 and Table 3). Visually, the spatial distribution of the *LS* factor remains completely homogeneous across all four configurations, consistently mapping minimal values on the flat terrace benches and identifying increased erosion susceptibility along the steep terrace risers.

The geostatistical comparison of the residuals demonstrates that the choice of UAV platform and the omission of physical ground control targets introduce negligible variation in the structural core of the erosion models.

When analyzing the absolute differences under both configurations ("With GCPs" and "Without GCPs"), the mean discrepancy between the two drone systems was confined to 1.3, with a median variation of just 0.5 in both workflows. The absolute difference between the two operational scenarios for both the mean and median was mathematically zero, displaying a minimal relative change of –0.3% in the median structural alignment.

This exceptionally high geometric synchronization between the Mavic 3M and Matrice T4 is further confirmed across the lower and intermediate topographic percentiles (P5, P25, and P75), where the absolute difference between having or not having a GCP network remains fixed at 0.0. Even at the extreme upper boundaries of the landscape dynamics—represented by the 95$^{th}$ percentile (P95)—the spatial discrepancy between platforms shifts by a negligible in absolute terms, translating to a minor relative change of only 0.9% shifts by a negligible 0.0 in absolute terms.

Conversely, localized maximum discrepancies reached outlier peaks of 1636.5 (With GCPs) and 1548.0 (Without GCPs), yielding an absolute maximum difference of –88.5. These localized errors, which account for the exceptionally high coefficients of variation (553%), represent mathematical artifacts induced by the D8 flow accumulation routing algorithm on the extreme edges of the photogrammetric blocks. Because these edge effects are completely unrelated to actual slope morphology or landform features, they were filtered out of the cartographic legends (Fig. 5A–D) as commanded to preserve map legibility. The exploratory boxplot distribution (Fig. 5E) visually records these findings: the interquartile ranges (IQR) and median lines are identically positioned across all four scenarios.

The spatial distribution of the Topographic Wetness Index (TWI) was mapped to assess how platform constraints and ground control configurations impact the delineation of potential runoff accumulation zones (Fig. 6 and Table 4).

The spatial patterns of hydrological convergence and divergence remain highly uniform across all four generated models, clearly distinguishing the drier, well-drained conditions of the sub-vertical terrace risers from the localized accumulation pathways situated along the inner terrace benches.

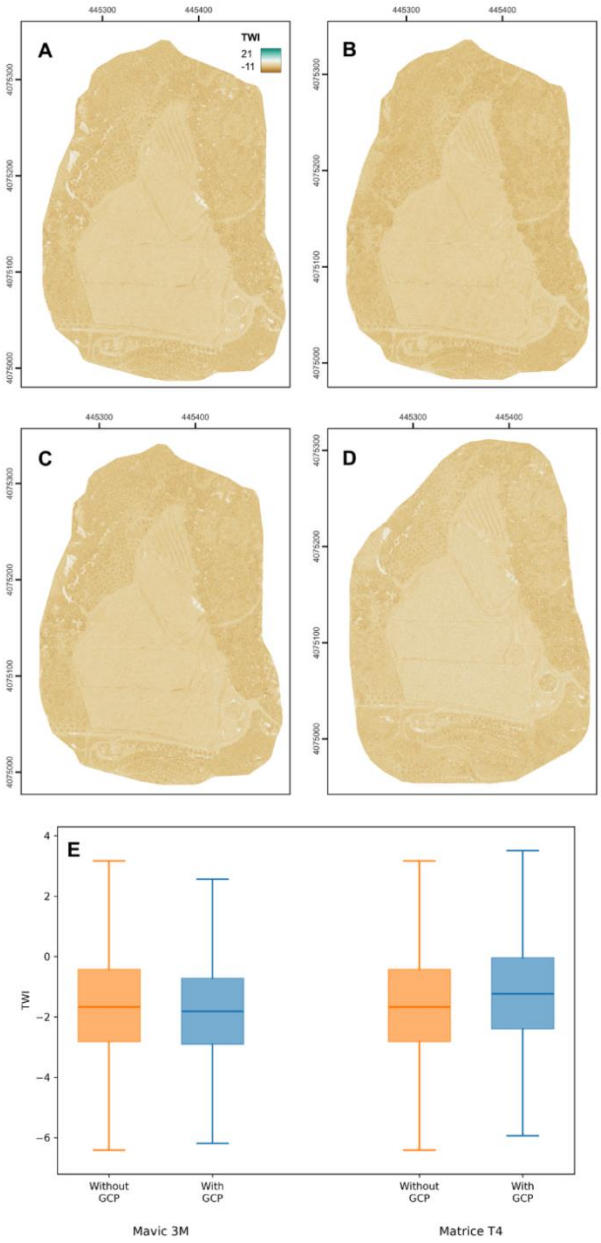


**Figure 6. Comparison of Topographic Wetness Index (TWI) maps and statistical distributions obtained from the four UAV photogrammetric workflows using RTK direct georeferencing and RTK combined with Ground Control Points (GCPs). (A) DJI Mavic 3 Multispectral (RTK only); (B) DJI Mavic 3 Multispectral (RTK + GCPs); (C) DJI Matrice T4 (RTK only); (D) DJI Matrice T4 (RTK + GCPs); (E) Boxplot comparison of Topographic Wetness Index (TWI) distributions**

The geostatistical comparison of the TWI residuals establishes that bypassing the ground control network yields minimal absolute structural variation. Under a fully controlled workflow ("With GCPs"), the mean cell-by-cell TWI discrepancy between the DJI Mavic 3M and DJI Matrice T4 was restricted to –1.1, while shifting slightly to –1.5 in the direct direct-georeferencing approach ("Without GCPs"). This variance yields a minor absolute difference of just –0.4. While the relative change metrics register high percentages in certain sectors—such as the 37.8% in the mean or the anomalous 1032.1% in the 75th percentile (P75)—these values represent statistical amplification artifacts induced by dividing minor absolute variances by baselines near or at the zero threshold.

The exploratory boxplot analysis visually clarifies this stability, showing a tight alignment between the interquartile ranges (IQR) and median lines across all configurations. The absolute shifts across the entire topographic spectrum are systematically capped under a value of 0.9. Specifically, the lower drainage limits (P5) present an absolute difference of –0.4 (moving from –4.2 to –4.6), whereas the upper saturation limits (P95) display a variation of only –0.3 (from 2.7 to 2.4). Furthermore, the total standard deviation remains perfectly constant at 2.2 for both georeferencing scenarios, indicating that the structural roughness and overall statistical dispersion of the hydrological surfaces are not degraded by the omission of GCPs.

**Table 4. Descriptive statistics of cell-by-cell Topographic Wetness Index (TWI) discrepancies between DJI Mavic 3M and DJI Matrice T4 photomorphometric models under different georeferencing configurations (With GCPs vs. Without GCPs), including absolute differences and relative changes (%)**

| Parameter | With GCPs | Without GCPs | Difference | Change (%) |
|---|---|---|---|---|
| Mean | -1.1 | -1.5 | -0.4 | 37.8 |
| Median | -1.2 | -1.7 | -0.4 | 35.2 |
| Minimum | -10.1 | -11.0 | -0.9 | 9.2 |
| Maximum | 19.8 | 20.7 | 0.9 | 4.6 |
| Standard deviation | 2.2 | 2.2 | 0.0 | 0.9 |
| Coefficient of variation (%) | -207.2 | -151.7 | 55.5 | -26.8 |
| Percentile 5 (P5) | -4.2 | -4.6 | -0.4 | 9.3 |
| Percentile 25 (P25) | -2.4 | -2.8 | -0.4 | 17.7 |
| Percentile 75 (P75) | 0.0 | -0.4 | -0.4 | 1032.1 |
| Percentile 95 (P95) | 2.7 | 2.4 | -0.3 | -10.8 |

The local micro-topographic variations associated with surface convergence (drainage channels and gully systems) and divergence (crests and terrace boundaries) were evaluated utilizing the Convergence Index (CI) (Fig. 7 and Table 5). The spatial distribution of the CI limits highlights the highly complex geometric layout of the steep slope terraces. However, due to the presence of absolute minimum and maximum computational values constrained at the mathematical limits of –100.0 and 100.0, respectively, the cartographic visualization

requires optimized local contrast stretching (between –20 and 20) to fully resolve the subtle linear features of the hillslope layout.

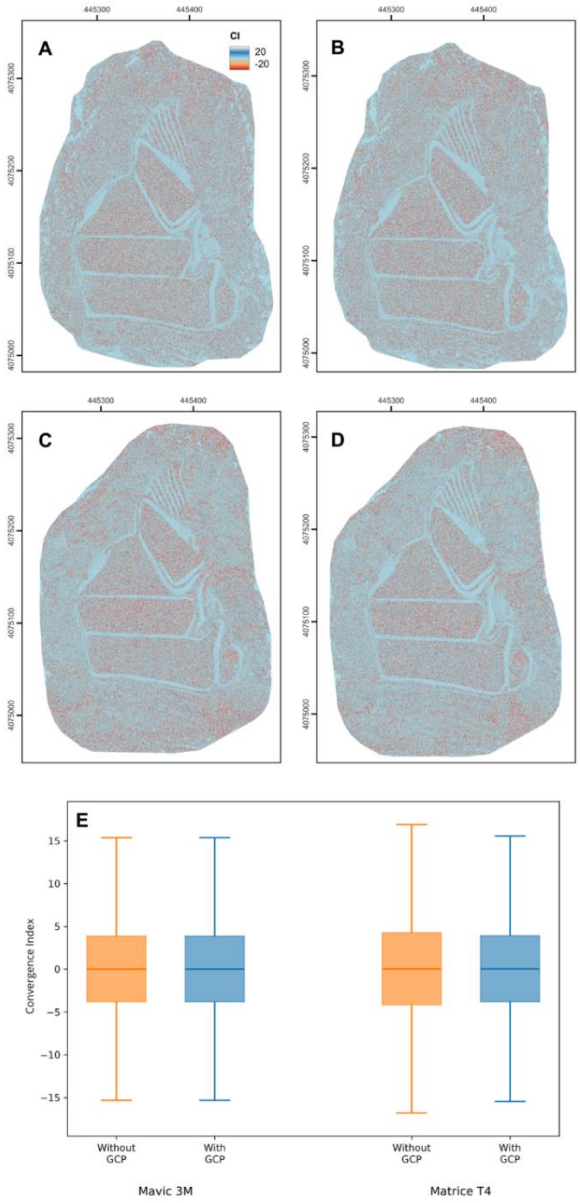


**Figure 7. Comparison of Convergence Index (CI) maps and statistical distributions obtained from the four UAV photogrammetric workflows using RTK direct georeferencing and RTK combined with Ground Control Points (GCPs). (A) DJI Mavic 3 Multispectral (RTK only); (B) DJI Mavic 3 Multispectral (RTK + GCPs); (C) DJI Matrice T4 (RTK only); (D) DJI Matrice T4 (RTK + GCPs); (E) Boxplot comparison of Convergence Index (CI) distributions**

The geostatistical residual matrix demonstrates an outstanding structural match between the digital elevation derivatives of both UAV systems. Under both georeferencing strategies ("With GCPs" and "Without GCPs"), the mean and median cell-by-cell CI discrepancies between the DJI Mavic 3M and DJI Matrice T4 remained locked at an absolute baseline of 0.0, yielding a net difference of 0.0. The extreme coefficients of variation recorded in the statistical summary (reaching –3,292,368.5% and –6,739,567.3%) do not indicate model instability; rather, they represent a well-known mathematical artifact triggered when dividing standard deviations by a global mean value that is practically zero, which is typical for balanced convergent/divergent landforms.

**Table 5. Descriptive statistics of cell-by-cell Convergence Index (CI) discrepancies between DJI Mavic 3M and DJI Matrice T4 photogrammetric models under different georeferencing configurations (With GCPs vs. Without GCPs), including absolute differences and relative changes (%)**

| Parameter | With GCPs | Without GCPs | Difference | Change (%) |
|---|---|---|---|---|
| Mean | 0.0 | 0.0 | 0.0 | −47.9 |
| Median | 0.0 | 0.1 | 0.0 | 8.5 |
| Minimum | −100.0 | −100.0 | 0.0 | 0.0 |
| Maximum | 100.0 | 100.0 | 0.0 | 0.0 |
| Standard deviation | 11.9 | 12.7 | 0.8 | 6.6 |
| Coefficient of variation (%) | −3292368.5 | −6739567.3 | −3447198.8 | 104.7 |
| Percentile 5 (P5) | −17.0 | −18.5 | −1.5 | 9.1 |
| Percentile 25 (P25) | −3.8 | −4.2 | −0.3 | 8.9 |
| Percentile 75 (P75) | 3.9 | 4.3 | 0.3 | 8.5 |
| Percentile 95 (P95) | 16.6 | 18.2 | 1.5 | 9.2 |

This absolute structural alignment is visually summarized in the exploratory boxplot analysis, where the interquartile ranges (IQR) and internal median indicators show perfect horizontal synchronization across all four scenarios. When evaluating the spatial distribution across the percentiles, the absolute discrepancies caused by omitting the ground control network remain exceptionally narrow. The intermediate terrain positions (P25 and P75) exhibit minor absolute deviations of only 0.3 (representing an 8.9% relative change baseline). Even at the extreme geometric boundaries of the terraced steps, represented by the 5th (P5) and 95th (P95) percentiles, the absolute inter-platform variations do not exceed 1.5 units.

### Absolute Positioning Accuracy and Structural Block Behavior

To decipher the geometric nature of the errors, the absolute spatial coordinates (X, Y, Z) of 10 independent checkpoints were compared between the RTK direct georeferencing and the optimized GCP-supported workflows for both platforms (Table 6). The coordinate tracking reveals an identical, highly rigid systematic block shift across the study area rather than internal geometric distortion.

For the DJI Mavic 3M workflow, the direct RTK georeferencing introduced a uniform systemic offset, exhibiting a mean deviation of Delta X = 0.2 m, Delta Y = 5.3 m, and a vertical displacement of Delta Z = -2.8 m. The horizontal vector error remained locked at a constant 5.3 m. Tthe standard deviation for all directional components was 0.0 m, verifying that no internal warping or scale tilting occurred within the photogrammetric model. An identical pattern was captured with the DJI Matrice T4 platform. The structural model obtained a mean systematic translation of Delta X = 0.2 m, Delta Y = 5.4 m, and Delta Z = -2.8 m, resulting in a horizontal shift of 5.4 m. The internal coherence remained exceptionally high, with standard deviations capped between 0.0 m and 0.1 m across all checkpoints.

**Table 6. Summary of absolute positioning errors and deviations (meters) at checkpoints**

| UAV Plaform | Metric | ΔX (m) | ΔY (m) | ΔZ (m) | Total Er-ror_XY (m) |
|---|---|---|---|---|---|
| DJI Mavic 3M | Mean | 0.2 | 5.3 | -2.8 | 5.3 |
| | Std. Dev. | 0.0 | 0.0 | 0.0 | 0.0 |
| DJI Matrice T4 | Mean | 0.2 | 5.4 | -2.8 | 5.4 |
| | Std. Dev. | 0.0 | 0.1 | 0.1 | 0.1 |

This spatial behavior confirms a rigid-body translation artifact. The displacement is not an operational failure of the internal RTK modules; instead, it represents a standard datum or baseline reference initialization offset between the autonomous DJI D-RTK 3 broadcasting station and the post-processed multi-band Emlid Reach RS3 reference frame.

## Discussion

The geomorphometric and pedogeomorphological implications of our results establish a new operational paradigm for monitoring high-energy agricultural landforms, such as the steep terraced vineyards evaluated in this study. The statistical distribution of the slope derivatives, RUSLE LS-factor, TWI, and Convergence Index (CI) demonstrated that next-generation RTK direct georeferencing achieves structural parity with traditional, labor-intensive Ground Control Point (GCP) networks. Across all four terrain indices, the median values and interquartile ranges remained almost unaltered between configurations, showing absolute discrepancies that rarely exceeded single-digit thresholds (e.g., a median slope variation of just 0.7° and an absolute mathematical variance of 0.0 in the structural boundaries of the Convergence Index). This high-performance internal consistency across the topographic spectrum proves that the micro-topography of terrace risers, flat benches, and developing gully systems can be modeled with identical morphological fidelity using either the compact DJI Mavic 3M or the heavy-duty DJI Matrice T4.

The physical explanation for this high geometric compliance is fully unraveled by the absolute checkpoint coordinate residual matrix. Instead of presenting localized photogrammetric warping, internal scale distortions, or vertical tilt—which are typical systematic errors associated with historical drone configurations—the pure RTK block acted as a perfectly rigid body (Rodrigo-Comino et al., 2026). The checkpoint analysis revealed an identical, systematic three-dimensional translation vector (ΔX≈0.2 m, ΔY≈5.4 m, and ΔZ≈-2.8 m) across the entire study site, accompanied by near-zero standard deviations (≤0.1 m) for both platforms. This spatial translation is an expected coordinate system calibration offset between the autonomous DJI D-RTK 3 base station and the post-processed Emlid Reach RS3 GNSS datum. Because the internal relative topography remains entirely unaffected by this rigid block shift, derivative calculations that rely on neighborhood cell algorithms—such as slope gradients, flow direction, and drainage accumulation—remain mathematically identical regardless of the absolute geographic anchoring.

This finding carries vital practical weight when contextualized within current vineyard degradation and UAV photogrammetry literature. Seminal studies in the Iberian Peninsula and Italy have heavily documented that steep terraced viticultural systems exhibit some of the most critical soil erosion rates, landslide vulnerabilities, and gully development processes due to structural abandonment or extreme rainfall events. Authors such as Romero-Díaz et al. (2017) in the Murcia region, Martínez-Casasnovas et al. (2016) in the Penedès region, and Rodrigo-Comino et al. (2019) in the Málaga province have consistently stressed the urgent need for high-resolution spatial tools to monitor these laderas before catastrophic

soil loss occurs. Furthermore, on an international scale, researchers like Tarolli and Pijl have successfully utilized UAV photogrammetry in Italian terraced landscapes to detect and track active gully erosion and bank failures, confirming the extreme vulnerability of these agricultural systems (Pijl et al., 2022, 2020; Tarolli et al., 2015)).

However, executing traditional drone campaigns in these complex terrains is inherently inefficient and hazardous. As noted by classic authors in UAV methodologies (James et al., 2017; Turner et al., 2007), distributing and measuring dozens of physical targets (GCPs) across sub-vertical terrace walls introduces high operational risks, long fieldwork timelines, and significant economic costs. While recent evaluations of direct georeferencing workflows (Forlani et al., 2018; Benassi et al., 2017) have shown promising results for standard topographic tracking, their application in agricultural geometries of steep inclination remained unverified.

Our work successfully bridges this methodological gap by providing the first empirical evidence that direct RTK georeferencing via the DJI D-RTK 3 ecosystem completely eliminates the operational dependency on physical ground control for geomorphological monitoring. The lightweight Mavic 3M and the industrial Matrice T4 performed with equivalent geometric accuracy, proving that platform weight and sensor payloads do not degrade the internal consistency of the topographic models under identical flight constraints (40 m AGL, 80% overlap, solar noon). Consequently, this research establishes that managers and geomorphologists can confidently deploy direct RTK workflows to generate highly accurate risk maps, track active erosion channels, and design sustainable management practices in real time, bypassing the need for physical GCPs without losing any thematic or scientific rigor.

Furthermore, the clear interaction between the extracted geomorphometric parameters and the rigid body displacement results in key implications for predicting active surface hydrology in newly terraced mountain terrains. Because indices such as the TWI, CI, and RUSLE LS-factor rely entirely on relative neighborhood-cell pixel derivatives, the 5.4-meter horizontal and 2.8-meter vertical systematic translation vector does not distort the computed topographic flow paths. This explains why the resulting geomorphological maps remain virtually identical regardless of the GCP infrastructure. From an environmental perspective, this spatial consistency is highly valuable for anticipating the spatial activation of surface runoff and concentrated erosive processes, which are notoriously aggressive during the first high-intensity rainfall events on bare, newly prepared agricultural soils (Arnáez et al., 2017; Tarolli et al., 2015). By mapping these high-risk areas with direct RTK photogrammetry without the time-consuming constraints of ground control networks, land managers can rapidly identify critical connectivity pathways and design immediate mitigation strategies. In the context of our ongoing research, monitoring the site after upcoming rainfall events will establish an empirical baseline to assess nature-based solutions adapted to mountainous environments. Specifically, evaluating the strategic application of shredded pruning residues, grass cover or controlled, temporary animal grazing (e.g., targeted cover management via livestock) on the inner benches could provide a highly efficient mechanism to increase surface roughness, enhance infiltration, and curb initial runoff velocity, successfully mitigating soil and nutrient depletion before severe gully networks can develop (Mincu et al., 2025; Minea et al., 2019; Boardman & Vandaele, 2023; Centeri, 2022; Cerdà & Rodrigo-Comino, 2021).

## Conclusions

This study allowed us to quantify the geometric and geomorphometric implications of utilizing direct RTK georeferencing workflows—bypassing traditional Ground Control Point (GCP) networks—for high-resolution mapping in newly steep terraced viticultural landscapes. By executing synchronized flight campaigns with the DJI Mavic 3M and DJI Matrice T4 platforms supported by the DJI D-RTK 3 base station, several critical conclusions can be drawn. The cell-by-cell algebraic comparison proved that advanced geomorphometric derivatives (Slope Gradient, TWI, Convergence Index, and RUSLE LS-factor) maintain structural parity regardless of GCP deployment. The core statistical distributions, interquartile ranges, and median thresholds remained virtually unaltered, validating that both platforms capture the intricate micro-topography of terrace risers and erosion channels with equivalent morphological fidelity. Checkpoint residual analysis unraveled that the unanchored RTK photogrammetric block behaves as a structurally rigid body. Rather than exhibiting local warping, horizontal scale distortions, or vertical tilting, the direct georeferencing workflow only introduced a uniform, systematic three-dimensional translation vector ($\Delta X \approx 0.2$ m, $\Delta Y \approx 5.4$ m, $\Delta Z \approx -2.8$ m) across the entire study site, maintaining near-zero standard deviations ($\leq 0.1$ m).

Because local geomorphological and hydrological indices are computed via spatial neighborhood matrices, their mathematical outputs are completely independent of absolute geographic anchoring. Consequently, the localized systematic block shift does not degrade the internal data quality or the interpretive capacity of the final geomorphological risk maps. The empirical evidence establishes that for localized pedogeomorphological tracking and agricultural risk modeling, the deployment of physical ground control targets can be confidently omitted. Bypassing GCP infrastructure significantly reduces field execution times, minimizes operational costs, and mitigates the physical risks associated with surveying sub-vertical terraced slopes. We concluded that this research provides a robust methodological endorsement for the implementation of direct RTK

georeferencing in extreme agricultural geometries. It establishes a highly efficient framework for land managers and geomorphologists to monitor active soil degradation processes in real time, ensuring that scientific and thematic accuracy are fully preserved while operational workflows are thoroughly optimized.

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## Author contribution

JG-V: Investigation, Visualization, Writing – original draft, Writing – review & editing. LC-R: Data curation, Visualization, Writing – original draft, Writing – review & editing. MTG-M: Data curation, Visualization, Writing – original draft, Writing – review & editing. JR-C: Conceptualization, Investigation, Resources, Data curation, Visualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

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# The impact of using Google Earth Pro on the development of geography-specific competencies in different educational contexts

Marioara PASCU[1,2,3,*], Natacha DUROISIN[1], Nelly PERICHON[1]

[1] University of Mons, Department of Education and Learning Sciences, Mons, Belgium
[2] Technical College "Dimitrie Ghika", Comănești, Romania
[3] Bacău County School Inspectorate, Bacău, Romania
* *Corresponding author*: marioarapascu1@gmail.com

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**Abstract**

The purpose of this research is to analyse the impact of using the Google Earth Pro application on the development of Geography-specific competences among lower secondary school students. The experiment on teaching geography with Google Earth Pro was conducted simultaneously in two different educational environments, in Belgium and Romania. The study was designed as an experimental model with a pre-test and post-test applied to the entire sample, which consisted of an experimental group and a control group.
The research follows a mixed-methods approach, as the data were analysed both qualitatively and quantitatively. The statistical analysis involved the application of nonparametric tests to compare the median distribution (Mann-Whitney U test), frequency, and means between groups, as well as the calculation of the effect size (Cohen's *d*) for each item.
The statistical tests validated all three research hypotheses: (1) the use of Google Earth Pro produced a significant change in the formation of Geography-specific competences; (2) Google Earth Pro had a significant impact on the development of geographical competences among lower secondary students; and (3) the effect size of the intervention—teaching geography with Google Earth Pro—was statistically significant in shaping these competences.Google Earth Pro influenced the development of competences such as the interpretation of graphic representations, the ability to construct explanatory arguments, and spatial skills in both samples (Belgian and Romanian). The comparative analysis of the two samples from Belgium and Romania, belonging to different educational contexts, revealed some differences regarding the level of spatial skill formation—Belgian students encountered greater difficulties in developing this ability. The competence of constructing explanatory arguments was better developed within the Romanian experimental group.
**Keywords:** *geography, GIS, Google Earth Pro, competences, argumentation, spatial skills*

## Introduction

In every national education system, the general educational goals of school Geography are explicitly stated in the curriculum for both lower and upper secondary education. These curricula establish and require the development of a set of general and specific competences. It is up to the teacher to determine the didactic strategies to be employed in order to achieve these competences. Geography, as a science, has a dual character—being both a natural and a social science. The issues of the contemporary world, the methodology of investigating reality, and the thematic approaches common to both dimensions support the unitary character of Geography (MEN, 2021). Geography involves the knowledge and understanding of spatial phenomena and processes, as well as the analysis and interpretation of spatial units—from the global scale to the micro-local one (Jackson, 2006; NRC, 2006). Geography emphasises the creation of interconnections both at a global level (Allen & Massey, 1995; Hardwick & Holtgrieve, 2013) and among its numerous subfields, which include disciplines such as transport (Hay, 1977), geomorphology (Cantón et al., 2011), economics (Dicken, 1986), hydrology, demography, and ecology.

With the emergence of the *digital earth* (Goodchild, 2008) and Geographic Information Systems (GIS), these interconnections between the Earth's geospheres can now be studied in a new context—through the use of GIS tools and geo-browsers. GIS has been recognised among the 25 most important technological innovations that influenced the development of humanity in the 20$^{th}$ century (Demirci, 2008) and has been acknowledged as the most effective technology that can be implemented in teaching geography (Lam et al., 2009; Lateh & Muniandy, 2010). Geography, as a school subject, provides an ideal framework for GIS integration because it establishes the foundation for these interconnections (Kemp et al., 1992). Teaching basic geographical concepts such as water, climate, and natural disasters is particularly well suited to GIS tools, since they use real-world data that help students think critically and solve authentic problems related to different locations on Earth (Kerski, 2023).

Buzo et al. (2022) conducted a study among experts and teachers of geography at the university and high school levels, which revealed a consensus that GIS helps to understand territory in an experiential and non-memorising way and supports the development of spatial thinking. GIS has begun to be used even in primary schools as a didactic tool because it provides valuable map resources for students of all ages (Kerski, 2003; Jo et al., 2016). GIS offers diverse datasets and tools that assist teachers in delivering fundamental content and concepts—such as change, scale, ratios, historical events, and biomes—in line with national educational standards (Kerski, 2023).

Google Earth uses GIS technology to create 3D images of the entire planet based on high-resolution satellite imagery. The latest version, Google Earth Pro, offers several benefits, such as the import of thematic maps from QGIS and ArcGIS, shape and GeoJSON files, kmz/kml files, and ESRI MapInfo tables. It also allows for surface measurements, drawing of circles and polygons, viewing of historical imagery, printing and saving of high-resolution maps, and the creation of collaborative maps. Although Google Earth does not provide as many tools or capabilities as a full GIS, it enables students to explore spatial examples and develop spatial thinking (Alfatikh et al., 2020).

Since its introduction, Google Earth has been used in academic teaching (De Paor et al., 2017) and in numerous research studies. In recent years, the use of geospatial technologies, including Google Earth Pro (GEP), in secondary education has become a global trend (Avdić et al., 2020), possibly because of their user-centred design (Hong, 2018). Alfatikh et al. (2020) argue that no other science benefits more from the use of Google Earth than the geosciences. Whereas in the traditional model students needed multiple printed thematic maps to conduct geographical investigations, digital tools such as Google Earth Pro now offer a more interactive interface, allowing multiple maps to be overlaid and queried simultaneously. These tools are easier to use than traditional maps and more effective when used as teaching materials (Pickles, 1997).

The benefits of Google Earth are numerous. Palmer (2013) asserts that Google Earth has significantly influenced students' learning of landforms and their acquisition of spatial perception skills; it allows for instant collection of information from various sources (Goodchild, 2008), helps understand natural and cultural events (Guertin & Neville, 2011), supports critical thinking and spatial analytical operations, stimulates student-centred learning and motivation (Awada & Diab, 2018), and provides opportunities to observe and interpret natural changes, enhancing understanding of complex environmental structures (Xiang & Liu, 2017). Alfatikh et al. (2020) also found a positive correlation between the use of Google Earth and students' participation in task completion, showing increased engagement in classroom activities. A previous study highlighted students' interest in learning geography using Google Earth Pro; the main benefits cited by students were: an opportunity to discover places on the Earth's surface that otherwise would never be seen, spatial orientation, real-time visualization of the Earth's surface, analysis of geospatial data for educational purposes, and assistance in everyday life, not just for school (Pascu & Duroisin, 2026).

In the United Kingdom and other countries, there is growing pressure for schools to teach GIS as part of their curriculum, and Google Earth Pro provides this opportunity by functioning as a "simple" GIS system that introduces basic concepts such as data formats (e.g., vector—point, line, polygon; raster—a matrix of pixels, such as an image). These are already present in the software package (e.g., satellite imagery, road networks) and can be customised by users to create their own resources (Mather et al., 2015).

The development of argumentation skills is a goal of geographical education as defined in national educational standards and curricula (DGFG, 2014). Studies have shown that students often struggle to formulate complete, technically correct, and convincing arguments (Budke & Kuckuck, 2020; Chase, 2011; Lytzerinou & Iordanou, 2020; Uhlenwinkel, 2015) or to generate valid evidence to support their claims (Sampson et al., 2013). Researchers have emphasised the need to implement didactic strategies that help teachers integrate tools and instructional methods to develop students' argumentation skills (Chen et al., 2017).

Geographical argumentation is usually written with the help of supporting materials (Budke, 2021)—maps, diagrams, texts, and images. To improve the quality of arguments, students should be provided with supporting elements that enable them to produce more coherent reasoning during argumentation. Visual representations can facilitate students' understanding of argument structure (Akpınar et al., 2014) and increase their awareness. Google Earth Pro offers all these resources—maps, images, visual representations, and data—that can support the development of students' argumentation skills.

Based on Toulmin's model (1990), Google Earth Pro is an extremely useful information source in directly supporting two of the model's components: it provides the necessary *data* (in the form of satellite images, thematic maps, altitudes, geographic coordinates, etc.) and additional *backing* (through thematic layers and extracted measurements).

Indirectly, Google Earth Pro supports the remaining components of Toulmin's model by providing information that helps students interpret data and formulate the *claim*, *warrant* and *qualifier*. Out of the six components of Toulmin's model, GEP directly supports two, indirectly supports three, while the last one—*rebuttal*—remains the student's own creation.

## Methodology

The purpose of this research is to analyse the impact of using the Google Earth Pro application on the development of geography-specific competences among lower secondary students (aged 14–15).

### Research Questions:

• To what extent has the use of the Google Earth Pro application influenced the formation of Geography-specific competences among lower secondary students?

• How effective has the use of Google Earth Pro proven to be in developing Geography competences in lower secondary education?

• How significant was the impact of introducing Google Earth Pro on the formation of Geography-specific competences?

• To what extent do the research results on the effectiveness of Google Earth Pro in developing geographical competences differ between the two educational contexts—Romanian and Belgian?

The sample consisted of a total of 86 students from two different educational environments, Belgium and Romania. The Belgian sample included 43, S3 students, of whom 29 formed the experimental group and 14 formed the control group. The Romanian sample also included 43 ninth-grade students, of whom 20 formed the experimental group and 23 the control group. Students were selected based on availability. In Romania, the implementation stage of the research was carried out by two Geography teachers from different educational institutions, while in Belgium, the experiment was implemented by the researcher in two different educational institutions, assisted by the Geography teachers teaching those classes. Before starting the experiment, the researchers prepared the course materials for the *Hydrosphere* chapter, lesson plans for teachers, worksheets for students, a blog page with all the teaching resources required for the experiment, as well as thematic files in KMZ and Shape file formats for use with Google Earth Pro.

**Figure 1. Teaching hydrography using Google Earth Pro**

Before implementing the didactic scenario of teaching and learning Geography with Google Earth Pro, a student knowledge questionnaire was administered (Fig. 1).

**The experiment** took place between April and May 2025 and lasted three weeks (6 hours in total). During these three weeks, students learned Geography content using the Google Earth Pro application. The study was designed as an experimental model with a pre-test and a post-test applied to the entire sample, consisting of both an experimental and a control group. The experiment was conducted simultaneously in two different educational contexts, in Belgium and Romania. Both target groups — the Romanian and the Belgian students — had previously studied some general aspects of the hydrosphere, as well as fundamental elements related to it. Therefore, it was assumed that students already possessed certain knowledge, skills, and competencies specific to Geography, which had been progressively acquired in previous years. Consequently, a pre-test was administered to determine the students' initial level of knowledge and competence related to the *Hydrosphere* chapter.

At the end of the three weeks, a post-test was applied in order to identify changes that occurred after the experiment, as well as to evaluate the impact of using Google Earth Pro on the development of specific Geography competencies: interpreting graphical representations, constructing explanatory arguments, and developing spatial abilities. The post-test aimed to determine the effectiveness of this digital tool in fostering these three specific geography competencies. The research used an identical structure for both the pre-test and post-test, with only one modification applied to the evaluation of the *Interpretation of a graphical representation* competence — the diagram/image used was slightly adjusted in the post-test (the order of numbers and the position of some elements were changed). Educational research often employs pretesting to rank participants based on their test scores, to create teaching materials suited to students' current levels of knowledge, and to identify what they already know or what deficiencies they have (Kim & Willson, 2010). Prior knowledge occupies a central position in three major learning theories: schema theory, mental models (Johnson-Laird, 1983), and constructivism (Roth & Roychoudhury, 1992; Von Glasersfeld, 1989). The pre-test aimed to identify the initial level of development of the specific Geography competencies before the experiment was applied. The three competencies were assessed in both the pre-test and post-test through three items.

Willson & Putnam (1982) reported that pretest effects on cognitive outcomes are generally greater than on affective measures. Furthermore, it was observed that the effects of pretesting vary depending on the characteristics of the participants (e.g., age and ability level) as well as the characteristics of the testing (e.g., the time interval between the pre-test and post-test;

Gunasekera, 1997; Willson & Putnam, 1982). Students' responses to each of the three items were evaluated using a scoring grid on a scale from 0 to 10 points. The level of competence development was coded on a four-point scale (1–4).

**Use of Google Earth Pro**. The first lesson was of a mixed type, with time resources allocated both to a brief presentation of the content related to *running waters* and to the introduction of the Google Earth Pro application. Students were introduced to the program, its menu, and its main functions. They were divided into teams of 2–3 students, each team having access to a laptop. Several exercises were conducted to practice searching for, identifying, and locating different places, in order to familiarise students with the local and regional scales, the transition from the 3D virtual globe to Google Street Map, and the 3D physical map of the world — all while maintaining north–south orientation and developing geo-visualisation skills of the Earth's surface.

The second lesson focused on reviewing previous content related to *running waters* and conducting collaborative learning activities using Google Earth Pro. The learning tasks involved: importing into Google Earth Pro the map *The Major River Basins of the World* and importing KMZ and GeoJSON files of selected river basins (Amazon, Nile) (Fig. 2). Using these materials, students were asked to identify and locate the river basins of the world's major rivers (Mississippi, St. Lawrence, Colorado, Amazon, Congo, Nile, Niger, Ganges, Indus, Huang He, Chang Jiang, Ob, Yenisei, Danube, Murray–Darling). With the help of thematic layers, they learned about the components of a river (drainage basin, tributaries, confluences, source, flow direction, etc.) and completed a worksheet focused on the Nile River. Students worked on the worksheet by investigating the thematic KMZ file from Locations with *Primary Data* (boundaries, limits, and water sources). Google Earth Pro was used as a tool for gathering information, exploring, and developing spatial orientation.


**Figure 2. Sequence from the teaching scenario based on the use of Google Earth Pro, Belgian target group**

The third lesson focused on learning about *fluvial landforms* and *flooding*. The same method was maintained — collaborative learning using Google Earth Pro. The tasks involved identifying and locating regions at risk of flooding and analyzing and interpreting landforms as a contributing factor to the occurrence of floods.

## Research Hypotheses

• The use of Google Earth Pro produced a significant change in the development of Geography-specific competencies.

• The Google Earth Pro application had a significant impact on the development of geographical competencies among lower secondary students.

• The effect size (r) of teaching Geography using Google Earth Pro was statistically significant in the formation of these competencies.

To validate the research hypotheses, the SPSS 28.0 software was used. The statistical analysis involved the application of nonparametric tests for comparing: the Mann–Whitney median distributions (to verify whether the distributions of a variable were similar in the two groups — experimental and control), the means between groups, the frequency, and the effect size (Cohen's *r*) for each of the three items. The research adopted a mixed-methods approach, with data analysed both qualitatively and quantitatively.

## Results

In the first stage, the data were statistically (according to the nationality criterion) and later comparatively analysed.To ensure that both samples were homogeneous and comparable in terms of students' knowledge, skills, and competencies, the Independent-Samples Mann–Whitney U Test was applied to the pre-test results. Both samples (Belgium and Romania) obtained Mann–Whitney U test values (Table 1) above the significance threshold of 0.05 for all three items, which means there were no differences between the scores obtained by students in the two groups (control and experimental) at the pre-test stage. This demonstrates that the groups were homogeneous and comparable in terms of their initial knowledge and skills.

**Table 1. The Mann–Whitney U test values at pre-test**

| The Belgian sample | | |
|---|---|---|
| | Test | Sig. |
| Interpreting graphical representations | Independent- Samples Mann- Whitney U test | 0.376 |
| Constructing an explanatory argument/ Argumentation | Independent- Samples Mann- Whitney U test | 0.466 |
| Spatial abilities | Independent- Samples Mann- Whitney U test | 0.829 |
| The Romanian sample | | |
| Interpreting graphical representations | Independent- Samples Mann- Whitney U test | 0.478 |
| Constructing an explanatory argument/ Argumentation | Independent- Samples Mann- Whitney U test | 0.970 |
| Spatial abilities | Independent- Samples Mann- Whitney U test | 0.127 |

For the Belgian sample, the Mann–Whitney U test recorded the following values for the three items: $p = 0.376$, $p = 0.466$, $p = 0.829$. A similar situation was observed for the Romanian sample, where $p = 0.478$, $p = 0.970$, $p = 0.127$. These values indicate that there were no statistically significant differences between the groups, confirming their eligibility for a comparative analysis of post-test results after implementing the teaching experiment using Google Earth Pro.

First Research Hypothesis: *The use of Google Earth Pro produced a significant change in the development of Geography-specific competencies*. To validate or invalidate this hypothesis, the t-test for independent samples was employed. Given that in both countries the groups were small and unequal in size, the students' post-test results were statistically analysed using the nonparametric Independent-Samples Mann–Whitney U Test.

The statistical results show that for the Belgian sample, the Independent-Samples Mann–Whitney U Test (Table 2) recorded values below the significance threshold of 0.05 for all three post-test items*:* $p = 0.005$, $p = 0.031$, $p = 0.001$, indicating statistically significant differences between the two groups. These differences may be attributed to the use of the Google Earth Pro application. Thus, for the Belgian sample, the research hypothesis is validated — the use of Google Earth Pro produced a significant change between the two groups. The differences observed in the post-test are a consequence of introducing this digital tool in Geography learning and in the formation of the three competencies. The groups started off with similar scores (pre-test), supporting baseline equivalence. After the intervention with Google Earth Pro, their scores differed significantly (post-test), indicating that the treatment likely had an impact.

**Table 2. Mann–Whitney U test values at post-test**

| The Belgian sample | | |
|---|---|---|
| | Test | Sig. |
| Interpreting graphical representations | Independent- Samples Mann- Whitney U test | 0.005 |
| Constructing an explanatory argument/ Argumentation | Independent- Samples Mann- Whitney U test | 0.031 |
| Spatial abilities | Independent- Samples Mann- Whitney U test | 0.001 |
| The Romanian sample | | |
| Interpreting graphical representations | Independent- Samples Mann- Whitney U test | 0.647 |
| Constructing an explanatory argument/ Argumentation | Independent- Samples Mann- Whitney U test | 0.414 |
| Spatial abilities | Independent- Samples Mann- Whitney U test | 0.922 |

For the Romanian sample, all Independent-Samples Mann–Whitney U Test values were above the 0.05 significance threshold, indicating no statistically significant differences between the two groups for any of the three post-test items. Therefore, the research hypothesis was invalidated — the use of Google Earth Pro did not produce a statistically significant change in the development of geography-specific competencies among the Romanian students.

Although the statistical analysis did not show a significant difference between the experimental and control groups, a statistically significant change could still be observed *within* the experimental group using the Paired Samples Test (Table 3). This test indicates whether students' results improved between the pre-test and post-test, and whether a significant change occurred between the two measurements. The research hypothesis can therefore be validated through the paired samples test.

The Paired Samples Test (Table 3) showed that within the experimental group, significant differences were recorded between the pre-test and post-test for all three items ($p = 0.036$, $p = 0.048$, $p < 0.001$). These results demonstrate that Google Earth Pro positively influenced students' performance, producing a significant change. The hypothesis is thus validated.

Considering that other factors could have influenced students' results between pre-test and post-test — such as motivation, teacher experience, and teaching style — a Paired Samples Test was also calculated for the control

group to determine whether their performance changed between the two tests. The Paired Samples Test (Table 4) showed values above the significance threshold of 0.05 for all three items (*p = 0.117*, *p = 0.278*, *p = 0.676*). Consequently, students in the control group did not show progress; no significant change occurred between pre-test and post-test. In this context, it can be concluded that the Google Earth Pro application played an important role in the formation of competencies among students in the experimental group.

**Table 3. Paired samples test results for the Romanian experimental group**

| Paired Differences | Mean | t | df | One-Sided p | Two-Sided p |
|---|---|---|---|---|---|
| Interpreting graphical representations : pre-test – post-test | -2.14550 | -2.251 | 19 | .018 | .036 |
| Constructing an explanatory argument/ Argumentation : pre-test – post-test | -1.18750 | -2.111 | 19 | .024 | .048 |
| Spatial abilities : pre-test – post-test | -2.71500 | -5.792 | 19 | <.001 | <.001 |

**Table 4. Paired samples test results for the the Romanian sample, control group**

| Paired Differences | Mean | t | df | One-Sided p | Two-Sided p |
|---|---|---|---|---|---|
| Interpreting graphical representations : pre-test – post-test | -1.02071 | -1.680 | 13 | .058 | .117 |
| Constructing an explanatory argument/ Argumentation : pre-test – post-test | .62500 | 1.132 | 13 | .139 | .278 |
| Spatial abilities : pre-test – post-test | .06000 | .428 | 13 | .338 | .676 |

Second Research Hypothesis: *The Google Earth Pro application had a significant impact on the development of geographical competencies among lower secondary students*. To validate this hypothesis, statistical tests comparing means (Table 5) and frequencies (Table 6) of the results obtained by students in the two groups (experimental and control) were used for the three items at pre-test and post-test.

**Table 5. Mean Comparison test results**

| Skills/items | Control group | Experimental group |
|---|---|---|
| The Belgian sample | | |
| Interpreting graphical representations - Pretest | *N= 14** | *N=29** |
| | 4.4 | 3.9 |
| Interpreting graphical representations - Posttest | 5.4 | 7.9 |
| Constructing an explanatory argument/ Argumentation Pretest | 3.0 | 2.5 |
| Constructing an explanatory argument/ Argumentation Posttest | 2.5 | 4.2 |
| Spatial abilities Pretest | 0.5 | 1.1 |
| Spatial abilities Posttest | 0.4 | 2.3 |
| The Romanian sample | | |
| Interpreting graphical representations - Pretest | N= 23 | N=20 |
| | 3.65 | 4.06 |
| Interpreting graphical representations - Posttest | 6.26 | 6.21 |
| Constructing an explanatory argument/ Argumentation Pretest | 5.59 | 5.68 |
| Constructing an explanatory argument/ Argumentation Posttest | 5.97 | 6.87 |
| Spatial abilities Pretest | 2.41 | 3.51 |
| Spatial abilities Posttest | 6.59 | 6.22 |

**Table 6. Results of the frequency comparison test**

| The Belgian sample | | Control | | Experiment | |
|---|---|---|---|---|---|
| | | PRE_POST | | PRE_POST | |
| Skills | | Pre test | Post Test | Pre test | Post Test |
| Interpreting graphical representations | Level | *14** | *14** | *29** | *29** |
| | Insufficient | 71.4 | 50.0 | 75.9 | 10.3 |
| | Satisfactory | 7.1 | 14.3 | 13.8 | 10.3 |
| | Good | 21.4 | 28.6 | 10.3 | 62.1 |
| | Very Good | 0.0 | 7.1 | 0.0 | 17.2 |
| Constructing an explanatory argument/ Argumentation | Insufficient | 85.7 | 92.9 | 93.1 | 72.4 |
| | Satisfactory | 7.1 | 7.1 | 0.0 | 10.3 |
| | Good | 7.1 | 0.0 | 6.9 | 17.2 |
| | Very Good | 0.0 | 0.0 | 0.0 | 0.0 |
| Spatial abilities | Insufficient | 100.0 | 100.0 | 96.6 | 89.7 |
| | Satisfactory | 0.0 | 0.0 | 0.0 | 6.9 |
| | Good | 0.0 | 0.0 | 3.4 | 0.0 |
| | Very Good | 0.0 | 0.0 | 0.0 | 3.4 |
| The Romanian sample | | | | | |
| Interpreting graphical representations | Level | *23** | *23** | *20** | *20** |
| | Insufficient | 69.6 | 30.4 | 80.0 | 35.0 |
| | Satisfactory | 17.4 | 8.7 | 10.0 | 15.0 |
| | Good | 13.0 | 60.9 | 10.0 | 20.0 |
| | Very Good | 0.0 | 0.0 | 0.0 | 30.0 |
| Constructing an explanatory argument/ Argumentation | Insufficient | 30.4 | 26.1 | 45.0 | 10,0 |
| | Satisfactory | 30.4 | 30.4 | 20.0 | 50,0 |
| | Good | 30.4 | 13.0 | 10.0 | 25.0 |
| | Very Good | 8.7 | 30.4 | 25.0 | 15,0 |
| Spatial abilities | Insufficient | 82.6 | 8.7 | 70.0 | 30,0 |
| | Satisfactory | 8.7 | 47.8 | 20.0 | 25.0 |
| | Good | 8.7 | 30.4 | 10.0 | 35.0 |
| | Very Good | 0.0 | 13.0 | 0.0 | 10.0 |

In the Belgian sample, statistically significant differences were observed between the two groups in post-test results:

For *Interpreting graphical representations*, the experimental group's mean score (7.9) was much higher than that of the control group (5.4).

For *Constructing an explanatory argument*, the experimental group scored 4.2, higher than the control group's 2.5.

For *Spatial abilities*, the experimental group's mean (2.3) exceeded that of the control group (0.4).

In the Romanian sample, the test comparing means indicated significant differences between groups for Item 2 of the post-test: the control group had a mean of 5.97, while the experimental group scored slightly higher, at 6.87.

However, the difference in mean scores between pre-test and post-test does not fully reflect the impact of using Google Earth Pro in geography teaching, nor does it capture students' actual progress, given that the items were evaluated on a 0–10 point scale. To clarify this, students' results for the three items were classified into four performance categories — *Insufficient*, *Sufficien*t, *Good*, and *Very Good* — and their frequencies were calculated and compared (Table 6).

The Belgian sample showed that experimenting with learning Geography using Google Earth Pro had a significant positive impact on the experimental group (Figure 3). The proportion of students who scored very poorly on the pre-test, with an insufficient level (75.9%) of competence in interpreting cartographic representations, decreased significantly to 10.3% in the post-test.

**Figure 3. Doing some exercises during geography class— the Belgian target group**

We also observe that the frequency of students who achieved scores corresponding to the Good performance level increased substantially — from 10.3% on the pre-test to 62.1% on the post-test — while 17.2% of students reached a Very Good performance level. Google Earth Pro had a very strong impact on this competence. Google Earth Pro also appears to have influenced the level of development of the Argumentation competence. The proportion of students in the experimental group who had an Insufficient performance level on the pre-test decreased from 93.1% to 72.4%; 20.7% of students improved to Satisfactory (10.3%) and Good (17.2%) levels. However, no student achieved a high level of performance. The use of Google Earth Pro produced modest progress at the post-test, while the control group recorded a regression. The most difficult competence and task seemed to be the spatial ability. The impact of the Google Earth Pro application was not as great as in the case of the first competence. A slight improvement was observed, with the proportion of students at the Insufficient performance level decreasing from 96.6% to 89.7%, and a slight increase in those at Satisfactory (6.9%) and Very Good (3.4%) levels.

At the level of the Romanian sample, the experimental group recorded an improvement in the Interpretation of graphic representations competence. The proportion of students with an Insufficient level at the pre-test (80%) decreased considerably; at the post-test, it was 35%. A positive evolution was also found in the improvement of performance at the Satisfactory, Good, and Very Good levels. Google Earth Pro also had a major impact on the performance level of students in developing the Argumentation of an explanatory approach competence. Compared to the pre-test, the share of students with an Insufficient level decreased from 45% to 10%; the proportion of those at a Satisfactory level increased from 20% to 50%, and those at a Good level from 10% to 25%. Students' performance level in the third competence — spatial abilities — improved after using Google Earth Pro. The proportion of students with a very low performance level decreased from 70% to 30% at the post-test. Moreover, the proportion of students with a Good level increased to 35%, and those with a Very Good level to 10%. For both samples, the research hypothesis is confirmed: the Google Earth Pro application had a significant impact on the level of development of the three geography-specific competences. The third hypothesis, concerning the effect size of the intervention (Cohen's d) of teaching geography with Google Earth Pro, was statistically significant in developing geography-specific competences.

The Cohen's d values (Table 7) recorded for the Belgian experimental sample show that the effect size of the Google Earth Pro intervention for item 1 is d = -1.444, demonstrating a substantial impact on developing the competence *Interpretation of cartographic representations*; for item 2, d = -0.576, indicating a moderate impact on *Argumentation of an explanatory approach*; and for item 3, d = -0.766, indicating a large impact on Spatial ability development.

For the Romanian sample, the effect size of the Google Earth Pro intervention indicates that the application had a significant impact in developing all three competences. The obtained Cohen's d coefficients are significant: for *Interpretation of cartographic representations*, d = -0.503; for *Argumentation of an explanatory approach*, d = -0.472; and for *Spatial abilities*, d = -1.295. The use of Google Earth Pro had a

medium effect on competences 1 and 2, and a very large effect on competence 3.

The Cohen's d values validate the research hypothesis for both samples: the effect size (Cohen's d) of teaching geography with Google Earth Pro was statistically significant in developing geography-specific competences.

**Table 7. Paired samples effect sizes (Cohen's *d* coefficients)**

| Paired Samples Effect Sizes | | Standardizer[a] | Point Estimate | 95% Confidence Interval | |
|---|---|---|---|---|---|
| | | | | Lower | Upper |
| The Belgian sample | | | | | |
| Interpreting graphical representations pre-test – post-test | Cohen's d | 2.76541 | -1.444 | -1.961 | -.914 |
| | Hedges' correction | 2.84234 | -1,405 | -1.908 | -.889 |
| Constructing an explanatory argument/ Argumentation pre-test – post-test | Cohen's d | 2.91769 | -.576 | -.965 | -.178 |
| | Hedges' correction | 2.99887 | -.561 | -.939 | -.173 |
| Spatial abilities pretest – post-test | Cohen's d | 1.60453 | -.766 | -1.176 | -.346 |
| | Hedges' correction | 1.64917 | -.745 | -1.144 | -.336 |
| The Romanian sample | | | | | |
| Interpreting graphical representations pre-test – post-test | Cohen's d | 4.26193 | -.503 | -.964 | -.031 |
| | Hedges' correction | 4.43992 | -.483 | -.925 | -.030 |
| Constructing an explanatory argument/ Argumentation pre-test – post-test | Cohen's d | 2.51558 | -.472 | -.929 | -.004 |
| | Hedges' correction | 2.62064 | -.453 | -.892 | -.003 |
| Spatial abilities pre-test – post-test | Cohen's d | 2.09624 | -1.295 | -1.885 | -.687 |
| | Hedges' correction | 2.18379 | -1.243 | -.1.810 | -.659 |

## Comparative analysis of the research results in the context of the two educational systems: Romanian and Belgian

Similarities: Both samples consist of homogeneous and comparable groups, and the research hypotheses are validated for both samples.

Differences: A statistically significant change after the experiment involving teaching–learning geography using the Google Earth Pro application was demonstrated for the Belgian sample using the Mann–Whitney U test, while for the Romanian sample, it was validated using the paired sample test. The frequency comparison test indicates a more pronounced improvement in the performance level of the *Interpretation of graphic representations* competence for the Romanian sample, as the proportion of students at a Very Good level (30%) is higher than in the Belgian sample (17.2%). However, the Belgian sample has a higher proportion of students at a Good level (62.1%) compared to the Romanian sample (20%) and a lower proportion of students at an Insufficient performance level (10%). The Argumentation of an explanatory approach competence is better developed in the Romanian experimental group, which recorded a lower proportion of students at an Insufficient performance level (10%) compared to 72.4% in the Belgian group. Also, the proportion of students at a Very Good performance level (15%) is higher than in the Belgian group (0%). Spatial abilities are much better developed in the Romanian sample at all performance levels: 30% of students have an Insufficient level compared to 89.7% in the Belgian group; 35% have a Good level compared to 0.0%, and 10% a Very Good level compared to 3.4%.

After the experiment using Google Earth Pro for geography teaching, at the post-test, the Belgian experimental group achieved a higher performance level than the Romanian group only for the competence *Interpretation of a cartographic representation*, and lower values for the other two competences (*Argumentation of an explanatory approach* and *Spatial abilities*). The effect size (Cohen's d) shows that Google Earth Pro had a very strong impact in the Belgian sample for developing the competence *Interpretation of cartographic representations*, while in the Romanian sample, the impact was very strong in developing *spatial abilities*.

# Discussion

## To what extent has the use of the Google Earth Pro application influenced the development of Geography-specific competencies among lower secondary education students?

Considering that the research was conducted in two different national educational contexts with very few similarities in the geography curriculum for Grade 9 (Romanian system) and S3 (Belgian system), demonstrating that Google Earth Pro (GEP) produced

significant changes in the development of competencies in the experimental group was possible through different statistical methods, while the purpose and effect remained consistent under research conditions using different methods. Our objective was to determine whether the research hypothesis was validated in both educational contexts. Although both samples (Belgian and Romanian) consisted of two groups, experimental and control, homogeneous and comparable in terms of students' initial competencies, skills, and knowledge of the hydrosphere, the validation of the first research hypothesis could be achieved through different but complementary statistical methods. Unlike the Belgian sample, in the Romanian sample, the significant change produced by Google Earth Pro in the development of Geography-specific competencies could not be statistically demonstrated using the same method (by comparing it to the control group and calculating the Independent-Samples Mann-Whitney). Another statistical method, the Paired Sample Test, was required to show a change as a result of using GEP. The research hypothesis was validated in both educational contexts.

**Figure 4. Developing specific skills using Google Earth Pro—the Romanian target group**

The introduction of the Google Earth Pro application into the educational process was a novelty for students in both samples, as they had not previously experienced learning geography content with this digital tool. In the teaching-learning-assessment process of geography, both samples had previously experienced learning through games, and teachers typically assessed and reinforced new knowledge and skills using quizzes, online encyclopaedias, and websites, which were the only digital resources used. The introduction of Google Earth Pro changed students' learning styles because learning activities involved observation and analysis of rivers based on thematic layers imported into GEP. Traditional graphical representations from textbooks were replaced by a 3D geo-visualisation of the Earth's reality, requiring students to conduct investigations of terrestrial surfaces and establish correlations and connections between physical Geography elements.

Hydrography content taught with Google Earth Pro, such as river components, river analysis, and factors influencing flow and fluvial relief, required students to observe, think, and reason more extensively. They had to manipulate and operate multiple information sources simultaneously, including temporary locations (imported thematic layers such as drainage basins, major landforms, climate maps) and primary databases (Fig. 4). GEP influenced the development of competencies in interpreting graphical representations, arguing an explanatory approach, and spatial skills in both samples (Belgian and Romanian).

## How effective was the use of Google Earth Pro in developing geography-specific competencies among lower secondary students?

Studies have shown that students who develop geographic competencies and acquire specialized knowledge will be able to adopt solid geographic perspectives and strengthen their capacity to become change agents in the future (Kerski, 2023). Numerous documented examples in pre-university settings (Fitzpatrick, 2020) and community colleges (Kerski, 2019) show that many students already fulfill this transformative role during their studies, before graduation.

The effectiveness of Google Earth Pro in teaching and learning geography had a very significant effect on Belgian students. The proportion of students with very poor results (Insufficient) decreased, as they moved to the category of passing grades (Satisfactory), thereby reducing the percentage of students at high risk of academic failure and low motivation to learn. Introducing GEP into geography lessons positively affected Belgian

students' attitudes toward geography lessons, particularly among students with very low or low results.

Teaching geography with GEP was highly effective in the Belgian sample in developing the competency of interpreting graphical representations. In the pre-test, this competency had a very low performance level, with 75.9% of students at an Insufficient level and only 10.3% achieving a Good score. After the experiment, the post-test showed a considerable increase in performance, with 62.1% of students at a Good level and 17.2% at a Very Good level.

This competency was assessed through an item requiring students to know and identify seven elements of a drainage basin based on an image. The increase in performance can be attributed to multiple factors that complemented and supported GEP's effectiveness. Pre-test effects are sometimes explained as motivational factors or as serving a direct teaching function (Gunasekera, 1997). GEP's effect may have been reinforced by increased student motivation and interest in geography lessons, which became more interactive and engaging due to the introduction of a new digital tool that captured their attention. Pre-testing may also increase excitement or attention toward upcoming events, such as the treatment and post-test (Sime & Boyce, 1969), especially since the experiment was conducted by researchers who taught the content and worked with students using the application. The presence of these new figures as "teachers" in the experimental pedagogical scenario stimulated student attention throughout the lessons, creating a novel learning context both in terms of the teaching tool and the facilitator.

GEP was highly effective in developing the competency of arguing an explanatory approach in the Belgian sample when considering Cohen's d coefficient. However, performance-level analysis shows that students did not fully progress between pre-test and post-test; 72.4% of students did not reach a satisfactory level of this competency. While the percentages of students achieving Satisfactory (10%) and Good (17.2%) levels increased compared to the pre-test, students still struggled to develop this competency. Teachers should focus more on remedial plans and personalised learning to improve competency.

Cohen's d indicates a high effect of GEP in developing spatial skills in the Belgian sample. This efficiency is reflected in the decrease of students at the Insufficient level (89%), with slight increases at Satisfactory (6.9%) and Very Good (3.4%). Despite these statistical results, the fact that 89% of students have not developed spatial skills is alarming, as this competency is fundamental in geography. No student reached a Good level, and only 3.4% reached Very Good. These results should prompt geography teachers to reflect on methods and teaching tools to improve spatial skills. The same situation is observed in the Romanian sample. GEP had a medium effect on interpreting graphical representations and arguing an explanatory approach, and a very high effect on spatial skills. Cohen's d indicates effect size, but performance-level analysis is needed to determine whether students progressed from Insufficient to Satisfactory, Good, or Very Good. Teachers must be aware of the proportion of students at Insufficient and Satisfactory levels, as these students are vulnerable and at high risk of failing or dropping out. The effect of GEP on interpreting graphical representations is evident in a 30% increase in students at the Very Good level and a 45% decrease in students at the Insufficient level. However, students at Insufficient and Satisfactory levels still constitute 50% of the total, requiring teacher reflection to improve outcomes. GEP had a medium effect on the argumentation competency, reducing the Insufficient level to 10% post-test, but 50% of students remained at Satisfactory. In spatial skills, GEP had a very high effect, improving students at Good and Very Good levels; still, 55% of students remained at Insufficient or Satisfactory.

## How relevant was the impact of introducing Google Earth Pro in developing Geography-specific competencies?

Although the impact of introducing GEP was significant (Cohen's coefficient), the level of development of the three competencies is still not very high in any sample—neither in the Belgian nor in the Romanian sample—despite the fact that these competencies are developed over several years. One possible explanation for this situation could be the general evaluation approach used by teachers in class: if the teacher is more lenient and overestimates students, they become accustomed to this style, put less effort into learning geography, and when faced with standardised assessments using a 0–10 grading scale, they achieve much lower results than they normally do.

The research highlighted the relevance of GEP in teaching content and developing subject-specific competencies. However, the mere introduction of a digital tool into the geography teaching–learning process cannot guarantee sustainable long-term results with substantial improvement in argumentative and spatial skills. If the tool is not integrated into the teaching strategy alongside the teaching methods used by the teacher, educational resources, content, and learning activities adapted to the digital tool, it is difficult to achieve performance in developing students' competencies.

The curricular context, the marginalisation of Geography as a science within the curriculum, and the emphasis placed on mathematics, the native language, modern languages, and other sciences could equally explain the results of this research.

### How much do the research results regarding the efficiency of the Google Earth Pro application in developing geographical competencies differ in the two educational contexts: Romanian and Belgian?

The research results differ between the two samples in terms of improvement in performance levels and the development of the specific competencies analysed. The findings highlight that in the educational process, the mere use of a digital tool is insufficient to guarantee an increase in students' academic performance through a significant improvement in the development of fundamental geographical competencies. Students' learning characteristics, the national educational context, school curricula, student motivation, and the teaching methods used by teachers in the teaching–learning–assessment process support the achievement of performance in developing students' competencies through the use of a digital tool. These factors play a complementary role, supporting the digital tool.

This conclusion was reached by analyzing the results of the two samples. Although statistical analysis indicated that Google Earth Pro produced a significant change with considerable impact on competency development, the proportion of students with an insufficient level in Argumentation of an explanatory process and Spatial Skills is very high in the Belgian sample. By comparison, the Romanian sample shows a lower proportion of students with insufficient levels, raising important questions regarding the causes behind the different results observed in the Belgian sample.

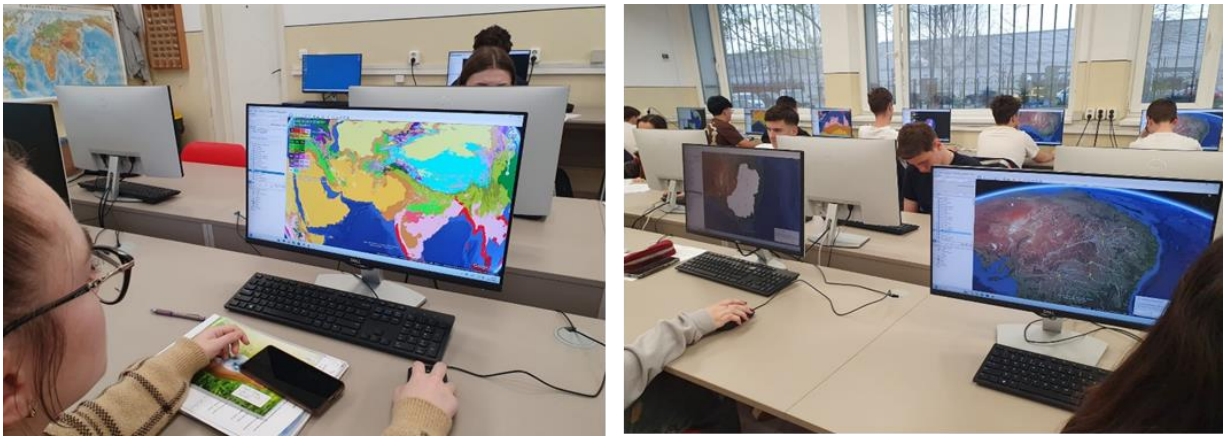

**Figure 5. Teaching scenario focused on developing specific skills using Google Earth Pro—Romanian target group**

The Romanian sample (Fig. 5) showed improvement in all three competencies analysed, while the Belgian sample improved only one. The Romanian sample achieved better results than the Belgian sample in Argumentation of an explanatory process. The "Insufficient" grade indicates very poor results, placing students in a non-passing situation. From this perspective, the non-passing rate in the Belgian sample is very high at 72.4%—this is the proportion of students who have not developed this argumentative competency. In contrast, the non-passing rate in the Romanian sample is much lower at only 10%. The absence in the Belgian sample of students with a Very Good level of argumentative competency indicates serious issues related to academic performance.

Although these competencies are developed over several school years, the very high proportion of students with an insufficient level raises multiple questions regarding students' motivation, interest in Geography, quality of teaching, and the methods and tools used in the teaching process. Among the possible causes explaining this situation are: the short duration of piloting the teaching scenario (three weeks were insufficient for students to acquire digital learning skills with GEP), the precarious level of prior knowledge in argumentation (students need to draw on previous knowledge, but their background is weak), and the practice of content-focused teaching rather than competency-focused teaching. Teachers face difficulties implementing student-centred teaching, and students are not accustomed to learning activities during geography lessons, which explains the lack of attention to experimental activities.

Other causes explaining the difficulties students encountered in argumentation include: lack of specialised vocabulary or a limited vocabulary, incorrect use of specialised terminology, and insufficient knowledge and skills to explain, justify, reason, and support arguments.

The results are concerning, especially since argumentation is a cross-disciplinary competency. Students solve argumentative tasks in many other subjects within the curriculum: native language, history, geography, civic education, etc.

In the Romanian sample (Fig. 6), the results are better: the proportion of students with a Good or Very Good level of argumentative competency is high at 40%. This performance may result from the combination of Google Earth Pro with other factors such as: the structure of the school curriculum (this competency is

progressively developed from 7th grade, and students had previously engaged in learning activities requiring argumentation, even if with other tools), the evaluation system (periodic and systematic evaluation in the Romanian system provides faster feedback and allows teachers to identify learning issues), and the higher competitiveness of 9th-grade students, motivated by university admission criteria.

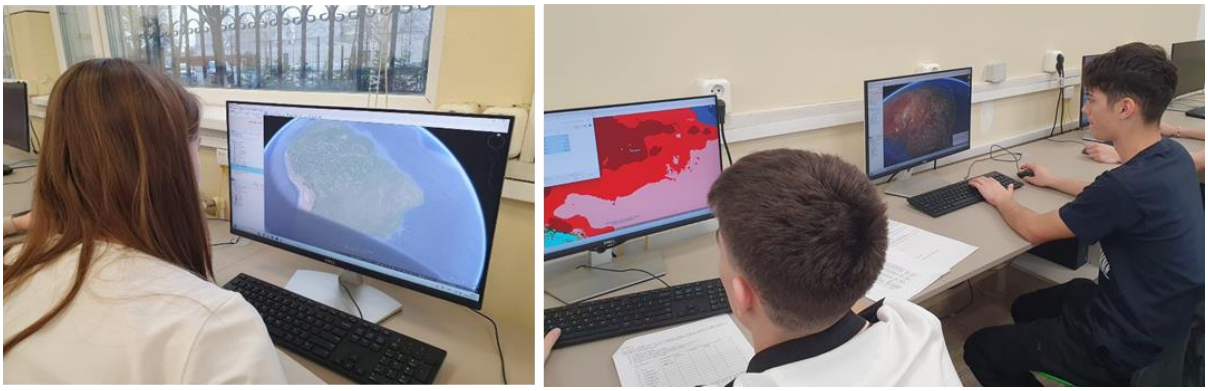

**Figure 6. Piloting the teaching scenario—the Romanian target group**

Significant differences were observed between the two educational contexts regarding the development of spatial skills. Belgian students face major difficulties, with 89.7% at an insufficient level, indicating they have practically not developed this competency. Equally worrying is the very small proportion of students at Good and Very Good levels (3.4%). Spatial skills are included in the primary school geography curriculum, and working with maps, locating, and identifying fundamental geographical elements are among the most frequent tasks students should practice. The failure to develop these skills can be partly attributed to the curriculum in Belgium, which is not clear and concise, gives teachers significant freedom in content selection, and does not encourage the development of spatial skills from a global to regional and local scale. Students' geographical thinking is mainly developed at local and national scales. In this context, it is difficult to develop global-scale spatial skills within a three-week experiment if students are not accustomed to learning activities that require developing this competency, motivating students, and helping them gain a global perspective.

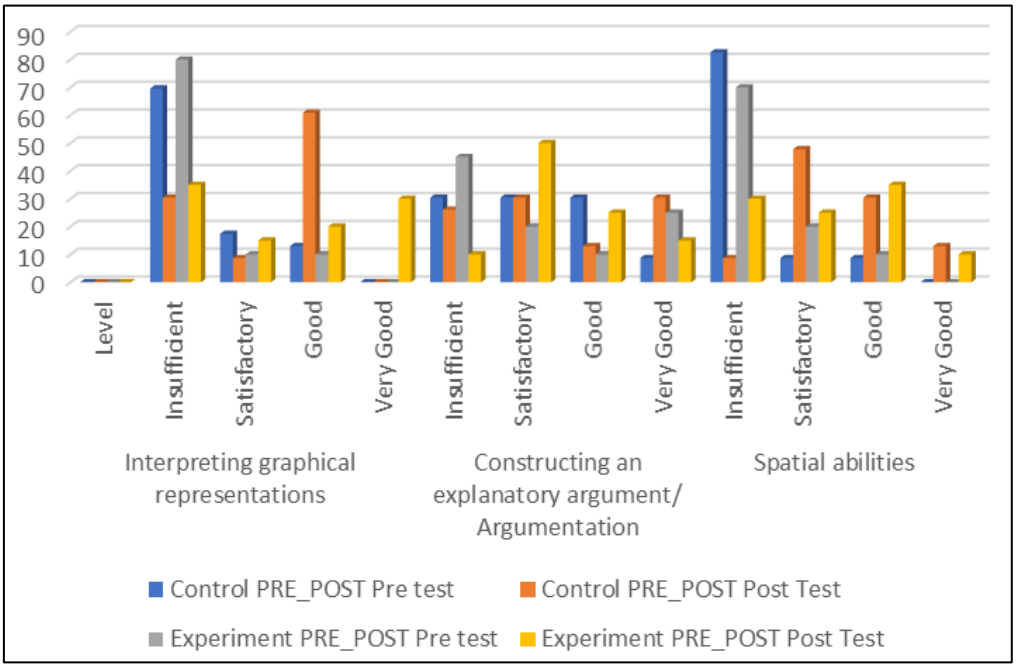


**Figure 7. A graphical representation of the development of proficiency levels in the three competencies analyzed for the two groups (control and experimental) within the Romanian target group**

In the Romanian sample (Fig. 7), students show a much better level of spatial skills: only 30% are at an insufficient level, while 45% are at Good or Very Good levels. Google Earth Pro contributed to these results, but its effect cannot be separated from complementary factors: the geography curriculum emphasizes spatial skill development from local to global scales from 5th grade onward (VI, VII, VIII, IX). This fundamental competency is continuously assessed, and educational reforms require teachers to integrate it into learning activities using digital tools.

Poorer student results and lack of performance may also stem from a lack of social awareness regarding geography's capacity to solve problems and an inadequate understanding of the subject's importance in education (Kerski, 2023). In the Romanian experimental group, there was a significant improvement in the competency of Graphical Representation Interpretation, with a sharp decrease in students at the Insufficient level (by 45%), an increase in Satisfactory (5%) and Good (10%), and the emergence of Very Good (30%). The Argumentation competency showed significant improvement, with a 35% decrease in students at Insufficient level, a 10% increase in Very Good, and increases in Satisfactory (30%) and Good (15%). Students also made substantial progress in the third competency, Spatial Skills, with a 40% decrease in Insufficient level, increases in Satisfactory (5%), Good (25%), and emergence of Very Good (10%).

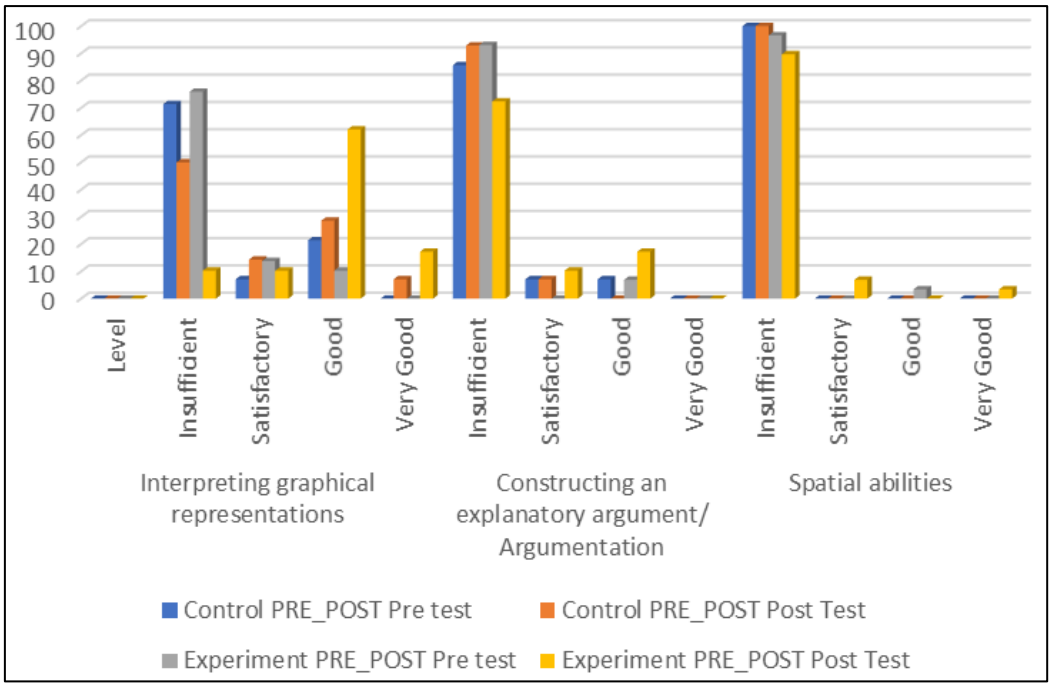


**Figure 8. A graphical representation of the development of proficiency levels in the three competencies analyzed for the two groups (control and experimental) within the Belgian target group**

The Belgian experimental (Fig. 8) group recorded a significant improvement in Graphical Representation Interpretation, with a massive decrease in Insufficient level (65.3%), and increases in Good (51.8%) and Very Good (17.2%). There was modest improvement in Argumentation: although the Insufficient proportion decreased by 20.7%, it remained very high at 72.4%, with the Satisfactory segment at 10.3% and Good at 10.3%. A slight improvement was also observed in Spatial Skills, with a 6.9% decrease in Insufficient, disappearance of Good (3.4%), and increases in Satisfactory (6.9%) and Very Good (3.4%).

## Limitations

Experimental research based on analyzing the evolution of pre-test and post-test results highlights the need to consider several additional aspects. Kim & Willson (2010) also point out that pre-testing can alert subjects to relevant topics and may direct their attention selectively toward what the researchers intend to analyse, with the possibility of memorising pre-test questions.

The similarity between pre-test and post-test encourages content-focused learning rather than competency-focused learning. In the case of experimenting with the teaching of Geography using digital tools such as Google Earth Pro, it would be more appropriate to design pre-tests and post-tests focused on evaluating competencies. This would involve including in the post-test images and datasets downloaded from Google Earth Pro to observe how students handle cartographic materials used during the experiment.

Designing competency-focused pre-tests and post-tests means that only the evaluated competencies remain identical, while the questions and tasks are similar in model and expression but not identical. This ensures that we are truly assessing a competency developed through Google Earth Pro.

Using the same didactic illustrations in pre-tests and post-tests—depicting river components that do not correspond to geographic reality—does not prove that a student successfully completed the item in the post-test due to the Google Earth Pro experiment. Only by integrating in the post-test an image downloaded from Google Earth Pro that corresponds to a real geographic basin can we directly evaluate the impact of the digital tool on competency development. Didactic images and conceptual models are visual, often artistic representations that explain geographic elements visually. The main challenge arises when students must transfer and apply this information, knowledge, and skills to a cartographic support that corresponds to geographic reality. The level of difficulty is perceived as slightly higher: students may easily identify simplified hydrological elements such as tributaries, confluences, and deltas in didactic illustrations but may not be able to do so in Google Earth Pro.

The use of a digital tool such as Google Earth Pro requires careful supervision by the teacher. Students seated in front of the tool tend to act freely, sometimes ignoring the teacher's instructions, wasting valuable time exploring Google Street View, or searching for answers on Wikipedia or ChatGPT instead of investigating the virtual globe. This risk increases, especially if students are not accustomed to analyzing, observing, locating, and working with cartographic supports in general.

Another limitation is the small sample size, which requires cautious interpretation of the obtained results.

It is also necessary to discuss the difficulties encountered in identifying common elements between the Geography curricula of the two education systems, including the subject-specific competencies outlined in the programs and the theoretical content studied in Grade 9 (Romanian system) and S3 (Belgian system). The two educational systems approach hydrosphere content differently. In the Romanian Geography curriculum, students learn about the fundamental elements of the hydrosphere in Grade 5 (middle school cycle), focusing on general aspects and characteristics. In Grades 6 and 7, these topics are further developed for all continents, while in Grade 8 students study the hydrography of Romania. By Grade 9, students are expected to have acquired certain subject-specific competencies, general knowledge, and information about the hydrosphere from previous grades, alongside revisiting theoretical concepts and developing new knowledge.

Experimental research often focuses on differences between control and experimental groups and between experimental groups. From our perspective, comparative analyses between the two control groups (Belgian and Romanian) should not be neglected, as their evolution from pre-test to post-test can influence the statistical results at the level of the experimental groups.

The frequency analysis of students' results (Table 6) shows that the Belgian control group achieved moderate progress in developing the competence Interpretation of Cartographic Representations, with a 21.4% decrease in students at the Insufficient level and increases in the Satisfactory (+7.2%), Good (+7.2%), and Very Good (+7.1%) levels. For the competence Argumentation of an Explanatory Approach, a regression was observed, with an increase in students at the Insufficient level (+7.2%) and a complete disappearance of students at the Good level. Regarding Spatial Abilities, the situation remained constant between pre-test and post-test, with all students at an Insufficient level.

The Romanian control group showed major progress in both competencies. For Interpretation of Cartographic Representations, the percentage of students at the Insufficient level decreased by 39.4%, at the Sufficient level by 8.7%, while the proportion of students at the Good level increased significantly by 47.9%. For Argumentation of an Explanatory Approach, progress was recorded with a decrease of students at the Insufficient level by 4.3% and an increase in those at the Very Good level by 21.7%. A very large improvement was also observed for Spatial Abilities, with a significant reduction in students at the Insufficient level (-73.9%) and increases at Satisfactory (+39.1%), Good (+21.7%), and Very Good (+13%) levels.

## Conclusion

The data confirmed the research hypotheses for both samples, showing that the digital tool Google Earth Pro was effective in teaching Geography, capable of producing significant changes with a positive impact on the development of the analysed subject-specific competencies. The Mann-Whitney U test results indicated that, prior to the intervention, there were no statistically significant differences between the groups for variables S1, S2, and S3 ($p > 0.05$). However, at post-test, significant differences were observed between groups for all three variables: S1_post test ($p = 0.005$), S2_pos ttest ($p = 0.031$), and S3_post test ($p = 0.001$). These findings suggest that the intervention had a substantial impact on participants' performance, clearly differentiating the groups after the treatment.

Once differences between the two groups were established—differences attributable to the use of Google Earth Pro in teaching Geography—it became important to measure the effect size of this experimental intervention and assess the impact of Google Earth Pro. Cohen's d values (Table 6) for the Belgian experimental sample indicate that the effect size of the Google Earth Pro intervention for item 1 was $d = -1.444$, demonstrating

a substantial impact on the development of the competence Interpretation of Cartographic Representations. For item 2, d = -0.576, indicating a moderate impact on Argumentation of an Explanatory Approach, and for item 3, d = -0.766, reflecting a large effect on the development of Spatial Ability.

For the Romanian sample, the effect size of the Google Earth Pro intervention showed that, in the experimental group, the application had a significant impact on the development of all three competencies. The Cohen's d values were significant: for competence 1 (Interpretation of Cartographic Representations) d = -0.503; for competence 2 (Argumentation of an Explanatory Approach) d = -0.472; and for Spatial Ability, d = -1.295. The use of Google Earth Pro had a moderate effect on competencies 1 and 2, and a very large effect on competence 3.

The effectiveness of Google Earth Pro in teaching and learning Geography had a strong positive effect on the Belgian students. The proportion of students with very poor results (Insufficient grade) decreased, as after the experiment, these students moved to the passing category (Satisfactory grade), reducing the percentage of students at high risk of academic failure and with low motivation to learn. Introducing GEP into Geography lessons positively influenced Belgian students' attitudes toward the subject, particularly among those with very low and low initial results.

However, the observed improvement in Geography learning with Google Earth Pro—primarily reflected in the progression from Insufficient to Satisfactory and only slightly to Good or Very Good—suggests that the level of knowledge, competencies, and skills remains limited. Students either face learning difficulties or lack sufficient motivation to engage with Geography, highlighting the need for remedial measures, personalised learning, and adaptive teaching strategies to optimize learning outcomes and enhance student competencies.

The study emphasised the relevance of GEP in teaching content and developing subject-specific competencies. Nevertheless, the mere introduction of a digital tool into the teaching-learning process of Geography cannot guarantee sustainable long-term results or substantial improvements in argumentative and spatial competencies. Effective integration of the tool into the teacher's instructional strategy, alongside appropriate teaching methods, resources, content, and learning activities, is essential to achieve sustainable improvements in students' competencies.

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## Author contribution

Conceptualization, MP and ND; methodology, MP and NP; validation, MP; formal analysis, MP; investigation, MP and NP; writing—original draft preparation, MP; writing—review and editing, MP and ND; supervision, ND. All authors have read and agreed to the published version of the manuscript.

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All participants were informed in detail that their anonymity would be guaranteed, about the purpose of the study, and about how their data would be used.

## Conflicts of interest

The authors declare no conflict of interest.

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# The role of geographic and socio-demographic factors in socio-cultural adaptability of international students

Vesna LUKIĆ[1,*]

[1] Institute of Social Sciences, Centre for Demographic Research, Kraljice Natalije 45, Belgrade, Serbia
* *Corresponding author*: vlukic@idn.org.rs

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**Abstract**

International students constitute a temporary population within the host country. In the age of increasing global mobility, societal fluidity, and the internationalization of higher education, studying abroad requires complex adaptation to new academic and socio-cultural environments. Focusing on the Serbian context, this paper examines the relations between international students' geographic and socio-demographic characteristics and changes in various aspects of their lives and personalities following their experiences abroad, particularly as influenced by socio-cultural adaptation and cross-cultural interaction. Data were collected using Limesurvey. Statistical analyses included a series of t-tests and a one-way analysis of variance (ANOVA). The findings are interpreted within the frameworks of acculturation theory and cross-cultural adaptation theory.

The results indicate that most respondents view studying abroad as transformative, with nearly half reporting significant personal change. Geographic factors, such as country and continent of origin, and socio-demographic characteristics, including sex, age, education level attaining abroad, and length of stay, influence both the nature and extent of these changes following their study abroad experiences.

**Keywords:** *adaptation, international students, migration, temporary migration, Serbia*

## Introduction

The internationalization of higher education has become increasingly prominent amid globalization. This trend significantly influences the transformation of higher education and impacts both the societies of origin and destination for academic migrants. The most widely accepted definition of internationalization in higher education is "the process of integrating an international, intercultural or global dimension into the purpose, functions or delivery of post-secondary education" (Knight, 2004). However, recent scholarship has highlighted limitations in this definition (Marginson, 2023) and has raised ethical concerns, including cultural imperialism and linguistic hegemony (Hou, 2025). Altbach & Knight (2007) and de Wit et al. (2015) argue that internationalization should evolve into a more comprehensive and inclusive process that serves the public good and contributes meaningfully to society, rather than focusing solely on profit.

The International Association of Universities (IAU) 3rd Global Survey Report identifies improving student preparedness for a globalized world as the most frequently cited reason for internationalizing higher education. Additional institutional goals include enhancing reputation, strengthening research and knowledge production, and internationalizing the curriculum (Egron-Polok & Hudson, 2010). In its Strategy 2030, the IAU emphasizes societal benefit as the ultimate goal of the internationalization process (Marinoni et al., 2024).

Jones & de Wit (2014) note that scholarly and public discourse on internationalization in higher education has predominantly centered on the Western world. However, there is increasing recognition that internationalization should not be confined to a Westernized, Anglo-Saxon, or English-speaking framework (Jones & de Wit, 2020). Tight (2022), through a systematic review, confirms that most research in this area originates from the UK, USA, and Australia, with additional national studies identified in Finland, Sweden, and Switzerland for the rest of Europe. Key themes in the literature include international students' adaptation experiences to new educational, linguistic, and social environments (Tight, 2022), as well as their pursuit of personal growth, which fosters intercultural development (Yakunina et al., 2012).

The interdisciplinary nature of migration research is a key strength, as international students are studied by demographers, geographers, sociologists, educators, psychologists, and other scholars. Since 2010, there has been a marked increase in publications on international student mobility. Acculturation theory is frequently employed to examine the experiences and outcomes of these students, with adaptation to new social environments identified as a central component of the acculturation process (Luo et al., 2023). Luo et al. (2023) report that much of the existing research focuses on psychological and socio-cultural adaptation, as outlined by Ward & Rana-Deuba (1999), and explores antecedents

and outcomes of cross-cultural adaptation through acculturation and cross-cultural adaptation theories (Kim, 2001; Berry et al., 2006; Ward & Kennedi, 1999; Shafae & Razak, 2016). Acculturation is assessed by examining changes in practices and values across domains such as language, food preferences, social interactions, clothing, and cognitive patterns. Lifestyle, closely linked to culture (Cormoș, 2022), is also subject to change through interactions in new social environments (Ng et al., 2018). Unlike other populations, international students experience academic adaptation in addition to psychological and socio-cultural adaptation (Zhou et al. 2008; Zhou & Todman, 2009; Jindal-Snape & Ingram, 2013), and socio-cultural adaptation influences academic outcomes. Cultural background plays a crucial role in adaptation (Guzel & Glazer, 2019; Perez-Encinas & Rodriguez-Pomeda, 2019), while other relevant variables include age, sex, education, and duration of study abroad (Duru & Poyrazli, 2011; Guzel & Glazer, 2019). Consequently, international students should not be regarded as a homogeneous group to deconstruct the homogenous portrayal of international students (Popadiuk & Arthur, 2004; Schartner & Young 2016).

Marginson (2023) highlights the dual geography of cross-border education, which encompasses both national and global relationships. In the context of migration research, King (2020) expands upon the foundational questions posed by White & Woods (1980a) by introducing a sixth key question: What are the effects of migration on the migrants themselves?

In light of these considerations, the present study examines the adaptation processes of international students in Serbia, given that international students represent a central component of international mobility in higher education. Namely, the increasing number of students studying abroad (OECD, 2024) is often used as an indicator of internationalization. The primary objective of this study is to investigate the relationships between international students' geographic and socio-demographic characteristics and the changes in various aspects of their lives following their experiences abroad, with particular attention to socio-cultural and academic adaptation in the Serbian context.

## International students in the Serbian context

Although a limited number of studies, including Vasojević (2022), Lukić (2025), Markov & Periklieva (2023), Vulić-Prtorić & Oetjen (2017), Németh et al. (2025), and Țirban et al. (2012), have examined international students in Serbia and neighbouring countries, research on their transition, cross-cultural experiences, and adaptation to university and social life remains scarce. Nevertheless, Serbia has a longstanding tradition of educating international students, dating back to its period as part of the Federal People's Republic of Yugoslavia (FNRY) and, from 1963, the Socialist Federal Republic of Yugoslavia (SFRY). Following World War II, the FNRY, under Tito's leadership, pursued closer relations with countries in Asia, Africa, and Latin America. One manifestation of this policy was the provision of scholarships to students from African and Asian countries to study in Yugoslavia. The number of international students increased notably after the 1961 Belgrade Non-Aligned Conference (Lazić, 2009). Most of these students, originating from African and Asian non-aligned countries, received Yugoslav scholarships and pursued studies in technical sciences, medicine, economics, and agriculture. At that time, learning Serbo-Croatian was mandatory for international students to facilitate their integration into university and social life and to serve as a means of cultural influence. The primary challenges these students faced involved adapting to a new social environment while maintaining their national and cultural identities (Bondžić, 2011). Drawing on the example of African students in socialist Yugoslavia, Radonjić (2018) argues that the prevailing image of the other is characterized by solidarity. This image was initially constructed by state authorities and, since 1970, has been embraced by the broader population, contributing to the perception of Yugoslavia as a nation of global significance.

In 2010, the Government of the Republic of Serbia, as a successor state to the Socialist Federal Republic of Yugoslavia, launched the World in Serbia scholarship project to commemorate the 50th anniversary of the Non-Aligned Movement's founding in 1961. This initiative provides scholarships for study in Serbia in Serbian to candidates from 127 member and observer countries of the Non-Aligned Movement across Africa, Asia, Central, and South America. The scholarships are available for all levels of study. Recipients are accommodated in the student residence on Avala and participate in a Serbian language course, which is a prerequisite for maintaining scholarship status and commencing academic studies. The scholarship package includes a Serbian language course, a monthly stipend in dinars, free accommodation and meals in student dormitories, basic health insurance as stipulated by regulations and international agreements, a free residence visa, and complimentary recognition of high school or university diplomas. Approximately 200 scholarships are awarded annually through the World in Serbia project. The majority of international students pursue studies in medicine, organisational sciences, technical sciences, and political sciences (Government of the Republic of Serbia, 2024).

Data from the Statistical Office of Serbia indicate a gradual increase in the number of international students in Serbia, both self-funded and scholarship recipients. In the 2015/2016 academic year, there were 10,690 international students, representing 4.3% of the total student population. By 2023/2024, this figure had risen to 11,573, or 4.6% of all students, with projections suggesting continued growth. The number of countries represented by international students also increased from 109 in 2015/2016 to 135 in 2023/2024. In 2015/2016, the largest groups of international students came from Libya

and Saudi Arabia, while in 2023/2024, the leading countries of origin were the Russian Federation, India, Iran, and Nigeria (Statistical Office of the Republic of Serbia, 2017; Statistical Office of the Republic of Serbia, 2024).

Currently, fourteen countries provide scholarships enabling Serbian students to pursue studies abroad (Government of the Republic of Serbia, 2025). Germany and Austria represent prominent destinations for temporary educational migrants from Serbia (Predojević Despić & Lukić, 2024). Participants in international exchange programmes, as well as returnees, frequently emphasize the advanced practical training equipment available at foreign institutions (Vidicki, 2024). For nationals of Western Balkan countries, obtaining a European Union diploma confers a competitive advantage in the labour market (Predojević Despić & Lukić, 2024). Beyond the increased likelihood of employment with a foreign diploma, the perceived quality of academic programmes and the opportunity to experience life abroad also influence students' decisions to study outside Serbia (Stojšin et al., 2023).

## Methodology

### Data collection

In the Serbian statistical system, international students are defined as those who hold foreign citizenship. This article reports findings from a broader study employing both quantitative and qualitative methods, including an online survey, three focus group discussions, and 19 in-depth interviews (Stojšin, 2025). The data analyzed in this paper were derived from an online LimeSurvey platform conducted between late 2023 and early 2024. The online survey included two versions of the questionnaire. One was for students currently studying outside their home country, and the other was for students who had studied abroad and then returned or moved elsewhere. Both versions were available in Serbian (for students from Serbia studying/studied abroad) and English (for international students studying/studied in Serbia), and making a total of four questionnaires, one for each group. The questionnaires for students studying abroad had 32 questions, while the versions for returnees had one extra question about the year they returned. All questions were closed-ended, but respondents could also provide their own answers. The questionnaires featured four Likert scales with 36 total opinions and five assessment scales. The last ten questions asked about the respondents' socio-demographic details (Stojšin, 2025). After incomplete questionnaires were removed, 222 respondents remained. They were divided into four groups, but the sample was not representative, leading to uneven group sizes. Specifically, it included 127 Serbian students studying abroad or who had returned to Serbia after studying abroad, as well as 95 foreign students studying in Serbia or who had completed their studies in Serbia and returned to their countries of origin. Eligibility required that participants have studied abroad for at least one academic year, and that they were not older than 35.

### Data processing

The data from an online Limesurvey platform were subsequently transferred to Microsoft Excel. After coding, we had a total of 111 variables. A range of statistical techniques was applied in the analysis. Descriptive statistics and bivariate analyses, including t-tests and one-way ANOVA, were conducted based on the data's characteristics. When assumptions for classical ANOVA were not met, Welch's ANOVA was employed. Post hoc comparisons utilized Tukey's and Games-Howell's tests to identify group differences. Effect sizes were calculated and interpreted according to Cohen's criteria (Cohen, 1988). Analyses were performed using SPSS 20.0 for Windows to identify factors influencing specific outcomes.

Recognizing that adaptation levels vary across personal and situational factors, the analysis incorporated statements reflecting respondents' attitudes toward various life domains and their self-perceived changes resulting from studying abroad. Bivariate analyses were conducted to assess statistically significant relationships between these statements and a range of geographic and socio-demographic variables. Initially, participants' perceptions of whether studying abroad had changed them (V1) were examined, followed by an analysis of statements about the types and degrees of changes they had experienced since studying abroad (V2). Responses were collected using a five-point Likert scale. The geographic and socio-demographic variables included sex (male/female) (V3); respondent groups (Serbian students studying abroad and returnees; international students in Serbia and those who returned to their country of origin) (V4); continent and country of origin (Europe/Asia/Africa ; Serbia/Ghana/Nigeria/UAE ) (V5 and V6); level of study pursued or completed abroad (V7) (faculty/master's, specialization/PhD), time spent studying abroad (groups with number of years) (V8), and age (up to 24/25-30/over 30) (V9). Given the small number of respondents from the American continents, responses from these respondents were excluded from the analysis of attitudes towards the continent of origin. The analysis by country of origin included only countries with at least 5 respondents in the survey.

## Results

### Perspectives of respondents regarding the impact of studying abroad on personal development

The sample included 222 students, of whom 122 identified as female and 11 did not declare their sex. Foreign students represented 46 countries, primarily from Europe (40.5%), Africa (27.9%), and Asia (18%), with a

smaller proportion from other continents. Most participants (63%) were aged 20-29 years. The mean duration of residence abroad was 4.27 years (SD = 3.52). The majority of students were enrolled in master's, specialization, or degree-seeking programs.

Survey participants were initially asked to indicate whether, and to what extent, studying abroad had changed them. The largest proportion of respondents (49.5%) reported that studying abroad changed them significantly, whereas only a small minority (3.7%) indicated no change at all (Lukić, 2025). To investigate the relationship between respondents' perceptions of change (V1) and various geographic and socio-demographic characteristics, a series of t-tests and a one-way analysis of variance (ANOVA) were conducted.

A series of t-tests compared responses between two independent groups for the variable under analysis. The results indicated no statistically significant differences in attitudes between male and female respondents, nor between Serbian and foreign respondents, regarding the impact of studying abroad. An ANOVA was conducted to compare attitudes across three or more respondent groups regarding the extent to which studying abroad had changed them (Table 1). The analysis revealed statistically significant differences between respondents' attitudes and their highest level of education attained or anticipated. Specifically, those with a doctorate reported greater perceived change from studying abroad compared to those with lower educational attainment (a bachelor's or master's degree). The effect size (eta squared = 0.02) suggests a weak association between these variables.

**Table 1. Variations in respondents' attitudes regarding the impact of studying abroad based on the highest level of education attained during their studies abroad**

| Attitude about the change they experienced while studying abroad (V1) | | Mean value | | | F | *p** |
|---|---|---|---|---|---|---|
| | V7 | Faculty (70) | Master's/Msc. Specialization (88) | PhD (46) | | |
| | | 3.29 | 3.17 | 3.52 | 3.44 | **0.035** |

*(*p< 0.05)*

The ANOVA test revealed a relationship between attitudes regarding the impact of studying abroad and the duration of the respondents' stay in the host country. Post hoc analyses identified significant differences between specific groups. Respondents who remained abroad for seven years reported greater changes than those who stayed for five years (Table 2). The effect size, measured by eta-squared, was 0.08, indicating a medium effect.

**Table 2. Differences in respondents' attitudes regarding the impact of studying abroad as a function of the length of stay in the host country**

| Attitude about the change they experienced while studying abroad (V1) | | Mean value | | | | | | | F | *p** |
|---|---|---|---|---|---|---|---|---|---|---|
| | V8 | One year (28) | Two years (38) | Three years (26) | Four years (30) | Five years (21) | Six years (17) | Seven and more years (34) | | |
| | | 3.11 | 3.45 | 3.46 | 3.03 | 3.00 | 3.29 | 3.65 | 2.877 | **0.014** |

*(*p< 0.05)*

Analysis of this statement by continent and country of origin, including respondents from Europe, Asia, Africa, Serbia, and several other countries, revealed no statistically significant relationships, as indicated by ANOVA results. Similarly, examination of attitudes by age indicated no statistically significant differences among respondent age groups. No differences in respondents' attitudes regarding the impact of studying abroad were observed.

## Attitudes regarding the types and extent of changes experienced by respondents since commencing their studies abroad

Participants were presented with statements regarding various types and degrees of personality changes, such as clothing style and eating habits, that may have occurred since studying abroad (Table 3). Most respondents reported a change in eating habits (60.2%), whereas the majority indicated no change in clothing style (57.1%). Approximately half (50.7%) reported a change in their opinion about their country of origin, while 40.7% did not, and 8.6% remained neutral. Over half (52.5%) stated that their attitude towards friends from their own country had not changed, though 37.9% reported some change and 9.6% were neutral. Regarding attitudes towards family, 55.3% indicated little or no change, 32.8% reported a change, and 11.9% were neutral. Most respondents (60.3%) reported changes in how they spend their free time, and 68.1% noted a shift in their desired lifestyle. Similarly, 61.6% indicated that their career aspirations had changed, either completely or partially, since studying abroad. A majority (59.4%) also reported that their attitude towards other cultures had changed to some extent during their time abroad.

**Table 3. Perspectives on the nature and magnitude of changes experienced by respondents since departing to study abroad**

| Variables | Mean value |
|---|---|
| My eating habits ($V2_1$) | 2.68 |
| The way I feel about my country of origin ($V2_2$) | 2.96 |
| The way I dress ($V2_3$) | 3.42 |
| My attitude toward friends from my country of origin ($V2_4$) | 3.36 |
| My attitude towards my family ($V2_5$) | 3.55 |
| The way I spend my free time ($V2_6$) | 2.64 |
| The way I want to live my life ($V2_7$) | 2.34 |
| The relationship toward a career I wish to pursue ($V2_8$) | 2.48 |
| My attitude toward other cultures ($V2_9$) | 2.59 |
| *What has changed in your life since you went abroad and to what extent? 1 – entirely; 2 – mostly; 3 – undecided; 4 – partly; 5 – not at all* | |

Consistent with the previous chapter, the influence of geographic and socio-demographic characteristics on the statements in Table 3 was examined using a series of t-tests and a one-way analysis of variance.

The t-tests revealed a statistically significant relationship between respondent groups and the variables $V2_7$ and $V2_9$. Respondents from Serbia reported a greater change in their views on lifestyle compared to students who are currently studying or have studied in Serbia. Similarly, respondents from Serbia indicated a greater change in attitudes towards other cultures than international students studying or having studied in Serbia (Table 4).

The effect sizes for $V2_7$ (eta squared = 0.04) and $V2_9$ (eta squared = 0.02) indicate a weak relationship between the analysed variables.

**Table 4. Differences in respondents' attitudes concerning changes in their perspectives on lifestyle and attitudes toward other cultures by respondent group**

| Variables | | Mean value | | t | *p** |
|---|---|---|---|---|---|
| | | Students from Serbia (studying abroad/had studied abroad) (126) | International students (studying in Serbia/had studied in Serbia) (93) | | |
| The way I want to live my life ($V2_7$) | V4 | 2.12 | 2.65 | -2.986 | **0.004** |
| My attitude toward other cultures ($V2_9$) | | 2.40 | 2.84 | -2.307 | **0.022** |

**Table 5. Sex-based differences in respondents' attitudes toward changes in their preferred way of life**

| The way I want to live my life ($V2_7$) | | Mean value | | t | *p** |
|---|---|---|---|---|---|
| | V3 | Male (89) | Female (122) | | |
| | | 2.15 | 2.57 | -2.348 | **0.020** |

*(*p< 0.05)*

The analysis confirmed a relationship between respondents' sex and variable $V2_7$. Specifically, male respondents reported a greater change in their desired lifestyle compared to female respondents (Table 5). The effect size in this case (eta squared = 0.03), consistent with most previous findings, indicates a small effect.

Further analysis indicated that the continent of origin influences specific attitudes. The results demonstrated differences in the perspectives of European, African, and Asian students regarding variables $V2_2$ and $V2_5$ (Table 6). Post hoc tests identified that European and Asian students were significantly more likely to report a change in their opinion about their own country, whereas most African respondents indicated that such a change had not occurred. Similarly, analysis of attitudes toward family revealed a distinction between African students and their European and Asian counterparts. African students predominantly reported no change in family relationships, while the majority of European and Asian students indicated that their relationships had changed since studying abroad. For both variables analyzed (eta squared = 0.06 for $V2_2$ and $V2_5$), a medium effect size was observed.

The analysis of attitudes by country of origin revealed an association between attitudes toward changing the way people dress ($V2_3$), attitudes toward family ($V2_5$), and country of origin (Table 7).

In the country-level analysis, only countries with at least five respondents (Nigeria, Ghana, and the UAE) were included, and their attitudes were compared to those of students from Serbia.

**Table 6. Differences in respondents' attitudes toward changes in perception of their country and attitudes toward family by continent of origin**

| Variables | | Mean value | | | F | *p** |
|---|---|---|---|---|---|---|
| | | Europe (152) | Africa (32) | Asia (26) | | |
| The way I feel about my country of oigin ($V2_2$) | V5 | 2.89 | 3.69 | 2.58 | 6.213 | **0.002** |
| My attitude towards my family ($V2_5$) | | 3.42 | 4.31 | 3.19 | 6.533 | **0.002** |

*(*p< 0.05)*

**Table 7. Differences in respondents' attitudes toward changes in dress style and attitudes toward family, based on the country of origin**

| Variables | | Mean value | | | | F | *p** |
|---|---|---|---|---|---|---|---|
| | | Serbia (109) | Nigeria (7) | Ghana (7) | UAE (5) | | |
| The way I dress ($V2_3$) | V6 | 3.44 | 3.29 | 2.43 | 4.40 | 5.028 | **0.021** |
| My attitude towards my family ($V2_5$) | | 3.47 | 4.14 | 4.71 | 3.00 | 9.683 | **0.002** |

*(*p< 0.05)*

**Table 8. Differences in respondents' attitudes toward changes in leisure activities by age group**

| Free time ($V2_6$) | | Mean value | | | F | *p** |
|---|---|---|---|---|---|---|
| | V9 | Up to 24 (82) | 25-30 (71) | Over 30 (58) | | |
| | | 2.38 | 2.63 | 2.98 | 4.268 | **0.015** |

Subsequent analyses revealed differences in attitudes toward dressing between respondents from Serbia and the UAE. Respondents from Serbia were more undecided about changes in their dressing style since studying abroad, whereas most respondents from the UAE reported that their dressing style had changed. Differences were also observed regarding attitudes toward family relationships. Specifically, Serbian respondents were more likely to report changes in their relationships with their families, whereas most respondents from Ghana reported no such change (Table 7). The effect sizes for both variables (eta squared = 0.05 for $V2_3$ and for $V2_5$) suggest a small effect.

Analysis of attitudes by age group indicated an association between age and perceptions of changes in free-time activities (V26). Younger respondents (up to 24 years old) were more likely to report changes in how they spend their free time compared to older respondents (over 30 years old) (Table 8). An eta squared value of 0.04 indicates a small effect.

Further analysis indicated that, for variables $V2_1$, $V2_4$, and $V2_8$, none of the examined geographic or socio-demographic characteristics -including sex, age, respondent group (students from Serbia studying abroad, those who returned from studies abroad, international students in Serbia, and international students who studied in Serbia and returned to their country of origin), continent and country of origin, level of study pursued abroad, or duration of study abroad—significantly influenced the respondents' answers.

## Discussion

Findings on international students in Serbia support Findlay et al. (2012) observation that international student mobility is shaped by cultural, political, societal, and economic factors. These students encounter various challenges as they adapt to their new environment, including unfamiliar societal values, customs, and norms. Changes (personal growth and transformations) due to studying abroad as noticed by participants and their family and friends in the Serbian context are seen as beneficial (Lukić, 2025). We found significant changes in how international students from/in Serbia spend their free time, their career aspirations and a shift in their desired lifestyle. Empirical data from Poland also show that most international students adopt new life perspectives (75%). The origin of students affected the level of personal and cultural changes, while socio-economic factors and the value placed on free time also differed between the groups (Mutlu et al., 2010). Our findings show that geographic background does not affect respondents' perceptions of personal change from studying abroad. Among socio-demographic factors, only the highest level of study and length of stay in the host country are statistically significant. Students with a PhD and those

students who lived longer abroad reported greater personal change, with length of stay having a stronger effect. These findings align with previous research indicating that longer residence in the host country is associated with reduced acculturative stress, improved psychological adjustment, and increased familiarity with the host culture (Kashima & Loh, 2006; Thomas & Sumathi, 2016). Previous research show that the length of stay abroad is a key factor that directly influences acculturative stress levels and the quality of international students' adaptation. Students who remain in a foreign country for extended periods of time, particularly beyond the first year, report significantly lower stress levels compared to those in the initial stages of their stay. The passage of time facilitates "cultural learning," a central concept in cultural adaptation theory, suggesting that duration of stay serves as a resource for acquiring specific competencies. This process enables students to develop enhanced social skills, broaden their interactions and networks with the local population, and improve language proficiency. Increased engagement with local residents and a deeper understanding of host country norms directly mitigate feelings of isolation and culture shock (Yu & Wright, 2016; Ward & Kennedy, 1999). Nevertheless, research on international students in Croatia, that was also part of Yugoslav federation, did not identify significant differences in socio-cultural adaptation by length of stay, contradicting earlier findings. Students who demonstrated better socio-cultural adaptation also exhibited improved socio-psychological adjustment (Vulić Prtorić & Oetjen, 2017).

Although the length of stay is often cited as a key factor in adaptation, Schartner & Young (2016) indicate the difference between different levels of study and how acculturation develops over time. They emphasize that the level of study (undergraduate vs. graduate) is a critical variable that may fundamentally determine how students adjust, suggesting that academic demands and developmental stages shape socio-cultural and psychological outcomes differently. Undergraduate students are more susceptible to nostalgia. In contrast, postgraduate students, including those pursuing master's and doctoral degrees, tend to adapt to socio-cultural environments more rapidly due to prior life experience and more clearly defined academic and professional goals. Younger students at the undergraduate level are more likely to depend on peer support (Kashima & Loh, 2006). Our findings show that students pursuing/gained PhD abroad reported greater personal change, compared to other students.

Gender analysis is essential in migration studies and constitutes a significant factor influencing migration processes. Identifying and emphasizing gender-specific changes experienced by male and female international students is essential for adopting a gender-sensitive approach in migration research. Female international students may face greater challenges in socio-cultural adaptation due to cultural restrictions, prevailing social norms in the host society, or perceived discrimination. Guzel & Glazer (2016) found that self-identified male and female international students in the northern California University did not differ regarding socio-cultural adaptation difficulty although male international students reported more social interaction difficulty than women, that could hinder adaptation. Our findings indicate that gender differences are evident only in the extent of change regarding preferred lifestyles, with men exhibiting more pronounced shifts.

We found that age is associated with changes in leisure activities, as younger students report greater confidence that their free-time habits have changed since studying abroad. In contrast, older students typically encounter greater difficulty in modifying their established habits. According to a literature review by Luo & Zhang (2021), duration of stay and age are key demographic factors influencing cross-cultural adaptation of international students. While a longer duration of stay increases familiarity with social norms, older individuals often demonstrate reduced adaptability due to a lower willingness to alter established values, heightened social isolation, and more complex responsibilities, including family and career obligations, in comparison to younger students.

Both individual characteristics and varied socio-cultural backgrounds shape the experiences and adaptation processes of international students. Students from collectivistic cultures, such as those in many Asian societies, often encounter acculturation stress when exposed to unfamiliar cultural norms and values. Research from the United States demonstrates that Asian students are more likely to use passive coping strategies for stress and face greater difficulties with social adaptation than their European peers. In contrast, European students tend to integrate more quickly, which may be attributed to reduced cultural distance and more closely aligned academic expectations (Fritz, 2008). Studies by Tullah (2024) and Ngwira et al. (2024) suggest that an international student's continent and country of origin play a significant role in determining their adaptation trajectory. Tullah (2023) argues that geographical distance serves as an indicator of cultural and structural barriers, with greater physical distance often resulting in slower socio-cultural integration. Ngwira et al. (2024) further note that these challenges manifest as continent-specific stressors encountered by international students as they navigate new social environments. Furthermore, differences in living standards between the country of origin and the host country contribute to financial insecurity-related stress, which frequently serves as a primary factor in unsuccessful adaptation. Students from conflict zones, such as Ukraine and the Middle East, experience concerns about family members that impede their adaptation.

We found variations in international students' attitudes toward their families based on continent and country of origin. African students, particularly those from Ghana, predominantly reported no change in family relationships, whereas Asian and European students, as well as those from Serbia, reported the opposite. These findings are significant, as Mutlu et al. (2010) demonstrate that maintaining strong relationships with parents after studying abroad is crucial. Family and friends serve as key support systems for international students from diverse backgrounds. Disconnection from established social networks, due to challenges in sustaining these relationships, increases vulnerability to loneliness and impedes adaptation to new social environments (Ng et al., 2018).

As higher education becomes increasingly international, cross-cultural adaptation emerges as a significant source of stress and anxiety for international students. It is essential for education policymakers to understand and address this issue. Previous research offers a comprehensive understanding of how cultural adaptation and the embrace of cultural diversity positively influence international students, including their academic achievement, mental health, and intercultural competence (Shafaei & Razak, 2016; Oleganju et al., 2024). In Serbia, personal growth and transformation resulting from studying abroad, as observed by participants, their families, and friends, are also regarded as beneficial (Lukić, 2025).

Crăciun (2018), through an analysis of national higher education policy documents, determined that higher education internationalization remains limited globally. Specifically, 80% of countries lack a national higher education internationalization strategy, while only 11%—22 out of 195—have an official strategy. These countries are primarily European, economically developed, and attract substantial numbers of international students. In 2021, the Government of Serbia adopted the Strategy for the Development of Education in Serbia by 2030. Specific objective 2.2 aims to enhance the relevance of higher education at both national and international levels by increasing enrolment in study programs offered in foreign languages (both face-to-face and online), expanding participation in joint international study programs, and raising the number of students in internationally accredited programs. Achieving this objective requires targeted support for internationalizing higher education. In the context of internationalization, the Ministry of Education, Science, and Technological Development of the Republic of Serbia provides ongoing support to higher education institutions for developing, accrediting and promoting study programs in foreign languages at all levels. Financial resources are aimed to be allocated for the development of high-demand online study programs in foreign languages, as well as for the creation of joint international study programs at all levels. To support foreign students in Serbia, the Ministry of Foreign Affairs and Trade aims to coordinate with relevant ministries, institutions, and bodies to simplify procedures for foreign citizens wishing to study in the Republic of Serbia (Government of the Republic of Serbia, 2021).

## Conclusions

Broader patterns of social transformation linked to international education highlight the necessity for further research and a more comprehensive understanding of the effects of internationalisation. International students constitute a distinct temporary migrant group that seeks to enhance their human capital at particular stage of the life course. Studying abroad facilitates substantial personal transformation for international students. Moreover, socio-cultural shifts in identification and sense of belonging, driven by mobility, can affect their decisions to stay in the country of study or return to their country of origin. The results indicate that, among international students from and in Serbia, only the highest level of study gained abroad and the duration of stay in the host country are statistically significant predictors of life changes and socio-cultural adaptation. A medium effect size was identified solely for the duration of stay.

The most pronounced changes among international students from and in Serbia were observed in attitudes toward other cultures, leisure activities, preferred lifestyles, and career aspirations. The types and extent of changes experienced since commencing studies abroad varied by respondent group, sex, age, continent, and country of origin. These findings corroborate previous research, which has demonstrated that such variables influence the acculturation and adaptation of international students across diverse cultural backgrounds and geographic regions. A medium effect size was found exclusively for attitudes regarding changes in perceptions of one's country and family when analyzed by continent of origin. By focusing on Serbia, this study contributes to broadening the predominantly Western perspective in research on international student adjustment in a new socio-cultural setting. Successful cross-cultural adaptation among international students can enhance satisfaction with academic performance and contribute to the positive reputation of Serbia’s educational institutions.

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## Informed Consent Statement

Based on insights from the project documentation regarding the anonymity of respondents, the use of data,

and data storage, the overall research was approved by the Ethics Committee of the Institute of Social Sciences under No. 527/2022. Furthermore, for an online survey, the positive decision of the Ethics committee of the Institute of Social Sciences was given additionally (No. 00-1637/2023) after the adopted changes in the questionnaire, which related to the omission of a question about respondent's academic discipline (faculty), which the Ethics committee saw as a possibility to identify the respondents. The questionnaire included a brief introductory section that informed participants of the research's purpose, data confidentiality, and data use.

## Conflicts of interest

The author declares no conflict of interest.

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# Bibliometric analysis of forced migration

Lucian BRATU[1,*], Ionel MUNTELE[2,3]

[1] Alexandru Ioan Cuza University of Iasi, Faculty of Geography and Geology, Doctoral School of Geosciences, Carol I Boulevard, No. 11, 700506, Iasi, Romania
[2] Alexandru Ioan Cuza University of Iasi, Faculty of Geography and Geology, Carol I Boulevard, No. 11, 700506, Iasi, Romania
[3] Romanian Academy, Iași Branch, Geography Research Centre, Carol I Boulevard, No. 8, 700505, Iași, Romania
* *Corresponding author*: lucianbratu99@gmail.com

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**Abstract**

This bibliometric analysis systematically examines the evolution of scientific research on forced migration between 1974 and 2025. Using data extracted from the Scopus database and processed through the Bibliometrix package in R, the study investigates publication trajectories, international collaboration patterns, and thematic developments across five decades. The analysis aims to identify major research areas, influential authors and institutions, and emerging conceptual directions within this geographically diverse field. Results indicate a steady and substantial growth in scholarly output, with an annual growth rate of 9.41% and an average of 15.56 citations per document, reflecting the increasing global relevance of displacement as a social, political, and humanitarian challenge. Collaboration networks show strong academic linkages among Europe, North America, and parts of Asia, although notable regional disparities persist, particularly in areas heavily affected by displacement but underrepresented in academic production. Thematic clustering and Multiple Correspondence Analysis (MCA) reveal three dominant research fields, including determinants and governance of migration, humanitarian responses and conflict induced displacement, and typologies and trajectories of forced migration. These findings clarify the field's conceptual landscape and emphasize the need for broader international engagement and increased research contributions from understudied regions. The analysis offers a structured foundation for future investigations and supports the development of more informed and context sensitive approaches to understanding contemporary displacement dynamics.
**Keywords:** *forced migration, bibliometric analysis, research trends, population movements, armed conflicts, refugee displacement*

## Introduction

Forced migration represents one of the most complex and persistent forms of human mobility, with profound implications for security, development, and human rights. According to United Nations High Commissioner for Refugees (2023a), over 110 million people are displaced globally due to a wide range of causes, including armed conflicts, political persecution, natural disasters, economic collapse, and imposed development projects. In a global landscape marked by instability and interdependence, forced migration is no longer a marginal phenomenon but a reality of the 21st century.

Despite its scale, academic research on forced migration remains fragmented and dispersed across disciplines and methodological approaches. Studies often focus on specific regional contexts, particular types of migration such as displacement caused by armed conflict or natural disasters, legal and humanitarian dimensions. This diversity, while valuable, makes it difficult to achieve an integrated understanding of the evolution of scientific knowledge in the field.

In this context, bibliometric analysis becomes an essential tool for identifying dominant trends, influential authors, recurring sources, and areas of insufficient thematic coverage. Using the Bibliometrix platform, this article aims to provide a systematic synthesis of the scientific literature on forced migration, analyzing articles indexed in the Scopus database over recent decades.

The main objective is to highlight the dynamics of research on forced migration, identify emerging themes, and contribute to the consolidation of a coherent conceptual framework. In a world where imposed mobility is increasingly frequent, understanding how forced migration is addressed in scientific literature is not only relevant but urgent.

Recent studies have documented a significant increase in scholarly attention to forced migration, particularly in relation to its economic, social, and policy dimensions. Forced migration is not a homogeneous phenomenon but a heterogeneous field shaped by distinct drivers, legal categories and research traditions. For instance, Quinn & Ruiz (2022) highlight the challenges of integrating forced migrants into host economies and the policy frameworks required to support them effectively. Similarly, Rozo & Grossman (2025) identify over 250 studies published

between 2010 and 2024 that examine the effects of forced displacement using experimental and quasi-experimental methods, reflecting a surge in evidence-based research on this topic.

In the same direction, Crawley & Skleparis (2018) analyse how the Syrian conflict has reshaped research on refugee governance and border regimes, while Schrooten (2025) examines how the Ukrainian refugee crisis has generated new research on temporary protection, solidarity mechanisms, and the reconfiguration of European migration governance. Likewise, Alam (2019) explores the Rohingya crisis in Myanmar and shows how its historical depth and the dynamics of statelessness have stimulated extensive scholarship on forced displacement and minority persecution.

A growing body of work by authors such as McAdam (2020), who analyses the protection gaps faced by people displaced by climate impacts through the framework of international human rights law, and Boas et al. (2019), who challenge dominant narratives surrounding climate related mobility and show how political and epistemic assumptions shape interpretations of environmental movement, illustrates the consolidation and maturation of research on climate induced displacement and environmental mobility.

These contributions reveal both the richness and fragmentation of the field, reinforcing the need for a systematic bibliometric analysis to map dominant trends, identify underexplored areas, and support the development of a more integrated research agenda.

## Theoretical framework

### Conceptualizing forced migration

Forced migration is a multidimensional phenomenon situated at the intersection of political violence, structural inequalities, environmental pressures, and development dynamics. In institutional definitions, forced migration refers to the movement of individuals or groups compelled to leave their habitual residence due to factors beyond their control. As noted by United Nations High Commissioner for Refugees (2023b), displacement arises from persecution, armed conflict, generalized violence, or systematic human rights violations. The International Organization for Migration (2019) expands this definition by including disaster-induced displacement, environmental degradation, and development-induced relocation.

Academic literature has progressively refined this conceptual field. Castles (2003) emphasizes the structural and political determinants of displacement, arguing that forced migration is embedded in global systems of inequality and conflict. Richmond (1994) introduces the continuum between voluntary and involuntary mobility, challenging binary distinctions and highlighting the role of constrained agency. Black (2001) further conceptualizes forced migration as a spectrum shaped by coercion, vulnerability, and limited decision making capacity.

### Debates in forced migration studies and the interdisciplinary nature of the field

Forced migration studies are shaped by several enduring conceptual debates that reflect both the complexity of displacement processes and the diversity of disciplinary approaches that examine them. One of the most persistent debates concerns the distinction between voluntary and involuntary mobility. Rather than treating these categories as mutually exclusive, scholars argue that most migration decisions fall along a continuum of constraint. Richmond (1994) articulated this position through his influential concept of a continuum of coercion, emphasizing that displacement is rarely the result of entirely free choice or absolute compulsion, but instead emerges from varying degrees of structural pressure, risk, and limited agency.

A second major debate revolves around the tension between agency and victimhood. Early research tended to portray displaced persons primarily as passive victims of conflict, persecution, or structural violence. More recent scholarship challenges this reductionist view by highlighting the capacity of displaced individuals to act, negotiate constraints, and develop adaptive strategies. Bakewell (2010) argues that migration theory must account for the agency of individuals even in highly constrained contexts, while Malkki (1995) demonstrates how humanitarian narratives have often simplified the lived experiences of refugees by reducing them to administrative labels and legal categories.

The securitization of migration constitutes another central area of debate. In many political contexts, states increasingly frame forced migration as a security issue, shaping border regimes, asylum procedures, and humanitarian responses. Huysmans (2000) shows how the European Union has incorporated migration into broader security discourses, while Bigo (2002) explains how practices of surveillance and control emerge from what he terms the “governmentality of unease,” producing new forms of exclusion and regulation.

A further conceptual tension concerns the divergence between legal and sociological definitions of displacement. Legal categories such as “refugee,” “asylum seeker,” and “internally displaced person” are essential for international protection frameworks, yet scholars note that these classifications do not always capture the complexity of lived experiences. Zetter (2007) argues that legal labels are political and administrative constructs that can obscure rather than clarify the realities of displacement, and Turton (2003) emphasizes that social experiences often transcend the rigid boundaries imposed by international law.

These debates unfold within a field that is profoundly interdisciplinary. Forced migration research draws on

geography, sociology, political science, anthropology, economics, law, and environmental studies, each discipline contributing distinct theoretical perspectives and methodological approaches. Fiddian-Qasmiyeh et al. (2014) highlight the breadth of theoretical and methodological diversity within the field, while Castles et al. (2014) situate forced migration within broader global transformations. Black (2001) traces the evolution of refugee studies from normative and policy-oriented approaches toward more analytically complex frameworks that account for structural forces, agency, and global change.

This interdisciplinarity produces a rich but fragmented body of literature in which concepts, methods, and terminologies vary significantly across fields. Such fragmentation underscores the value of a bibliometric analysis, which can systematically map dominant paradigms, emerging themes, and structural gaps in knowledge production. Aria & Cuccurullo (2017) demonstrate that bibliometric methods are particularly well suited for synthesizing research in interdisciplinary domains, while Börner (2010) shows how science mapping and network visualization can illuminate the conceptual architecture of complex research fields.

### Analytical structure of forced migration studies

Forced migration studies have developed as an interdisciplinary field situated between anthropology, geography, sociology, political science, and international law. Since the 1980s, the field has progressively moved beyond the narrow legal definition of the refugee, shifting toward the analysis of social, political, and spatial processes that generate constrained mobility (Castles et al., 2014). This evolution has produced a diversified methodological landscape in which qualitative, quantitative, and spatial approaches are combined to explain coercion, structural violence, and the governance of mobility (Turton, 2003).

Qualitative approaches remain central because they capture the lived experiences of displacement and the meanings individuals assign to coercion. Ethnographic fieldwork documents processes of uprooting, identity reconstruction, and interactions with state institutions (Malkki, 1995). In depth interviews trace mobility trajectories, coping strategies, and perceptions of constraint, while discourse analysis examines how institutional actors construct categories such as refugee, asylum seeker, or internally displaced person (Zetter, 2007). These methods illuminate the symbolic, identity related and political dimensions of forced migration.

Quantitative and demographic perspectives analyse the scale, direction, and socio demographic characteristics of displaced populations (Castles et al., 2014). Statistical modelling identifies structural drivers of forced migration, including conflict, institutional collapse, and environmental disasters (Hatton & Williamson, 2003). Survey data measure living conditions, access to services, and socio economic integration, while demographic reconstruction examines mortality, fertility, and age structures in crisis contexts (Bilsborrow, 1992). These techniques enable comparability and generalisation, complementing qualitative insights.

Spatial and geographical approaches provide tools for understanding territorial patterns and constrained mobility. GIS mapping visualises displacement routes, camp locations, conflict zones, and humanitarian corridors (Jacobsen & Landau, 2003). Spatial network analysis models the connections among actors, territories, and infrastructures of control, while diachronic mapping traces temporal changes in territorial distributions (Hyndman, 2000). These procedures clarify the spatiality of coercion and the territorial governance of mobility.

Critical and post structural approaches have expanded the field since the 1990s by analysing how states and international organisations produce, classify, and manage forced mobility. Governmentality studies examine technologies of control and surveillance (Bigo, 2002). Labeling theory investigates how institutional categories shape social and political outcomes (Zetter, 2007). Securitization theory explains how migration becomes framed as a security issue (Bigo, 2002), while post colonial perspectives explore power relations, representation, and global hierarchies (Malkki, 1995). These approaches foreground the institutional and political dimensions of forced migration.

Forced migration studies are characterised by pronounced methodological pluralism. Researchers combine qualitative methods to analyse experiences and representations, quantitative methods to measure large scale patterns, spatial methods to understand territorial distributions, and critical approaches to examine institutional and political structures. This pluralism enables a comprehensive understanding of displacement as both a human experience and a structural phenomenon.

In a fragmented and rapidly expanding field, bibliometric analysis offers a systematic tool for identifying thematic evolutions, mapping networks of authors, institutions, and concepts, highlighting dominant paradigms and epistemological shifts, and understanding how the field reconfigures in response to political and institutional transformations (Börner, 2010). Through its capacity to synthesise large bodies of literature, bibliometrics contributes to clarifying the intellectual structure of forced migration studies.

## Mehodology

Bibliometric analysis provides a structured pathway to transform dispersed scholarly outputs into cumulative scientific knowledge. This method provides a systematic and quantitative approach to evaluating scholarly production, dissemination, and utilization. As a methodological framework, bibliometrics employs

statistical and mathematical techniques to assess both the quality and quantity of academic outputs, including journal articles, books, and reviews (Durieux & Gevenois, 2010).

The bibliometric approach unfolds through a sequence of stages that include defining the research problem, reviewing the relevant literature, selecting appropriate databases, search terms, and inclusion or exclusion criteria, establishing the methodological framework and analytical software, collecting and organizing the data in line with the research objectives, importing the dataset into the software for analysis, and finally visualizing and reporting the results.

In this study, bibliometric methods are applied to the domain of forced migration research with the aim of identifying publication trends, citation networks, and thematic clusters. The dataset was extracted from the Scopus database, which offers comprehensive coverage of peer-reviewed literature across disciplines. The analysis focuses on publications between 1974 and 2024, ensuring both historical depth and contemporary relevance.

Bibliometric indicators were computed using the Bibliometrix R package through its Biblioshiny interface, which provides integrated tools for descriptive statistics, network construction, and thematic exploration. The methodological approach combined quantitative indicators with visual mapping techniques to capture publication dynamics and conceptual structures within the literature on forced migration.

## Database selection and justification

Scopus was selected as the primary data source because it provides broad multidisciplinary coverage of peer reviewed journals and is widely used in scientometric research across the social sciences. Its structured metadata, standardized indexing of authors, affiliations, and keywords, and advanced search functionalities make it suitable for mapping publication trends and thematic structures in an interdisciplinary field such as forced migration.

At the same time, several limitations of Scopus must be acknowledged. In this regard, Mongeon & Paul-Hus (2016) show that major bibliographic databases tend to privilege English language and Western journals, which leads to the underrepresentation of research produced in the Global South or published in regional outlets. Similarly, Chavarro et al. (2018) demonstrate that commercial indexing systems reproduce structural imbalances in global knowledge production, particularly affecting fields with strong regional or interdisciplinary components. Scopus also offers limited coverage of legal sources, policy documents, and institutional reports, materials that are highly relevant for forced migration studies.

## Search strategy, data collection and sampling

The dataset used in this bibliometric study was obtained from Scopus, one of the main international databases widely employed in academic research. Scopus has been consistently used for bibliometric analyses across various scientific fields (Baas et al., 2020). For the present analysis, records related to forced migration and associated topics were identified through the application of specific search terms and logical operators (Table 1). The use of English language search terms is justified by the fact that most publications indexed in Scopus are written in English, and for articles published in other languages, abstracts and keywords are generally provided in English as well. The database was queried on 3 November 2025, ensuring the inclusion of the most recent publications available at that time.

**Table 1. Search parameters employed in the Scopus database**

| Search terms and logical operators |
|---|
| "displacement" AND "forced migrations" |
| OR |
| "deportation" AND "forced migrations" |
| OR |
| "refugees" AND "forced migrations" |

The resulting dataset covered the period 1974-2025. This time span was not predefined by the authors but reflects the chronological range of the publications retrieved by Scopus, with 1974 representing the earliest indexed document matching the search criteria and 2025 the most recent year with available records. The temporal interval therefore corresponds to the distribution of the literature identified through the search strategy rather than to an a priori selection of years.

Because Scopus indexes multiple document types, the initial search results included journal articles, books, and book chapters, all of which were retained in the dataset. The inclusion of books and book chapters is justified by the fact that forced migration is an interdisciplinary field in which significant theoretical and conceptual contributions are frequently published in monographs or edited volumes.

A key stage in bibliometric research on forced migration is the establishment of explicit inclusion and exclusion criteria to guide the selection of relevant publications. Transparent and well defined rules ensure consistency, reproducibility, and validity in the search process, while reducing errors and securing comprehensive coverage of the literature. Clearly delimiting the scope of the review is therefore essential to maintaining methodological rigor and to capturing the complexity of scholarly contributions addressing this phenomenon.

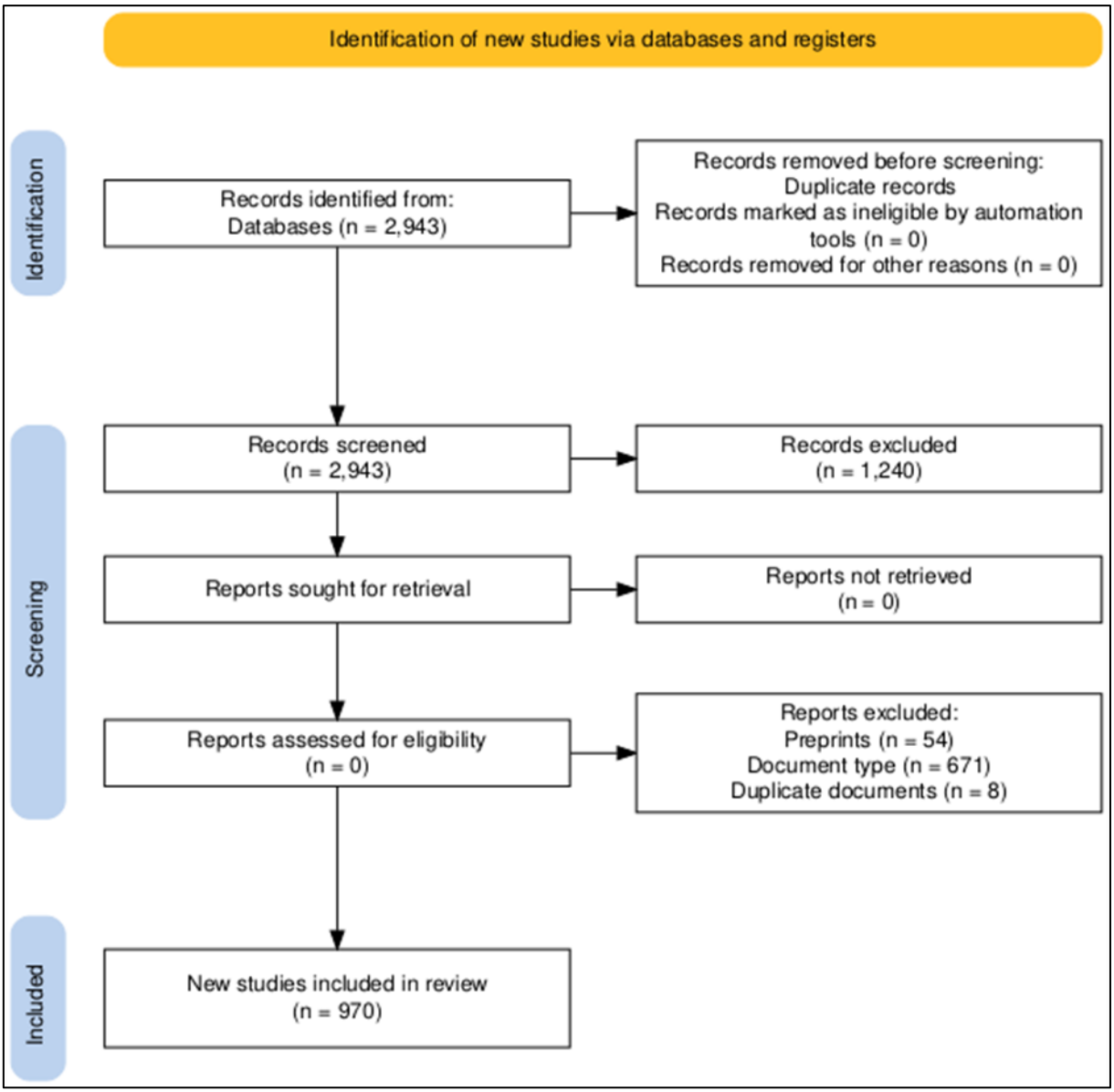


**Figure 1. Selection process of studies included in the analysis according to PRISMA 2020 criteria**

To support standardized reporting, the study follows the PRISMA 2020 framework, which enables systematic documentation of the identification, screening, eligibility assessment, and inclusion stages. The application of PRISMA is particularly relevant in interdisciplinary fields such as forced migration, where conceptual boundaries may be fluid and the bibliographic corpus must be clearly and reproducibly defined (Rethlefsen et al., 2021). The PRISMA flow diagram (Fig. 1) synthesizes the decision making pathway and illustrates how the final dataset was constructed, thereby strengthening methodological transparency and facilitating comparability with other studies (PRISMA Statement, 2025).

The selection process began with the exclusion of records that did not explicitly address forced migration. At this initial stage, duplicate entries were not removed due to the large number of documents retrieved. Subsequent filtering applied predefined inclusion criteria, retaining only publications that substantively engaged with forced migration or related phenomena. Eligible studies were required to fall within relevant disciplinary domains, particularly the social sciences and Earth and planetary sciences. Duplicate records were removed at a later stage.

The final corpus was constructed through a systematic screening procedure illustrated in Figure 1 which documents the number of records identified excluded and retained at each stage. This structured approach ensures transparency and reproducibility in delimiting the analyzed literature.

## Data processing and analysis

Before conducting the bibliometric analysis, the dataset underwent a structured cleaning and pre processing procedure to ensure accuracy, consistency, and analytical reliability. The bibliometric data retrieved from Scopus were exported in CSV format and imported into

the R statistical environment, where the Bibliometrix package (Aria & Cuccurullo, 2017) automatically performed an initial validation of the dataset. This automated step included the detection of incomplete records, the standardization of basic metadata fields, and the identification of potential inconsistencies in author names, affiliations, and keywords.

Following this automated validation, additional manual checks were carried out to refine the dataset. Duplicate records, initially retained during the screening phase due to the large number of retrieved documents, were identified and removed at this stage. Author names were standardized to correct variations in spelling, initials, and diacritics, ensuring accurate attribution in subsequent analyses of productivity and collaboration networks. Institutional names were harmonized to address inconsistencies arising from alternative spellings or changes in institutional structure over time.

Keyword harmonization constituted another essential step in the pre processing workflow. Because Scopus records often contain heterogeneous author provided keywords, synonymous or semantically overlapping terms were unified to improve the accuracy of co occurrence and thematic analyses. This process enhanced the interpretability of conceptual structures and ensured that related terms were consistently grouped within the same analytical categories.

This process resulted in a corpus of 970 studies, which were examined through a comprehensive bibliometric approach. The analysis was conducted using the Bibliometrix package within the R statistical environment (Aria & Cuccurullo, 2017). As an open source tool, Bibliometrix offers an extensive set of functions for quantitative research in scientometrics and bibliometrics, enabling detailed investigation of publication patterns, citation structures, and the intellectual and social networks that characterize the analyzed literature.

Once the dataset was cleaned and standardized, Bibliometrix extracted citation networks and generated the matrices required for advanced bibliometric techniques, including co citation analysis, bibliographic coupling, and keyword co occurrence. All visualizations, such as thematic maps, collaboration networks, and citation trend plots, were produced using functions within Bibliometrix, supplemented by the ggplot2 package in R for enhanced graphical representation (Wickham, 2009).

The analysis was conducted in two sequential phases. The first phase consisted of a descriptive analysis designed to provide an overview of the bibliometric data on forced migration. This step offered a preliminary understanding of the dataset by summarizing key indicators such as publication volume, citation counts, and the distribution of contributions across units of analysis including authors, institutions, countries, and journals. These metrics, presented in Table 2, highlighted the productivity and impact of different entities within the field.

In the second stage, bibliometric techniques were applied to analyse thematic, collaboration, and co citation networks for the period under review. This included the examination of co-citation patterns, bibliographic coupling, and collaboration structures, enabling a deeper understanding of the thematic development and scholarly interactions shaping research in this domain.

**Table 2. Essential data related to the analyzed scientific papers**

| Topic | Total period (1974-2025) |
|---|---|
| Sources | 316 |
| Documents | 970 |
| Annual growth rate | 9.41% |
| Authors | 1826 |
| Authors of single-authored documents | 0 |
| International Co-authorship | 16.8% |
| Co-authors per document | 3.68 |
| References | 7261 |
| Average citation per document | 15.56 |

Keyword co-occurrence analysis was applied to identify the most frequently used terms and their interconnections. In this approach, keywords are represented as nodes and their co-occurrence as links, thereby forming a network that reflects the conceptual proximity of terms. The strength of the links indicates how often keywords appear together within the same publication. This method enables the identification of core research topics and their relationships, the detection of emerging or declining themes based on keyword frequency over time, and the recognition of interdisciplinary connections and hybrid research areas (Aria & Cuccurullo, 2017).

As a complementary technique, multiple correspondence analysis was employed to explore the relationships between categorical variables such as authors, institutions, countries, and research themes. Multiple correspondence analysis reduces the dimensionality of the dataset, facilitating the visualization of complex associations in a low-dimensional space. This approach provides a clear representation of structural patterns and enhances the interpretation of categorical data in bibliometric studies (Di Franco, 2016).

## Analytical procedures and Bibliometrix functions

The analytical procedures applied in this study were implemented using Biblioshiny, the graphical user interface of the Bibliometrix package in R (Aria & Cuccurullo, 2017). Biblioshiny integrates the core functions of Bibliometrix into an interactive environment, allowing the execution of descriptive, network based, and multivariate bibliometric analyses without requiring direct scripting. This interface provides access to the full analytical capabilities of Bibliometrix while ensuring reproducibility and methodological transparency.

Within Biblioshiny, descriptive indicators, such as annual scientific production, citation counts, and author productivity, were generated using the platform's built in modules for summary statistics. These modules rely on the underlying Bibliometrix functions for data conversion, descriptive analysis, and metric computation, but present the results through an interactive dashboard.

Network analyses were conducted using Biblioshiny's dedicated tools for constructing co citation, bibliographic coupling, co authorship, and keyword co occurrence networks. These modules internally call the Bibliometrix routines responsible for generating adjacency matrices and visualizing network structures, allowing the exploration of intellectual, social, and conceptual relationships within the dataset. Thematic mapping and conceptual structure analysis were performed through Biblioshiny's co word analysis interface, which identifies thematic clusters and illustrates their interconnections. Multiple correspondence analysis (MCA) was also carried out within the platform, providing automated dimensionality reduction and graphical representations of associations between categorical variables such as authors, institutions, countries, and research themes. When necessary, graphical outputs generated by Biblioshiny were refined using the ggplot2 package (Wickham, 2009), which offers enhanced control over visual aesthetics.

## Results and discussions

### Research productivity

The growing interest in forced migration is highlighted by the notable annual growth rate of publications (9.41%) and the solid average number of citations per document (15.56). These indicators suggest that forced migration has not only remained a relevant issue throughout the study period, but has also consistently attracted scholarly attention.

These statistics indicate that forced migration has emerged as an increasingly significant issue in recent years (Fig. 2).

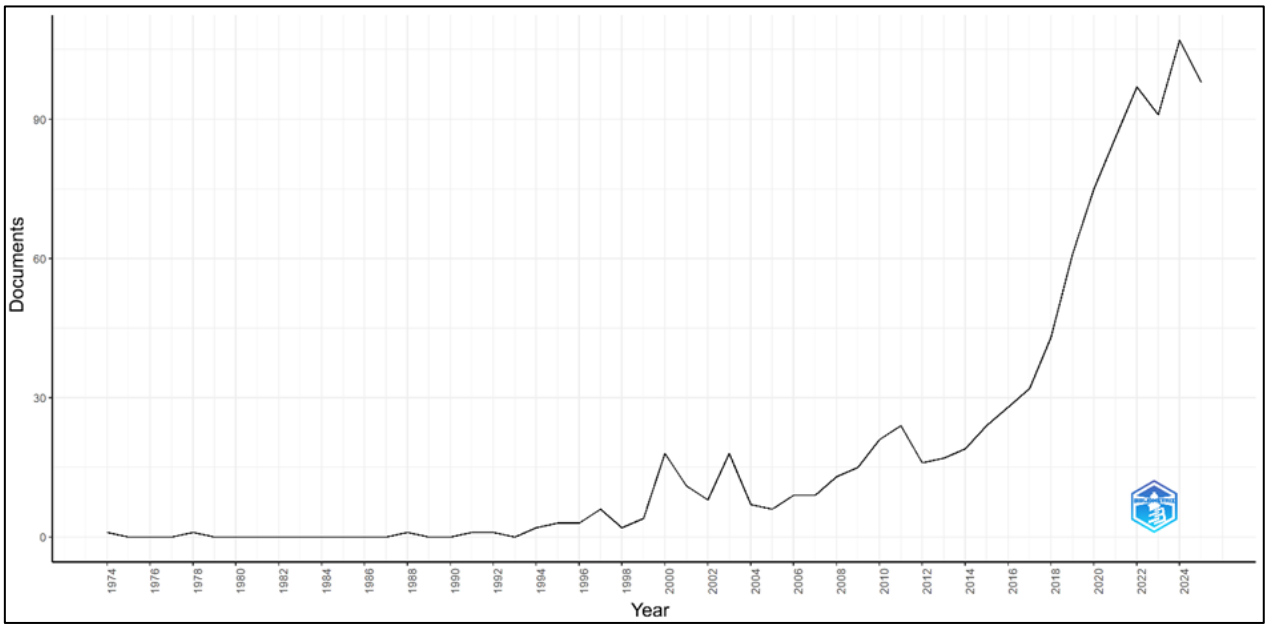


**Figure 2. Research papers published annually**

The annual growth rate is further emphasized by the fact that a significant share of documents has been concentrated in recent years, reflecting the intensification of research activity. Moreover, nearly one-sixth of the publications (16.8%) were produced through international co-authorship, underscoring the collaborative potential of this field. This tendency towards cooperation illustrates the increasingly global character of research on forced migration.

The temporal evolution of publications shows a pronounced increase after 2022, reflecting the academic response to the large scale displacement triggered by Russia's full scale invasion of Ukraine. This surge corresponds to a growing body of research that examines the dynamics, motivations, and social consequences of Ukrainian forced migration. Tarkhanova & Pyrogova (2024) analyze the decision making processes underlying displacement, highlighting how individuals navigate uncertainty, risk, and rapidly changing security conditions. Complementing this perspective, Maidanik (2024) documents the evolving drivers of mobility in the immediate aftermath of the invasion, emphasizing how shifting frontlines and institutional responses shaped migration trajectories. At the same time, Malynovska (2024) explores the broader demographic and geopolitical implications of the exodus, noting the potential for subsequent waves of emigration as the conflict endures. From a host country perspective, Fomina & Pachocka

(2024) examine the initial reactions of Polish society to the arrival of Ukrainian forced migrants, illustrating how public attitudes and community responses influenced early reception conditions. Together, these studies demonstrate that the post 2022 rise in publications is closely tied to the unprecedented scale and complexity of displacement from Ukraine, underscoring the field's responsiveness to major geopolitical shocks.

Beyond the quantitative increase, the diversification of subject areas indicates that forced migration research has become increasingly interdisciplinary. Contributions now emerge not only from sociology and political science but also from geography, environmental studies, public policy, and development research, reflecting a broader integration of methodological and conceptual approaches. This expansion suggests a progressive shift toward a more cross sectoral understanding of displacement and its multifaceted implications.

A further structural pattern concerns the mismatch between the geography of displacement and the geography of knowledge production. As already noted by Chimni (1998), refugee and forced migration studies have long been shaped by epistemic hierarchies in which institutions from the Global North dominate the conceptual framing, methodological agendas, and visibility of research. This pattern persists today: while the vast majority of forcibly displaced populations are located in the Global South, most academic publications originate from universities and research centers in Europe and North America. Such asymmetry reflects enduring inequalities in research capacity, funding, as well as access to global academic publishing networks, and underscores the need for greater inclusion of perspectives from regions most directly affected by forced migration.

## Sources

The analysis of the most relevant sources (Fig. 3) highlights the journals that have made substantial contributions to the field of forced migration research. The Journal of Refugee Studies emerges as the most productive outlet, with 183 documents (18.87%), followed by Refugee Survey Quarterly (77 documents, 7.94%) and International Migration (60 documents, 6.19%). Together, these three journals account for over one-third of the total publications analyzed (970 documents), underscoring their central role in shaping scholarly discourse on displacement, refugee policy, and migration governance. Other notable sources include Refuge (20 documents, 2.06%), Migration Studies (14 documents, 1.44%), and Disasters (13 documents, 1.34%), reflecting the interdisciplinary nature of the field, which spans humanitarian response, development practice, and crisis management.

The presence of journals such as the Journal of Immigrant and Refugee Studies and the Journal of Development Studies further illustrates the thematic diversity and evolving scope of forced migration research.

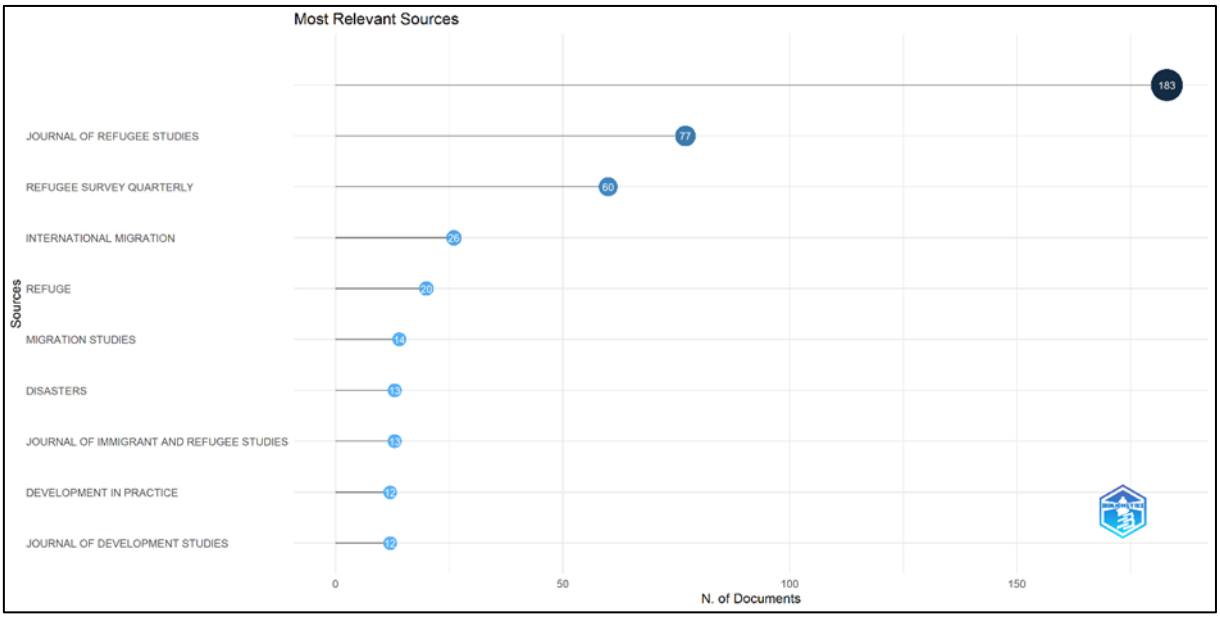


**Figure 3. Distribution of documents across sources**

The temporal analysis of source productivity reveals a sustained upward trajectory in the number of publications across the principal journals in forced migration research, particularly from the early 2000s onward. The Journal of Refugee Studies exhibits a consistent increase in scholarly output, with a marked acceleration after 2010, reflecting its central role in shaping academic discourse on displacement and refugee governance. Refugee Survey Quarterly follows a similar pattern, registering notable growth in recent years and consolidating its position as a key outlet in the field. This trend points to a growing academic engagement with issues of forced migration,

policy frameworks, and transnational mobility. The data also indicate the emergence of newer journals, such as Migration Studies and the Journal of Immigrant and Refugee Studies, which, despite lower publication volumes, contribute meaningfully to the diversification of research agendas and the incorporation of interdisciplinary approaches. Overall, the distribution of publications across these sources illustrates the dynamic evolution of forced migration scholarship, where established journals continue to dominate, while newer platforms contribute to broadening thematic scope and advancing methodological approaches.

## Author affiliations

The analysis of the most relevant authors' affiliations reveals a strong concentration of research productivity in a few key institutions (Fig. 4), with a notable presence of European and North American universities and research centers.

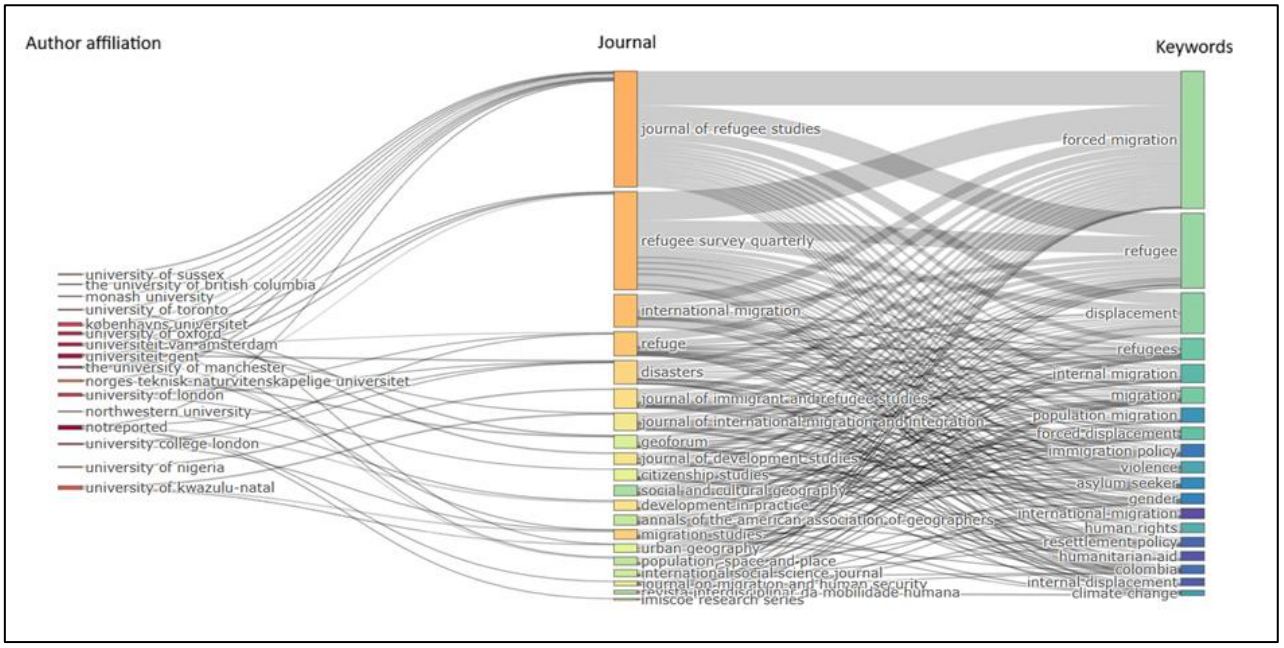


**Figure 4. Three way plot illustrating the connections between leading affiliations, publication sources and document keywords**

The University of Oxford, Universiteit Gent, and the University of British Columbia lead with 11 documents each, underscoring their significant contribution to the field. They are followed by the University of Manchester (10 documents) and the University of London (9 documents), ranking among the top five most productive affiliations. Other prominent institutions include Københavns Universitet and University College London (8 documents each), which reflect Europe's long standing expertise in migration and refugee studies. Additionally, the presence of universities such as the University of Sussex and the University of Toronto (7 documents each) indicates a strong contribution from both European and North American academic environments. Overall, the data illustrate a global network of research collaboration, with a particular emphasis on the leading roles played by European and Anglophone institutions in advancing knowledge in forced migration scholarship.

## Country production and cooperative networks

The analysis reveals a strong concentration of research contributions from the United States and the United Kingdom, which lead the field with 332 and 257 publications, respectively (Fig. 5). This highlights the prominent role of Anglophone academic environments in shaping forced migration scholarship. Following these top contributors, Canada (107 publications), Germany (94 publications), and Australia (79 publications) also demonstrate significant research output, reflecting their active engagement in global debates on displacement and refugee governance.

Other notable contributors include Mexico (47 publications), Spain (44 publications), and the Netherlands (43 publications), which further emphasize the diverse European and transatlantic involvement in the field. The presence of countries such as Colombia (40 publications), India (40 publications), and Brazil (35 publications) underscores the growing participation of institutions from the Global South. Collectively, the data illustrate a geographically distributed and interconnected research landscape, with contributions from both established and emerging academic hubs worldwide.

Beyond showing spatial patterns, the network map highlights the structure of international collaborations in forced migration research (Fig. 6). Each cluster is represented by a distinct color, allowing for a clear

depiction of regional and thematic groupings. This graphical representation provides valuable insights into the global structure of scholarly collaboration and the dynamics of knowledge production in the field.

The central position of the United States is significant, as it appears as the largest node with extensive connections to countries such as India, France, Nigeria, Switzerland, Australia, and South Africa. This indicates a high level of international engagement and a coordinating role in global research efforts. Surrounding this core, several regional clusters emerge, including a European group (France, Germany, Netherlands, Spain, Greece), a South American cluster (Brazil, Chile, Peru, Argentina), and a set of African countries (South Africa, Nigeria, Kenya, Ethiopia) that reflect linguistic, cultural, or historical collaborative connections.

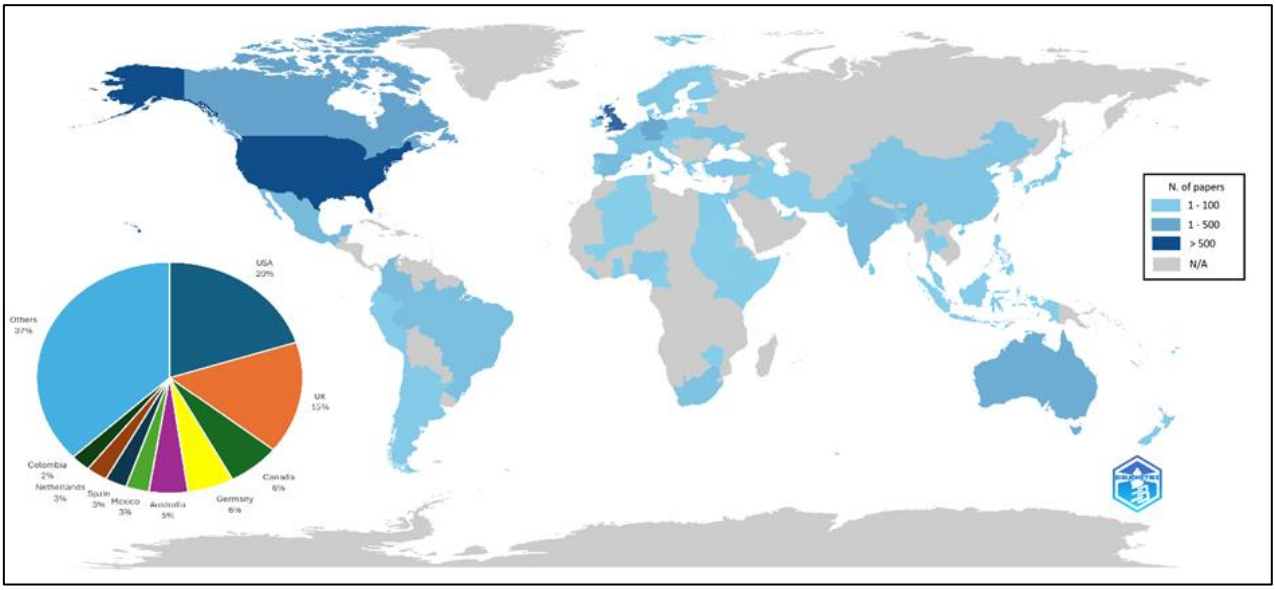


**Figure 5. Geographic distribution of research output in the analyzed field**

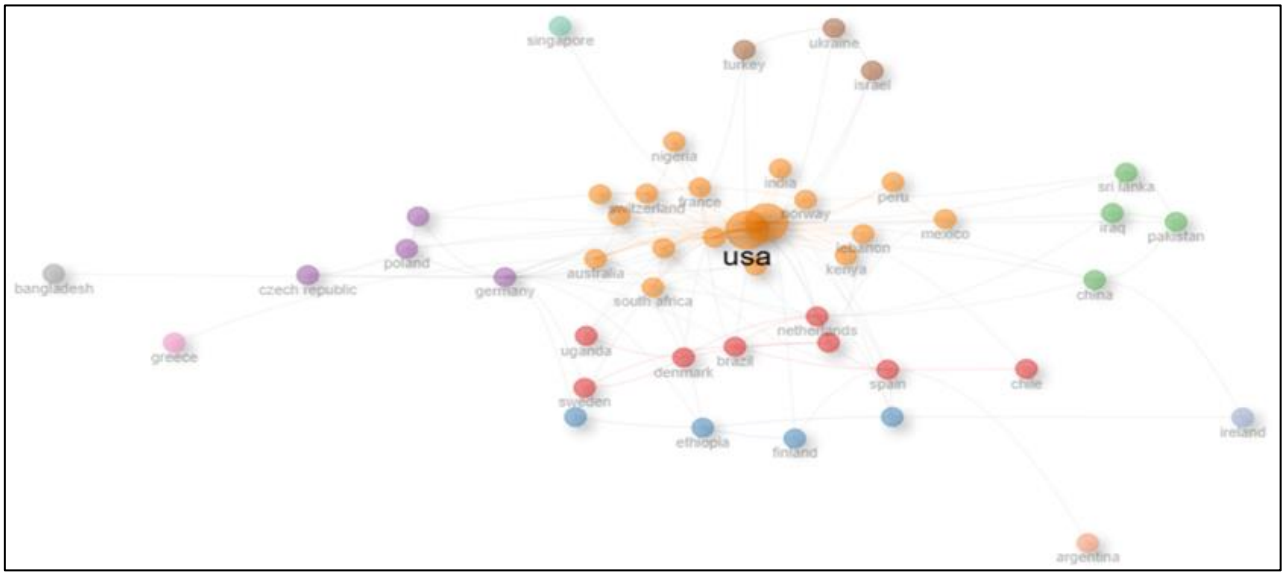


**Figure 6. The collaborative network linking the authors of the analyzed studies**

A less cohesive cluster includes countries from South and East Asia, such as China, Pakistan, Sri Lanka, and Iraq, suggesting more limited integration into the central research network. Ukraine, Poland, and Czech Republic appear as isolated nodes, indicating weaker collaborative links with major international research centers.

This lack of connectivity may hinder knowledge exchange and limit the visibility of regional scholarship. Addressing these gaps through targeted partnerships and inclusive funding mechanisms is essential for fostering a more equitable and interconnected global research landscape.

## Research trend topics

Bibliometric analysis offers critical insights into the thematic evolution of forced migration research, enabling the identification of dominant concepts, geographic patterns, and emerging areas of scholarly interest. A more detailed inspection (Fig. 7) reveals distinct thematic clusters and shifting patterns of scholarly attention, reflecting the evolving priorities and conceptual developments within forced migration research.

Foundational concepts such as “refugees,” “forced migration,” and “displacement” maintain a persistent presence across the entire period, underscoring their central role in shaping academic discourse. Their sustained prominence indicates the enduring relevance of core debates surrounding involuntary mobility, protection frameworks, and humanitarian governance.

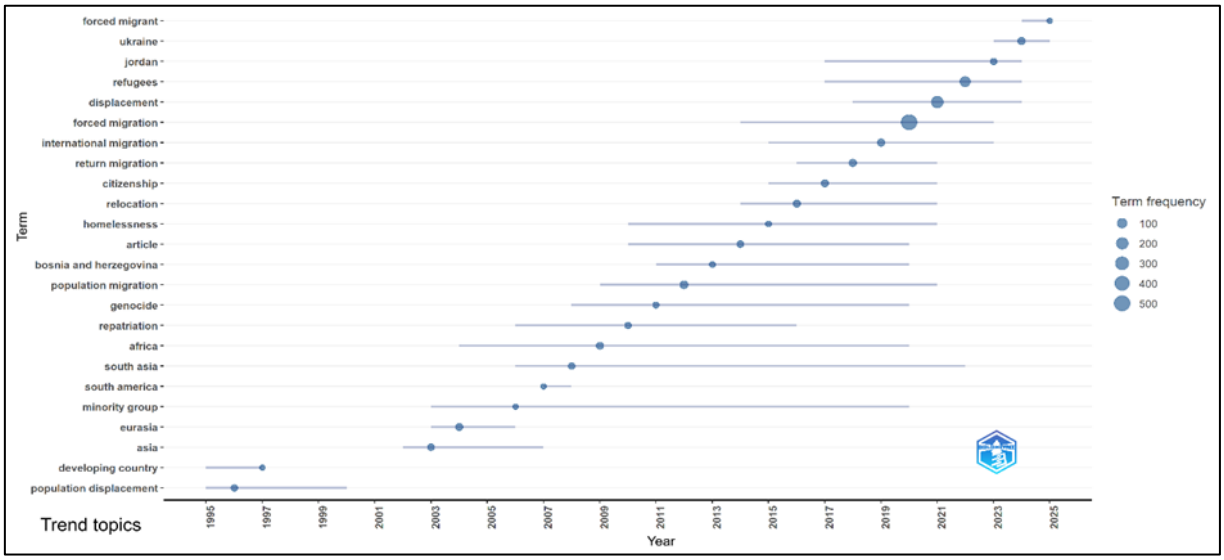


**Figure 7. Evolution of research topics over recent decades**

Geopolitical references including Bosnia and Herzegovina, Ukraine, Jordan, and the African continent appear in concentrated temporal intervals, often corresponding to major displacement crises or regional conflicts. The increased visibility of Ukraine in the 2010s and 2020s, for example, reflects the scholarly response to escalating conflict and mass population movements.

Newly prominent terms such as “citizenship,” “return migration,” and “repatriation” signal increasing scholarly attention to post-displacement trajectories, integration processes, and the legal-political dimensions of mobility. Meanwhile, concepts like “homelessness” and “relocation” underscore the intersections between forced migration, urban vulnerability, and social exclusion.

Broader regional identifiers comprising South Asia, South America, Eurasia, and Asia, together with categories like minority group and developing country, point to the widening geographic and sociopolitical scope of the literature. Their presence reflects a growing shift toward comparative, interdisciplinary, and development oriented perspectives that draw on multiple disciplinary frameworks.

The thematic structure of the field indicates that research on forced migration remains dominated by policy oriented and protection focused approaches, particularly those examining legal frameworks, asylum governance, and state responses. These themes form the core of the largest clusters, suggesting that institutional and regulatory perspectives continue to shape the mainstream of the literature.

In contrast, topics related to long term integration, psychosocial well being, and everyday experiences of displacement appear comparatively underrepresented. These themes emerge in smaller clusters with lower centrality, indicating that micro level and experiential perspectives, although present, have not yet achieved the same visibility as macro institutional analyses.

The temporal distribution of keywords suggests a gradual decline in studies focused on protracted refugee situations and camp based governance, themes that were more prominent in earlier decades. Their decreasing frequency reflects a shift away from traditional humanitarian settings toward more diversified forms of mobility and displacement. Several niche topics also appear, including climate induced displacement, statelessness, and digital migration infrastructures. Although these areas generate coherent micro clusters, their limited size indicates that they remain emerging rather than consolidated research directions.

Such trends are further exemplified by several recent studies. Howlader et al. (2025) examine the Rohingya crisis as a complex humanitarian and geopolitical challenge, showing how protracted statelessness, regional insecurity, and limited international accountability shape one of the most complex forced displacement situations in South Asia. At a broader regional scale, Hadibi et al. (2025)

analyze the contemporary genealogy of forced displacement in Africa, demonstrating how border conflicts interact with colonial legacies, local governance, and evolving security dynamics to produce heterogeneous displacement patterns across the continent.

Boom-Cárcamo et al. (2025) document how displaced women in northern Colombia experience intersecting violations of economic, social, cultural, and environmental rights, highlighting the structural inequalities and stigmatization that shape everyday survival in informal settlements. Extending the focus to transcontinental mobility regimes, Lumley-Sapanski & Schwarz (2025) investigate the selective (in)visibility of Eritrean migrants along the Central Mediterranean Route, revealing how hypervisibility, invisibilization, and strategic border governance contribute to a trafficking industrial complex that exploits the precarious conditions faced by migrants.

Lastly, within the European context, Rock & Yanaşmayan (2025) analyze the experiences of Ukrainian refugee mothers in Germany, showing how displacement reshapes maternal subjectivity through urgency, protective labor, and forms of "active waiting" that help rebuild stability amid temporal disorientation.

Overall, the field shows a clear thematic shift from classical humanitarian and legal perspectives toward more interdisciplinary approaches that incorporate geography, sociology, public policy, and development studies, reflecting an expanding interest in the social, spatial, and political complexities of forced mobility and the growing analytical breadth of contemporary forced migration research.

## Conceptual framework and thematic connections

The conceptual landscape of the field has been clarified through the mapping of frequently co-occurring terms and their relational patterns. This method enables the construction of thematic clusters and network maps that reveal both overarching and specialized areas of inquiry within forced migration research. As illustrated in the co-occurrence network (Fig. 8), three principal thematic clusters emerge: policy-oriented and environmental drivers of displacement, including terms such as "climate change," "war," and "resettlement policy"; socio-political and humanitarian dimensions, reflected in concepts like "refugees," "gender," "violence," and "humanitarian aid"; and geographic and demographic markers, notably "Asia," and "Eurasia". Together, these groups show the diverse directions of forced migration research and how it connects to global governance, vulnerability, and mobility of affected populations.

In order to enhance the analysis of the conceptual architecture underpinning forced migration research, Multiple Correspondence Analysis (MCA) was conducted on the most frequently occurring terms within the selected corpus (Fig. 9). This technique facilitated the delineation of three core thematic clusters, each corresponding to a specific domain of scholarly inquiry:

• *Migrantion determinant and population migration*. This cluster synthesizes research on the factors that generate and redirect population movements, focusing on the interplay between demographic pressures, economic opportunities, and spatial mobility. Studies in this domain examine how determinants such as labor market disparities, demographic transitions, political instability, and regional development inequalities influence both internal and international migration flows. For example, Gómez-Álvaro & Caro-Carretero (2025) show that migratory movements in West and East Africa are shaped by a set of push factors, including economic instability, environmental triggers, demographic pressures, and governance deficits, which interact to generate distinct regional mobility patterns. Drawing on a comparative framework, their analysis demonstrates how variations in state capacity, livelihood vulnerability, and exposure to climatic risks produce differentiated migration trajectories, thereby underscoring the centrality of structural determinants in explaining population movements across African regions. Viewed in this cluster, migration outcomes reflect the combined influence of economic restructuring and demographic pressures, highlighting the need for integrated frameworks that explain how population mobility patterns take shape.

• *Political conflict and violence*. This thematic core centers on the role of political conflict and violence as primary forces shaping patterns of forced displacement and influencing the broader dynamics of population mobility. Scholarship in this thematic area focuses on uncovering how political conflict and violence shape the conditions that lead to forced displacement and reconfigure broader mobility dynamics. In particular, Czaika & Kis-Katos (2009) demonstrate that variations in armed clashes, military presence, and insurgent activity systematically alter local security conditions, thereby increasing the likelihood of household displacement and revealing how micro level exposure to violence translates into broader forced migration patterns. A notable case is provided by Fakhoury & McCulloch (2023), who investigate how Lebanon's political order responds to conflict induced displacement, demonstrating that patterns of mobility are deeply conditioned by sectarian power sharing arrangements, institutional fragmentation, and the strategic deployment of violence by political actors. Their work reveals how conflict dynamics simultaneously generate displacement and shape the political environments into which displaced populations must navigate, highlighting the intricate interplay between violence, governance, and forced migration. Mulaj (2008) offers an in depth examination of the Darfur conflict, showing how systematic violence, state supported militias, and targeted attacks on civilian groups generate large scale displacement while complicating the legal and political classification of the crimes committed. His analysis highlights how forced migration in Darfur emerges not only from acute insecurity but from

deliberate strategies of territorial control and demographic engineering, illustrating the central role of political violence in shaping mobility outcomes. Analyses within this cluster frequently rely on advanced approaches developed in conflict studies and security analysis, employing event based modeling, spatial analysis, and long term assessments of violence dynamics to clarify how armed confrontations, coercive state practices, and localized insecurity evolve over time, ultimately shaping the mechanisms through which political conflict produces forced displacement and reconfigures broader mobility patterns.

• *Internal displacement and refugee*. The last cluster brings together research centered on internal displacement and refugee movements, examining how these forms of forced mobility unfold across diverse social, geopolitical, and institutional contexts. A key example is provided by Abebe (2010), who presents a detailed examination of internal displacement across African contexts, showing how armed confrontations, coercive state practices, and chronic insecurity converge to uproot communities and erode the institutional mechanisms intended to safeguard them. His analysis underscores that violence operates not merely as a triggering event but as a persistent structural force that shapes the trajectories, vulnerabilities, and long term prospects of displaced populations. A relevant case comes from Lanjouw et al. (2000) as they examine the dynamics of internal displacement in Burma, showing how military operations, forced relocations, and systematic human rights violations disrupt local livelihoods and compel communities to move repeatedly, thereby revealing how state driven violence and territorial control shape the everyday realities of displaced populations. Mithun & Arefin (2020) explore the situation of Hindu Rohingya refugees in Bangladesh, tracing how persecution, targeted violence, and successive waves of conflict induced displacement shape their migration trajectories and everyday life in the camps, thereby showing how minority status and prolonged insecurity compound vulnerability within refugee settings. As a whole, this cluster reflects a consolidated body of scholarship that advances a deeper understanding of internal displacement and refugee experiences, highlighting how violence, repressive state practices, and protracted insecurity shape the trajectories and everyday realities of affected populations.

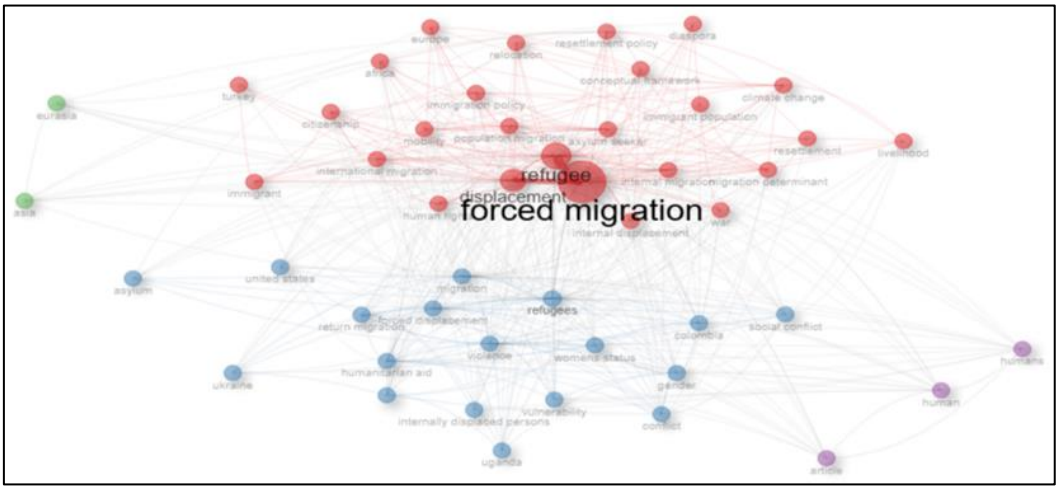


**Figure 8. Co-occurrence network of the most common terms in the dataset**

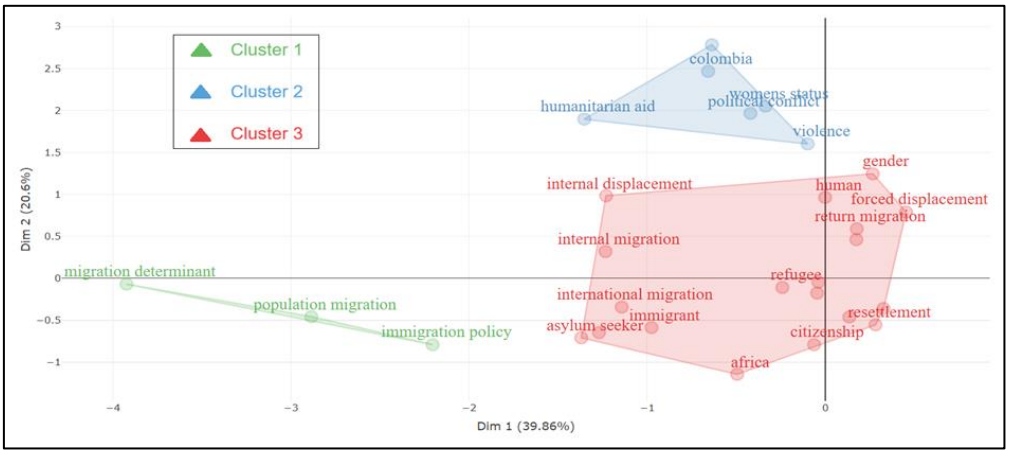


**Figure 9. Multiple Correspondence Analysis (MCA) of the most frequent terms in the reviewed literature**

The methodological choices informing this study, which employ Multiple Correspondence Analysis (MCA) to identify conceptual clusters, differ substantially from the bibliometric techniques used in recent analyses. Whereas many studies rely on citation network analysis or keyword co occurrence mapping to identify research trends, this approach focuses on term based conceptual relationships that reveal deeper thematic linkages across the literature. Other research directions employ process based modelling or systematic reviews to investigate specific mechanisms, offering fine grained insights but without structurally portraying broader thematic configurations. Taken together, these methodological approaches prove complementary: bibliometric analyses trace the evolution of research fields, MCA uncovers underlying conceptual structures, and process oriented studies help substantiate the dynamics they examine.

In any event, some limitations need to be acknowledged. The analysis depends on term frequencies within the selected corpus, which may introduce a systematic selection error if certain disciplinary niches or regional contexts are represented more heavily than others. Terminological inconsistencies across studies may further obscure thematic connections. A further structural limitation concerns the well documented dominance of Global North publications in forced migration research, which shapes both the visibility of specific topics and the conceptual frameworks through which displacement is analyzed. This imbalance may lead to the underrepresentation of perspectives from regions most affected by forced mobility, thereby reinforcing existing epistemic asymmetries within the field.

## Conclusions

This bibliometric analysis, covering the period 1974-2025, provides a comprehensive examination of research on forced migration, tracing the evolution of scholarly interest, thematic orientations, and collaborative structures within this increasingly complex field. By applying bibliometric methods, the study examines how academic production has expanded, diversified, and reorganized in response to shifting geopolitical contexts and humanitarian crises.

The findings indicate a sustained growth in publications, driven by the intensification of global displacement and the rising visibility of forced migration as a geographically diverse research domain. Strong scholarly engagement emerges particularly from Europe, North America, and parts of Asia, reflecting both the geographic distribution of academic infrastructures and the uneven global exposure to displacement dynamics. These patterns underscore the dual nature of forced migration research: global in relevance yet regionally shaped by specific historical, political, and institutional conditions.

Through co-occurrence networks, Multiple Correspondence Analysis (MCA), and thematic analysis, the study identifies several well established research clusters, such as refugee protection, conflict induced displacement, integration policies, and human rights, alongside emerging areas including climate induced mobility, border governance, and quantitative modeling of displacement flows. This thematic landscape illustrates the field's growing interdisciplinarity, where insights from demography, political science, sociology, geography, and environmental studies converge to address the multifaceted realities of forced migration.

Despite these advances, the analysis points to enduring asymmetries, especially regarding imbalanced geographical representation and limited international scholarly engagement. Strengthening these dimensions will be essential for developing a more comprehensive and analytically robust understanding of displacement dynamics.

In summary, this bibliometric analysis contributes a structured overview of the conceptual landscape of forced migration studies. By documenting long term trends, identifying emerging themes, and revealing collaborative dynamics, it provides a foundation for future research aimed at strengthening comparative perspectives, enhancing methodological diversity, and broadening the inclusion of underrepresented regions and perspectives within the global study of forced migration..

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## Author contribution

Conceptualization, methodology, data curation, writing, LB; supervision, review, IM. All authors have read and agreed to the published.

## Conflicts of interest

The authors declare no conflict of interest.

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