Babeș-Bolyai University, Cluj-Napoca
Faculty of Geography
Doctoral School of Geography

DOCTORAL THESIS

The Effect of Climate Change on River Discharge in the Maramureș Depression

- summary -

PhD supervisor,
Prof. univ. habil. dr. Adina-Eliza Croitoru

PhD Student,
Mugurel Raul Sidău

CLUJ-NAPOCA
2025

Contents

KEYWORDS**:** Climate change, hydrological regime, Maramureș Depression, GIS model, spatial interpolation, river discharge, climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5), NAM model, GIS spatial analysis, extreme events (floods, drought), climate trends, hydrological modeling, frequency analysis, climate change adaptation, remote sensing.

1. Introduction

Climate is an important factor in the development of society, and climate change can profoundly affect the evolution of civilizations. History offers numerous examples of societies impacted by extreme climatic phenomena.

According to the Intergovernmental Panel on Climate Change (IPCC, 2023), climate change is evident and global, reflected in variations of climatic parameters and in the intensification of extreme events. The sixth IPCC report indicates that the global average temperature has increased by approximately 1.1°C compared to the pre-industrial period. Studies show that the warming process is correlated with anthropogenic greenhouse gas emissions and is expected to continue, even if emissions were to be significantly reduced.

In the context of climate change, Romania pays increased attention both to water scarcity as a resource and to the way it is used. The growing demand for water, amid population growth and increasingly rapid economic development, puts pressure on available resources, which are undergoing a decline in both quantity and quality.

By developing climate models and scenarios for the analyzed region, tools are needed for regional administrations to support the development of river basin management plans, basin planning schemes, flood risk management plans, etc. These tools allow authorities to anticipate possible evolutions of water resources and to adopt preventive and adaptive measures.

Future development strategies must take these challenges into account and include measures such as:

- improving water quality by reducing and/or controlling pollution;
- developing guidelines and procedures for rational water consumption, promoting efficiency and minimizing waste in household, industrial, and agricultural sectors, as well as through public education and awareness campaigns that promote responsible actions toward water resources;
- implementing integrated water resources management, coordinating water use across sectors to balance supply and demand and to protect aquatic ecosystems;
- promoting research and innovation in water-saving technologies, such as efficient irrigation, water recycling, or reuse of wastewater.

By focusing on the Maramureș Depression, a region with sensitive ecosystems and important water resources, this research aims to understand how climate change affects the local hydrological regime. This area serves as a natural laboratory for studying hydrological phenomena in the context of current climate variability and change.

The main goal of this research is to evaluate how climate change influences the flow of watercourses in the Maramureș Depression. Specific objectives include:

a. Analysis of climate variability – identifying trends and climatic changes in the region based on historical and current meteorological data.
b. Analysis of surface water resources – assessing the flow of major watercourses (Vișeu, Iza) and identifying seasonal and annual changes in the context of climate change.
c. Analysis of hydrological modeling results and estimation of future evolution and impacts – developing hydrological models to estimate future impacts of climate change on river discharge.

2. State of Scientific Research on the Addressed Topic

2.1. International Scientific Research

International research on climate change is supported by prestigious organizations such as the IPCC, UNEP, NASA, and NOAA. The IPCC synthesizes global knowledge on climate change through Global Climate Models (GCMs), using socio-economic scenarios (SSPs) and emission trajectories (RCPs). These scenarios help assess future developments in climate change and identify climate-related risks.

NASA contributes to global climate research through satellite missions that monitor variables such as temperature, precipitation, and water masses. NOAA uses regional station networks to develop localized climate scenarios. In Europe, the Copernicus Climate Change Service (C3S), the European Space Agency (ESA), and the European Environment Agency (EEA) provide essential climate data for analyzing and modeling climate change in Romania.

However, international studies and methods need to be contextualized and adapted for application at smaller scales. In this regard, recent regional and local research is particularly relevant to this study, as it addresses specific hydrological dynamics and their relationship with climatic and geomorphological characteristics.

Recent studies highlight the significant impact of climate change on the hydrological regimes of small catchments, emphasizing their increased vulnerability to extreme climatic variations. Research conducted by Blöschl et al. (2019) and Steimke et al. (2017) underlines the importance of local factors, including topography and soil permeability, in modulating the hydrological response to these changes. Notably, the study by Viviroli et al. (2011) on mountain catchments in the Alps underscores their high sensitivity to temperature increases and accelerated snowmelt. Similar analyses by Muelchi et al. (2021), Secci et al. (2021), and Yeste et al. (2024) use climate and hydrological models to evaluate seasonal and long-term changes in streamflow in alpine basins and various global regions, stressing the importance of an integrated approach in assessing the climatic effects on water resources.

2.2. National Scientific Research

In Romania, numerous studies and research projects have evaluated the impact of climate change on water resources and the hydrological regime of rivers, using various approaches and methods. The report of the National Meteorological Administration (ANM, 2008) describes the evolution of climate characteristics using historical data and regional climate models to identify long-term trends. Cuculeanu et al. (2002) analyzed the climatic impact on ecosystems and biodiversity by applying ecological vulnerability assessment methods and climate models in various case studies.

Bojariu et al. (2015) investigated the physical mechanisms of climate change, presenting detailed scenarios, associated risks, and recommendations for adaptation. The World Bank study (2013) assessed the magnitude of climate change impacts on integrated water resources in Romania, proposing adaptation strategies based on detailed climate and hydrological models.

Research conducted by Croitoru and Minea (2015) and Croitoru et al. (2013) focused on changes in river discharges in Eastern Romania and on extreme events in the Black Sea coastal area, using time series analysis and specific statistical tests. Mic and Corbus (2013) evaluated the climate impact on the Someș River through detailed hydrological analyses and simulations of time series.

Official documents, such as the “National Climate Change Strategy 2013–2020” (Ministry of Environment, 2013), emphasize the importance of proactive adaptation and climate risk management measures. The recent study by Chendeș et al. (2024) uses global and regional climate models for simulating and predicting future climate variables. Bîrsan (2017) and Croitoru et al. (2012) employ advanced statistical tests (such as Mann-Kendall and change point analysis) to identify significant changes in the hydrological and climatic regimes of the Romanian Carpathians. The works of Micu et al. (2021), Zaharia et al. (2018), Sandu et al. (2010), and Minea (2020) further contribute by analyzing the impact of climate change on rivers in the Carpathians and Eastern Romania, using advanced modeling approaches.

All these studies demonstrate Romania's concern with monitoring and understanding the phenomenon of climate change, highlighting the need for continuous adaptation and the implementation of effective policies to respond to future climate challenges..

3. Geographical Characterization of the Study Area

3.1. Selection of the Study Area

Maramureș Depression, located in northern Romania, is ideal for studying the effects of climate on hydrological resources due to its diverse topography, varied climatic conditions, and the limited impact of anthropogenic activities. The catchment areas of the Vișeu and Iza rivers are entirely situated within Romania. Both rivers originate in the Rodna Mountains and flow through the Maramureș Depression, following a southeast to northwest direction, contributing to the shaping of the natural landscape and the ecosystems throughout the region.

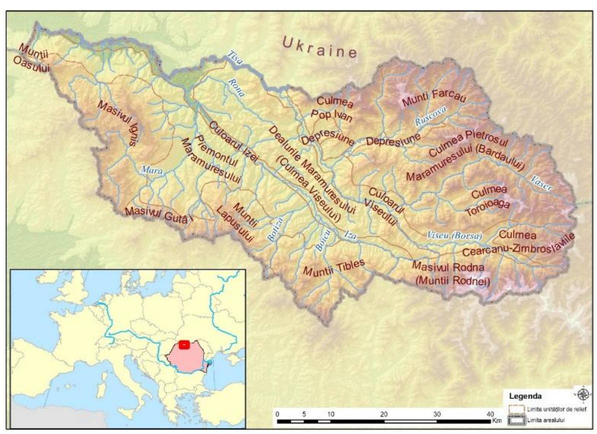


Figura 1. Geographical Delimitation of the Study Area in the Maramureș Depression

3.2. Geographical Boundaries

The study area is bordered to the north by the Tisa River, which forms the boundary with Ukraine. To the west lie the Gutâi and Oaș Mountains, to the east the Maramureș Mountains, and to the south the Rodna, Țibleș, and Lăpuș Mountains. These mountain ranges significantly influence the region's climate and hydrology (Fig. 1).

3.3. Relief

The analyzed region presents varied altitudes, ranging from 200–400 m in the north and 500–700 m in the south. It is surrounded by mountains that frequently exceed 1500 m in elevation, including Pietrosu Rodnei Peak, the highest (2303 m), which directly influences the regional climate (Fig. 1).

3.4. Hydrography

The hydrographic network of the studied area is dense and relatively uniformly distributed, with values ranging between 0.5 and 0.7 km/km², according to the Cadastrul Apelor (2005). It consists of rivers that flow into the Tisza River, the main collector of the region (Fig. 2). Due to the natural opening of the region toward the northwest, air circulation from this direction favors the accumulation of large amounts of precipitation, which contributes to the formation of high discharges in the hydrographic network.

The Tisza River, which marks the natural border between Romania and Ukraine over a distance of 62 km, receives as important tributaries from Romania the Vișeu, Iza, and Săpânța rivers.

The hydrological regime of the area is of the mountainous (Carpathian) type, characterized by maximum

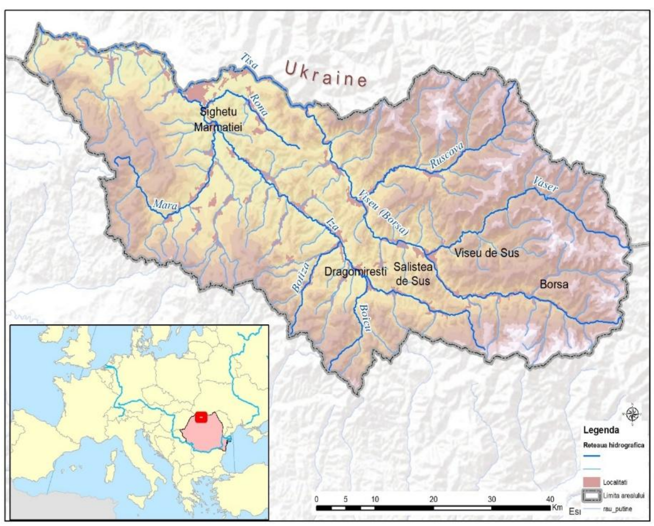


Figura 2. Rețeaua hidrografică a arealului

discharges in spring (especially in April), due to snowmelt, and minimum discharges in autumn, in September.hidrografică.

3.5. Climate

The region's climate is moderately temperate-continental, influenced by the surrounding mountains. Annual average precipitation ranges between 800–1400 mm, with the highest amounts recorded on the ridges of the Rodna and Maramureș Mountains. Temperatures and precipitation show significant seasonal variations.

3.6. Geological Characteristics and Their Influence on the Hydrological Regime

As observed in Figure 3, the geology of the region is dominated by sedimentary, metamorphic, and volcanic rocks, which influence water infiltration and runoff. The predominant sedimentary rocks allow for moderate infiltration, directly affecting the local hydrological regime.

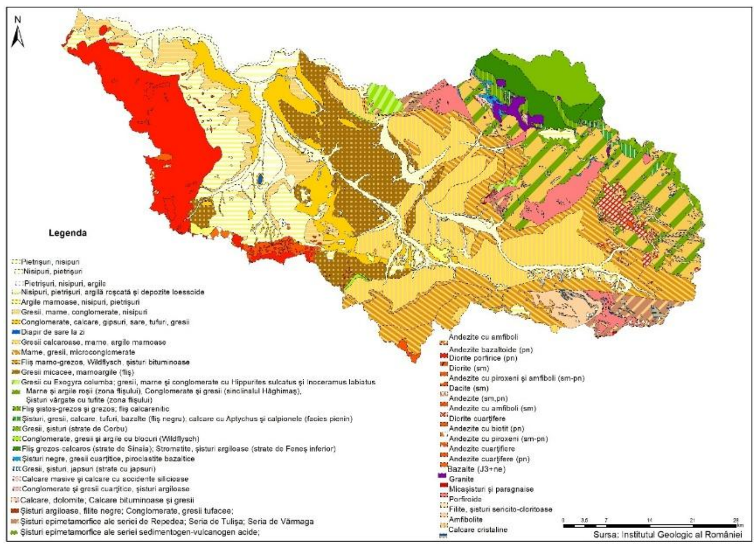


Figura 3. Geology of the study area

4. Data Used and Analytical Methodologies

4.1. Data

Various datasets and data formats were used in this study, each playing a role in understanding and modeling climatic and hydrological processes: climate data, hydrological data, satellite imagery, and land use data.

4.1.1. Historical Climate Data

Observed Data

The climate data used include both point-based meteorological observations and gridded datasets. Daily observations of maximum temperature, minimum temperature, and precipitation were collected from the meteorological stations in Baia Mare and Ocna Șugatag (Fig. 4) for the period 1961–2010.

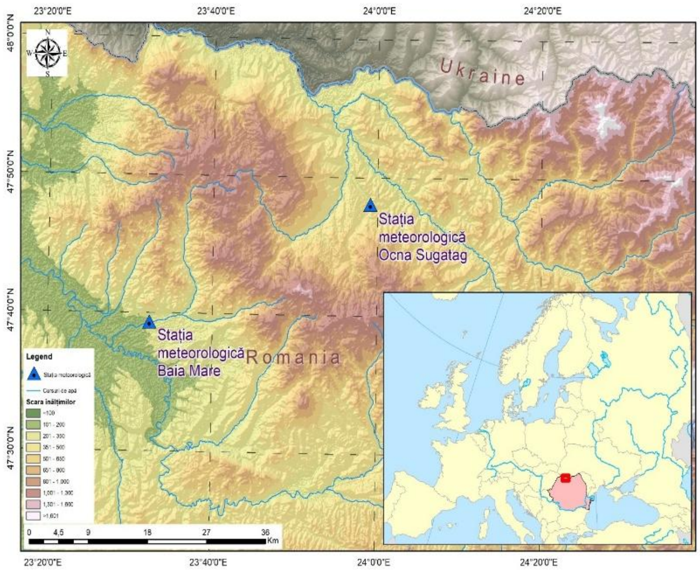


Figura 4. Location of the meteorological stations considered

Seturi de date gridate/modelate

The data extracted from three gridded daily datasets were analyzed:

(i) • **ROCADA** covers the period 1961–2013 and has a spatial resolution of 0.1° x 0.1°, developed by the Romanian National Meteorological Administration (ANM) (Fig. 5a).

(ii) • **CarpatClim** provides similar data for 1961–2010, derived from an extensive network of 585 stations (Fig. 5b).

(iii) • **E-OBS**, a European database (1950–2024), updated annually, is recognized for its accuracy in detecting climate extremes (Fig. 5c).

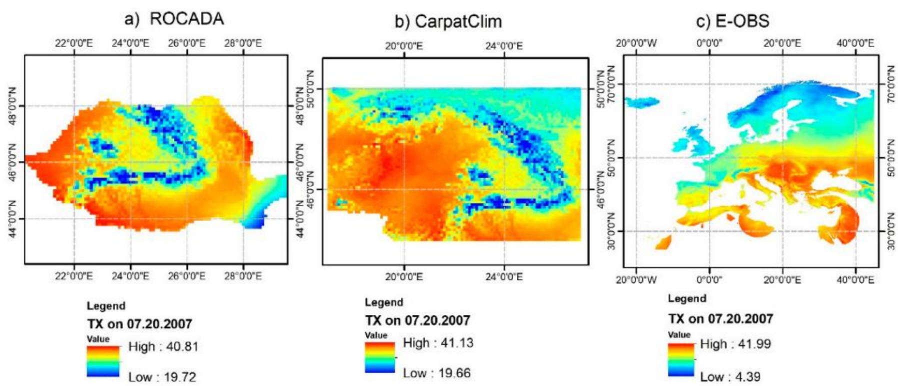


Figura 5. *Spatial domains of the datasets used in this study.*

(iv) **Copernicus Climate Change Service (C3S)** or three RCP scenarios (2.6, 4.5, 8.5) and three time intervals (2011–2040, 2041–2070, 2071–2100), derived from CDS models (2024).

4.1.2. Hydrological Data

The hydrological data include daily average discharges collected at the hydrometric stations of the National Administration "Apele Române" network for the Vișeu and Iza river basins (Fig. 6). The data, collected for different time intervals, were used for the calibration and validation of the NAM hydrological model. These datasets are extremely important, as they allow the evaluation and monitoring of the hydrological regime, contributing to the understanding of the impact of external factors on water resources.

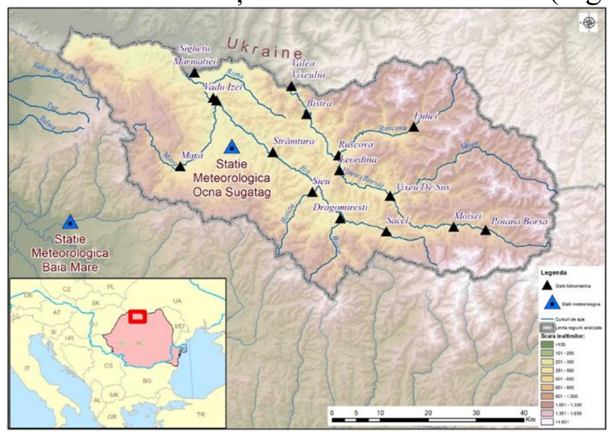


Figura 6. Distribution of hydrometric stations in the Maramureș Depression

4.1.3. Satellite Images

For monitoring land cover changes, Landsat images (1985–2019, provided by USGS) were used. Only clear, cloud-free images converted to 8-bit format were selected. Their validation was performed by comparison with orthophotos provided by ANCPI.

4.1.4. Land Use Data

The land use data originate from the CORINE Land Cover (CLC) database, 2018 edition, managed by the European Environment Agency (EEA). These data are used to analyze how changes in land use affect hydrological and climatic processes.

4.1.5. Digital Elevation Model (DEM)

The DEM used in this study originates from the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 30 meters. The DEM was employed to extract topographic parameters such as slope, aspect, terrain fragmentation, and accumulation zones, as well as for generating thematic maps.

4.2. Data Used and Analytical Methodologies

The chapter details the methods and techniques used for the collection, analysis, and interpretation of climatic and hydrological data. The study included descriptive statistics, correlation analyses, trend analyses, and advanced methods of spatial and hydrological analysis.

4.2. 1. Statistici descriptive

Descriptive statistics used included the arithmetic mean, standard error, median, mode, standard deviation, variance, skewness, and confidence interval (95%). Descriptive statistics were calculated for each dataset and serve as the basis for subsequent analyses.

4.2. 2. Statistical Correlations

The section on statistical correlations analyzes the relationships between climatic variables (temperature and precipitation) and river discharges, in order to understand how these elements interact and influence the hydrological regime in the context of climate change. The **coefficient of determination (R^2)** was used to assess the performance of the regression models, and the **Pearson correlation coefficient (r)** was applied to quantify the strength and direction of the relationship between variables. Data were standardized to allow fair **comparisons** between series with different units and scales. The analysis focused on both annual and seasonal values, identifying significant links between climatic factors and variations in river discharges.

4.2. 3. Distribution Analysis and Model Performance

This subchapter addresses the analysis of distributions and the evaluation of the performance of climate and hydrological models, which are essential for validating the accuracy of predictions. Two main methods are used: Taylor diagrams and the Kolmogorov-Smirnov (K-S) test.

Taylor diagrams provide a comprehensive graphical representation of the agreement between simulated models and observed data, using the Pearson correlation coefficient, root mean square error (RMSE), and standard deviation. These diagrams allow for a quick visual assessment of the models in terms of their fidelity to actual measured values.

In parallel, the **K-S** test is used to compare statistical distributions—either between an observed dataset and a theoretical one, or between two empirical datasets—to verify whether they originate from the same distribution. A low p-value in this test indicates a significant difference between the distributions..

4.2. 4. Trend Analysis

The subchapter details the methods used to identify and quantify long-term trends in climatic and hydrological variables such as temperature, precipitation, and river discharge. Two main methods were applied: *regression analysis* (linear and multiple) and *non-parametric statistical tests* (Mann-Kendall and Sen's slope).

Simple *linear regression* was used to evaluate the temporal evolution of individual variables, such as temperature or discharge, and the coefficients obtained using the least squares method (OLS) indicated whether the trends were statistically significant. *Multiple regression* allowed the analysis of complex relationships between several predictive factors (climatic and geographic) and discharge variations, in order to determine their influence.

To detect monotonic trends in time series, the *Mann-Kendall* and *Sen's* slope tests were applied. The *Mann-Kendall test* determines whether a climatic or hydrological variable exhibits an increasing or decreasing trend without assuming a normal distribution of the data. After identifying a trend, Sen's slope was used to estimate its magnitude, providing an accurate estimation of the long-term rate of change.

Examples from the scientific literature (Kumar et al., Tabari & Talaee, Şen) have demonstrated the applicability of these methods in various regions of the world for evaluating climatic and hydrological trends. The combination of methods ensures a comprehensive analysis of climatic and hydrological data, necessary for the interpretation and prediction of environmental changes.

4.2. 5. Analysis of Extreme Events

This subchapter highlights the influence of extreme weather-climatic events, such as heatwaves and torrential rains, on the hydrological regime, particularly on river discharges and channel morphology. In the context of climate change, a shift in the frequency and intensity of these phenomena has been observed, which necessitates a thorough analysis for risk assessment and appropriate adaptation.

The analysis was conducted in two main directions: *(i) identification and analysis of extreme climatic events*, and *(ii) evaluation of their impact on river discharges*. For the first stage, daily gridded data (E-OBS) on temperature and precipitation were used, processed in R and ArcGIS Pro. The datasets were clipped to the extent of the Maramureș Depression, and extreme events were defined based on POT thresholds (90th percentile for high values and 10th percentile for low values). The frequency of these events over time was analyzed, and based on the C3S dataset, climate projections were developed up to the year 2100.

In the second stage, the identified climatic events were correlated with the measured discharge values. Statistical methods (including EFA and POT) were applied to assess the influence of extreme events on hydrological values. The time series were divided into four intervals (1961–2020) to compare temporal developments. Additionally, climatic and hydrological data were standardized to allow direct comparisons, eliminating the influence of differing units. The analysis enabled the identification of relationships between temperature, extreme precipitation, and peak discharges, indicating periods of increased hydrological risk..

4.2. 6. Spatial Analysis

The spatial analysis focused on identifying areas affected by climate change, evaluating how temperature and precipitation influence deviations from the average values of the reference period 1961–1990. Climate data, obtained from the E-OBS datasets, were grouped into three intervals: 1991–2001, 2002–2012, and 2013–2023. For each interval, annual averages of temperature and precipitation were calculated and then compared with the reference period using the t-test to verify the statistical significance of the changes. The analysis was conducted using GIS techniques.

4.2. 7. Analysis of Long-Term Discharge Deviations

This subchapter presents the analysis of long-term streamflow deviations relative to a reference period, using climate and hydrological data provided by C3S, in NetCDF format. The climate scenarios RCP 2.6, 4.5, and 8.5 were analyzed for three time intervals (2011–2040, 2041–2070, 2071–2100), and the data were initially processed on a monthly basis and then aggregated seasonally and annually. The climatic seasons (winter, spring, summer, autumn) were investigated to assess the impact of climate change on the hydrological regime depending on the period. The results are presented in the form of raster maps, with the aim of identifying the spatial variations in streamflow and the areas at increased risk.

4.2. 8. Hydrological Modeling

This subchapter details the application of hydrological modeling to assess the impact of climate change on streamflow regimes, using the conceptual NAM model integrated into the DHI MIKE 11 platform. The model was calibrated based on historical data (2008–2017) from 16 hydrometric stations in the Vișeu–Iza basin. Calibration was carried out through iterative adjustment of model parameters (such as Umax, Lmax, CQOF, CK1, etc.), and performance was evaluated using statistical indicators such as NSE, MAE, and R^2.

Subsequently, future climate scenarios (GFDL CM2.0 SRES B1, HadCM3 SRES B1, HadGEM1 SRES A1B) were integrated into the model, using statistically corrected and spatially-temporally adapted data. These scenarios allowed for the simulation of potential changes in streamflows through the end of the century, highlighting increased risks of floods or droughts depending on the scenario considered.

Model validation was performed over a different period than calibration, in order to test its robustness and accuracy. In addition, sensitivity analyses were conducted to identify the parameters with the greatest influence on the results. By using an ensemble of models and scenarios, climate uncertainties were addressed, reducing the risk of reliance on a single set of assumptions and providing a broad range of projections for hydrological evolution in the context of climate change.

4.2. 9. Extraction of the Forest Canopy Density (FCD) Indicator

The subchapter details the use of the **Forest Canopy Density (FCD)** indicator as a remote sensing tool for evaluating forest canopy density and analyzing the impact of forest cover changes on the hydrological regime, applied in the upper Ruscova River basin. The area was selected due to its high degree of forest cover, the absence of significant anthropogenic interventions, and the presence of reforestation/deforestation activities (Fig. 8).

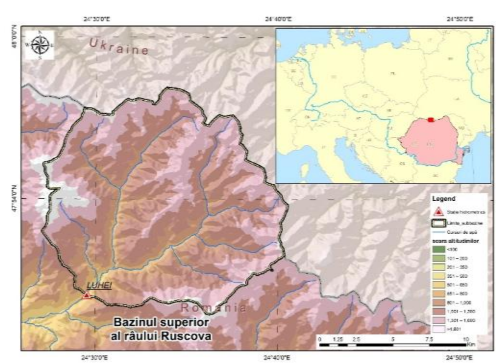


Figura 8. Case study area and the location of the considered hydrometric station

The analysis was based on Landsat satellite imagery (1985–2019), from which four vegetation indices were derived: AVI, SI, BI, and TI. These were calculated using standardized methods, after normalization of spectral bands, and allowed the derivation of two essential components: **VD (Vegetation Density)** and **SSI (Scaled Shadow Index)**. Their combination led to the calculation of the FCD value, expressed as a percentage (0–100%) (see Figure 9).

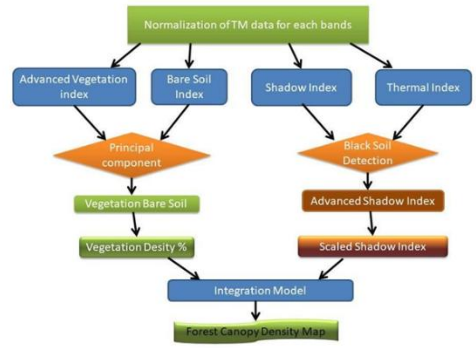


Figura 9. Workflow diagram for deriving the FCD index.

The model was implemented in Model Builder within ArcGIS Desktop, and the accuracy of the method was evaluated using the kappa coefficient (κ), based on 20 verification points compared with 2018 orthophotos. The automatic classifications (forested vs. non-forested) were validated in the field, and discrepancies were analyzed to identify potential sources of error (geolocation, spectral variability, etc.).

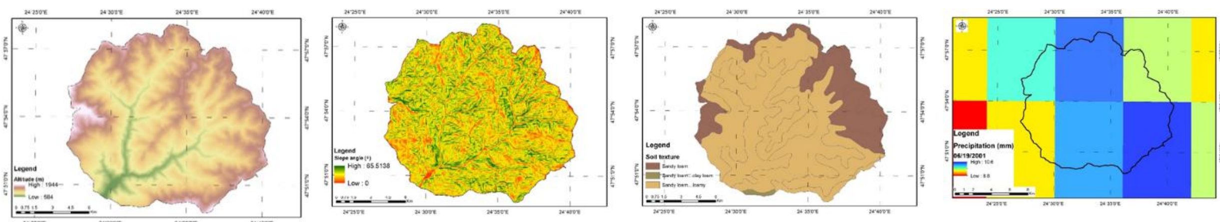
4.2. 10. Analysis of Precipitation Values and Discharge Hydrographs in Relation to Forest Area Evolution

The relationship between precipitation, discharge, and the evolution of forested areas is analyzed, highlighting the role of forests in regulating surface runoff. Comparing discharge values with the evolution of the forest canopy density index provides insights into the influence of forests on the hydrological regime and runoff coefficients. However, these comparisons cannot precisely isolate the effect of forests due to the influence of multiple external variables such as climate, soil, geology, and land use, which may distort the results.

4.2. 11. Simulation of Hydrological Processes Using a Hydrological Model

This subchapter presents the application of the Unit Hydrograph Model (UHM), integrated into the *Mike Hydro River module* by DHI, for simulating hydrological processes and evaluating the influence of forests on runoff regimes in the Maramureș Depression. The UHM model was chosen due to its ability to analyze the impact of forest cover changes on streamflow, being the only model available in the MIKE Hydro River platform that allows such an analysis. However, the model cannot accurately simulate runoff influenced by snowmelt, which is why only events from the warm season (June–September), when snow influence is minimal, were selected.

The modeling is based on the *SCS-Curve Number (CN)* method, which estimates surface runoff depending on soil characteristics, land use, and hydrological condition. In this study, thematic maps were processed (digital elevation model – DEM, slope, soil texture, daily precipitation), using ArcGIS Pro (see Figure 10). Based on these data, the hydrological parameters required by the model were calculated: hydraulic length, slope, baseflow, and catchment area. Soil texture data was obtained from ICPA, and daily precipitation was extracted from the E-OBS dataset, spatially distributed using Thiessen polygons..



(a) Digital Elevation Model **(b) Slope Angle** **(c) Soil Texture** **(d) Gridded Daily Precipitation Dataset**

Figura 10. Thematic maps used in the model.

The CN index was determined based on the hydrological soil group and land use, using a classification adapted to Romanian conditions (see Table 1). Based on this index, a weighted average of CN values was calculated for the entire basin. The model was calibrated on a single isolated annual event, selected so that the simulated discharge would closely match the observed one. Parameters such as time of concentration (calculated using the standard SCS formula), slope, and basin area were extracted directly from the DEM (see Table 2).

Tabel 1. CN values for land use types and hydrologic soil groups used in this study.

No	**Land Use Category**	**Hydrologic Soil Group**			
		A	**B**	**C**	**D**
1	Discontinuous Urban Area	-	89	-	-
2	Pastures	-	69	-	-
3	Deciduous Forest	-	66	-	-
4	Coniferous Forest	34	60	73	-

5	Mixed Forest	38	62	75	-
6	Natural Meadows	49	69	79	-
7	Marshes and Peatlands	49	69	-	-
8	Forest–Shrub Transitional Areas	45	60	-	-

CN values adapted for Romania according to Chendeș (Chendeș, 2011).

Tabel 2. Parameter values used for model calibration.

Hydraulic lenght (km)	**Slope (%)**	**Baseflow (m^3/s)**	**Catchment Area km^2**
6.124 km	42,5	2	185.656

To evaluate the effect of forest vegetation changes, three scenarios were analyzed:

- **S1** – the baseline scenario, reflecting the current situation, used for the calibration of each annual event,
- **S2** – the scenario with the maximum forested area (determined in 1986, 162 km²),
- **S3** – the scenario with the minimum forested area (calculated for 2003, 135 km²).

The purpose of these scenarios was to assess the influence of forests on peak flood reduction, against the background of annual variability in precipitation amount and intensity. Since the UHM model does not include temperature as an input parameter, it cannot accurately simulate snowmelt episodes, which led to discrepancies between simulated and observed discharges in March–April.

Taking the above into account, the best method to evaluate the influence of forests on peak flood reduction is to consider three scenarios: Scenario 1 (S1) is the initial one, used to calibrate the model for each annual event; Scenario 2 (S2) assumes that the forested area reaches its potential maximum extent and represents the largest area within the analyzed period, calculated using the FCD index method (the forested area determined in 1986 was the largest, 162 km²); Scenario 3 (S3), opposite to S2, refers to the minimum area calculated using the FCD index and corresponds to the surface estimated for the year 2003 (135 km²) (Figure 11).

Figura 11. Evolution of forested area.

e. Accuracy assessment of the method

To evaluate the accuracy of the analysis method, the orthophoto images were compared with the processed Landsat satellite images. This comparison involved checking the consistency between the land use boundaries identified in the Landsat images and those observed in the orthophoto images. Areas of interest, such as forested areas, agricultural land, and urban zones, were analyzed in detail to identify any discrepancies.

5. Results and Discussion

5.1. Determining the Optimal Gridded Daily Dataset

5.1.1. Analysis of Historical Extreme Values of the Analyzed Variables

The subchapter provides a detailed evaluation of the performance of three gridded climate datasets (ROCADA, CARPATCLIM, and E-OBS) compared to observed values from the Baia Mare and Ocna Șugatag meteorological stations, regarding historical extremes of temperature (Tmax and Tmin) and daily precipitation (RR). The analysis is based on the method described by Sidău et al. (2021) and aims to identify the dataset that best replicates the actual observed values.

A first relevant observation concerns the interpolation anomalies identified in the ROCADA and CARPATCLIM datasets, where abrupt spatial variations in temperature (Figure 18) suggest a possible limitation of the MISH and MASH methods used in the interpolation process. In contrast, the E-OBS dataset, which applies kriging, provides a more realistic spatial distribution for temperature, but shows lower accuracy for precipitation due to the reduced density of meteorological stations used (Figure 12).

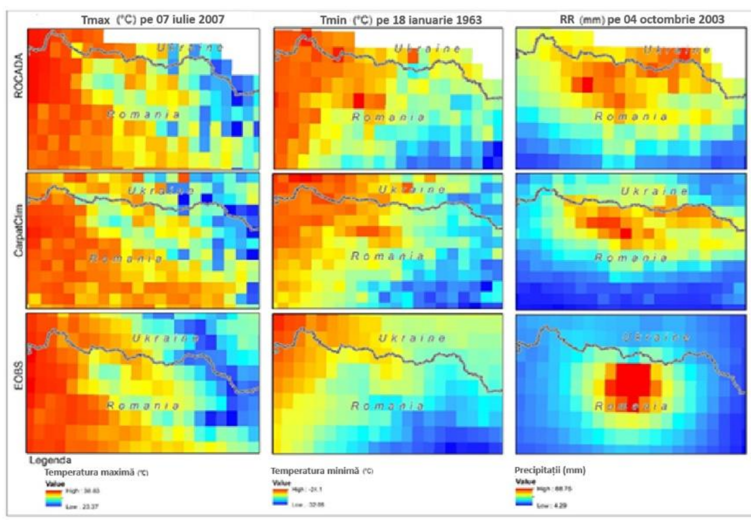


Figura 12. Spatial distribution of historical Tmax, Tmin, and RR values in the study area (Sidău, Croitoru, et al., 2021)

The descriptive statistics analysis (Tables 3 and 4) shows that:

- Mean values are generally closer to observations in the case of ROCADA.
- Parameters describing the shape of the distribution (skewness, kurtosis) indicate a better match between observed values and the E-OBS dataset, especially for minimum and maximum temperature..

Tabel 3. Descriptive statistics for the Baia Mare meteorological station (Sidău et al., 2021)

	Tmax				Tmin				Rain			
	Obs.	**Rocada**	**Carpat Clim**	**E-OBS**	**Obs.**	**Rocada**	**Carpat Clim**	**E-OBS**	**Obs.**	**Rocada**	**Carpat Clim**	**E-OBS**
Mean	**15.16**	15.16	16.13	15.12	**5.32**	4.69	4.72	5.17	**2.47**	2.09	2.13	2.13
Standard Error	**0.075**	0.076	0.078	0.074	**0.059**	0.060	0.060	0.059	**0.04**	0.032	0.032	0.034
Mediana	**16.2**	16.3	17.48	16.17	**6.1**	5.47	5.53	5.95	**0**	0.15	0.14	0
Mode	**24**	26.33	24.68	23.72	**10**	0.57	10.64	10.06	**0**	0	0	0
Standard Deviation	**10.08**	10.24	10.48	10.03	**8.03**	8.07	8.12	7.94	**5.70**	4.31	4.37	4.54
Sample Variance	**101.63**	104.88	109.75	100.60	**64.42**	65.12	65.94	63.06	**32.43**	18.61	19.13	20.64
Kurtosis	**-0.98**	-1.01	-1.07	-0.99	**-0.14**	-0.04	-0.07	-0.16	**30.99**	23.12	22.46	25.80
Skewness	**-0.22**	-0.23	-0.23	-0.22	**-0.52**	-0.55	-0.56	-0.52	**4.30**	3.83	3.79	3.85
Range	**53.7**	54.53	53.59	53.25	**54.8**	50.18	50.1	53.29	**121.4**	77.25	76.09	92.7
Minimum	**-16.1**	-16.81	-13.48	-16.04	**-29.9**	-28.59	-28.68	-29.01	**0**	0	0	0
Maximum	**37.6**	37.72	40.11	37.21	**24.9**	21.59	21.42	24.28	**121.4**	77.25	76.09	92.7
Confidence level (95%)	**0.146**	0.149	0.152	0.145	**0.116**	0.117	0.118	0.115	**0.083**	0.063	0.064	0.066

Tabel 4. Descriptive statistics for the Ocna Șugatag meteorological station (Sidău, et al., 2021)

	Tmax				Tmin				RR			
	Obs.	**Rocada**	**Carpat Clim**	**E-OBS**	**Obs.**	**Rocada**	**Carpat Clim**	**E-OBS**	**Obs.**	**Rocada**	**Carpat Clim**	**E-OBS**
Mean	**13.20**	14.24	15.70	12.51	**3.80**	4.31	4.05	3.25	**2.05**	2.02	2.11	2.07
Standard Error	**0.072**	0.073	0.079	0.072	**0.059**	0.061	0.061	0.058	**0.036**	0.032	0.032	0.033
Mediana	**14.2**	15.24	16.97	13.50	**4.6**	5.08	4.89	4.04	**0**	0.15	0.190	0
Mode	**21**	24.99	25.43	21.49	**10**	6.87	10.92	-0.51	**0**	0	0	0
Standard Deviation	**9.53**	9.66	10.44	9.46	**7.78**	8.05	8.07	7.75	**4.87**	4.24	4.32	4.39
Sample Variance	**90.86**	93.40	109.07	89.58	**60.52**	64.72	65.17	60.11	**23.72**	17.94	18.63	19.28
Kurtosis	**-0.972**	-1.006	-1.070	-0.981	**-0.387**	-0.254	-0.238	-0.360	**33.635**	24.102	21.729	24.166
Skewness	**-0.214**	-0.194	-0.225	-0.204	**-0.479**	-0.511	-0.534	-0.483	**4.656**	4.005	3.837	3.894
Range	**50.6**	51.69	53.59	50.41	**46.6**	47.78	47.06	45.98	**82.2**	67.74	65.8	76.5
Minimum	**-15.6**	-15.5	-13.48	-16.25	**-25.7**	-27.24	-26.93	-26.65	**0**	0	0	0
Maximum	**35.0**	36.2	40.1	34.2	**20.9**	20.5	20.1	19.3	**82.2**	67.7	65.8	76.5
Confidence level (95%)	**0.142**	0.144	0.155	0.141	**0.116**	0.120	0.120	0.114	**0.071**	0.062	0.063	0.064

The Pearson correlation coefficients (Table 5) confirm a very strong correlation (above 0.95) between all datasets and the observed values, with superior performance for ROCADA at the Baia

Mare station and for E-OBS at Ocna Șugatag. The best results were obtained for minimum temperatures, while precipitation yielded lower values, which can be explained by the high spatial variability of this parameter in mountainous areas.

Tabel 5. Pearson correlation coefficient between gridded datasets and observed values for extreme temperatures (maximum and minimum) and precipitation (1961–2010) (Sidău et al., 2021)

	Gridded dataset	MS Baia Mare	MS Ocna Șugatag
Tmax	ROCADA	0.998	0.997
	CARPATCLIM	0.949	0.997
	E-OBS	0.996	0.999
Tmin	ROCADA	0.995	0.992
	CARPATCLIM	0.994	0.994
	E-OBS	0.989	0.998
Precipitation	ROCADA	0.954	0.888
	CARPATCLIM	0.952	0.892
	E-OBS	0.913	0.925

Further, the analysis of extreme percentile values (1 and 99) was deepened using linear regressions and Taylor diagrams. The results show that:

- At Ocna Șugatag, for the 99th percentile, E-OBS is the closest to observations (Figure 13), while for Baia Mare, ROCADA fits best, especially for Tmax (Figure 14).
- Table 6 shows the highest Pearson coefficients for Tmax and Tmin at Ocna Șugatag in the case of E-OBS, while for Baia Mare, ROCADA provides the best results.
- Regarding the 1st percentile (minimum values), E-OBS performs better at Ocna Șugatag for both variables (Tmax and Tmin), while in Baia Mare, E-OBS stands out with a very high coefficient for Tmin (Table 7).

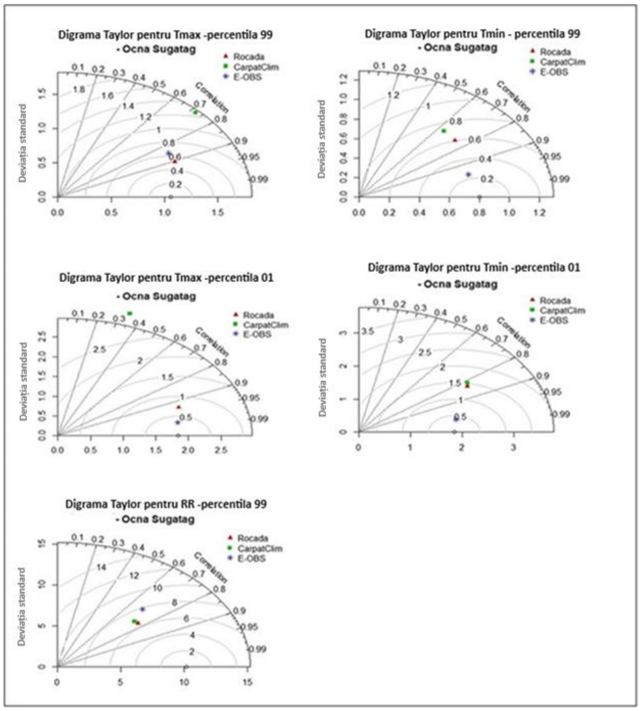


Figura 13. Taylor diagram for the 1st and 99th percentiles for the Ocna Șugatag meteorological station (Sidău, et al., 2021)

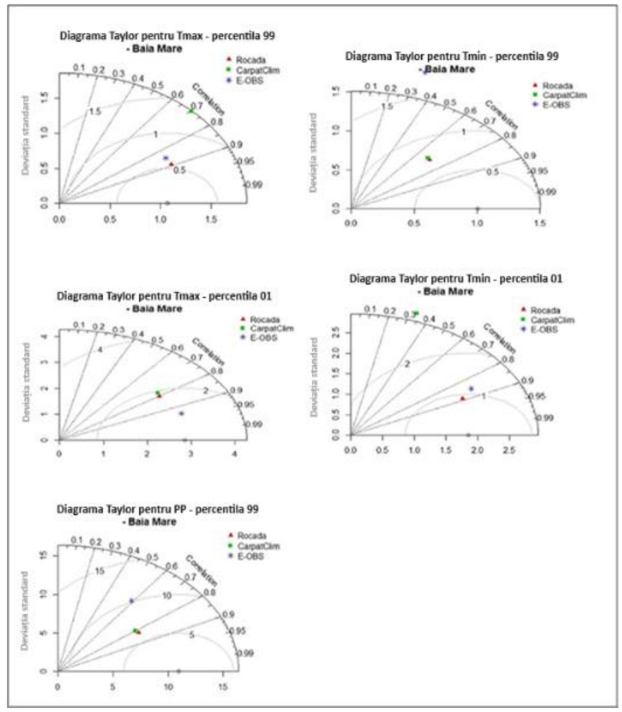


Figura 14. Taylor diagram for the 1st and 99th percentiles – Baia Mare meteorological station (Sidau, et al., 2021)

Tabel 6. Pearson correlation coefficient between gridded and observational datasets for the 99th percentile values (maximum and minimum) of temperature and precipitation (1961-2010) (Sidău, et al., 2021)

	Gridded dataset	MS Baia Mare	MS Ocna Șugatag
Tmax	ROCADA	0.7983	0.8895
	CARPATCLIM	0.4994	0.2806
	E-OBS	0.7267	0.9542
Tmin	ROCADA	0.4981	0.5445
	CARPATCLIM	0.4667	0.4097
	E-OBS	0.1018	0.9073
Precipitation	ROCADA	0.6779	0.5855
	CARPATCLIM	0.6374	0.5447
	E-OBS	0.3458	0.475

Tabel 7. Pearson correlation coefficient between gridded datasets and observational data for the 1st percentile (maximum and minimum) temperature values (1961-2010)(Sidau și colab, 2021)

	Gridded dataset	MS Baia Mare	MS Ocna Șugatag
Tmax	ROCADA	0.7958	0.8677
	CARPATCLIM	0.1096	0.1132
	E-OBS	0.7367	0.9678
Tmin	ROCADA	0.6423	0.6951
	CARPATCLIM	0.6035	0.6676
	E-OBS	0.8784	0.9585

Extreme annual values were also extracted for each parameter (50 years), allowing for additional analysis.

In conclusion, although ROCADA provides a better fit for mean values and at certain locations, the E-OBS dataset captures extreme values more accurately, especially for temperatures, making it suitable for analyses focused on severe climate events. However, for precipitation, ROCADA remains the most performant dataset, mainly due to the high density of meteorological stations used.

5.1.2. Seasonal Value Analysis

This subsection presents a comparative evaluation of the seasonal distributions of the main gridded climate datasets (E-OBS, ROCADA, CarpatClim), compared to observed data from the Baia Mare and Ocna Șugatag meteorological stations, for the period 1961–2010. The analysis was carried out using the Kolmogorov-Smirnov (K-S) test and Taylor diagrams, for the parameters maximum temperature, minimum temperature, and precipitation, in winter and summer seasons.

In the winter season, the E-OBS dataset values show the closest cumulative distribution to the observed values, except for the minimum temperature at Ocna Șugatag, where ROCADA provides a better fit. In general, ROCADA has K-S values relatively close to those of E-OBS, while CarpatClim shows greater deviations, especially for precipitation.

In the summer season, the analysis highlights a slight shift: ROCADA presents the smallest deviations (D) for both maximum and minimum temperatures, while E-OBS shows a distribution closer to the observed data series.The analysis was completed with Taylor diagrams. The results indicate that, for the Baia Mare station, the ROCADA dataset provides the best statistical match in both the cold and warm seasons. In contrast, for the Ocna Șugatag station, E-OBS shows a better fit compared to the other datasets.

5.2. Evaluation of Long-Term Trends in Climate Variables (Temperature, Precipitation) and River Discharges

5.2.1. Evaluation of Gridded Datasets for Trend Identification

The subchapter focuses on evaluating gridded climate datasets (ROCADA, CarpatClim, E-OBS) for the identification of long-term climate trends, using the Mann-Kendall (MK) test and the Sen's slope estimator.The results of the test, applied to maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (RR), highlight that during the winter season, statistically significant trends were identified for Tmax and Tmin in most datasets, especially at the Ocna Șugatag station, where p-values fall below the significance threshold ($p < 0.05$), indicating upward trends. In contrast, for RR, the trends are weaker or even negative, and statistical significance is low. In the summer season, clear upward trends in maximum and minimum temperatures were observed, but no significant trends in precipitation were found in any of the analyzed datasets. It is noteworthy that the CarpatClim dataset did not indicate any significant change for any of the analyzed parameters.

The E-OBS dataset, although less effective in analyzing long-term trends, is superior in capturing extreme climate values – both annual and historical – thus representing an excellent source for the study of severe climate events. Moreover, its extended temporal coverage (1950–2022) makes it valuable for long-term climate analyses.

The ROCADA gridded dataset is the most suitable for trend analysis in northwestern Romania, whereas E-OBS provides the best accuracy in analyzing extreme values. Both datasets can be effectively used as input in agrometeorological and hydrological models, provided they are cross-validated with observational data, especially in regions with complex topography..

5.2.2. Statistical Analysis of the Temperature–Precipitation–Discharge Relationship

In this subchapter, the results of statistical analyses conducted to identify long-term trends in climatic variables (temperature and precipitation) and river discharge are presented. The temperature and precipitation values are extracted from the gridded E-OBS datasets, meaning they represent spatially interpolated and basin-averaged values, covering a larger geographical area. In contrast, river discharge values are point measurements recorded at the specified hydrological stations.

Temperature – The analysis of annual mean temperature was carried out for four stations: Moisei, Săcel, Vadu Izei, and Bistra, and shows a clear and statistically significant increasing trend in all four locations. This is confirmed by both Sen's Slope test (with p-values < 0.001 and narrow confidence intervals) and the Mann-Kendall test, which indicates positive values for the z and tau coefficients. Polynomial regressions offer a better fit than linear ones, suggesting a complex and non-linear climatic evolution.

Precipitation – For precipitation, Sen's test reveals no significant trend, while the Mann-Kendall test indicates weak negative trends, suggesting a slight long-term decrease. The negative coefficients in the linear regressions and the low R^2 values – for both linear and polynomial regressions – confirm the high variability of precipitation and the weakly defined trend.

Discharge – Discharge is measured at hydrometric stations, representing characteristic values for a basin, which may explain some of the differences compared to the climatic parameters of temperature and precipitation described above.

The discharges measured at hydrometric stations reflect a different evolution, with Sen's Slope test indicating a statistically significant increase in annual mean discharges at Moisei and Bistra, with very low p-values and confidence intervals that do not include 0. At Vadu Izei, the trend is at the limit of significance ($p = 0.049$). The Mann-Kendall test confirms these results, with positive z and tau values, the strongest being at Moisei and Bistra. Polynomial models better explain the discharge variation than linear ones, indicating that hydrological evolution is influenced by multiple factors and does not follow a strictly linear dynamic.

Long-term evolution graphs for annual mean temperature, annual precipitation, and annual mean discharge for four locations – Moisei, Săcel, Vadu Izei, and Bistra – were also presented in the thesis. These graphs are consistent with the statistically analyzed values and the tabular data described in the previous subchapters.

The detailed analysis of each category highlights the following: Temperatures show a clear and consistent increase in all locations, with polynomial regressions providing a better fit to the data. Precipitation exhibits significant annual fluctuations and a weak downward trend, which is difficult to interpret without additional context. Discharges show an extremely slight increasing trend, especially in Moisei and Bistra.

5.3. Evaluation of Long-Term Discharge Deviations

This chapter presents the results of the analysis on the impact of climate change on river discharges in the Maramureș Depression, based on the premise that climatic changes can significantly influence the region's hydrological regime, both in terms of volume and seasonal distribution of runoff. The assessment was carried out by analyzing the seasonal deviations of the modeled discharges compared to a reference climatic period (1971–2000), following the methodology described in subchapter 4.2.7 Analysis of long-term discharge deviations.

The analysis was based on three projection intervals: 2011–2040, 2041–2070, and 2071–2100, within three RCP climate scenarios (2.6, 4.5, and 8.5), which reflect different levels of greenhouse gas emissions projected by the IPCC. The aim of this approach is to capture possible developments in the hydrological regime over the short, medium, and long term.

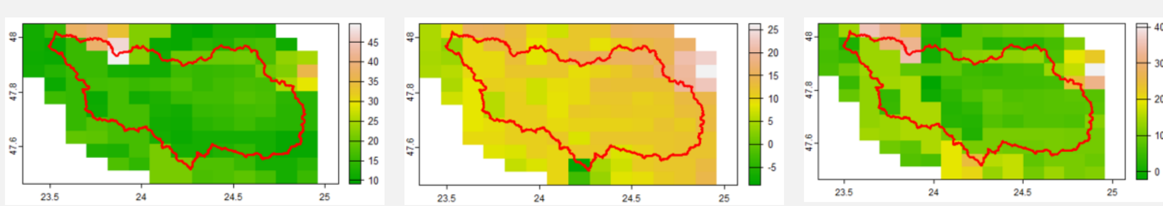
5.3.1. Analysis of Estimated Changes at the Seasonal Scale

The analysis used the deviations of mean discharges from a reference period, differentiated by season, according to the climate scenarios RCP 2.6 (optimistic), RCP 4.5 (moderate), and RCP 8.5 (pessimistic).

The winter season (Fig. 15) is characterized by general increases in discharge across all scenarios, explained by intensified liquid precipitation and faster snowmelt. The largest increases occur under RCP 8.5, reaching up to 69% in the last analyzed period (2071–2100), suggesting an increased risk of flooding. RCP 2.6, although optimistic, shows a fluctuating evolution, while RCP 4.5 indicates a progressive upward trend in discharges.

RCP 2.6 ***RCP 4.5*** ***RCP 8.6***

2011-2040



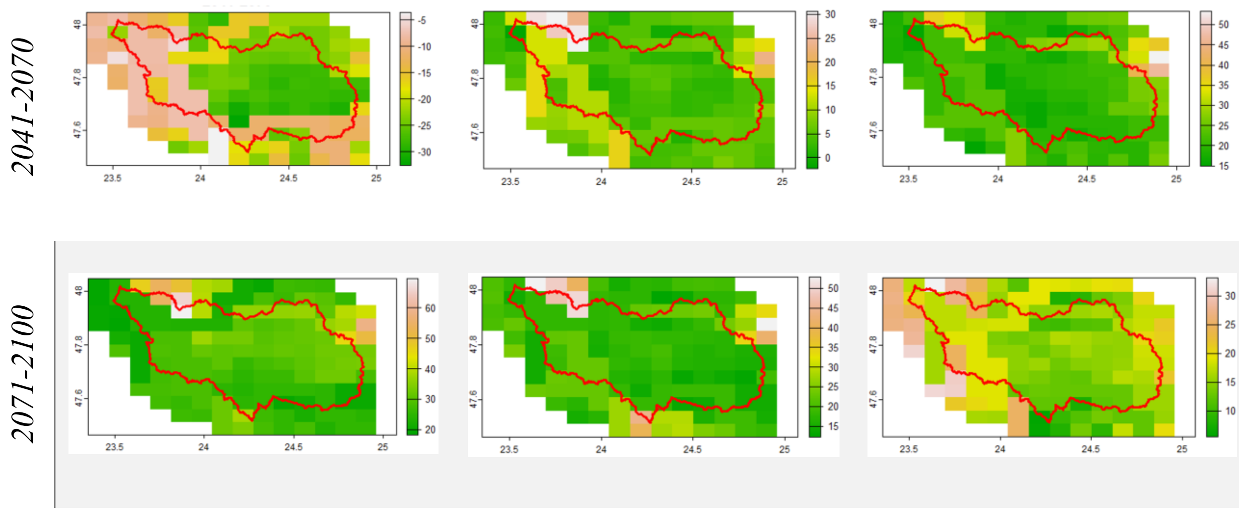
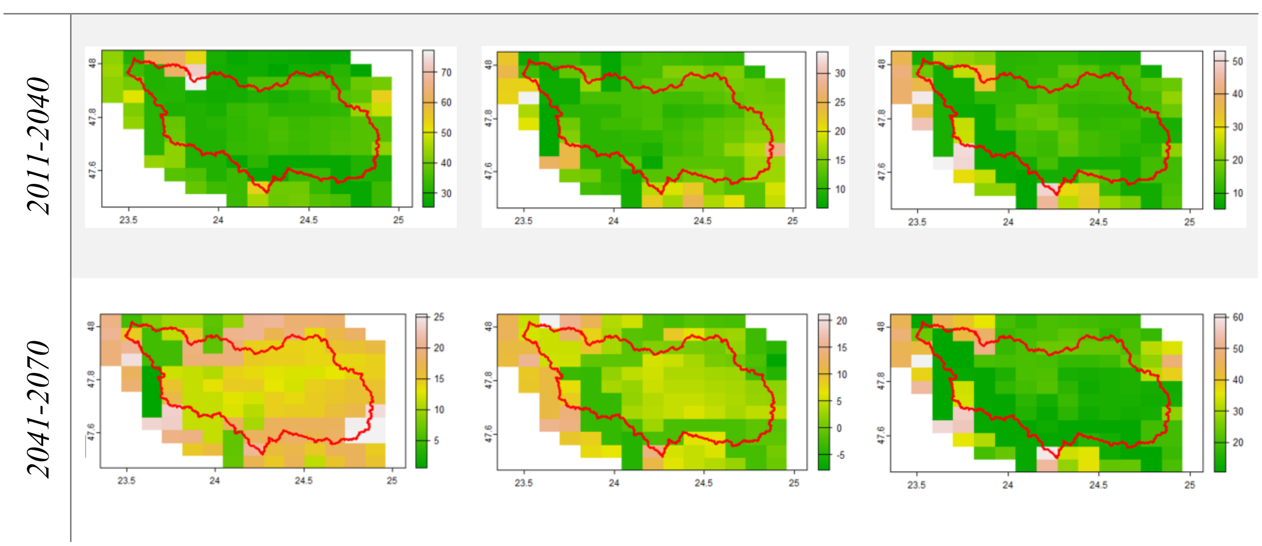


Figura 15. Seasonal deviations of mean discharge values – Winter season

The spring season (Fig. 16) maintains high positive deviations, especially under RCP 8.5, where values reach up to 60.9%. The hydrological regime is characterized by rapid snowmelt and more frequent precipitation, increasing the risk of floods. The decreases observed during the 2041–2070 period, particularly under RCP 2.6 and RCP 4.5, reflect earlier snowmelt and reduced spring contributions, especially in mountainous areas. However, values increase again in the final decades of the century.

RCP 2.6 ***RCP 4.5*** ***RCP 8.6***



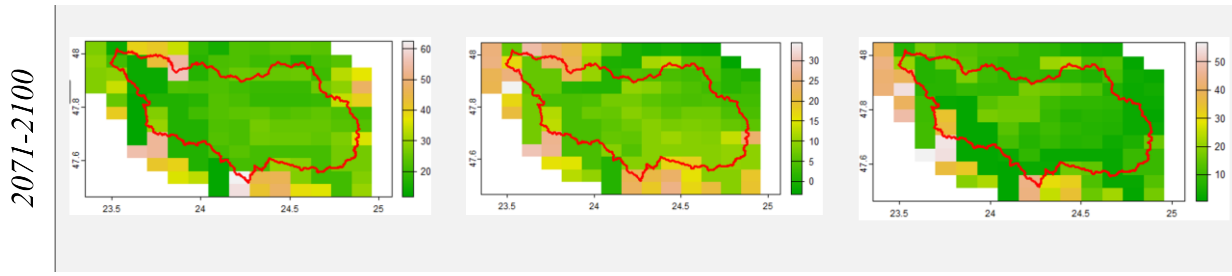


Figura 16. Seasonal values of mean streamflow anomalies – Spring season

The summer season (Fig. 22) is the one with the highest hydrological variability. RCP 8.5 highlights extreme anomalies (up to +182% in 2011–2040), with torrential rainfall and a major risk of flash floods, as well as severe droughts in lowland areas. RCP 2.6 and RCP 4.5 indicate alternations between droughts and episodes of intense precipitation, but with lower amplitude. Mountainous catchments are most exposed to floods, while the depression areas are prone to water deficits.

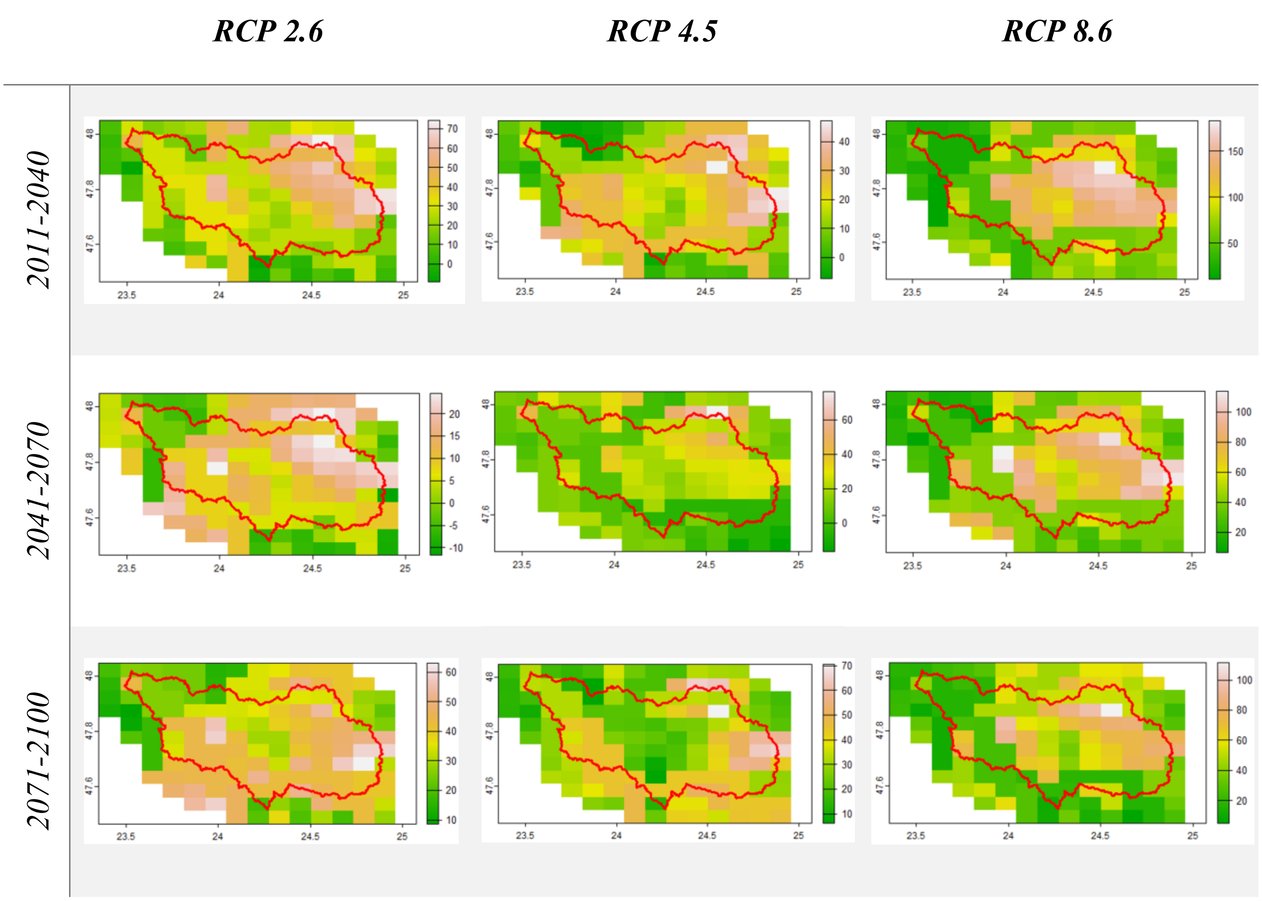


Figura 17. Seasonal deviations of mean river discharge – Summer season

The autumn season (Fig. 23) reflects an unstable transition between warm and cold seasons. RCP 2.6 shows a fluctuating pattern – with initial increases in discharge, followed by a drastic decrease (–54.8%) and a subsequent recovery. RCP 4.5 maintains moderate positive deviations until 2100, suggesting wetter autumns. RCP 8.5 initially signals a wet regime (+35–50%), but later (2071–2100) a significant decline (–36.6%), indicating high risks of post-summer drought.

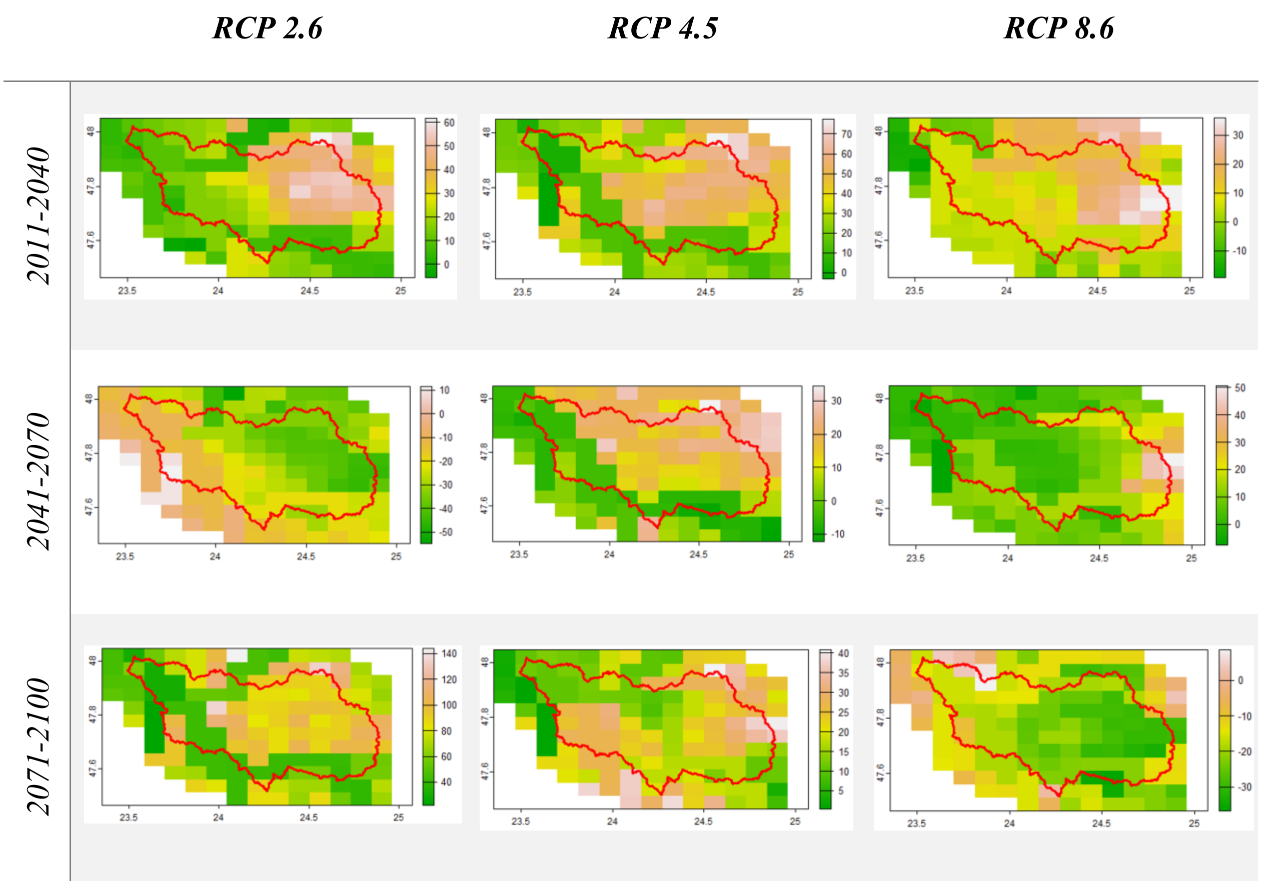


Figura 18. Valorile sezoniere ale abaterilor debitelor medii de apă - Sezonul de toamnă

Rezultatele arată o influență puternic sezonieră și diferențiată a schimbărilor climatice asupra regimului hidrologic, cu impacturi majore asupra riscurilor de inundații și secetă. Variabilitatea este mai accentuată în scenariile RCP 8.5, în timp ce RCP 2.6, deși mai stabil, nu elimină complet riscurile.

5.3.2. Combined Analysis Based on the Three Scenarios

The RCP 2.6 scenario (optimistic) indicates a relative long-term stability of river discharges in the Maramureș Depression, with moderate fluctuations especially in spring and summer (2041–

2070), characterized by a slight reduction in flows. Discharges gradually recover during the 2071–2100 period, suggesting a possible stabilization of water resources.

The RCP 4.5 scenario shows greater variability in flows, with increases during 2011–2040, followed by notable decreases in 2041–2070, particularly in winter and summer. In the 2071–2100 period, a moderate recovery is observed, but with persistent risks for extreme events.

The RCP 8.5 scenario (pessimistic) indicates extreme variability and intensification of extreme climatic phenomena. In 2011–2040, discharges increase considerably in spring and summer, followed by significant decreases towards 2071–2100, especially in autumn and summer, indicating an increased risk of drought and reduced water availability.

Comparatively, the RCP 2.6 scenario offers stability and favorable conditions for effective water resource management, while RCP 4.5 and RCP 8.5 bring uncertainty and major risks related to drought and floods, especially in warm seasons. These changes may affect agriculture, ecosystems, and water management, requiring adaptation measures in vulnerable regions..

5.4. Hydrological Projections Based on Climate Scenarios: Impact Analysis Using Projections up to 2100

Using the methodology described in subchapter "*4.2.8. Hydrological Modeling*", the anticipated changes in the hydrological regime were simulated and analyzed up to the year 2100.

This analysis was based on climate scenarios derived from Global Circulation Models (GCMs) and applied to the conceptual hydrological model NAM, developed by the Danish Hydraulic Institute (DHI).

The climate scenarios used in this study – GFDL CM2.0 SRES B1, HadCM3 SRES B1, and HadGEM1 SRES A1B – reflect various greenhouse gas emission pathways, offering the possibility to estimate the potential impact of climate change on streamflow regimes in the studied catchment areas.

This subchapter presents the results of the hydrological projections, organized by seasons and climate scenarios, and outlines the specific impact of climate change on river discharges up to the year 2100.

Unlike the model presented in chapter "*5.3 Evaluation of long-term discharge deviations*," which uses gridded datasets as data sources, the model described in this subchapter is based on input parameters extracted from data collected at hydrometric stations.

5.4.1. Initial Parameters of the NAM Model

The values of these initial parameters used in the calibration process are presented in Tables 19 and 20. These parameters are divided into three main categories: surface and root zone parameters, groundwater parameters, and initial condition parameters.

Surface and Root Zone Parameters include:

- Umax and Lmax – represent the maximum water storage capacity at the surface and in the root zone. High Lmax values, such as those for RB SH Moisei or RB SH Strâmtura, indicate a large water retention capacity in the soil, reducing rapid runoff.
- CQOF – the surface runoff coefficient. High values, such as 0.994 for RB SH Vadu Izei (Mara), suggest a high capacity for surface runoff during intense rainfall events.
- CKIF, CK1, CK2 – control the infiltration and transfer of water from the surface zone to the subsurface zones.
- TOF and TIF – indicate the moisture thresholds above which surface runoff (TOF) and interflow (TIF) are generated. High TIF values, such as 0.990 for SH Vișeul de Sus, indicate increased water retention in the soil before runoff generation.

Groundwater:

- TG and CKBF – TG is the transit time of water through the groundwater zone, while CKBF controls the rate of groundwater flow into rivers. High CKBF values for certain catchments (e.g., 3894.6 for RB SH Moisei) indicate a greater groundwater contribution to river discharge, especially during dry periods.
- U/Umax, L/Lmax – the ratio between current storage and maximum storage capacity provides information on the degree of saturation. These values help calibrate the model to reflect soil saturation.

Initial Conditions:

- QOF and QIF – the initial surface and interflow discharges are set at the start of the simulation. These values are necessary for accurately simulating the catchment response to precipitation. In our case, these initial values were set to "0".

- BF and BF-low – indicate the initial baseflows, which reflect the amount of water already present in the system at the start of the simulation.
- Snow – the initial amount of snow (in units of water volume) is important for catchments located in mountainous areas, influencing spring discharges as snow melts.

5.4.2. Results of the Hydrological Model Calibration

Before applying climate scenarios for hydrological projections up to the year 2100, it was necessary to calibrate and validate the conceptual hydrological model NAM, in order to ensure the accuracy and reliability of the simulations. The calibration was based on historical discharge data collected during the reference period 2008–2017.

The calibration process involved adjusting the parameters of the NAM model to achieve an optimal fit between the simulated and observed discharges. The calibrated parameters included infiltration, percolation, and evapotranspiration coefficients, time constants for interflow, the recharge coefficient of the lower groundwater reservoir (CQLow), time constants for surface runoff, as well as the controlled parameters of the linear reservoirs used in modeling flow and recession processes.

The calibration results indicate a variability in model performance depending on each subbasin. For example, the subbasins RB SH Vișeul de Sus and RB SH Moisei show high R^2 and NSE coefficients, indicating a good model fit, while subbasins with different altitudes and soil types, such as RB SH Ruscova and RB SH Dragomirești, show lower values of these coefficients, suggesting a high variability of local hydrological factors.

The statistical indicators used to assess the model performance were:

- *Nash–Sutcliffe Efficiency Coefficient (NSE):* Most of the analyzed basins exceeded the acceptable threshold of 0.5, indicating the model's capacity to reproduce the variability of observed discharges.
- *Coefficient of Determination (R^2):* The average R^2 value of approximately 0.61 indicates a relatively good fit between observed and simulated values. R^2 measures the proportion of variability in the observed data explained by the model, and a value around this level is considered satisfactory. However, individual R^2 values range between 0.44 and 0.76, showing that the model accuracy varies depending on the subbasin.

The analysis of the calibration results revealed that the NAM model is suitable for simulating the hydrological regime of the studied basin. The high values of NSE and R^2 indicate that the model accurately reproduces both the amplitude and the trends of the observed discharges. Thus, the NAM model succeeded in properly capturing the temporal variability and magnitude of the observed flows. The calibrated parameters reflected the specific hydrological characteristics of the studied basins and provided a solid foundation for future simulations (DHI, 2017).

Therefore, the calibrated model provides confidence in the hydrological projections carried out for the different climate scenarios and time intervals analyzed.

5.4.3. Comparative Interpretation of Climate Scenarios

The following section presents the interpretation of the hydrological projection results for the studied basin, analyzing both annual and seasonal deviations from a baseline scenario. Figure 19 graphically illustrates the discharge deviations recorded under each scenario.

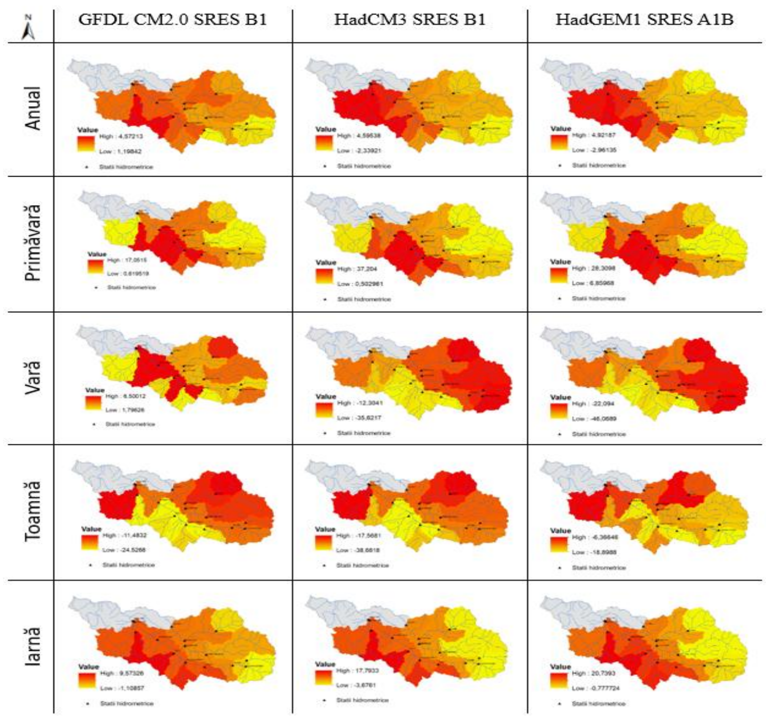


Figura 19. Differences between hydrological projection scenarios and the baseline scenario

For annual values, the following characteristics are observed:

- *Scenario GFDL CM2.0 SRES B1:* Indicates a moderate increase in discharge, with values ranging from 1.2 to 4.57, concentrated in the central and southern parts of the basin. Although mountainous areas are also affected, the risks remain moderate.

- *Scenario HadCM3 SRES B1*: The distribution shows greater variability, with discharge ranging between -2.3 and 4.6, and significant increases in the northeast and center, suggesting potential flood risks in runoff generation zones.
- *Scenario HadGEM1 SRES A1B*: The most pessimistic scenario, showing deviations between -2.96 and 4.92, with the highest discharges in the central and western parts of the basin, indicating an increased probability of extreme climatic events and hydrological risks.

From the seasonal values perspective, the following features are noted:

- *Spring:* In all scenarios, there is an increase in discharge, with maxima of 37.204 in HadCM3 and 28.3098 in HadGEM1. The central and southeastern areas become vulnerable to intense rainfall, with an increased risk of flooding.
- *Summer:* Emerges as the season with the highest risk of drought. The HadCM3 and HadGEM1 scenarios anticipate significant decreases in discharge, with minimum values of -46.068 in the HadGEM1 scenario, especially in the central basin area.
- *Autumn:* Continues the downward trend in discharge, particularly in the HadCM3 scenario (down to -38.682), with the central and southern areas being most affected. This season reflects a potential prolonged drought and increased pressure on water resources.
- *Winter:* Shows a slight recovery in discharge, especially in the HadGEM1 scenario, which suggests wetter winters and the potential for water resource replenishment in mountainous areas. However, this recovery does not compensate for the significant losses during summer and autumn.

5.5. Climate Change Adaptation Strategies in Relation to Water Resources and the Hydrological Regime

Integrating climate change impact mitigation strategies is essential for mountainous and depression areas, such as the Maramureș Depression, where runoff formation in the mountain regions contributes to the stability of the hydrological regime, especially during periods of intense precipitation and snowmelt.

According to climate projections, water resource management in this region must be adapted to seasonal variability and future climatic effects. Three main directions are emphasized:

- *Flood risk management*, especially in winter and spring seasons, according to the HadGEM1 SRES A1B scenarios, through appropriate infrastructure (levees, dams, retention areas);
- *Drought adaptation*, intensified during summer and autumn, in line with HadCM3 SRES B1 and HadGEM1 SRES A1B scenarios, through measures such as water-saving, groundwater recharge, and water storage during surplus periods;
- *Protection of mountain areas*, with a focus on reforestation and conservation, to reduce erosion and stabilize water runoff.

The analysis of historical data and climate projections (RCP 2.6, RCP 4.5, RCP 8.5) highlights the risk of a combination of drought and flash floods under moderate and pessimistic scenarios, particularly in small mountainous catchments. This extreme variability requires solutions that ensure minimum flows during dry periods and protection against sudden floods.

An effective measure is *the expansion or restoration of forested areas*, especially in runoff formation zones. Forests help regulate runoff by reducing water velocity, increasing soil retention, decreasing flood peaks, and preventing erosion. During dry periods, forests contribute to maintaining soil moisture and minimum discharge levels.

Therefore, reforestation strategies provide dual benefits: reducing flood risk and stabilizing discharge during drought periods. The study proposes a case study in the Maramureș Depression to analyze the impact of these measures on the hydrological regime, with the potential to offer a methodology applicable to decision-makers and local authorities.

5.5.1. Recommendations for Adapting to Anticipated Changes in Runoff Regime

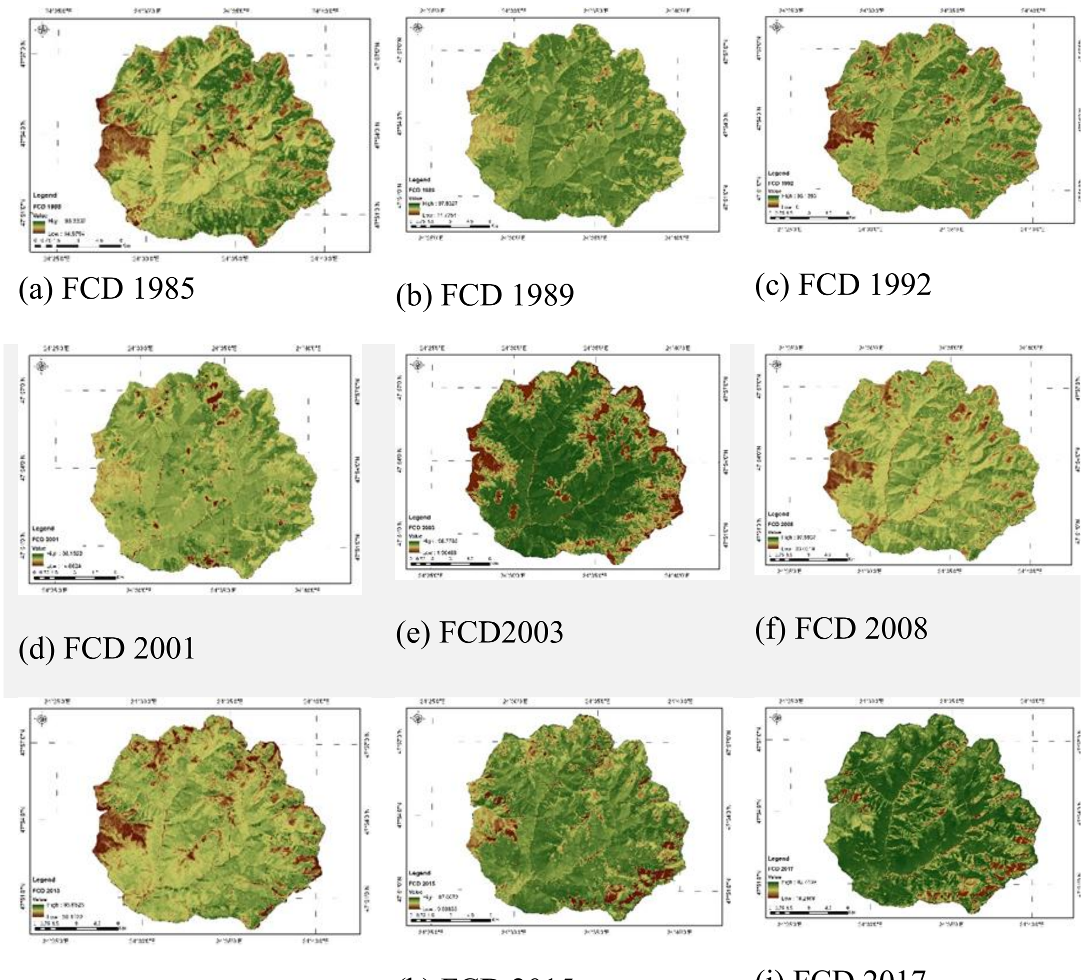
The results of the analyses highlight the significant impact of climate change on the runoff regime in the river basins within the studied area. These changes affect both the availability of water resources and the vulnerability of ecosystems and local communities. In this context, adaptation represents an important component for managing the impact of climate change and ensuring the sustainable use of water resources (FAO, 2016).

This chapter proposes a series of practical and strategic recommendations, based on the hydrological projections developed in this study. These are structured into three major categories: structural, non-structural, and green (ecological) measures.

5.6. Evaluation of the Hydrological Impact of Changing Forest Areas: A Remote Sensing-Based Case Study

5.6.1. Delineation of Forest-Covered Areas Using the FCD Index

According to the methodology described in the methods chapter, the FCD index values for the analyzed years are presented in Figure 20.



(a) FCD 1985 (b) FCD 1989 (c) FCD 1992

(d) FCD 2001 (e) FCD2003 (f) FCD 2008

(g) FCD 2013 (h) FCD 2015 (i) FCD 2017

Figura 20. FCD index extracted from satellite images (Sidau și colab, 2021)

The assessment of the accuracy of the FCD index determination method revealed discrepancies between satellite maps and 2018 orthophoto images, particularly for the years 1985 and 2015. The low kappa coefficient for 1985 reflects a larger forested area in the past, while for

2015, the differences suggest a possible underestimation of forested areas in the satellite images compared to recent orthophoto maps.

5.6.2. Impact of Changes in Forest Cover on Flood Peaks

Three scenarios were used to evaluate the impact of forest vegetation on river runoff:

The modification of forest cover values, according to scenarios S2 and S3, leads to changes in the average CN (Curve Number) values. This alteration in the average CN values results in changes in the estimated volume and discharge.

The simulation results for the three scenarios are presented in Figure 21 and Table 8. Once the model is set up and calibrated, in accordance with the methodology described in Section 2, the discharge hydrograph is analyzed for each selected event (Figure 27).

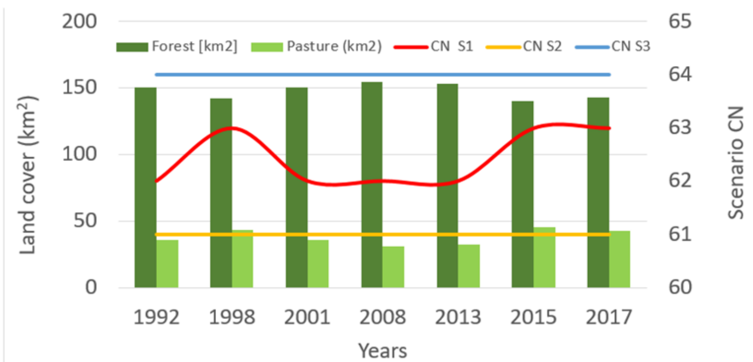


Figura 21. CN values considered for model calibration.(Sidau și colab, 2021)

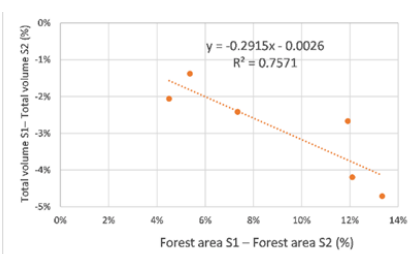
Tabel 8. Simulation results for the 3 scenarios. (Sidau și colab, 2021)

Scenario	Event Period	Total Simulated Volume [10^6 m^3]	Total Observed Volume [10^6 m^3]	Volume Difference Observed-Simulated (%)	Q Max [m^3/s] Simulated	Q Max [m^3/s] Observat	Q Difference Observed (S1) - Simulated (%)	Q Difference - Compared cu S1
S1	04.09.1992–10.09.1992	4.873	5.623	13.35%	14.245	18.6		
S2		4.758	5.623	15.39%	13.851	18.6	25.53%	−2.84%
S3		5.112	5.623	9.10%	15.070	18.6	18.97%	8.09%
S1	04.07.1998–10.07.1998	12.16	11.544	−5.35%	40.710	31.7		
S2		11.672	11.544	−1.11%	39.018	31.7	−23.09%	−4.34%
S3		12.411	11.544	−7.51%	41.567	31.7	−31.13%	6.13%
S1	17.06.2001–23.06.2001	4.182	4.637	9.81%	14.334	14.8		
S2		4.083	4.637	11.94%	13.958	14.8	5.69%	−2.70%

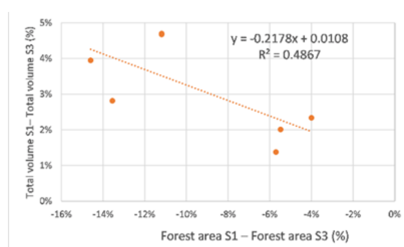
S3		4.388	4.637	5.36%	15.119	14.8	−2.16%	7.68%
S1	21.07.2008–29.07.2008	13.598	16.271	16.43%	44.685	57.6		-
S2		13.324	16.271	18.11%	43.923	57.6	23.74%	−1.74%
S3		14.157	16.271	12.99%	46.205	57.6	19.78%	3.29%
S1	10.09.2013–15.09.2013	1.227	1.176	−4.30%	5.194	3.78		
S2		1.210	1.176	−2.88%	5.079	3.78	−34.39%	−2.25%
S3		1.262	1.176	−7.32%	5.437	3.78	−43.84%	6.57%
S1	24.06.2015–27.06.2015	1.173	1.272	7.76%	7.507	6.24		
S2		1.121	1.272	11.91%	7.131	6.24	−14.28%	−5.28%
S3		1.201	1.272	5.55%	7.706	6.24	−23.51%	7.47%
S1	24.07.2017–27.07.2017	0.647	1.256	48.49%	4.490	5.659		
S2		0.630	1.256	49.83%	4.295	5.659	24.10%	−4.53%
S3		0.656	1.256	47.77%	4.594	5.659	18.82%	6.51%

The results of the simulations for the three scenarios show a significant influence of forest cover on reducing flood peaks, up to a considerable percentage of the runoff volume during flood periods. Even though the differences between forest cover values for different years on the one hand, and the values in S2 and S3 on the other, are not very large, the influence of forested areas on flood peaks is evident, ranging from -5.28% (S2) to 8.09% (S3) (Table 8).

The magnitude of this influence can also be analyzed through the correlation graph based on the differences in forest area between the three scenarios and the cumulative runoff volumes for each scenario: forest area S1 – forest area S2 compared to total volume S1 – total volume S2 (Figure 22a); forest area S1 – forest area S3 compared to total volume S1 – total volume S3 (Figure 22b).



(a) S1 comparated to S2



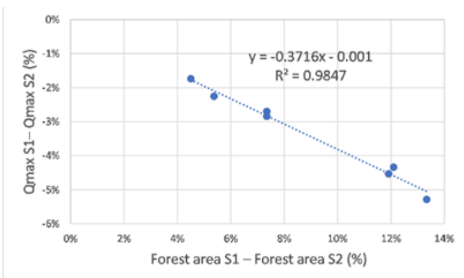
(b) S1 comparated to S3

Figura 22. Comparative analysis of the total runoff volume during the events and of the differences in forested areas between scenarios S1 with S2 and S3. (Sidau și colab, 2021)

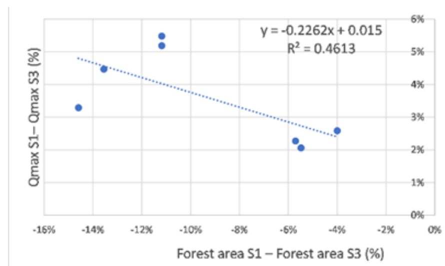
The basin's response to the increase in forested area was a reduction in the total runoff volumes for the selected event (Figure 22a). In the case of a decrease in forested area (scenario S3), the total runoff increased during the analyzed event (Figure 22b).

A similar situation was detected when the comparative analysis was performed for the peak discharge of the considered events. In this case, the analyses were conducted considering the following differences:

- The difference between forest area S1 and forest area S2 was compared to the difference between peak discharge S1 and peak discharge S2 (Figure 23a);
- The difference between forest area S1 and forest area S3 was compared to the difference between peak discharge S1 and peak discharge S3 (Figure 23b);



(a) S1 compared to S2



(b) S1 compared to S3

Figura 23. Comparative analysis of peak discharge recorded during events and differences in forested area between scenarios S1 and S2, and S3. (Sidau și colab, 2021)

A negative trend can be observed in all the presented graphs, indicating that an increase in forested area corresponds to a decrease in peak discharge, and vice versa (Fig. 22 and 23). Furthermore, the Pearson correlation coefficient R^2 in both Figures 23a and 23a (i.e., the relationship between S1 and S2) indicated a stronger correlation compared to the S1–S3 relationships (Figures 22b and 23b).

Given the similar direction of both types of relationships—S1–S2 and S1–S3—regardless of whether referring to volume or discharge, the linear regression equation of the best-fit correlation can be chosen to establish the relationship between forest area and discharge. The correlation coefficient shown in Figure 23a has the highest value; thus, it can be used as the equation for estimating the influence of forest cover on runoff::

$$y = -0.3716x - 0.001$$

Where:
y – estimated percentage of peak discharge;
x – percentage of forested area relative to the S1 reference value;

−0.3716 – slope of the regression line;
−0.001 – y-axis intercept..

The analysis highlights several methodological limitations, such as the use of low-resolution satellite imagery (30 m) for estimating forest cover and daily climate data with a spatial resolution of 0.1°, which are not ideal for small catchments. Although validation was performed using high-resolution orthophoto maps, the accuracy of the estimates could be significantly improved with more detailed data. Nevertheless, the study clearly demonstrates the role of forests in reducing flood peaks and stabilizing the hydrological regime, supporting reforestation as an effective and sustainable alternative to traditional structural measures. Since 2003, forest policies and digital monitoring tools have led to an increase in forested areas, and the FCD index derived from Landsat imagery proved useful in the absence of complete official databases. The results enabled the formulation of an equation that quantifies the influence of forest cover on peak discharge, providing a valuable tool for planning flood protection measures..

6. 6. Conclusions

The main objective of this study was to assess the impact of climate change and land use changes on the hydrological regime in the Maramureș Depression. Through the analysis of climatic variables (temperature and precipitation), the long-term evolution of streamflows, and hydrological projections based on different scenarios, valuable insights were obtained regarding how these elements interact and influence the region's water resources.

The analysis of climatic variables revealed a significant and consistent increase in annual average temperatures in all studied locations (Moisei, Săcel, Vadu Izei, and Bistra). The applied statistical tests, such as Sen's Slope and the Mann-Kendall test, confirmed the upward trend in temperatures, with very low p-values, indicating strong statistical significance. This temperature increase is consistent with global warming trends and suggests clear climatic changes in the area.

In contrast to temperature, precipitation did not show a clear statistically significant increasing or decreasing trend. Sen's Slope test indicated zero slopes in all locations, suggesting relative stability in annual precipitation amounts. However, the Mann-Kendall test revealed a slight downward trend in some locations, indicating possible gradual decreases in long-term precipitation.

The discharge analysis showed a significant increase in most studied locations. Statistical tests confirmed upward trends in streamflows, especially in Moisei and Bistra, where the most significant increases were recorded. This increase in streamflow may be associated with rising temperatures, which influence processes such as snowmelt and evaporation, thereby altering the hydrological regime.

Using outputs from **climate and hydrological models**, the situation was analyzed through to the year 2100 under various emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). The results highlighted the following:

- RCP 2.6 (optimistic scenario): Streamflows show relative stability, with moderate fluctuations. However, there are periods, such as 2041–2070, where a slight reduction in discharge is observed, possibly due to decreased precipitation or increased evaporation.
- RCP 4.5 (intermediate scenario): A greater variability in streamflows is observed, with increases in some seasons and decreases in others. The risk of drought in certain seasons and floods in others becomes more pronounced.
- RCP 8.5 (pessimistic scenario): An intensification of extreme events is anticipated, with significant increases in streamflows during some seasons and sharp decreases in others. This scenario suggests a heightened risk of floods and severe droughts, affecting water resources and ecosystems.

Hydrological modeling based on climate scenarios projected to 2100 highlighted potential changes in the hydrological regime of the studied basins, indicating increased seasonal variability and associated flood and drought risks.

In the high-risk scenario (e.g., HadGEM1 SRES A1B), spring and winter are critical flood seasons, requiring protective infrastructure such as levees and retention areas.

Summer and autumn are critical for drought, requiring water-saving and storage measures, groundwater resource restoration, and efficient water use planning.

Mountain areas are extremely important for maintaining hydrological balance. Reforestation and their conservation will contribute to stabilizing water flows and reducing erosion risk during critical periods.

Regarding the impact of forest cover changes, the study highlighted that changes in forest areas have a significant impact on the hydrological regime:

- Increase in forested areas: Leads to a reduction in total runoff volume and peak streamflows during floods. Forests act as a buffer, absorbing and retaining water, increasing surface roughness and reducing water flow velocity, thereby decreasing flood risk.
- Decrease in forested areas: Leads to an increase in runoff volume and peak flows, amplifying the risk of floods and soil erosion.

The use of remote sensing for monitoring forest cover has proven effective, enabling rapid and accurate assessment of land use changes.

The results of this study have significant implications for water resource management in the Maramureș Depression:

- Need for strategic adaptation: Rising temperatures and flow variability require the development of adaptation strategies in water management to address both water surpluses and deficits.
- Importance of forest conservation and expansion: Forests play a key role in attenuating flood peaks and maintaining hydrological balance. Promoting reforestation and preventing illegal logging are useful methods for flood prevention and reducing peak streamflows.
- Integrated planning: A holistic approach is necessary, integrating water, land, and ecosystem management to reduce vulnerability to climate change.

Reference

1. Administrația Națională "Apele Române". (2005). Ordinul nr. 1276 din 14 decembrie 2005 privind aprobarea "Metodologiei de organizare, păstrare și gestionare a Cadastrului apelor din România". Disponibil la: https://legislatie.just.ro/Public/DetaliiDocumentAfis/67640
2. Administrația Națională de Meteorologie. (2008). *Clima României*. Editura Academiei Române.
3. ARNELL, N. (1999). Climate change and global water resources. *Global Environmental Change*, *9*, S31–S49. https://doi.org/10.1016/S0959-3780(99)00017-5
4. Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, *14*(1), 31–52. https://doi.org/10.1016/j.gloenvcha.2003.10.006
5. Arnell, N. W., & Gosling, S. N. (2013). The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology*, *486*, 351–364. https://doi.org/10.1016/j.jhydrol.2013.02.010
6. Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (2008). *Climate Change and Water*. Technical Paper VI. Intergovernmental Panel on Climate Change (IPCC)
7. Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H. G., & Lindborg, R. (2019). Grasslands—more important for ecosystem services than you might think. *Ecosphere*, *10*(2). https://doi.org/10.1002/ecs2.2582
8. Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., & Woth, K. (2007). Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change*, *81*(S1), 71–95. https://doi.org/10.1007/s10584-006-9226-z
9. Beven, K. (2012). *Rainfall-Runoff Modelling*. Wiley. https://doi.org/10.1002/9781119951001
10. Birsan, M.-V. (2017). *Variabilitatea regimului natural al râurilor din România.* Editura ARS DOCENDI. https://www.researchgate.net/publication/318986963_Variabilitatea_regimului_natural_al_raurilor_din_Romania
11. Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., … Živković, N. (2019). Changing climate both increases and decreases European river floods. *Nature*, *573*(7772), 108–111. https://doi.org/10.1038/s41586-019-1495-6
12. Boehm, S., Jeffery, L., Hecke, J., Schumer, C., Jaeger, J., Fyson, C., Levin, K., Nilsson, A., Naimoli, S., Daly, E., Thwaites, J., Lebling, K., Waite, R., Collis, J., Sims, M., Singh, N., Grier, E., Lamb, W., Castellanos, S., … Masterson, M. (2023). State of Climate Action 2023. In *World Resources Institute*. https://doi.org/10.46830/wrirpt.23.00010
13. Bojariu, R., Bîrsan, M.-V., Cică, R., Velea, L., Burcea, S., Dumitrescu, A., Dascălu, S. I., Gothard, M., Dobrinescu, A., Cărbunaru, F., & Marin, L. (2015). *Schimbările climatice – de la bazele fizice la riscuri și adaptare* (Administrația Națională de Meteorologie, Ed.). Editura Printech.

14. Buckley, B. M., Anchukaitis, K. J., Penny, D., Fletcher, R., Cook, E. R., Sano, M., Nam, L. C., Wichienkeeo, A., Minh, T. T., & Hong, T. M. (2010). Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences*, *107*(15), 6748–6752. https://doi.org/10.1073/pnas.0910827107
15. Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* https://doi.org/10.59327/IPCC/AR6-9789291691647
16. Chendeş, Viorel (2011). *Resursele de Apă Din Subcarpaţii de la Curbură. Evaluări Geospaţiale*. Academia Română.
17. Chendeş Viorel, Corbus, C., Bojariu, R., Borcan, M., Matreata, M., & Matreata, M. (2024). Scenarii privind schimbările climatice și impactul asupra resurselor de apă. *Hidrotehnica*, *69*, 41–52.
18. Coles, S. (2001). *An Introduction to Statistical Modeling of Extreme Values*. Springer London. https://doi.org/10.1007/978-1-4471-3675-0
19. Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Hinton, T. J., Jones, C. D., Liddicoat, S., Gill M. Martin, O'Connor, F. M., Rae, J. G. L., Senior, C. A., Totterdell, I. J., Woodward, S., & Reichler, T. (2008). *Evaluation of the HadGEM 2 model*. https://www.inscc.utah.edu/~reichler/publications/papers/Collins_08_MetOffice_74.pdf
20. Copernicus Climate Data Store. (n.d.). *Copernicus Climate Data Store (CDS).* . Retrieved 1 March 2025, from https://cds.climate.copernicus.eu/
21. Copernicus Climate Change Service. (2023). *Copernicus Climate Change Service.* . https://climate.copernicus.eu/
22. Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of Geophysical Research: Atmospheres*, *123*(17), 9391–9409. https://doi.org/10.1029/2017JD028200
23. Croitoru, A. E., Piticar, A., Sfîcă, L., Roșca, C.-F., Tudose, T., Horvath, C., Minea, I., Ciupertea, A.-F., Scripcă, S., & Harpa, G. V. (2018). *Extreme temperature and precipitation events in Romania*. The Publishing House of the Romanian Academy. https://www.researchgate.net/publication/352226549_Extreme_Temperature_and_Precipitation_Events_in_Romania
24. Croitoru, A.-E., Chiotoroiu, B.-C., Ivanova Todorova, V., & Torică, V. (2013). Changes in precipitation extremes on the Black Sea Western Coast. *Global and Planetary Change*, *102*, 10–19. https://doi.org/10.1016/j.gloplacha.2013.01.004
25. Croitoru, A.-E., Drignei, D., Holobaca, I.-H., & Dragota, C. S. (2012). Change-point analysis for serially correlated summit temperatures in the Romanian Carpathians. *Theoretical and Applied Climatology*, *108*(1–2), 9–18. https://doi.org/10.1007/s00704-011-0508-7
26. Croitoru, A.-E., & Minea, I. (2015). The impact of climate changes on rivers discharge in Eastern Romania. *Theoretical and Applied Climatology*, *120*(3–4), 563–573. https://doi.org/10.1007/s00704-014-1194-z

27. Cuculeanu, V., Tuinea, P., & Bălteanu, D. (2002). Climate Change Impacts in Romania: Vulnerability and Adaptation Options. *GeoJournal* , *57*(3), 203–209. https://www.jstor.org/stable/41147721
28. Daniel S. Wilks. (2019). *Statistical Methods in the Atmospheric Sciences*. Elsevier. https://doi.org/10.1016/C2017-0-03921-6
29. DHI. (2017). *MIKE SHE User Manual*. Danish Hydraulic Institute.
30. Douglas C. Montgomery, Elizabeth A. Peck, & G. Geoffrey Vining. (2012). *Introduction to Linear Regression Analysis* (Fourth Edition). Wiley.
31. Drăgoi, M., & Toza, V. (2019). Did Forestland Restitution Facilitate Institutional Amnesia? Some Evidence from Romanian Forest Policy. *Land*, *8*(6), 99. https://doi.org/10.3390/land8060099
32. Draper, N. R., & Smith, H. (1998). *Applied Regression Analysis*. Wiley. https://doi.org/10.1002/9781118625590
33. Dumitrescu, A., & Birsan, M.-V. (2015). ROCADA: a gridded daily climatic dataset over Romania (1961–2013) for nine meteorological variables. *Natural Hazards*, *78*(2), 1045–1063. https://doi.org/10.1007/s11069-015-1757-z
34. Ellison, D., N. Futter, M., & Bishop, K. (2012). On the forest cover–water yield debate: from demand- to supply-side thinking. *Global Change Biology*, *18*(3), 806–820. https://doi.org/10.1111/j.1365-2486.2011.02589.x
35. European Commission. (2013). *An EU Strategy on adaptation to climate change*. https://climate.ec.europa.eu/system/files/2016-11/eu_strategy_en.pdf
36. European Environment Agency (EEA). (2019). *CORINE Land Cover 2018 – European land cover dataset*. European Environment Agency. https://climate.ec.europa.eu/system/files/2016-11/eu_strategy_en.pdf
37. FAO. (2016). *Forests and Climate Change: A Synthesis Report.* . https://openknowledge.fao.org/server/api/core/bitstreams/2a65d0eb-e782-464d-91cd-f9de198f4c53/content
38. Fischer, E. M., & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, *5*(6), 560–564. https://doi.org/10.1038/nclimate2617
39. Fowler, H. J., Blenkinsop, S., & Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology*, *27*(12), 1547–1578. https://doi.org/10.1002/joc.1556
40. Freedman, D., Pisani, R., & Purves, R. (2007). *Statistics* (Fourth edition). W. W. Norton & Company.
41. Geoportal ANCPI. Retrieved 1 March 2025, from https://geoportal.ancpi.ro/portal/
42. Ghinea, D. (2002). *Enciclopedia geografică a României* (3rd ed.). Editura Enciclopedică.
43. Global Water Partnership. (2009). *Integrated Water Resources Management.* https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04.-integrated-water-resources-management-rumanian.pdf
44. Gomes, L. C., Bianchi, F. J. J. A., Cardoso, I. M., Schulte, R. P. O., Fernandes, R. B. A., & Fernandes-Filho, E. I. (2021). Disentangling the historic and future impacts of land use changes and climate variability on the hydrology of a mountain region in Brazil. *Journal of Hydrology*, *594*, 125650. https://doi.org/10.1016/j.jhydrol.2020.125650
45. Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., & Wood, R. A. (2000). The simulation of SST, sea ice extents and ocean heat

transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, *16*(2–3), 147–168. https://doi.org/10.1007/s003820050010
46. Graham, L. P., Andréasson, J., & Carlsson, B. (2007). Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods – a case study on the Lule River basin. *Climatic Change*, *81*(S1), 293–307. https://doi.org/10.1007/s10584-006-9215-2
47. Haug, G. H., Günther, D., Peterson, L. C., Sigman, D. M., Hughen, K. A., & Aeschlimann, B. (2003). Climate and the Collapse of Maya Civilization. *Science*, *299*(5613), 1731–1735. https://doi.org/10.1126/science.1080444
48. Hay, L. E., Clark, M. P., Wilby, R. L., Gutowski, W. J., Leavesley, G. H., Pan, Z., Arritt, R. W., & Takle, E. S. (2002). Use of Regional Climate Model Output for Hydrologic Simulations. *Journal of Hydrometeorology*, *3*(5), 571–590. https://doi.org/10.1175/1525-7541(2002)003<0571:UORCMO>2.0.CO;2
49. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803
50. Hirsch, R. M., Slack, J. R., & Smith, R. A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research*, *18*(1), 107–121. https://doi.org/10.1029/WR018i001p00107
51. Hundecha, Y., Parajka, J., & Viglione, A. (2020). Assessment of past flood changes across Europe based on flood-generating processes. *Hydrological Sciences Journal*, *65*(11), 1830–1847. https://doi.org/10.1080/02626667.2020.1782413
52. IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/
53. IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar5/wg1/
54. IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. https://www.ipcc.ch/report/ar5/wg2/
55. IPCC. (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability*. Cambridge University Press. https://doi.org/10.1017/9781009325844
56. Jennings, S. (1999). Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. *Forestry*, *72*(1), 59–74. https://doi.org/10.1093/forestry/72.1.59
57. Johns, T. C., Durman, C. F., Banks, H. T., Roberts, M. J., McLaren, A. J., Ridley, J. K., Senior, C. A., Williams, K. D., Jones, A., Rickard, G. J., Cusack, S., Ingram, W. J., Crucifix, M., Sexton, D. M. H., Joshi, M. M., Dong, B.-W., Spencer, H., Hill, R. S. R., Gregory, J. M., … Searl, Y. (2006). The New Hadley Centre Climate Model (HadGEM1): Evaluation of Coupled Simulations. *Journal of Climate*, *19*(7), 1327–1353. https://doi.org/10.1175/JCLI3712.1
58. Jones, P. D., Lister, D. H., Osborn, T. J., Harpham, C., Salmon, M., & Morice, C. P. (2012). Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research: Atmospheres*, *117*(D5). https://doi.org/10.1029/2011JD017139

59. JRC. (2013). CARPATCLIM. In *CARPATCLIM Database © European Commission - JRC, 2013* .
60. Kiprotich, P., Wei, X., Zhang, Z., Ngigi, T., Qiu, F., & Wang, L. (2021). Assessing the Impact of Land Use and Climate Change on Surface Runoff Response Using Gridded Observations and SWAT+. *Hydrology*, *8*(1), 48. https://doi.org/10.3390/hydrology8010048
61. Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., … Petrovic, P. (2002). Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology*, *22*(12), 1441–1453. https://doi.org/10.1002/joc.773
62. Klemes, V. (1986). Operational testing of hydrological simulation models. *Hydrological Sciences Journal*, *31*(1), 13–24. https://doi.org/10.1080/02626668609491024
63. Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., & Meehl, G. A. (2010). Challenges in Combining Projections from Multiple Climate Models. *Journal of Climate*, *23*(10), 2739–2758. https://doi.org/10.1175/2009JCLI3361.1
64. Kocsis, I., Haidu, I., & Maier, N. (2020). *Application of a Hydrological MIKE HYDRO River – UHM Model for Valea Rea River (Romania). Case Study, Flash Flood Event Occurred on August 1st, 2019.* 257–272. https://doi.org/10.24193/AWC2020_24
65. Kumar, V., Jain, S. K., & Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal*, *55*(4), 484–496. https://doi.org/10.1080/02626667.2010.481373
66. Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, *59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411
67. Legea nr. 107 din 25 septembrie 1996 privind Legea Apelor, republicată în Monitorul Oficial al României, Partea I, nr. 244 din 26 martie 2006.
68. Loi, D. T., Chou, T.-Y., & Fang, Y.-M. (2017). Integration of GIS and Remote Sensing for Evaluating Forest Canopy Density Index in Thai Nguyen Province, Vietnam. *International Journal of Environmental Science and Development*, *8*(8), 539–542. https://doi.org/10.18178/ijesd.2017.8.8.1012
69. Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187
70. Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themeßl, M., Venema, V. K. C., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M., & Thiele-Eich, I. (2010). Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. *Reviews of Geophysics*, *48*(3), RG3003. https://doi.org/10.1029/2009RG000314
71. Massey, F. J. (1951). The Kolmogorov-Smirnov Test for Goodness of Fit. *Journal of the American Statistical Association*, *46*(253), 68–78. https://doi.org/10.1080/01621459.1951.10500769
72. Maurice G. Kendall. (1970). *Rank correlation methods* (4th ed.). Griffin.

73. McHugh, M. L. (2012). Interrater reliability: the kappa statistic. *Biochemia Medica*, 276–282. https://doi.org/10.11613/BM.2012.031
74. *Meteomanz*. Retrieved 1 March 2025, from www.meteomanz.com
75. Mic, R.-P., & Corbus, C. (2013, June 20). *Climatic Change Impact on the Mean Monthly and Annual Discharge of Some River and Theirs Tributaries*. https://doi.org/10.5593/SGEM2013/BC3/S12.008
76. Micu, D. M., Amihaesei, V. A., Milian, N., & Cheval, S. (2021). Recent changes in temperature and precipitation indices in the Southern Carpathians, Romania (1961–2018). *Theoretical and Applied Climatology*, *144*(1–2), 691–710. https://doi.org/10.1007/s00704-021-03560-w
77. Mihai, B.-A. (2007). *Remote Sensing. Introduction to Digital Image Processing (in Romanian—Teledetectie. Vol 1. Procesarea Digitala a Imaginilor)*. Edit. Universitatii din Bucuresti.
78. Minea, I. (2020). *The Vulnerability of Water Resources from Eastern Romania to Anthropic Impact and Climate Change* (pp. 229–250). https://doi.org/10.1007/978-3-030-22320-5_7
79. Ministerul Mediului si Schimbarilor Climatice. (2013). *Strategia națională a României privind schimbările climatice 2013-2020.*
80. Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885–900. https://doi.org/10.13031/2013.23153
81. Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., & Martius, O. (2021). River runoff in Switzerland in a changing climate – runoff regime changes and their time of emergence. *Hydrology and Earth System Sciences*, *25*(6), 3071–3086. https://doi.org/10.5194/hess-25-3071-2021
82. Mutihac, V., & Stratulat, M. (2007). *Geologia României*. Editura Tehnică.
83. NASA. (2020). *Earth Observing System Data and Information System* . https://www.earthdata.nasa.gov/about/esdis/eosdis
84. NASA. (2021). *Global Climate Change: Vital Signs of the Planet*. https://science.nasa.gov/climate-change/
85. NASA. (2022). *Applied Sciences Program: Water Resources*. https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset/arset-water-resources-trainings
86. Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6
87. Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and Water Assessment Tool Theoretical Documentation: Version 2009*. https://swat.tamu.edu/media/99192/swat2009-theory.pdf
88. NOAA. (2020). *National Weather Service: Hydrologic Information Center*. https://www.weather.gov/water
89. NOAA. (2021). *Climate Prediction Center: Monitoring and Data*. https://www.cpc.ncep.noaa.gov/products/monitoring_and_data
90. NOAA. (2022). *Regional Climate Centers: Climate Data and Services*. https://www.ncdc.noaa.gov/customer-support/partnerships/regional-climate-centers

91. Patriche, C. V. (2009). *Metode statistice aplicate în climatologie*. Terra Nostra. https://www.researchgate.net/publication/261239671_Metode_statistice_aplicate_in_climatologie
92. Pearson, K. (1895). Note on Regression and Inheritance in the Case of Two Parents. *Proceedings of the Royal Society of London*, *58*, 240–242. http://www.jstor.org/stable/115794
93. Pielke Sr., R. A., Adegoke, J., Beltrán-Przekurat, A., Hiemstra, C. A., Lin, J., Nair, U. S., Niyogi, D., & Nobis, T. E. (2007). An overview of regional land-use and land-cover impacts on rainfall. *Tellus B: Chemical and Physical Meteorology*, *59*(3), 587. https://doi.org/10.1111/j.1600-0889.2007.00251.x
94. Posea, G. (1974). *Geografia Fizică a României*. Editura Științifică.
95. Randall, D. A. , Wood, R. A., Bony, S., Colman, R., Fichefet, T., & et. al. (2007). Cilmate Models and Their Evaluation. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & Miller H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
96. Refsgaard, J. C., & Knudsen, J. (1996). Operational Validation and Intercomparison of Different Types of Hydrological Models. *Water Resources Research*, *32*(7), 2189–2202. https://doi.org/10.1029/96WR00896
97. Rikimaru, A. (1999). *The Concept of FCD Mapping Model and Semi-Expert System. FCD Mapper User's Guide*.
98. Rikimaru, A., Roy, P. S., & Miyatake, S. (2002). Tropical forest cover density mapping. *Tropical Ecology*, *43*, 39–47.
99. Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2007). *Global Sensitivity Analysis. The Primer*. Wiley. https://doi.org/10.1002/9780470725184
100. Sandu, I., Mateescu, E., & Vătămanu, V. V. (2010). *Schimbări Climatice în România şi efectele asupra agriculturii*. Sitech.
101. Schär, C., Frei, C., Lüthi, D., & Davies, H. C. (1996). Surrogate climate-change scenarios for regional climate models. *Geophysical Research Letters*, *23*(6), 669–672. https://doi.org/10.1029/96GL00265
102. Secci, D., Tanda, M. G., D'Oria, M., Todaro, V., & Fagandini, C. (2021). Impacts of climate change on groundwater droughts by means of standardized indices and regional climate models. *Journal of Hydrology*, *603*, 127154. https://doi.org/10.1016/j.jhydrol.2021.127154
103. Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934
104. Şen, Z. (2012). Innovative Trend Analysis Methodology. *Journal of Hydrologic Engineering*, *17*(9), 1042–1046. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000556
105. Sidău, M. R., Croitoru, A.-E., & Alexandru, D.-E. (2021). Comparative Analysis between Daily Extreme Temperature and Precipitation Values Derived from Observations and Gridded Datasets in North-Western Romania. *Atmosphere*, *12*(3), 361. https://doi.org/10.3390/atmos12030361
106. Sidău, M. R., Horváth, C., Cheveresan, M., Șandric, I., & Stoica, F. (2021). Assessing Hydrological Impact of Forested Area Change: A Remote Sensing Case Study. *Atmosphere*, *12*(7), 817. https://doi.org/10.3390/atmos12070817

107. Singh, V. P., & Woolhiser, D. A. (2002). Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering*, *7*(4), 270–292. https://doi.org/10.1061/(ASCE)1084-0699(2002)7:4(270)
108. Soil Conservation Service. (1972). *National Engineering Handbook, Section 4, Hydrology*. Department of Agriculture.
109. Sokal, R. R., & Rohlf, F. J. (1995). *Biometry: The Principles and Practices of Statistics in Biological Research* (Third (3rd) Edition). W.H. Freeman and Co.
110. Steimke, A., Flores, A., Han, B., Brandt, J., & Som Castellano, R. (2017). Modeled impacts of climate change on regional hydrology in the Upper Boise River Basin, Idaho. In *Boise State Data Sets*. The Lab for Ecohydrology and Alternative Futuring. https://doi.org/10.18122/B2LEAFD002
111. Szentimrey, T. (2011). *Manual of homogenization software MASHv3.03.* . Hungarian Meteorological Service.
112. Szentimrey T., & Bihari Z. (2005). *Manual of interpolation software MISHv1.01*. Hungarian Meteorological Service.
113. Tabari, H., & Hosseinzadeh Talaee, P. (2011). Analysis of trends in temperature data in arid and semi-arid regions of Iran. *Global and Planetary Change*, *79*(1–2), 1–10. https://doi.org/10.1016/j.gloplacha.2011.07.008
114. Tang, J., Niu, X., Wang, S., Gao, H., Wang, X., & Wu, J. (2016). Statistical downscaling and dynamical downscaling of regional climate in China: Present climate evaluations and future climate projections. *Journal of Geophysical Research: Atmospheres*, *121*(5), 2110–2129. https://doi.org/10.1002/2015JD023977
115. Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research: Atmospheres*, *106*(D7), 7183–7192. https://doi.org/10.1029/2000JD900719
116. Teutschbein, C., & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, *456–457*, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052
117. Truong, N. C. Q., Nguyen, H. Q., & Kondoh, A. (2018). Land Use and Land Cover Changes and Their Effect on the Flow Regime in the Upstream Dong Nai River Basin, Vietnam. *Water*, *10*(9), 1206. https://doi.org/10.3390/w10091206
118. UNEP. (2018). *The Adaptation Gap Report 2018.* . https://www.unep.org/resources/adaptation-gap-report-2018
119. UNEP. (2021). *Annual Report - Making peace with Nature*.
120. UNESCO World Water Assessment Programme. (2019). *The United Nations world water development report 2019: leaving no one behind*. https://unesdoc.unesco.org/ark:/48223/pf0000367306
121. United Nations Development Programme (UNDP). (2010). *Designing climate change adaptation initiatives: A UNDP toolkit for practitioners.* . https://sustainabledevelopment.un.org/content/documents/951013_Toolkit%20for%20Designing%20Climate%20Change%20Adaptation%20Initiatives.pdf
122. USGS. (n.d.). *Global Visualization Viewer (GloVis)*. Retrieved 1 March 2025, from https://glovis.usgs.gov/
123. van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration

pathways: an overview. *Climatic Change*, *109*(1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

124. Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., & Woods, R. (2011). Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, *15*(2), 471–504. https://doi.org/10.5194/hess-15-471-2011
125. Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., & Curnow, A. (1993). The Genesis and Collapse of Third Millennium North Mesopotamian Civilization. *Science*, *261*(5124), 995–1004. https://doi.org/10.1126/science.261.5124.995
126. Wilby, R. L., & Dawson, C. W. (2013). The Statistical DownScaling Model: insights from one decade of application. *International Journal of Climatology*, *33*(7), 1707–1719. https://doi.org/10.1002/joc.3544
127. William J. Mitsch, & James G. Gosselink. (2015). *Wetlands, 5th Edition* (5th Edition). John Wiley & Sons.
128. World Bank. (2013). *Evaluarea rapidă a resurselor integrate de apă*. https://documents1.worldbank.org/curated/pt/371451468296128229/pdf/842640ROMANIAN0ment0FINAL0ro0Mar03.pdf
129. World Meteorological Organization. (2017). *Integrating flood risks in development strategies for water resources management*.
130. Yeste, P., Rosa-Cánovas, J. J., Romero-Jiménez, E., Ojeda, M. G.-V., Gámiz-Fortis, S. R., Castro-Díez, Y., & Esteban-Parra, M. J. (2024). *Projected hydrologic changes over the north of the Iberian Peninsula using a Euro-CORDEX multi-model ensemble*. https://doi.org/10.1016/j.scitotenv.2021.146126
131. Zaharia, L., Perju, R., & Ioana-Toroimac, G. (2018). *Climate Changes and Effects on River Flow in The Romanian Carpathians*. 211–218. https://doi.org/10.24193/AWC2018_25