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CLIMATIC TRENDS AND CLASSIFICATION SHIFTS IN THE MAT RIVER BASIN IN ALBANIA, BASED ON THE KÖPPEN- GEIGER AND KÖPPEN-TREWARTHA CLIMATE CLASSIFICATION

Albana HASIMI [1*], Elvin ÇOMO [1], Gazmir ÇELA [1], Entela VAKO [2], Amarildo SHALLAS [1], Mirela DVORANI [2], Anira GJONI [2] & Blerina PAPAJANI [3]

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ABSTRACT

The Mati River flows in the centre of the northern geographical region of the Republic of Albania. From a climatic perspective, this region exhibits significant variability in temperature and precipitation, influenced by its diverse topography, with altitudes ranging from 1,800 meters above sea level to sea level at the estuary. The operation of multiple hydroelectric power plants along the Mati River underscores the significance of this study, as precipitation variability directly influences hydropower generation and, consequently, Albania's energy sector. On the other hand, the occurrence of extreme temperatures in this region directly impacts the quality of life, agricultural productivity, and the agro-industrial sector. Also, the presence of old mining dumps, along with the region's geological formation, which is known to be mineral-rich, explains the occurrence of heavy metals in the river's water. Climatic conditions directly influence the concentration of these pollutants, making this a key reason for undertaking this study. The comparative analysis of climatic data across seven meteorological stations within the Mat River Basin indicates a consistent and measurable warming trend, accompanied by spatially variable precipitation changes over the past three decades. The evolution of the Köppen Climate Classification (KCC) and Köppen -Trewartha Climate Classification (KTC) further supports an ongoing transition toward warmer and, in some cases, drier climatic regimes across the basin.

Keywords: *Climate data; Köppen climate classification; Köppen – Trewartha; Climatic shifts classification; Mati River basin.*

1. INTRODUCTION

Climate monitoring is mostly based either directly on station measurements of climate characteristics (surface air temperature, precipitation, cloud cover, etc.), or on some post-processed form of those measurements, such as gridded datasets. The analysis of climate patterns can be performed for each individual climate variable separately, or the data can be aggregated, for example, by using some kind of climate classification that integrates several climate characteristics (Belda et al., 2014). Climate, defined as a comprehensive statistical description of climatic conditions over a sufficiently long period at a wide range of temporal scales (D. Chen & Chen, 2013), is one of the most critical determinants of Earth's ecosystems (H. Chen et al., 2013; Schröter et al., 2005). Controlled by the dominant climatic conditions and prevailing vegetation formations, major ecosystems are distributed on land in a predictable pattern. Major ecosystem regions are largely defined based on the climate zones following the Köppen climate classification system (Köppen, 1931). This land climate classification can incorporate the amplitude and seasonal phase of temperature and precipitation

[1]*Department of Meteorology, Institute of Geosciences, Polytechnic University of Tirana, Albania.*
[*] *Corresponding author (AH) a.hasimi@geo.edu.al; (EC) e.como@geo.edu.al; (GC) g.cela@geo.edu.al; (AS) a.shallas@geo.edu.al, (AG) a.gjoni@geo.edu.al.*
[2] *Department of Hydrology, Institute of Geosciences, Polytechnic University of Tirana, Albania. (EV) e.vako@geo.edu.al; (MD) m.dvorani@geo.edu.al.*
[3]*Department of Physics, Faculty of Natural Science, University "Aleksander Xhuvani" of Elbasan, Albania. (BP) b.papajani@uniel.edu.al.*

annual cycles. It is a highly effective means to simplify spatial variability and aggregate climate gradients into simple but ecologically meaningful classes(C. Beck et al., 2005; H. E. Beck et al., 2018; Haidu, 2006).

Climatic classifications also represent a convenient tool for the validation of climate models and for the analysis of simulated future climate changes(Wang et al., 2023). Basic concepts are presented by applying climate classification to the global Climate Research Unit (CRU) TS 3.1 global dataset. We focus on definitions of climate types according to the Köppen-Trewartha climate classification (KTC) with special attention given to the distinction between wet and dry climates (Xin, 2023). The distribution of KTC types is compared with the original Köppen classification (KCC) for the period 1961−1990. In addition, we provide an analysis of the time development of the distribution of KTC types throughout the 20th century. There are observable changes identified in some subtypes, especially semi-arid, savanna and tundra (Belda et al., 2014). Global climate classifications were originally constructed in order to designate the manifold existing local climates to an adequate number of climate types and to determine the spatial distribution of these types on the basis of climatic data for a reference period. Thus, climate classifications are introduced in order to reflect the mean spatial climate characteristics. However, the underlying climate variables are subject to temporal variations and so are the results of climate classifications(C. Beck et al., 2005; Haidu et al., 2024).

Hydrographically, the Mati River Basin features a highly integrated network of watercourses, with increased density in its middle and lower sections, where ultrabasic lithological formations predominate. The presence of diverse lentic and lotic water bodies further enhances the basin's hydrological complexity, making it a significant subject for scientific investigation (Group of authors, 1984; Pano, 2008), (Grontmij et al., 2010; Magyari-Sáska & Magyari-Sáska, 2023).

1.1. Albania's Climate

According to the Albanian clime classification such as the Köppen Classification Albania's Climate primarily falls under the Csa – Hot-Summer Mediterranean Climate and, in some higher-altitude areas, the Csb – Warm-Summer Mediterranean Climate (H. E. Beck et al., 2018; Group of authors, 1985).

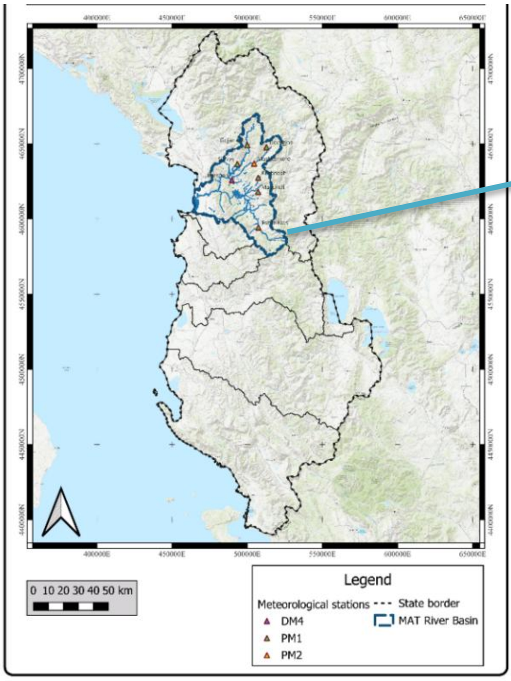
Csa – Hot-Summer Mediterranean Climate found in most coastal and lowland areas, including Tirana, Durrës, Vlorë, and Saranda. Summers are hot and dry, with temperatures often exceeding 30.0°C (86°F). Winters are mild and wet, with temperatures usually staying above 0.0°C (32°F). Annual precipitation is moderate, mostly occurring in the cooler months.

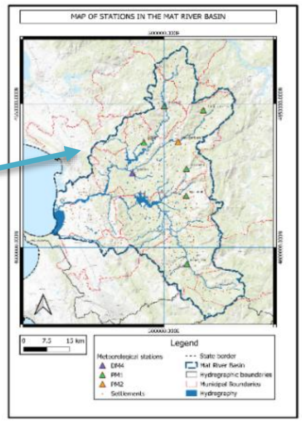
Csb – Warm-Summer Mediterranean Climate found in hilly and mountainous regions, such as Pogradec, parts of Korçë, and the Northern Highlands. Summers are cooler than in the lowlands, with temperatures usually staying below 30.0°C (86°F). Winters are wetter and mild, but snowfall is more common in elevated areas.

In the Albanian Alps and other high-altitude regions, there are some influences of the Dfb – Humid Continental Climate, characterized by cold, snowy winters and cool summers.

2. STUDY AREA

Based on the geographical classification of Albania, the Mat River basin belongs to the North Central Highlands (**Fig. 1**). This basin is characterized by a geographical diversity both in terms of relief and because it includes a range of altitudes, starting from 1800 m above sea level to 0 m at the mouth. From a climatic point of view, these areas are characterized by a variety of temperatures and precipitation. According the Albanian Climate classification the Mat River basin belongs to Mediterranean climate with continental tendencies and other high-altitude regions, there are some influences of the Dfb – Humid Continental Climate, characterized by cold, snowy winters (H. E. Beck et al., 2018; Group, 1985). From the entire database, the most representative and complete stations were selected, ensuring that the entire basin was covered with information regarding the typology of observations and the relief, so that all microclimates of the study area were represented. The selected meteorological stations are marked on the map shown in **Fig. 1** where the coordinates are also presented.





	Altitude	Width	Length
Shënkoll	10	41.68688	19.65046
Rrëshen	89	41.76764	19.87675
Fshat Klos	366	41.48401	20.08921
Gojan	428	41.97816	20.0003
Domgjon	652	41.96489	20.15431
Kurbnesh	761	41.78206	20.08814
Macukull	1007	41.69741	20.08666

Fig. 1. Map of Albania and Study Area. The watershed of the Mati River (left) and the meteorological stations with geographic coordinates (right).

3. DATA AND METHODS

3.1. Data Source and Description

Meteorological data from a decade (2014-2024) were previously filtered to perform some in-depth calculations and analyses to calculate monthly and annual average values, both in terms of temperatures and precipitation. All data sourced from Albania's National Meteorological Monitoring System which belong to the Department of Meteorology, Institute of Geoscience. In this analysis, daily data from several meteorological stations (**Fig. 1**) were used, which contained gaps distributed unevenly throughout the observation period. Since the gaps were not distributed at all stations simultaneously, an approach based on the inter-station daily average was applied, which is considered one of the most reliable methods in situations with sporadic gaps. The missing values for each station were replaced by the average calculated on this day. This step was performed carefully to maintain climate extremes. To fill data gaps, the reanalysed dataset from Copernicus ERA5 has been utilized (Copernicus Climate Change Service (C3S), 2025).

For the climate classification analysis, the historical average values from the reference period 1960–1990 were used as climatological norms, while the computed values for the last decade were applied for comparative evaluation (Cui et al., 2021). The database was processed using standard statistical procedures, and a custom algorithm developed in the Python programming language was employed to calculate and classify the climatic parameters. The algorithm was based on the modified Köppen–Geiger and Köppen–Trewartha climate classification criteria, following the methodological framework outlined by Belda et al (Belda et al., 2014). For data visualization and statistical interpretation, OriginLab Pro software was used to generate the graphical representations and comparative analyses.

4. RESULTS AND DISCUSSION

As preparatory work for the assessment we present in this paper, and within the broader project for the MAT River Basin, a series of works on extreme weather events, drought events and climate change have been carried out (Hasimi, Papajani, et al., 2025). **Table 1** shows the changes in temperatures and precipitation over the last decade compared to the norms, expressed as a percentage, for each meteorological station of Mati basin river, Albania.

The climatic data from meteorological stations within the Mat River Basin reveal a clear pattern of warming accompanied by a concurrent decline in annual precipitation during the period 1990–2025. These changes are consistently reflected in the observed shifts in both the Köppen Climate Classification (KCC) and the Köppen–Trewartha Climate Classification (KTC), indicating a progressive transformation of the basin's climatic regime.

Table 1.

The changes in temperatures and precipitation for meteorological station of Mati basin river, Albania and Climate type according to the Köppen-Geiger and the Köppen-Trewartha classification.

Meteo Station	**Altitude** m a.s.l	ΔT_{mes} annual	ΔP_{mes} annual	**KCC**		**KTC**	
		%	%	norms 1990	Last decade results	norms 1990	Last decade results
Shënkoll	10	*no last decade data*		Cfa		Cf	
Rrëshen	89	+ 8.15	**+12.96**	Cfa	Csa	Da	Da
F Klos	366	+ 19.60	-5.90	Cfa	Cfa	Da	Cf
Gojan	428	+ 11.77	-3.78	Cfb	Cfa	Da	Cf
Domgjon	652	+ 24.66	-21.63	Cfb	Bkf	Da	Da
Kurbnesh	761	+ 21.64	- 2.57	Cfb	Cfa	Da	Da
Macukull	1007	*no historical data*			Cfb		Da

4.1. Meteorological Data Analysis

The climate classification applied in this study relies exclusively on-air temperature and precipitation. Accordingly, the multiyear variability and long-term evolution of these two parameters across the Mati River Basin are analyzed below using stations with complete and reliable records.

4.1.1. Temperature Trends

Long-term temperature records reveal a coherent and statistically significant warming signal across all meteorological stations in the basin. Mean annual air temperature has increased by approximately **1.5–2.7 °C** relative to the 1961–1990 climatic norms, indicating a persistent basin-wide thermal shift over recent decades. This warming is evident from the coastal lowlands to the highest mountain stations, highlighting the pervasive influence of regional climate change

At the lowest elevation, Shën Koll (10 m a.s.l.) exhibits a humid subtropical climate with a long-term mean annual temperature of 15.47 °C. Although complete data for the most recent decade are unavailable, the station is retained as a climatological reference. Rrëshen (89 m a.s.l.; **Fig. 2**) shows a clear warming signal, with mean annual temperature increasing by **+1.09 °C**, indicating progressive inland warming even at low elevations. October–November temperatures display relative stability with a slight decreasing tendency, potentially linked to localized microclimatic effects associated with river regulation and the construction of small and medium hydropower reservoirs, during the past decade which may influence heat exchange and moisture conditions. Alterations to the riverbed and the creation of artificial reservoirs have modified the local microclimate, influencing both temperature and precipitation patterns and, consequently, the overall water balance of the basin.

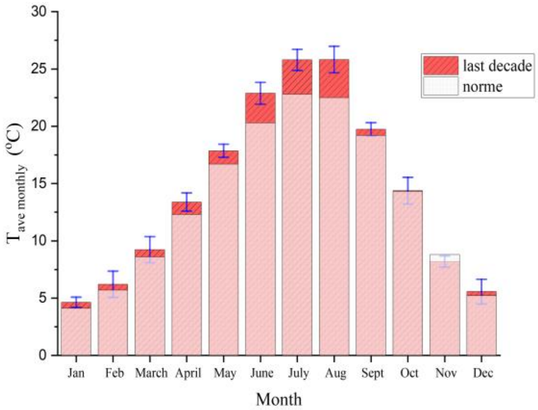


Fig. 2. Monthly average temperature (T_{ave}) at Rrëshen station. The last decade is presented with standard deviation (blue line).

Mid-altitude stations demonstrate more pronounced warming. F. Klos (366 m a.s.l.) records the strongest increase (+2.6 °C), suggesting thermal amplification at intermediate elevations where topography and atmospheric circulation may enhance heat retention. Gojan (428 m a.s.l.) exhibits a comparable rise of +1.5 °C, reinforcing the elevation-dependent nature of the warming trend.

High-elevation stations show similarly strong responses (**Fig. 3**). Domgjon (652 m a.s.l.) experiences an increase of +2.7 °C, with mean annual temperature rising from 10.9 °C to 13.6 °C. Kurbnesh (761 m a.s.l.) records a +2.2 °C increase, while Macukull (1007 m a.s.l.), the highest station in the basin, now exhibits a mean annual temperature of 11.6 °C. These results confirm that even traditionally cooler upland environments are undergoing substantial thermal shifts

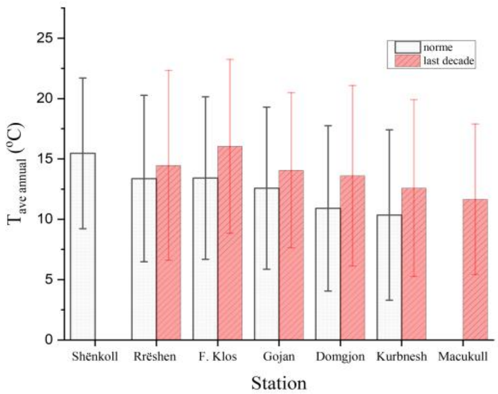
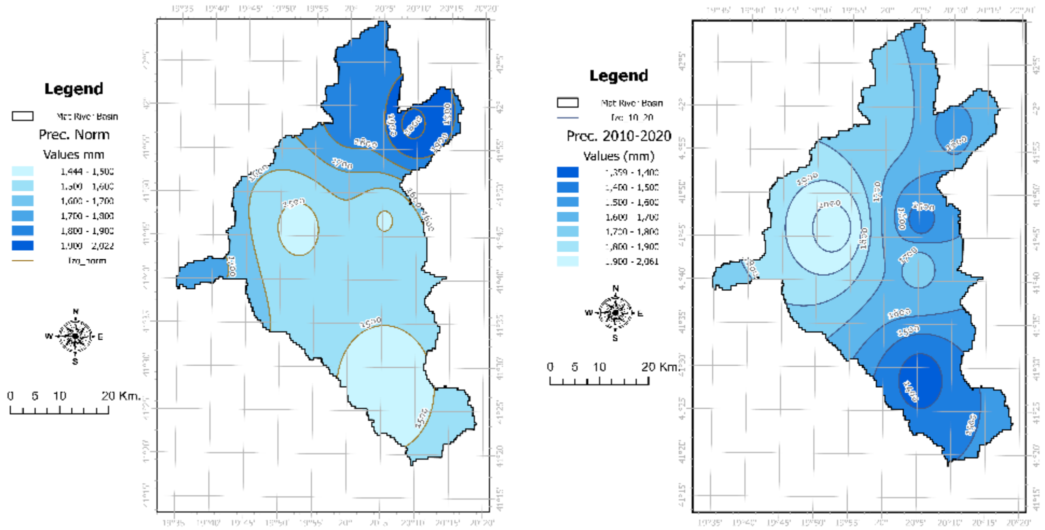


Fig. 3. Annual average temperature ($T_{ave\ annual}$) of all station with standard deviations, presented from low to higher-altitude.

Overall, the results indicate a consistent, elevation-dependent warming pattern across the basin, with stronger increases from coastal areas toward mountainous zones, suggesting that higher-altitude ecosystems may be experiencing accelerated climate impacts. Such spatial differentiation has important implications for hydrological processes, vegetation dynamics, and ecosystem resilience. The observed warming rates are consistent with regional trends reported for the Western Balkans, where mean temperature has increased by more than 0.4 °C per decade since the 1990s (European Commission. Joint Research Centre., 2024; Haidu et al., 2024)

4.1.2. Precipitation Trends

The spatial distribution of long-term precipitation norms (1961–1990) across the Mati River Basin shows a clear south–north and lowland–mountain gradient (**Fig. 4a**). Northern and northeast high-altitude zones receive the highest annual totals (>1900–2000 mm), driven by orographic uplift and moist Adriatic air masses. In contrast, southern and central low-elevation areas receive lower amounts, typically **1400 – 1600 mm yr^{-1}** consistent with the basin's topographic configuration and the prevailing circulation patterns.



a *b*

Fig. 4. The distribution of precipitation of the Mat River basin for the time period 1961-1990 (*a*) and anomalies in mm of precipitation for the last decade (*b*).

Precipitation anomalies for the most recent decade (Fig. 4b) reveal substantial departures from these historical norms. Central-western and southwestern sectors exhibit negative anomalies exceeding **–300 mm**, indicating a marked decline in annual rainfall. These areas coincide with stations showing the strongest warming (e.g., F. Klos and Domgjon), suggesting enhanced evapotranspiration and reduced effective moisture availability, with potential implications for hydrological balance and water resource sustainability.

Conversely, positive anomalies of **+200 to +400 mm** are observed in the northeast mountainous sector. This localized increase may reflect intensified orographic effects, microclimatic feedbacks, and possible land-surface modifications associated with hydropower infrastructure, including reservoir development, which can influence local humidity and convection. Overall, the precipitation regime appears increasingly irregular, characterized by declining totals in interior mountainous areas and relatively stable conditions in coastal and lowland zones(Nistor et al., 2020).

4.2. Climate Analysis

According The Köppen Climate Classification (KCC) reveals a gradual **transition from temperate oceanic (Cfb)** to **humid subtropical (Cfa)** or **Mediterranean (Csa)** types in several stations (**Table 1**).

On the other hand, the Köppen–Trewartha Climate Classification (KTC) shows consistent evolution, with most stations shifting from *Da* to *Cf*, reflecting warmer conditions and reduced thermal seasonality. **Figure 5** synthesizes the spatial distribution of observed climatic changes and classification shifts. The detected trends are consistent with previous regional studies of our group's studies for other regions of Albania.(Hasimi, Çomo, et al., 2025), (Çela et al., 2024), (Papajani et al., 2025).

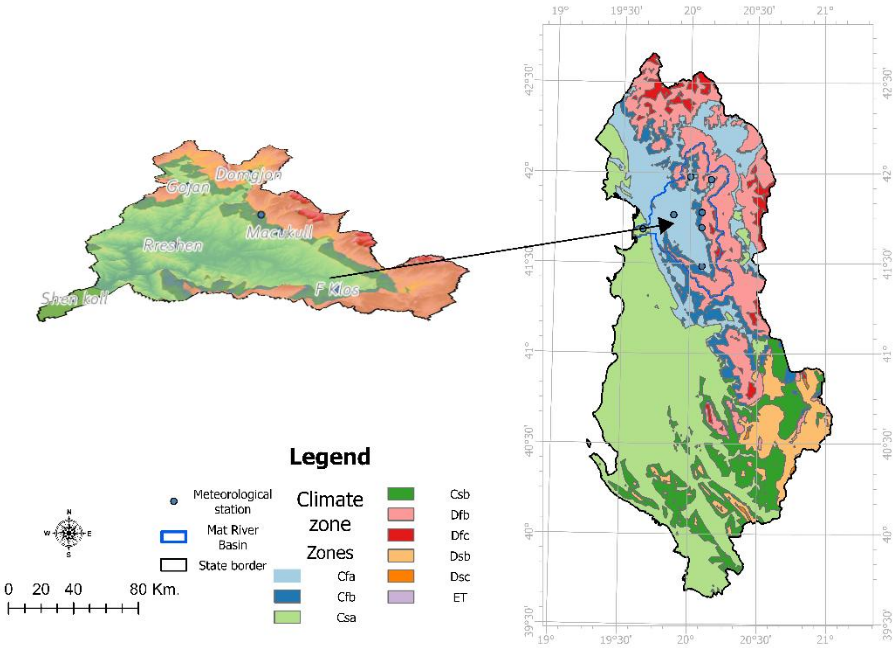


Fig. 5. Albania maps of Köppen climate classification KCC, data for the period of 1980−2016 (H. E. Beck et al., 2018) and the same maps generation from our results for Mati basin river for the period 2014-2024

At F. Klos station (366 m a.s.l.), Despite the reduced rainfall, the Köppen classification remains within the Cfa category (humid subtropical climate), while the KTC changes from Da to Cf, indicating a subtle thermal shift toward a warmer and slightly more humid microclimate. At Domgjon station (652 m a.s.l.), the transition from a Cfb to Bkf Köppen type, with the KTC remaining Da, suggests that Domgjon is undergoing a significant climatic transition from a temperate oceanic toward a drier, more continental climate regime. Similarly, Kurbnesh station (761 m a.s.l.) The shift from Cfb to Cfa in the Köppen classification further supports the warming tendency observed throughout the basin, indicating a gradual replacement of temperate oceanic features with those characteristics of a warmer and less humid climate. For Gojan station (428 m a.s.l.), the 1990 climatic data indicate a Cfb classification with Da thermal characteristics, spatial continuity and elevation similarity with the neighboring stations imply a parallel trend of warming and decreasing precipitation. Data for Macukull station (1007 m a.s.l.) based on altitudinal gradients and regional coherence, it can be inferred that this higher-elevation site experiences a smaller thermal increase compared to lower altitudes, but may still exhibit a decline in annual precipitation consistent with the overall basin trend.

The dataset provides robust evidence of climatic transformation within the Mat River Basin, characterized by: Systematic warming across all elevation zones (1.5–2.7°C increase); Moderate to significant precipitation decline in mid- and high-altitude stations; and Progressive reclassification of climates toward warmer and more arid types (Cfb → Cfa/Csa).

These changes align with broader Mediterranean and Balkan climate trends, marked by increased summer aridity and altered regional circulation patterns. (Knez et al., 2022) (Kostopoulou et al., 2009). Overall, when precipitation anomalies are interpreted together with temperature trends, they reveal a clear **spatial polarization of climate change** within the Mati River Basin. Low- and mid-altitude areas are experiencing progressive warming accompanied by drying, whereas upper catchment zones show signs of localized moistening, likely driven by topographic effects and anthropogenic influences. This divergence highlights the complex interactions among topography, land-use change, and regional climate forcing, all of which are reshaping the basin's the temperatures and hydrological regimes (Nigrelli & Chiarle, 2023; Nistor et al., 2022).

6. CONCULSIONS

The documented climatic shifts are expected to exert substantial impacts on the basin's hydrology and ecosystem dynamics (Palmer & Ruhi, 2019). The observed increase in mean annual temperature (**1.5–2.7 °C**) combined with reduced precipitation at several stations suggests intensified evapotranspiration, leading to declining surface runoff and groundwater recharge. As a result, river discharge is likely to decrease progressively, particularly during summer and early autumn, when precipitation deficits coincide with peak thermal stress(Hasimi, Çomo, et al., 2025) (De Castro et al., 2007).

The transition from temperate oceanic (*Cfb*) to warmer subtropical and Mediterranean climate types (*Cfa–Csa*) further indicates a shift in the basin's hydrological seasonality. Elevated temperatures enhance soil-moisture depletion and alter snow accumulation and melt processes in upland areas such as Domgjon, Kurbnesh, and Macukull. Consequently, streamflow peaks are expected to occur earlier in the hydrological year, while low-flow periods may become longer and more severe. These changes increase vulnerability to hydrological droughts, soil erosion, and fluctuations in sediment transport (Anghileri et al., 2014; Hasimi, Çomo, et al., 2025).

From an ecological perspective, rising temperatures and reduced moisture availability are likely to drive shifts in vegetation composition and distribution. Thermophilus and drought-tolerant species may expand to higher elevations, while mesophilic species adapted to cooler and wetter conditions may retreat or decline, with direct implications for biodiversity, forest productivity, and landscape stability (Kong et al., 2017; Sparey et al., 2023).

Socio-environmentally, these climatic changes pose growing challenges for water-resource management, agricultural planning, and ecosystem conservation within the Mati River Basin (D. Chen & Chen, 2013). Reduced dry-season water availability may limit irrigation potential and hydropower efficiency, while increased precipitation variability could heighten flood risk in downstream areas and drought frequency in upper sub-catchments (Forzieri et al., 2014).

Overall, the integration of climatic and hydrological evidence indicates a trajectory toward **warmer, drier, and more hydrologically unstable conditions** in the Mati River Basin. Continued long-term monitoring and high-resolution climate modelling are therefore essential to evaluate future water-balance scenarios and to support adaptive management strategies aimed at mitigating environmental and socio-economic impacts.

In summary, observed temperature increases of **2.0–2.5 °C** across all meteorological stations, together with a mean precipitation decline of **5–20 %**, demonstrate a systematic regional trend toward warming and drying. The spatial pattern of change suggests an elevation-dependent response, with stronger thermal increases and climate-classification shifts at low- and mid-elevations. These transformations imply a reorganization of hydrological processes, including evapotranspiration, runoff generation, and vegetation dynamics, with long-term consequences for water availability and ecosystem stability (Lenton et al., 2008).

The pronounced interannual variability detected in the dataset further reflects the influence of large-scale atmospheric and oceanic circulation patterns affecting the Balkan Peninsula. To enhance understanding of ongoing dynamics and improve anticipation of future environmental change, several key research priorities emerge. These include the establishment of long-term monitoring programs for climatic, hydrological, cryospheric, and ecological indicators in mountain regions, alongside integrated, model-based approaches that couple climate, hydrology, ecosystems, and land-use processes. Such approaches should explicitly account for land–atmosphere feedbacks and support policy-relevant impact assessments. In addition, process-oriented investigations across altitudinal gradients and headwater basins are needed to evaluate environmental sensitivity at critical climatic and ecological thresholds. Finally, the development of sustainable land- and water-management strategies is essential, particularly those addressing changes in forest cover, mountain agriculture, food security, and associated socio-economic pressures. Collectively, these research directions are fundamental to the design of adaptive management frameworks capable of responding to the accelerating impacts of climate change on mountain environments, including the Mati River Basin.

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