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Exploring Behavioral Intention Toward Sustainable Ecotourism Development among Local Residents Working in the Mekong Delta, Vietnam

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Abstract

This study aimed to explore various levels of local residents' behavioral intention toward sustainable ecotourism development in the Mekong Delta, Vietnam and identified their key determinants. Using convenience sampling method, a total of 302 responses were used for data analysis. The proposed model involving three dimensions of residents' perceptions (economic, sociocultural and environmental sustainability) and attitude was developed to determine the formation of local residents' participation intention. Furthermore, residents' intention in sustainable development of ecotourism was examined through a second-factor latent variable with four aspects including sustainable community development, natural resources conservation, cultural tradition preservation, and participation in planning and managing ecotourism development. The findings demonstrated that residents' perceptions had direct impacts on their participation intention, which were partially mediated by their attitude. Notably, perceived environmental benefits of local people had the strongest overall effect among the variables examined. Finally, theoretical and managerial implications are discussed.

Keywords: local resident; sustainable ecotourism development; perception; attitude; ***behavioral intention***.

Introduction

Over the years, tourism has developed into one of the world's largest and fastest-expanding industries, often accompanied by unsustainable practices that endanger ecosystems and natural resources (Chan, 2013). In address to environmental concerns, including climate change, pollution, and resource depletion, sustainable tourism has come to prominence. Ecotourism—a key form of sustainable tourism—is defined as responsible travel to natural areas that conserves the environment and benefits local communities (TIES, 1990). It promotes environmental awareness, cultural appreciation, and community wellbeing (Kong, 2014; Fennell, 2001), and is increasingly recognized as an effective strategy for conservation and sustainable development.

Among various stakeholders, local residents play a critical role in the sustainable development of ecotourism (Cheung, 2015; Muresan et al., 2016; Eshliki & Kaboudi, 2017; Pineda et al., 2023). Effective protected area management requires their support and cooperation (Mehta & Heinen, 2001), making it essential to understand their behaviors (Holladay & Ormsby, 2011). Community empowerment and participation in decision-making are also vital for sustainable outcomes (Newmark & Hough, 2000). To foster resident

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involvement, governments and ecotourism businesses must identify factors shaping positive attitudes and behavioral intentions, especially where livelihoods depend on local natural resources (Birendra et al., 2018). Residents' perceptions of ecotourism benefits directly influence their willingness to support and engage in related activities (Amuquandoh, 2010; Kim & Butler, 2015).

The existing literature has predominantly examined residents' perceptions, attitude, and behavioral intentions toward the sustainable development of ecotourism; however, empirical investigations that statistically assess these relationships remain limited (Prayag et al., 2013; Liu & Chamaratana, 2024). Furthermore, prior research has largely concentrated on general intention rather than specific participatory activities within ecotourism development (Choi & Murray, 2010; Vargas-Sánchez et al., 2011; Nunkoo & Ramkissoon, 2011; Ven, 2015; Morales et al., 2018; Khalid et al., 2019; Hsu et al., 2019; Ismail et al., 2020; Hassan, 2021; Shen et al., 2022; Pineda et al., 2023; Deb & Rout, 2023; Castillo et al., 2024; Liu & Chamaratana, 2024; Castillo-Vizuete et al., 2024; Jiang & Tian, 2025; Mussina et al., 2025). In response to these gaps, this study sought to provide a deeper understanding of local residents' perception, attitude, and behavioral intention—conceptualized as a second-order construct comprising four dimensions: conservation of natural resources, preservation of cultural traditions, sustainable community development, and participation in ecotourism planning and management. Specifically, the study employed statistical methods to assess the influence of residents' perceptions and attitude on their intention to engage in sustainable ecotourism development activities. The findings were expected to inform strategies aimed at enhancing community support for sustainability within the ecotourism sector.

Literature review

Ecotourism and sustainable development

Initially, ecotourism primarily centered on providing nature-based experiences; however, it has since been promoted as a strategy for developing countries to integrate economic growth with social and environmental objectives (Beaumont, 2011). Wallace and Pierce (1996) defined ecotourism as "travelling to relatively undisturbed natural areas for study, enjoyment, or volunteer assistance. It is travel that concerns itself with flora, fauna, geology, and ecosystems of an area, as well as the people who live nearby, their needs, their culture, and their relationship to the land." In contemporary discourse, the appeal of ecotourism as both a conservation and development tool lies in its potential to generate local economic benefits while preserving ecological integrity through low-impact, non-consumptive resource use (Stem et al., 2003). The concept of ecotourism is intrinsically linked to sustainable tourism and should align with the core principles of sustainable tourism and development (UNWTO, 2012). Overall, ecotourism is regarded as a specialized form of sustainable tourism, with both approaches sharing the overarching goals of environmental protection, socio-cultural preservation, and long-term economic enhancement of destinations.

Proposed conceptual framework and research hypotheses

Empirical evidence indicates that tourism development can yield economic, environmental, and socio-cultural benefits for local communities, thereby contributing to the restoration and enhancement of living conditions in tourist destinations (Andereck & Vogt, 2000; Kuvan & Akan, 2005). Ecotourism, in particular, has the potential to address environmental, social, cultural, and economic dimensions in a balanced and efficient manner; however, the extent to which these benefits are realized—or adverse impacts occur—depends largely on how such development is implemented (Okech & Bob, 2009). Achieving long-term success in sustainable tourism development necessitates securing the support of local residents (Ahn et al., 2002). As emphasized by Ap (1992), residents' perceptions and attitudes toward tourism play a critical role in informing planning and policy decisions, which in turn influence the effective development, marketing, and management of both existing and future tourism initiatives.

The Social Exchange Theory was first introduced in the field of behavioral psychology by Homans (1958) and has since been expanded and applied extensively across diverse disciplines (Ahmad et al., 2023). In the tourism context, Gursoy et al. (2010) applied this theoretical framework and argued that when local residents perceive the positive impacts of tourism to outweigh its negative consequences, they are more likely to support tourism development initiatives. Building on this premise, empirical research has examined the influence of residents' perceptions on their support for tourism development. Such studies have assessed residents' perceptions in economic, socio-cultural, and environmental dimensions as key determinants of local communities' behavioral intentions (Jiang, 2008; Tang et al., 2012; Muresan et al., 2016; Wu & Chen, 2016; Abeli, 2017; Haloi et al., 2017). However, prior research has largely focused on residents' support as a general behavioral intention within sustainable ecotourism development, without examining specific

activities (Choi & Murray, 2010; Vargas-Sánchez et al., 2011; Nunkoo & Ramkissoon, 2011; Ven, 2015; Morales et al., 2018; Landra et al., 2018; Khalid et al., 2019; Castillo-Vizuete et al., 2024; Jiang & Tian, 2025; Mussina et al., 2025). The present study aims to address this gap by investigating the influence of three dimensions of residents' perception—economic, socio-cultural, and environmental in positive perspective — on their behavioral intention, conceptualized as a second-order construct comprising four dimensions: natural resource conservation, cultural tradition preservation, sustainable community development, and participation in the planning and management of ecotourism development. These four dimensions are adapted from prior ecotourism research (Lai & Nepal, 2005; Haloi et al., 2017; Wu & Chen, 2016). Previous studies have further demonstrated that second-order factor models often provide a superior fit to the data compared to single-order solutions and offer a more comprehensive representation of the underlying construct (Milfont & Duckitt, 2004; Mansolf & Reise, 2017; Raykov et al., 2024). Accordingly, this study proposed the following hypotheses.

H1a: Positive perception of the economic impacts of tourism positively and significantly influences local residents' behavioral intention toward sustainable ecotourism development.

H1b: Positive perception of the sociocultural impacts of tourism positively and significantly influences local residents' behavioral intention toward sustainable ecotourism development.

H1c: Positive perception of the environmental impacts of tourism positively and significantly influences local residents' behavioral intention toward sustainable ecotourism development.

Rosenberg's model of attitude (1956) posited that an individual's positive or negative feelings toward an object or concept are determined by two cognitive factors: (a) the perceived instrumentality of the object in achieving or hindering a set of valued states, goals, or objectives, and (b) the relative importance of those values, goals, or objectives to the individual. Accordingly, stronger perceptions regarding an object or concept tend to be associated with more favorable attitude. Within tourism research, residents' attitude has been widely used as an indicator of tourism's appropriateness for a given community, with positive attitude reflecting the extent to which tourism development meets social and cultural expectations. For instance, Lepp (2007), using a qualitative approach, found that favorable attitude toward tourism was linked to beliefs that it fostered community development, generated income opportunities, enhanced agricultural markets, and provided prospects for improved livelihoods. Empirical studies in the context of festivals and special events had similarly demonstrated that residents' perceptions influenced their attitude toward such activities (Li et al., 2014; Kim et al., 2015; Li et al., 2018), though these investigations primarily assessed the relationship in terms of expected economic benefits or costs, thereby overlooking non-economic dimensions. Consistent with this focus, prior research has shown that economic benefits represented a major determinant of residents' attitude toward tourism (Lingberg & Johnson, 1997), with many residents perceiving tourism chiefly as an economic development tool, which in turn fostered positive attitude toward its sustainable growth (Gursoy et al., 2002; Andereck & Vogt, 2000). In contrast, a study in a national park context found no statistically significant relationship between residents' perceptions of environmental benefits and their attitude toward sustainable ecotourism development (Partiro et al., 2023). These gaps in the literature underscored the need for more comprehensive and context-sensitive analyses of the statistical relationship between perception and attitude. Drawing on sustainable ecotourism development theory, the present study examined the effects of positive perceptions in three domains—economic, sociocultural, and environmental—on local residents' attitude toward ecotourism development. So, the following hypotheses were proposed.

H2a: Positive perception of the economic impacts of tourism positively and significantly influences local residents' attitude toward sustainable ecotourism development.

H2b: Positive perception of the sociocultural impacts of tourism positively and significantly influences local residents' attitude toward sustainable ecotourism development.

H2c: Positive perception of the environmental impacts of tourism positively and significantly influences local residents' attitude toward sustainable ecotourism development.

The Theory of Reasoned Action (Fishbein & Ajzen, 1975) defined attitude as "a learned predisposition to respond in a consistently favorable or unfavorable manner with respect to a given object," emphasizing its acquired nature and role in shaping behavior. As a hypothetical construct, attitude preceded and predicted overt actions, serving as a stable basis for behavioral patterns. The Theory of Planned Behavior (Ajzen, 1991) further posited that individuals were more likely to engage in a behavior when they hold a positive attitude toward it, a relationship supported by empirical studies identifying attitude as a key determinant of

behavioral intention (Lita et al., 2014; Suki, 2016). In the context of sustainable tourism, existing literature has explored local residents' perspectives but has often neglected the explicit relationship between residents' attitude and their support for sustainable tourism development (Prayag et al., 2013). This gap could be attributed to the interchangeable use of the terms "attitude" and "support," which complicated the distinction and evaluation of these constructs (Moghavvemi et al., 2017). Some empirical studies had found that residents' support for sustainable tourism development is strongly influenced by their attitude (Nunkoo & Gursoy, 2012; Martin et al., 2017; Moghavvemi et al., 2017). Conversely, Morales et al. (2018) overlooked the attitude–support relationship in their analysis of sustainable development activities. Other research has examined residents' intentions to participate in tourism development, reporting a significant positive association between attitude and behavioral intention (Wu & Chen, 2016; Shen et al., 2019). Given these inconsistent findings and the limited attention to specific sustainable development activities within the ecotourism domain, the present study attempted to examine the influence of local residents' attitude on their behavioral intention toward sustainable ecotourism development, identified as second-order variable through four dimensions. Accordingly, the third hypothesis was proposed.

H3: Local residents' attitude toward ecotourism development positively and significantly influences their behavioral intention toward sustainable ecotourism development.

Additionally, previous studies have demonstrated that the perceived benefits of tourism—encompassing economic, socio-cultural, and environmental dimensions—positively influenced local residents' attitude (Li et al., 2014, Kim et al., 2015, Li et al., 2018) as well as their attitude has been shown to significantly affect their behavioral intention (Nunkoo & Gursoy, 2012, Martin et al., 2017, Moghavvemi et al., 2017). Drawing upon these empirical findings, this study proposed to evaluate the mediating role of local residents' attitude toward ecotourism development in the relationship between their perceptions of tourism benefits and their intentions to develop sustainable ecotourism. Accordingly, the following hypotheses are formulated:

H4a: Local residents' attitude toward ecotourism development positively mediates the relationship between their economic perception and behavioral intention toward sustainable ecotourism development.

H4b: Local residents' attitude toward ecotourism development positively mediates the relationship between their sociocultural perception and behavioral intention toward sustainable ecotourism development.

H4c: Local residents' attitude toward ecotourism development positively mediates the relationship between their environmental perception and behavioral intention toward sustainable ecotourism development.

Methodology

Questionnaire development

The questionnaire was developed through several stages. First, a comprehensive review of the relevant literature was conducted to identify validated measurement scales. In line with recommended practices in scientific research (e.g., Churchill, 1979; DeVellis, 2017; Hair et al., 2019), measurement items were adapted from prior studies to ensure theoretical grounding and content validity. Second, in-depth interviews with tourism experts were conducted to refine the wording, relevance, and contextual suitability of the items for the ecotourism context in the Mekong Delta. Expert consultation is commonly used to improve the content validity and contextual appropriateness of measurement instruments (DeVellis, 2017). Finally, the questionnaire was pretested with a small group of respondents to ensure clarity and comprehensibility before the main data collection, which is a recommended step in survey instrument development (Hair et al., 2019).

In specific, following the literature review, in-depth interviews with tourism experts were conducted as a preliminary step to refine and validate the potential attributes of the research constructs and measurement items related to sustainable ecotourism development. These experts were selected based on their professional experience in ecotourism management, tourism planning, or tourism operations in the Mekong Delta region. The purpose of these interviews was not to represent the perceptions of local residents, but rather to obtain professional insights to ensure that the proposed constructs and measurement items were contextually relevant, conceptually clear, and appropriate for the study setting. The feedback obtained from the experts helped refine the wording and relevance of the measurement items before the main research stage focusing on local residents' perceptions, attitudes, and behavioral intentions.

After that, a pilot test was conducted to refine the questionnaire prior to its formal administration. The instrument was administered to 30 local residents working in ecotourism enterprises in the Mekong Delta, Vietnam. Participants evaluated the clarity of

instructions, the comprehensibility of measurement scales, and the appropriateness of wording to minimize potential response difficulties in the main survey. Feedback from this preliminary stage informed revisions to the questionnaire and the final operational definitions of the study's constructs.

Data collection and sample characteristics

For data collection, a non-probability convenience sampling method was employed, using face-to-face interviews with a structured questionnaire. This data collection method was selected as the primary data collection method to allow participants to fully understand and answer questions related to their perceptions and viewpoints. In addition, most of local residents working in the ecotourism sector in the Mekong Delta have relatively limited formal education and little prior exposure to the concept of sustainable ecotourism development, making interviews more suitable for explaining questions and ensuring accurate responses. Eligibility was limited to individuals who had been employed in ecotourism enterprises in the Mekong Delta for a minimum of three years to ensure sufficient industry experience. Primary data were collected from enterprises listed on the official websites of the Departments of Culture, Sports, and Tourism.

A questionnaire was the principal instrument of data collection for the survey. It included three sets of questions: (1) The first section of the questionnaire incorporated those statements relating to local residents' perceptions toward sustainable development of ecotourism. (2) In the second section, respondents rated their level of agreement with statements pertaining to local residents' attitude toward sustainable development practices of ecotourism. (3) The third section expressed local residents' behavioral intentions toward sustainable ecotourism development strategies at ecotourism enterprises. Their level of agreement was rated on a scale of 1 = strongly disagree, and 5 = strongly agree. (4) The last section was designed to generate descriptive information about the respondents.

For the application of structural equation modeling (SEM), a sample size exceeding 200 is generally considered adequate for producing significant results (Kline, 2005; Hair et al., 2019), while Norusis (2005) recommends a minimum of 300 cases. A too large sample size may even be one of the causes of deterioration of statistical power of a structural equation model (Hair et al., 2019). Based on these guidelines, this study targeted approximately 300 respondents and ultimately obtained 302 usable questionnaires. These respondents presented 55.6% female and 44.4% male. Nearly half of respondents were married, and most of them earned less than 1000 USD per month. In term of age, 38.1% respondents were between 18-24 years of age, followed by 29.5% between 25 and 34 years of age. In addition, 52% of them had vocational training or bachelor degree, 44% finished high school or lower, and 3% had higher level of education. Especially, all of them has been working at current job for at least 3 years.

Results

Dimensions of local residents' perceptions, attitude and intentions

The dimensions of three research concepts including residents' perceptions, attitude and behavioral intentions toward sustainable ecotourism development were conducted reliability test with Cronbach's Alpha. Then, principal axis factoring analyses with the Promax rotation method were utilized to find out the underlying factors. A KMO test was conducted to identify whether the sample was adequate for factor analysis. Hair et al. (2019) recommended a KMO which measuring 0.6 or above is suitable for the data. In addition, Bartlett's test of sphericity should be less than 0.05 to assume the factorability of the correlation matrix. The minimum cut off point for final factor loading of items in factor analysis was 0.5. After deleting some items which had low item-to-total correlations in reliability test (smaller than 0.3), and some items which had low factor loading in EFA (smaller than 0.5) (Hair et al., 2019), the results were showed in table 1,2,3.

Table 1. Summary of the exploratory factor analysis results – residents' perceptions

Variables (Sustainable development of ecotourism…)	Loading	Eigen-value	Variable explained (%)	Reliability Alpha
Factor 1 - Sociocultural sustainability		9.90	45.65	0.88
1- Provides diverse cultural experiences, cultural exchange opportunities	0.80			

2- Improves tourists' awareness and appreciation about local traditional and cultural value…	0.77			
3- Upgrades local infrastructure, health care service, education…	0.73			
4- Makes good interaction between local resident and tourist	0.72			
5- Improves preservation activities for traditional and cultural ceremonies	0.67			
6- Builds up local resident's confidence, self-esteem, pride, and dignity	0.65			
7- Promotes the reputation of the local	0.63			
Factor 2 - Environmental sustainability		2.53	13.74	0.85
1- Promotes environmental protection and improves quality of living environment	0.90			
2- Makes opportunity for local resident actively participate in environment protection activities	0.81			
3- Increases public environmental awareness and directs local resident toward appropriate behaviors	0.70			
Factor 3 – Economic sustainability		1.04	8.00	0.82
1-Increases additional income to local residents	0.87			
2- Reinforces the local economy	0.74			
4- Diversifies the local economy	0.72			
Total variance explained: 57.387% **KMO: 0.869; Bartlett's Test of Sphericity (Sig.): 0.000**				

Table 2. Summary of the exploratory factor analysis results – residents' attitude

Factor – Residents' attitude	Loading	Eigen-value	Variable explained(%)	Reliability Alpha
		2.49	49.71	0.81
1-I am proud to participate in sustainable ecotourism development activities	0.76			
2-I am favorable to participate in sustainable ecotourism development activities	0.72			
3-I am enjoyable to participate in sustainable ecotourism development activities	0.72			
4-I think that sustainable ecotourism development is important	0.69			
5-I think that sustainable ecotourism development is necessary	0.62			
Total variance explained: 49.708% **KMO: 0.817; Bartlett's Test of Sphericity (Sig.): 0.000**				

Table 3. Summary of the exploratory factor analysis results – residents' behavioral intention

Variables	Loading	Eigen-value	Variable explained (%)	Reliability Alpha
Factor 1 - Sustainable community development		4.894	34.955	0.857
1- I am willing to participate in waste reduction, water conservation practices	0.86			
2- I am willing to join in solving security issues in the community	0.79			
3- I am willing to use eco-friendly instruments, machines and sustainable practices to improve energy efficiency	0.75			

5- I am willing to participate in and organize eco-friendly activities, events to improve tourists' awareness	0.65			
Factor 2 - Natural resources conservation		1.746	12.471	0.843
1- I am willing to support and participate in natural resources conservation activities of the local government	0.84			
2- I am willing to convince other local residents to minimize negative environmental impacts of their business/work	0.76			
3- I am willing to promote and convince other local residents NOT to trade products which are made from rare animals and plants	0.63			
4- I am willing to join in solving environmental issues	0.60			
Factor 3 – Cultural tradition preservation		1.395	9.963	0.862
1- I am willing to participate in traditional events and festivals to attract more tourists	0.87			
2- I am willing to participate in cultural tradition preservation activities	0.86			
3- I am willing to study and promote local historical and cultural traditions	0.67			
Factor 4 - Participation in planning and managing ecotourism development		1.00	6.450	0.871
1- I am willing to work in ecotourism enterprises where are applied sustainable practices	0.81			
2- I am willing to participate in ecotourism development and planning	0.80			
3- I am willing to encourage other local residents in preventing negative impacts for sustainable ecotourism development	0.71			
Total variance explained: 60.283% **KMO: 0.841; Bartlett's Test of Sphericity (Sig.): 0.000**				

By respecifying the principal axis factoring analysis, the above extracted factors represented for residents' perceptions, attitude and behavioral intentions toward sustainable ecotourism development were statistically vigorous and appropriately summarized the data

Research hypotheses testing and structural equation modeling

At the first stage, this study conducted confirmatory factor analysis (CFA) to evaluate the adequacy of the measurement components for the proposed model. The model fit for the measurement model was good (χ^2 = 871.026, *df* = 439, RMSEA = 0.057, CFI = 0.914, IFI = 0.915, TLI = 0.903). As showed in table 4, composite Reliability (CR) was calculated to assess the internal consistency of the constructs. The results indicate that the CR values ranged from 0.74 to 0.87 (0.74, 0.79, 0.82, 0.85, and 0.87), exceeding the recommended threshold of 0.70. This suggests that all constructs demonstrate satisfactory internal consistency and reliability. The CR results further supported the reliability of the measurement model (Hair et al., 2019). All of the average variance extracted (AVE) values were significant, with high factor loadings that ranged from 0.50 to 0.66 and thus surpassed the threshold value of 0.5 (table 4). The results showed that all the indicators are statistically significant at 0.01, which supports the theoretical assignment of the indicators to each construct (Anderson & Gerbing, 1988). As a result, convergent validity was ensured. The correlations among and between the exogenous and endogenous constructs ranged from 0.36 to 0.73, which show suitable level of intercorrelation. Moreover, the squared correlation coefficients between the constructs were smaller than the AVE value of each construct. They illustrated that discriminant validity was also passed. In short, the validity and reliability of the operationalization of the latent variables in the measurement model were appropriate.

Table 4. Correlations (squared correlations), AVEs and means

	SOC	ECO	ENV	ATT	INT
SOC	1				
ECO	0.41(0.17)	1			
ENV	0.47(0.22)	0.48(0.23)	1		
ATT	0.36(0.13)	0.38(0.13)	0.43(0.19)	1	
INT	0.51(0.26)	0.50(0.25)	0.73(0.53)	0.50(0.25)	1
CR	0.87	0.82	0.85	0.79	0.74
AVE	0.51	0.61	0.66	0.50	0.50
Mean	4.38	4.46	4.34	4.28	4.34

Note: SOC= Sociocultural sustainability; ECO= Economic sustainability; ENV= Environmental sustainability; ATT= Resident's Attitude; INT=Resident's Intention; AVE=Average Variance Extracted; CR= Composite reliability; Mean values are based on 5-point scales; All correlations are significant at $p<0.01$.

Structural equation modeling

With a satisfactory measurement model, the structural model was used to test the research hypotheses. The structural equation model was shown a good overall model fit. Specifically, Goodness-of-fit statistics for the structural model were $\chi 2 = 889.531$, df = 441, RMSEA = 0.058, CFI = 0.911, IFI = 0.912, TLI = 0.900. The model in general included the satisfactory prediction power for local residents' attitude toward sustainable ecotourism development ($R^2 = 0.28$), and behavioral intention toward sustainable ecotourism development ($R^2 = 0.69$). The details regarding the structural equation results are demonstrated in Table 5. Overall, the analysis revealed that all three dimensions of residents' perceptions exerted a statistically significant and positive influence on both their attitude and their behavioral intention toward sustainable ecotourism development. Additionally, residents' attitude was found to be a significant determinant of their behavioral intention. Accordingly, the results provided empirical supports for all seven proposed hypotheses of the study.

Table 5. Structural path estimates of the model

Hypothesis	Path	Standardized estimate	t-value	P	Support
H1a	ECO → INT	0.17	2.29	0.02	Yes
H1b	SOC → INT	0.19	2.64	0.01	Yes
H1c	ENV → INT	0.54	6.24	0.00	Yes
H2a	SOC → ATT	0.20	2.68	0.01	Yes
H2b	ECO → ATT	0.21	2.64	0.01	Yes
H2c	ENV → ATT	0.25	3.16	0.00	Yes
H3	ATT → INT	0.15	2.09	0.04	Yes

Note: SOC= Sociocultural sustainability; ECO= Economic sustainability; ENV= Environmental sustainability; ATT= Resident's Attitude; INT= Resident's Intention

The hypothesized effects of local residents' perceptions on their behavioral intentions toward sustainable ecotourism development were empirically supported. Perceptions of economic ($\beta = 0.17$, $p < 0.05$), sociocultural ($\beta = 0.19$, $p < 0.05$), and environmental ($\beta = 0.54$, $p < 0.01$) sustainability exerted positive and statistically significant influences on intention, confirming hypotheses H1a, H1b, and H1c. In addition, all three dimensions—economic ($\beta = 0.21$, $p < 0.05$), socio-cultural ($\beta = 0.20$, $p < 0.05$), and environmental ($\beta = 0.21$, $p < 0.01$) sustainability—were found to have significant positive effects on residents' attitude, confirming hypotheses H2a, H2b, and H2c. Moreover, the proposed relationship between residents' attitude and their intention was also tested. The estimation results revealed that attitude demonstrated a significant posi-

tive effect on intention (β = 0.15, $p < 0.05$), validating hypothesis H3.

Mediation hypotheses assessment

Subsequently, the indirect impact and total impact of variables were estimated. To examine the mediating role of local residents' attitude in the relationship between their perceptions and intention, the bootstrapping technique was employed (Byrne, 2013). As reported in Table 6 and Figure 1, the results revealed that local residents' perceptions significantly affected their behavioral indirectly through their attitude. In line with the criteria suggested by Cheung and Lau (2008), these findings provided evidences of partial mediations. Regarding the total influenced residents' behavioral intention, environmental benefits perceived by residents demonstrated the greatest total impact (β = 0.58, $p < 0.00$), followed by sociocultural benefits (β = 0.19, $p < 0.05$), and economic benefits (β = 0.17, $p < 0.06$).

Table 6. Estimation result of mediation effects

Hypothesis	Path	Standardized direct effect	Standardized indirect effect	Standardized total effect	P	Support (character mediation)
H4a	ECO → INT through the mediating role of ATT	0.17	0.03	0.20	0.06	Yes (Partial)
H4b	SOC → INT through the mediating role of ATT	0.19	0.03	0.22	0.05	Yes (Partial)
H4c	ENV → INT through the mediating role of ATT	0.54	0.04	0.58	0.00	Yes (Partial)

Note: SOC= Sociocultural sustainability; ECO= Economic sustainability; ENV= Environmental sustainability; ATT= Resident's Attitude; INT= Resident's Intention

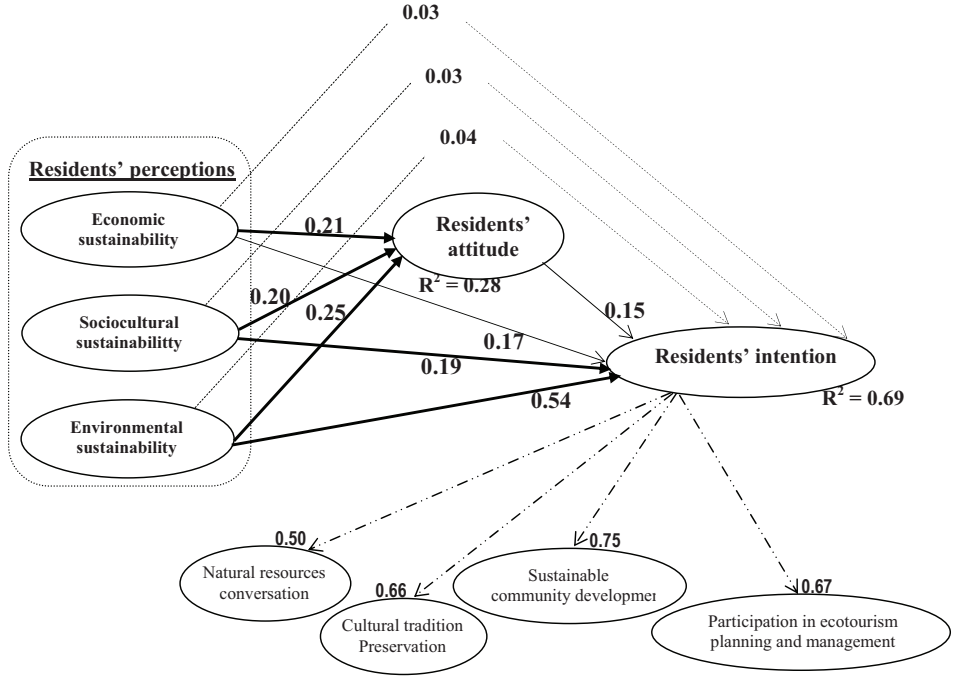

Figure 1. Structural equation model estimation
Note 1: statistically significant path coefficient at 0.01 level
Note 2: statistically significant path coefficient at 0.05 level
Note3: indirect impact
Note 4: second order factor
Note 5: Model fit indices: $\chi 2 = 889.531$, df = 441, RMSEA = 0.058, CFI = 0.911, IFI = 912, TLI = 0.900

Discussion and implications

The proposed conceptual model was an attempt to provide a comprehensive explanation of local residents' behavioral intentions toward sustainable ecotourism development. Within this context, existing academic research on residents' participation intentions remains limited, particularly when examined through the lens of specific sustainability dimensions. The proposed theoretical framework constituting residents' perceptions towards economic, sociocultural and environmental sustainability as independent variables, their attitude as mediator was demonstrated to be useful and satisfactorily predict local residents' behavioral. The hypothesized relationships among research constructs were generally supported, and subsequent results revealed statistically significant mediating effects. Overall, the findings offered a robust and integrative framework for research constructs and their relationships in local residents' behavioral intention toward sustainable ecotourism development.

Hypothesis 1a,b,c

According to Byrd et al. (2009), perceived impact of tourism on the community development was a predictor of residents' support for sustainable tourism development of a community. Besides, related research emphasized the importance of determining local residents' perception of ecotourism before implementation (Jiang, 2008; Tang et al., 2012; Muresan et al., 2016; Wu & Chen, 2016; Abeli, 2017; Haloi et al., 2017; Pineda et al., 2023). This study deeply investigated the significant determinants of local people's participation in sustainable ecotourism development through their perceptions. The results showed that their perception of environmental sustainability is much more important than economic and sociocultural aspects in contributing their intention to participate in sustainable ecotourism development. This was relevant to most of definitions stating that ecotourism emphasizes responsible practices, highlighting the conservation of natural environments (Stem, et al., 2003; Dhami et al., 2014; Sahahiri et al., 2023; Koliouska & Andreopoulou, 2023). In essence, ecotourism products sought to provide environmental education and experiences to tourists while protecting the ecological integrity of the destination (Kerimoğlu & Çıracı, 2008; Pujar & Mishra, 2020).

On the other hand, some other studies showed that culture was one of the most important attributes that significantly contributed to tourists' intention to visit ecotourism destinations (Abdurahman et al., 2016). This implied that the cultural aspect enhanced the attractiveness of the ecotourism product by expressing and positioning the local's pride in the destination. Furthermore, ecotourism has been showed to have a positive impact on the local economy. Ecotourism generated income for local communities through the provision of tourism-related products and services. These benefits significantly motivated the local to practice sustainability (Chirenje, 2017). In a developing country like Vietnam, some ecotourism sites simply developed tourism service from the nature and culture of the destination in the context of limited perception of conservation and development of these tourism resources. Moreover, most people may think that sustainable practices required large investments, leading to delays in implementing sustainable development practices. They need to better understand sustainable ecotourism development, which can be initiated step by step in their actions. This strategy pursues long-term economic efficiency while ensuring environmental responsibility and improving sociocultural value of tourism destination.

Existing literature have indicated that local residents' intention in sustainable ecotourism development is a multidimensional construct (Lai & Nepal, 2005; Haloi et al., 2017; Wu & Chen, 2016). However, most of studies have considered or combined them into a common variable while investigating the formation and determinants (Choi & Murray, 2010, Vargas-Sanchez et al., 2011, Nunkoo & Ramkissoon, 2011; Ven, 2015; Morales et al., 2018; Landra et.al., 2018; Khalid et al., 2019; Castillo-Vizuete et al., 2024; Jiang & Tian, 2025; Mussina et al., 2025). The current study filled this gap and identified sustainable behavior intention as second-order variable through four dimensions (natural resources conservation, cultural tradition preservation, sustainable community development, and participation in planning and managing ecotourism development). Figure 1 showed the rank order contribution of each dimension in local residents' behavioral intention in the Mekong Delta, Vietnam. Within the concept of local residents' intentions, these four dimensions ranged from simple to complex levels, emphasizing the importance of local residents' participation in sustainable development strategies. In particular, participation in ecotourism planning and management is the most difficult task of sustainability behavior. Therefore, local residents expressed their lowest intentions in these practices (in mean score value), requiring professional competency in proposing sustainable strategies for ecotourism industry. In a developing country, it is found that key factors leading to the low participation of local residents include limited financial resources, insufficient knowledge and skills related to tourism services, hospitality, and business operations, as well as a lack

of support from government and stakeholders. These barriers hindered the effective participation of local communities in ecotourism and undermined progress toward sustainable development goals (Bhatta & Joshi, 2023). While participation in ecotourism planning and management of local residents is vital for its long-term success of ecotourism development, this complex process requires strategic planning, meaningful commitment to addressing various needs and viewpoints of communities.

Hypothesis 2a,b,c

his study additionally evaluated the impact of local people's perceptions on their attitude toward sustainable ecotourism development. The results indicated that perceptions of environmental, economic, and sociocultural sustainability had significant influences on attitude of local communities. Specifically, when residents perceived ecotourism as contributing positively to environmental conservation, economic opportunities, and the preservation of sociocultural values, they were more likely to adopt favorable attitude toward sustainable development. Similarly, earlier empirical studies in the tourism industry have also demonstrated that positive perceptions are key predictors of supportive community attitude (Li et al., 2014; Kim et al., 2015; Li et al., 2018; Landra et al., 2018; Peters et al., 2018). Furthermore, several prior studies have simply assessed descriptive analysis of residents' perceptions and attitude, as well as explored the correlations between these variables. In contrast, a survey conducted in a national park reported no statistically significant relationship between residents' perception of environmental benefits and their attitude toward sustainable ecotourism development (Partiro et al., 2023). This impact may vary depending on contextual factors such as location, type of activity, level of community involvement, or previous experiences with sustainable tourism development. Therefore, the current study attempted to contribute to the literature through empirical evidence in the context of sustainability ecotourism development in a developing country as Vietnam.

In specifically, this study emphasized that environmental aspect showed the most important contribution to residents' attitude because natural resources are the primary factors in developing ecotourism products. From the perspective of local communities, the environmental benefits associated with ecotourism promote greater interest, pride, and a sense of responsibility for sustainable development. Then, the perception on economic benefits of ecotourism created better attitude than the sociocultural aspect. Practically, the majority of local residents considered tourism as a tool for economic development; therefore, they show a positive attitude toward sustainable development strategies (Gursoy et al., 2002; Andereck & Vogt, 2000). Economic efficiency represented the success of the business, was easy to evaluate and promote, and brought a better attitude in their participation. In the tourism field, the literature has demonstrated a link between residents' attitude and their perception of positive impacts within the local community. It was discussed that tourism development come with economic benefits in exchange for social and environmental impacts (Harril, 2004). Besides, tourism development can play a significant role in ensuring effective conservation of natural resources and the environment, strengthening local cultural identities and enhancing the overall well-being of local people (Baloch et.al., 2023).

Within the framework of sustainable ecotourism development, this study proposed that enhancing local residents perceived benefits across three key dimensions—environmental, socio-cultural, and economic sustainability—can positively influence their attitude toward sustainable ecotourism initiatives. When local communities recognized meaningful benefits in these aspects, they were more likely to adopt supportive and proactive attitude toward sustainable tourism practices. In particular, environmental benefits should be emphasized alongside socio-cultural and economic gains, as they played a critical role in fostering a coherent and consistently positive local attitude toward ecotourism development. This integrated approach was consistent with the principles of sustainability and highlighted the comprehensive perceptions of local residents in sustainable ecotourism development.

Hypothesis 3

This study further established local residents' attitude as a significant determinant of their intention toward sustainable ecotourism development. The role of attitude as a predictor of behavioral intention has been extensively examined in tourism research, with numerous studies confirming that fostering favorable attitude among local residents can substantially enhance their willingness to engage in tourism-related initiatives (Nunkoo & Gursoy, 2012; Wu & Chen, 2016; Martin et al., 2017; Moghavvemi et al., 2017; Landra et al., 2018; Shen et al., 2019; Xu et al., 2022). Consistent with this body of work, the present study made a distinct contribution by providing empirical evidence specifically within the context of sustainable ecotourism in the Mekong Delta, Vietnam, thereby extending the applicability of these theoretical insights to a unique geographical and cultural setting.

The findings demonstrated that residents' intentions were not only shaped by their overall attitude but

also manifested across four interrelated dimensions: (1) the conservation of natural resources, reflecting the recognition of ecological preservation as central to ecotourism; (2) the preservation of cultural traditions, indicating the value placed on safeguarding local heritage; (3) sustainable community development, which underscores the aspiration for long-term socio-economic benefits; and (4) active participation in the planning and management of ecotourism development, highlighting the importance of inclusive governance and local empowerment. By identifying and empirically validating these dimensions, the study offered deeper insights into how attitude translate into specific forms of engagement, thereby informing more targeted strategies to foster community involvement in sustainable ecotourism initiatives.

Hypothesis 4a,b,c

Finally, to examine the mediating role of local residents' attitudes in the relationship between their perceptions and intentions toward sustainable ecotourism development, the bootstrapping technique was employed (Byrne, 2013). The analysis results of the indirect effect indicated that both direct and indirect effects were statistically significant. These provided evidences of partial mediations. Accordingly, the findings demonstrated that local residents' perceptions had direct impact on their intention to engage in sustainable ecotourism development, which was partially mediated by their attitude. Notably, the results revealed that perceived environmental benefits of local people had the strongest overall effect among the variables examined. This finding reinforced support for the first hypothesis and emphasized the critical role of perceived environmental benefits in sharping residents' intention to participate in sustainable ecotourism initiatives.

Within the context of the ecotourism, the environmental benefits perceived by local residents have become the most influential determinant in shaping both their psychological and behavioral responses. This finding highlighted the central role of environmental considerations in sustainable ecotourism development and reflected the unique nature of ecotourism as a tourism model that fundamentally depends on the conservation and appreciation of natural environments. Furthermore, the emphasis on environmental sustainability is consistent with the long-term interests of local residents in maintaining the ecological integrity of their communities, which is often threatened by unsustainable tourism practices. Perceptions of tangible environmental benefits—such as improved conservation efforts, enhanced local environmental quality, and increased awareness of ecological issues—can foster a sense of pride, stewardship, and ownership among residents. These emotions, in turn, promote greater community involvement and support for sustainable ecotourism development. Overall, the prominent role of perceived environmental benefits in shaping residents' attitudes and behavioral intentions highlights the need for policymakers, planners, and tourism developers to prioritize environmental protection in sustainable ecotourism development strategies.

Conclusion and limitations

The current study primarily sought to explore various levels of local residents' behavioral intention toward sustainable ecotourism development in the Mekong Delta, Vietnam, and to identify the key determinants influencing these intentions. The dimensions of perceptions, attitudes, and behavioral intentions were adopted from established literature and used as constructs to examine their relationships within the proposed research model. The attributes of these three concepts were determined and validated through both qualitative and quantitative research methods. The proposed model involving such attributes and other related variables was developed to identify the formation of local residents' behavioral intention toward sustainable ecotourism development. Additionally, the current study contributed to the literature and identified sustainable behavioral intention as second-order variable through four dimensions (natural resources conservation, cultural tradition preservation, sustainable community development, and participation in planning and managing ecotourism development). Overall, the results showed that all three aspects of residents' perceptions had significant and positive effects on both their attitude and intention. Furthermore, residents' attitude was also identified as a significant predictor of behavioral intention. These findings provided empirical support for all proposed hypotheses, confirming both the direct effects of perceptions on intention and the mediating role of attitude in this relationship. These results highlighted the important role of perception factors in shaping community engagement in sustainable ecotourism strategies and reinforced the need for participatory and inclusive planning processes that address environmental, sociocultural and economic aspects. Especially, the results underscored the central importance of environmental considerations in the development of sustainable ecotourism and reflects the distinctive character of ecotourism as a tourism model inherently reliant on the conservation and appreciation of natural environments. By adopting a multidimensional approach and focusing on the specific context of sustainable eco-

tourism, this study adds depth to the existing body of knowledge and offers insights that can inform future planning and policy-making processes.

This study is limited by its exclusive focus on local residents' perspective, which constrains the generalizability of findings to other stakeholder groups in ecotourism. The data were specific to a single geographical region (the Mekong Delta, Vietnam), a single tourism category (ecotourism), and one stakeholder group (local residents). Future research could replicate the study with other stakeholders to enable cross-group comparisons, extend the investigation to different regions for destination-based comparisons, and track potential variations over time. Especially, further study research should include local residents who are not currently employed in ecotourism-related activities. While this study focused on individuals directly involved in ecotourism, residents outside the sector may hold different perceptions and intentions toward sustainable ecotourism development. Including this group would provide a more comprehensive understanding of community-wide support and help identify additional factors influencing residents' future participation and behavioral intentions. Given the dynamic nature of ecotourism, the identified attributes will require periodic updates; thus, further qualitative research is recommended to capture emerging trends and evolving perceptions.

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Questionnaire

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Exploring Behavioral Intention Toward Sustainable Ecotourism Development among Local Residents Working in the Mekong Delta, Vietnam

Part I: Please write down answer or tick ✓ in ☐ which corresponds to your answer

A. Personal information

1. Gender: 1. ☐ Male 2. ☐ Female

2. Marital status: 1. ☐ Single 2. ☐ Married

3. Age: 1. ☐ 18-24 2. ☐25-34
3. ☐35-44 4. ☐ 45-55
5. ☐ >55

4. Highest education completed:

1. ☐ Lower high school 2. ☐ High school
3. ☐ Vocational school 4. ☐ Bachelor degree
5. ☐ Master degree 6. ☐ Doctor degree

5. How long have you been working at the ecotourism site in the Mekong Delta:

1. ☐ 3-5 years 2. ☐ 5-7 years
3. ☐ 7-9 years 4. ☐ More than 10 years

Part II :

(1) The following set of statement relates to Perceptions of Sustainable Ecotourism Development. Please indicate your level of agreement with the following statements using the corresponding scale: 1=strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree

No.	Perceptions of Sustainable Ecotourism Development	Level of agreement				
		1	2	3	4	5
I	**Economic sustainability**					
1	Increases additional income to local residents	1	2	3	4	5
2	Reinforces the local economy	1	2	3	4	5
3	Diversifies the local economy	1	2	3	4	5
II	**Sociocultural sustainability**					
1	Provides diverse cultural experiences, cultural exchange opportunities	1	2	3	4	5
2	Improves tourists' awareness and appreciation about local traditional and cultural value…	1	2	3	4	5
3	Upgrades local infrastructure, health care service, education…	1	2	3	4	5
4	Makes good interaction between local resident and tourist	1	2	3	4	5
5	Improves preservation activities for traditional and cultural ceremonies	1	2	3	4	5
6	Builds up local resident's confidence, self-esteem, pride, and dignity	1	2	3	4	5
7	Promotes the reputation of the local	1	2	3	4	5
III	**Environmental sustainability**					
1	Promotes environmental protection and improves quality of living environment	1	2	3	4	5
2	Makes opportunity for local resident actively participate in environment protection activities	1	2	3	4	5
3	Increases public environmental awareness and directs local resident toward appropriate behaviors	1	2	3	4	5

(2) The following set of statement relates to Attitude toward sustainable ecotourism development. Please indicate your level of agreement with the following statements using the corresponding scale: 1=strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree

No.	Attitude toward sustainable ecotourism development	Level of agreement				
		1	2	3	4	5
1	I am proud to participate in sustainable ecotourism development activities	1	2	3	4	5
2	I am favorable to participate in sustainable ecotourism development activities	1	2	3	4	5
3	I am enjoyable to participate in sustainable ecotourism development activities	1	2	3	4	5
4	I think that sustainable ecotourism development is important	1	2	3	4	5
5	I think that sustainable ecotourism development is necessary	1	2	3	4	5

(3) The following set of statement relates to Behavioral intention toward sustainable ecotourism development. Please indicate your level of agreement with the following statements using the corresponding scale: 1=strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree

No.	Perceptions of Sustainable Ecotourism Development	Level of agreement				
		1	2	3	4	5
I	**Natural resources conservation**					
1	I am willing to support and participate in natural resources conservation activities of the local government	1	2	3	4	5
2	I am willing to convince other local residents to minimize negative environmental impacts of their business/work	1	2	3	4	5
3	I am willing to promote and convince other local residents NOT to trade products which are made from rare animals and plants	1	2	3	4	5
4	I am willing to join in solving environmental issues	1	2	3	4	5
II	**Cultural tradition preservation**					
1	I am willing to participate in traditional events and festivals to attract more tourists	1	2	3	4	5
2	I am willing to participate in cultural tradition preservation activities	1	2	3	4	5
3	I am willing to study and promote local historical and cultural traditions	1	2	3	4	5
III	**Sustainable community development**					
1	I am willing to participate in waste reduction, water conservation practices	1	2	3	4	5
2	I am willing to join in solving security issues in the community	1	2	3	4	5
3	I am willing to use eco-friendly instruments, machines and sustainable practices to improve energy efficiency	1	2	3	4	5
4	I am willing to participate in and organize eco-friendly activities, events to improve tourists' awareness	1	2	3	4	5
IV	**Participation in planning and managing ecotourism development**					
1	I am willing to work in ecotourism enterprises where are applied sustainable practices	1	2	3	4	5
2	I am willing to participate in ecotourism development and planning	1	2	3	4	5
3	I am willing to encourage other local residents in preventing negative impacts for sustainable ecotourism development	1	2	3	4	5

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The Settlement Network in Spatial Plans in the Republic of Serbia – Key Dilemmas

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Abstract

The settlement network represents one of the key segments of spatial plans in Serbia, as well as part of the broader framework that encompasses the population and public services within a given territory. The ways in which this segment has been addressed in practice show considerable variation, which points to the absence of a clearly established and widely accepted approach. This paper presents a comparative analysis of spatial plans at the national, regional, and local levels, with the aim of examining the methodological and substantive consistency in the treatment of this segment, as well as the degree to which individual subsegments and related concepts are included. The results of the research made it possible to identify key uncertainties and inconsistencies, which may serve as a basis for improving planning practice, that is, for enhancing its quality and relevance in the planning of settlement network development.

Keywords: spatial plans; settlement network; comparative analysis; methodological consistency; spatial planning practice

Introduction

By definition, spatial planning represents an activity aimed at designing the rational use, organization, regulation, and protection of space (Živanović, 2025). In this context, settlements, as places of residence, social interaction, economic activities, education, and many other functions, that is, places where people's everyday life takes place, constitute one of the key elements of space as the subject of spatial planning. In many countries and regions, the settlement network serves as the backbone and starting point for comprehensive and regional development planning (Stamenković & Bačević, 1992; Prus et al., 2017; Sołtys, 2017, Song et al., 2023). Thus, although a settlement is one of the most important elements in spatial planning and often its basic unit, only the settlement network, i.e., settlements in their entirety, represent a true factor of development.

In spatial planning, the settlement network is treated as a whole in which each member has a specific position and role, depending on the functions it performs in relation to other settlements (Piha, 1986; Vresk, 1980).

The study and planning of the spatial-functional organization of the settlement network are grounded in the concept of settlement and function centrality, developed within Walter Christaller's theory of central places. Although for the first few decades Christaller's theory did not achieve wider scientific and professional recognition, from the mid-twentieth century onward it became widely accepted in both academic circles and planning practice (Berry & Harris, 1970; Preston, 1983; Taylor, P. & Hoyler, 2021; Parr, 2025).

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In this way, the concept of centrality became fundamental to the spatial organization of systems of various services and settlement networks. Despite certain limitations and criticisms, this concept continues to represent a cornerstone of contemporary analyses and planning approaches to the organization of settlement networks, having moved from the sphere of scientific research into professional practice (Radica et al., 1997; Kovačič et al., 2000).

A central settlement is most commonly defined as a settlement in which tertiary and quaternary functions are concentrated in order to serve not only its own population but also that of the surrounding gravitational area (Laci, 1979; Malić, 1991). In this context, centrality represents a measure of the concentration and diversity of central functions and, consequently, of a settlement's functional significance within the network (Vresk, 2002; Tošić, 2012; Lukić, 2012; Marinković, 2018). Although strongly correlated with settlement size, centrality is not reducible to demographic magnitude alone (Grgurević, 1993).

In the European planning context, the organization of settlement systems and public service provision represents an important component of spatial development, particularly at the regional and local levels (Malý, 2018). The conceptual foundations of European policy in this field were largely shaped by the adoption of key strategic documents that introduced the principles of polycentric development, territorial cohesion, and accessibility of services of general interest. The European Spatial Development Perspective (European Commission, 1999) was among the first comprehensive policy documents to promote the concept of balanced territorial development through polycentric urban systems and improved accessibility. Shortly thereafter, the Green Paper on Services of General Interest (European Commission, 2003) emphasized the importance of ensuring the quality, accessibility, and sustainability of public services across all territorial levels. In parallel with these policy developments, contemporary research on settlement hierarchies and spatial organization of urban systems has increasingly relied on quantitative and network-based approaches, including accessibility modelling and spatial interaction analysis, to better understand the functional roles of settlements within broader territorial systems (Brezzi & Veneri, 2015; Ouwehand et al., 2022). Recent analyses also indicate a growing integration of settlement hierarchy research with fields such as urban systems analysis, regional development, and spatial network modelling (Elburz & Çubukçu, 2025).

Serbian human and urban geography has conceptualized the settlement network as a complex and dynamic geographical category in which functional characteristics, that is, the level and structure of functional equipment, constitute a fundamental determinant of settlement development and hierarchical differentiation (Stamenković & Bačević, 1992; Tošić & Nevenić, 2006). The spatial-functional organization of the network reflects the interplay between spatial relations (location, physical-geographical characteristics, transport connectivity) and functional relations (functional capacities, spheres of influence, and inter-settlement interactions), with functional linkages being particularly dynamic and sensitive to socio-economic change (Stamenković, 1990). Since the mid-twentieth century, especially within the framework of the so-called "new geography," research has increasingly relied on systemic approaches and quantitative methods to analyze functional equipment, interaction patterns, and the optimal spatial organization of human activities (Tošić & Nevenić, 2008; Nevenić, 2012).

In spatial planning practice in Serbia, the theoretical foundations have been operationalized through the identification of central settlements, the establishment of hierarchical levels, and the delineation of their spheres of influence (Simonović & Ribar, 1993; Vresk, 2002; Tošić, 2012, Maksin et al., 2014). This hierarchical arrangement of settlements, where central places provide services to surrounding areas, is considered a key instrument for fostering integrated functional regions and balanced regional development, particularly in the context of Serbia's historically urban-centric development patterns, which have often marginalized rural areas (Đerčan et al., 2024).

Spatial planning in Serbia has a long tradition, with its roots in the early second half of the twentieth century and the adoption of the first law in this field in 1961. In the decades that followed, a large number of plans of different levels and scopes were prepared. This process eventually led to the adoption of numerous spatial plans, resulting in 2015 in the complete spatial planning coverage of the entire territory of the Republic of Serbia at all territorial levels. With the adoption of the new Spatial Plan of the Republic of Serbia, a new planning cycle will begin, for which the critical review of previous documents is of particular importance. In this context, the paper is directed toward their reassessment and the systematization of key dilemmas and inconsistencies in the treatment of the settlement network segment.

Research Hypotheses

Based on the current understanding of spatial plans and the literature on settlement networks, the following research hypotheses have been formulated:

1. The significance of the settlement network in existing spatial plans is not fully operationalized

through clear criteria, indicators, and implementation measures.

2. There is a lack of consensus regarding the subject matter and structure of the settlement network segment in spatial plans, both across different territorial levels and within the same level.

3. The treatment of the settlement network segment is primarily focused on describing the current state and the development processes that led to it, while the specification of adequate objectives and spatially defined planning solutions is limited.

These hypotheses will be tested through a comparative analysis of spatial plans at different territorial levels in the Republic of Serbia. They provide a basis for identifying potential inconsistencies, gaps, and opportunities to improve the quality of planning solutions, thereby contributing to both the scientific and practical value of the study.

Data and Methods

The methodological approach is based on a comparative and content analysis of spatial plans at different territorial levels in the Republic of Serbia, with the aim of examining how the settlement network segment has been addressed in spatial planning practice. Plans at the national, regional, and local levels were analyzed. Although the Law on Planning and Construction defines four types of spatial plans, Spatial Plans of Areas of Special Purpose were not considered, given that the settlement network segment in these plans is addressed selectively and primarily in relation to the designated special purpose. Settlements are examined in a fragmented manner, mainly through the lens of the impacts of the special purpose on their development or the constraints arising from it, which reduces the comparability of the settlement network segment with the corresponding segment in other types of spatial plans.

The research was conducted through several interrelated phases, including the identification, analysis, comparison, and evaluation of planning documents, as well as the formulation of conclusions and recommendations for improving the methodological approach.

The analysis relied on qualitative and quantitative interpretation of the content, applying a tabular systematization of data to enable a more precise comparison of the scope and manner in which the settlement network segment is treated. This approach made it possible to determine the presence or absence of certain analytical and planning elements, as well as differences in terminology, hierarchy of centers, and criteria for defining spheres of influence.

Results

Settlement network in spatial plans at the national level

Spatial Plan of the Republic of Serbia, 1996.

In the Spatial Plan of the Republic of Serbia adopted in 1996 (Official Gazette of the Republic of Serbia, No. 13/1996), the settlement network was addressed within the chapter *Population, Settlements, Activities, and Regional Division*, specifically in the subchapter *System of Urban Centers and Functional Areas*. The settlement network was treated in line with the classical approach to spatial development, with a clearly defined hierarchical structure and designated levels of centers. The starting point of this document was the problem of excessive concentration of population, economic activities, and services in Belgrade and along the main development axes, namely the Danube–Sava and Morava corridors. As a response, the concept of polycentric development was adopted, aiming to integrate the national center (Belgrade), macro-regional centers (Novi Sad, Niš, Priština), as well as regional and sub-regional centers into a functional network that would mitigate spatial disparities.

Spatial Plan of the Republic of Serbia 2010–2020.

In the second Spatial Plan of the Republic of Serbia 2010–2020 (Official Gazette of the Republic of Serbia, No. 88/2010), the *settlement network* segment was addressed as part of the chapter *Population, Settlements, and Social Development*, within the subchapter *Polycentric Urban System*. The plan highlighted key problems in Serbia's settlement network, including uneven spatial and demographic distribution, long-term rural depopulation, functional imbalances between central and surrounding settlements, insufficient polycentric development, and inconsistencies with EU (Eurostat) statistical standards.

As in the previous plan, the foundation was the pursuit of polycentric development, this time enriched with modern European concepts and aligned with spatial development strategies. The polycentric model was complemented by the concept of Functional Urban Areas (FUA), shifting the focus from a purely hierarchical organization of the settlement network to functional connections and the interactive relations among urban centers. This approach made it possible to view cities of different ranks as integrated nodes within broader regional and transnational systems. Special importance was given to medium-sized towns, which were recognized as key actors of decentralization and as counterbalances to Belgrade and other major centers.

Spatial Plan of the Republic of Serbia until 2035.

In the Draft Spatial Plan of the Republic of Serbia until 2035, which is currently in the process of adoption, the *settlement network* segment is addressed as part of the chapter *Population and Social Development*, primarily within the subchapters *Urban Systems and the Organization of Urban Settlements* and *Rural Development and the Organization of Villages*. Urban centers with functionally dependent surroundings are defined as the basic units of the spatial organization of the urban system. The shift in the approach to the organization of urban systems involves moving from a hierarchical model of urban centers to a model of urban areas with a "general urban context." This model aims to equalize conditions for quality living across the entire urban system by serving as a tool for more balanced and rational spatial, demographic, and economic development, thereby supporting a stable economy and improved quality of life for the population.

Taken as a whole, these plans reflect the evolution in the approach to the settlement network in Serbia: from an emphasis on internal hierarchy and the pursuit of demetropolization, toward a more contemporary model that integrates European concepts of polycentric development, functional urban areas, sustainable rural–urban relations, and, ultimately, the model of urban areas with a "general urban context."

Settlement network in regional spatial plans

According to the Rulebook on the Content, Method, and Procedure for the Preparation of Spatial and Urban Planning Documents (Official Gazette of the Republic of Serbia, No. 32/2019), regional spatial plans are required to address the settlement network within the planning solutions of the second planning area entitled *Spatial Development and Distribution of Population, Settlements, and Public Services: population; functional integration of settlements and centers; organization of public services*.

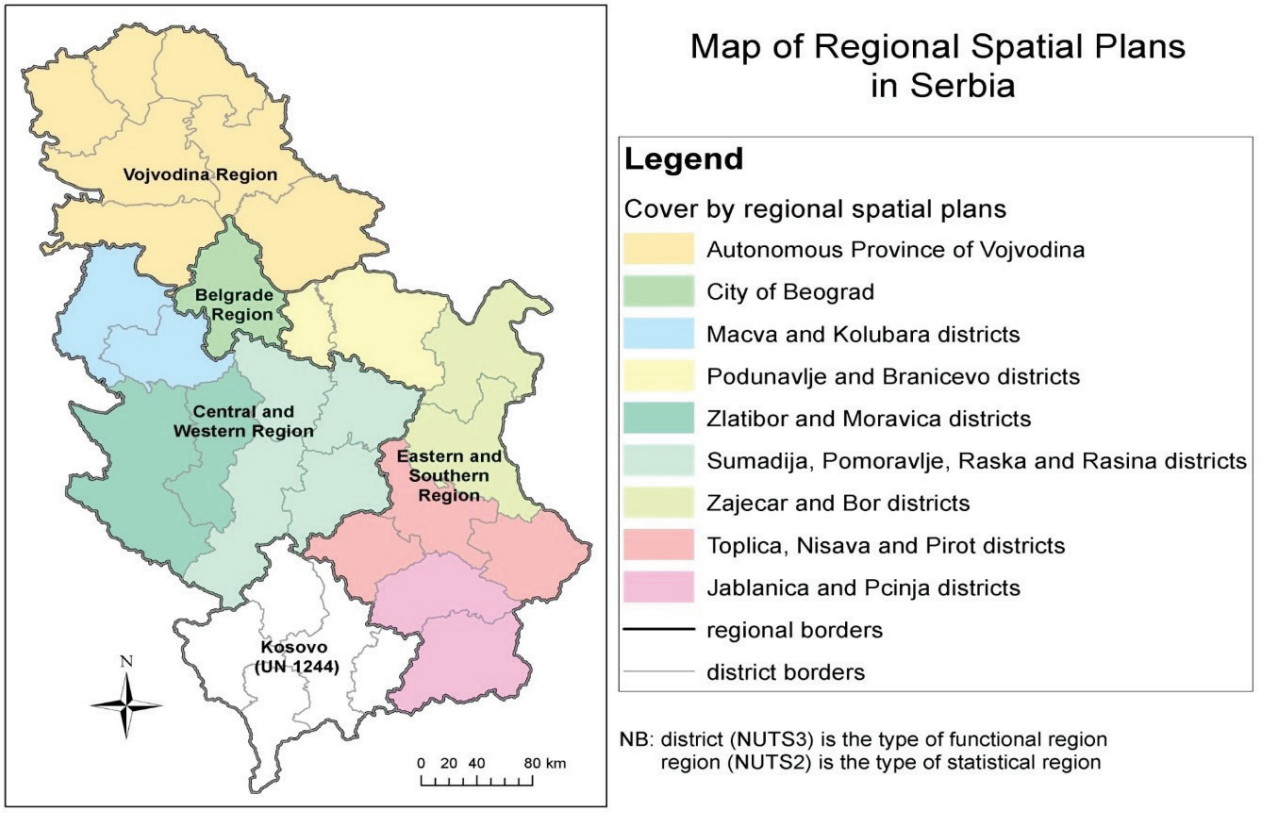

Figure 1. Map of Regional Spatial Plans
Source: Author's elaboration

In Regional Spatial Plans (RSPs), the settlement network is analyzed in the chapter entitled *Population, Settlement Network, and Public Services*. The only exceptions are the RSP of the Autonomous Province of Vojvodina, where the settlement network is addressed within two chapters (*Urban Settlement and System Development* and *Rural Development and the Organization of Villages*), and the RSP of the Administrative Area of the City of Belgrade, where the settlement network is treated in the chapter *Functional Integration of Settlements and Centers*. Based on the results of these analyses, goals and planning solutions are then defined. However, a detailed review of nine regional plans reveals that the *settlement network* segment is treated differently in terms of quality, scope, and content (Table 1).

Table 1. Settlement Network in Regional Spatial Plans

Contents of RSP related to the settlement network	Regional Spatial Plans								
	1	2	3	4	5	6	7	8	9
ANALYSIS AND ASSESSMENT OF THE SITUATION									
Number of settlements (urban/other)	+	+	+	-	+	+	+	+	+
Share of urban population	+	+	-	-	+	+	+	+	+
Functional Urban Areas	+	-	-	-	+	-	-	+	-
Average size of settlement area	-	-	+	-		+	+	-	-
Settlement size categories (by population)	-	+	+	-	+	+	+	+	+
Settlement size categories (by population) across the last three censuses	-	-	+	-	-	+	-	+	+
Typical rural settlements by municipalities and districts	-	-	-	-	+	-	-	-	-
Potentials and limitations	-	+	+	+	+	+	+	+	+
DEVELOPMENT GOALS	+	+	+	+	+	+	-	+	+
CONCEPTS, PROPOSALS, AND PLANNING SOLUTIONS FOR SPATIAL DEVELOPMENT									
Network of centers and settlements (number of hierarchical levels of centers)	5	5	8	4	5	5	5	4	5
Model of polycentric regional development – daily urban system	-	-	+	-	-	+	-	+	-
Integration, functional interdependence, and functional connectivity of settlement and spatial systems	-	-	+	-	-	+	+	-	-
Preservation and transformation of rural settlements and areas	-	-	+	-	-	+	+	+	-
Concept of spatial development of rural areas	-	-	-	-	+	-	-	-	-
Rural development and the organization of villages	-	+	-	-	-	-	-	-	-
Measures and instruments for the implementation of the plan	+	-	+	-	-	+	+	+	+
Planning solutions	-	-	2	-	-	2	2	2	1
Priority activities	5	3	2	-	14	7	6	7	4
Basic measures and instruments of settlement network development policy	-	-	+	-	-	-	-	+	+

Legend: 1 - RSP of the Administrative Area of the City of Belgrade (Official Gazette of the City of Belgrade, No. 10/2004); 2 - RSP of the Autonomous Province of Vojvodina 2021–2035 (draft); 3 - RSP for the Nišava, Toplica, and Pirot administrative districts (Official Gazette of the Republic of Serbia, No. 1/2013); 4 - RSP for the Podunavlje and Braničevo administrative districts (Official Gazette of the Republic of Serbia, No. 8/2015); 5 - RSP for the Šumadija, Pomoravlje, Raška, and Rasina administrative districts (Official Gazette of the Republic of Serbia, No. 56/2010); 6 - RSP of the Timok Region (Official Gazette of the Republic of Serbia, No. 15/2009); 7 - RSP of the municipalities of Southern Pomoravlje (Official Gazette of the Republic of Serbia, No. 83/2010); 8 - RSP for the Zlatibor and Moravica administrative districts (Official Gazette of the Republic of Serbia, No. 219/2013); 9 - RSP for the Kolubara and Mačva administrative districts (Official Gazette of the Republic of Serbia, No. 11/2015)

\+ exists

\- does not exist

Source: Authors' research

The analysis of the *settlement network* segment shows that the manner of its treatment is largely determined by the specific approach developed within the institution responsible for preparing the plan. When plans are compared, certain differences in approach are observed, but even more pronounced are the similarities within the plans prepared by the same institution. In addition, methodological specificities are particularly evident in the RSP of the Autonomous Province of Vojvodina and the RSP of the Administrative Area of the City of Belgrade, which clearly differ from other regional plans.

In all RSPs, as a planning solution, either a five-level or four-level hierarchy of centers was defined, except in the case of Vojvodina where only urban centers were considered. An exception is the RSP of the Nišava, Toplica, and Pirot administrative districts, which distinguished eight different hierarchical levels of centers. The lowest hierarchical level included village community centers (centri zajednice naselja), local centers, or micro-development centers, which could again fall into categories such as subcenters, village community centers, or settlements with specific functions. In the RSPs, except those for Belgrade, Vojvodina, and the Kolubara and Mačva districts, centers at the lowest hierarchical levels were identified, while the definition of their zones of influence was left for elaboration within local spatial plans (SPLSGUs).

In the draft RSP of the Autonomous Province of Vojvodina for the period 2021–2035, the analysis and assessment of the settlement network are presented in two chapters, *Urban System and Urban Settlements* and *Rural Development and the Organization of Villages.* Planning solutions related to the settlement network are included in the chapter *Functional Integration of Settlements and Centers*, which consists of three subchapters: *Urban Systems*, *Urban Settlement Development*, and *Rural Development and the Organization of Villages*.

The RSP of the Administrative Area of the City of Belgrade was adopted in 2004, with amendments adopted in 2011. The settlement network was addressed in the chapter *Functional Integration of Settlements and Centers*. The analysis also partially refers to daily migration, which in other RSPs, where present (plans 3, 6, and 8), is included under the section *Concepts, Proposals, and Planning Solutions for Spatial Development*. In the SWOT analysis, no potentials or limitations directly concerning the settlement network were identified. Thus, potentials and limitations concerning the settlement network were defined in all RSPs except the plan relating to Belgrade. Furthermore, in the RSPs marked 3, 6, 7, 8, and 9, the potentials include a detailed elaboration of nodal centers and areas.

In addition to the hierarchy of centers (as a planning solution), in the RSPs marked 3, 6, 7, and 8, two additional planning solutions related to the settlement network were provided: Functional Strengthening of the Role of Urban Centers and Preservation and Transformation of Rural Settlements and Areas. In plan no. 9, another planning solution was given, entitled Development of Functions of Centers within the Settlement Network. These were further elaborated through four to seven priority activities. Priority activities were not defined in the plan for the Podunavlje and Braničevo districts.

Integration, functional interdependence, and functional connectivity of settlement and spatial systems were addressed only in three RSPs, namely those for the Nišava, Toplica, and Pirot administrative districts, the Timok region, and the municipalities of Southern Pomoravlje. In the same plans, as well as in the plan for the Zlatibor and Moravica districts, the topic Preservation and Transformation of Rural Settlements and Areas was also included.

Measures and instruments for the implementation of the plan in the field of settlement networks were not defined in the RSPs for Vojvodina, the Nišava, Toplica, and Pirot districts, and the Šumadija, Pomoravlje, Raška, and Rasina districts, whereas they were included in the remaining six RSPs. Similarly, measures and instruments of settlement network development policy were not defined in three plans, namely those for Vojvodina, the Nišava, Toplica, and Pirot districts, the Zlatibor and Moravica districts, and the Kolubara and Mačva districts.

Settlement network in spatial plans of local self-government units

All local self-government units (LSGUs) in the Republic of Serbia have adopted spatial plans. The analyzed sample of eight Spatial Plans of Local Self-Government Units (Table 2) was selected so as to include territories with different physical-geographical characteristics (such as their position within the national territory, spatial size, relief, and natural resources) as well as different socio-geographical characteristics (including the level of economic development, transport position, and population dynamics). Another criterion considered during the selection was that the plans were prepared by different planning institutions (Figure 2).

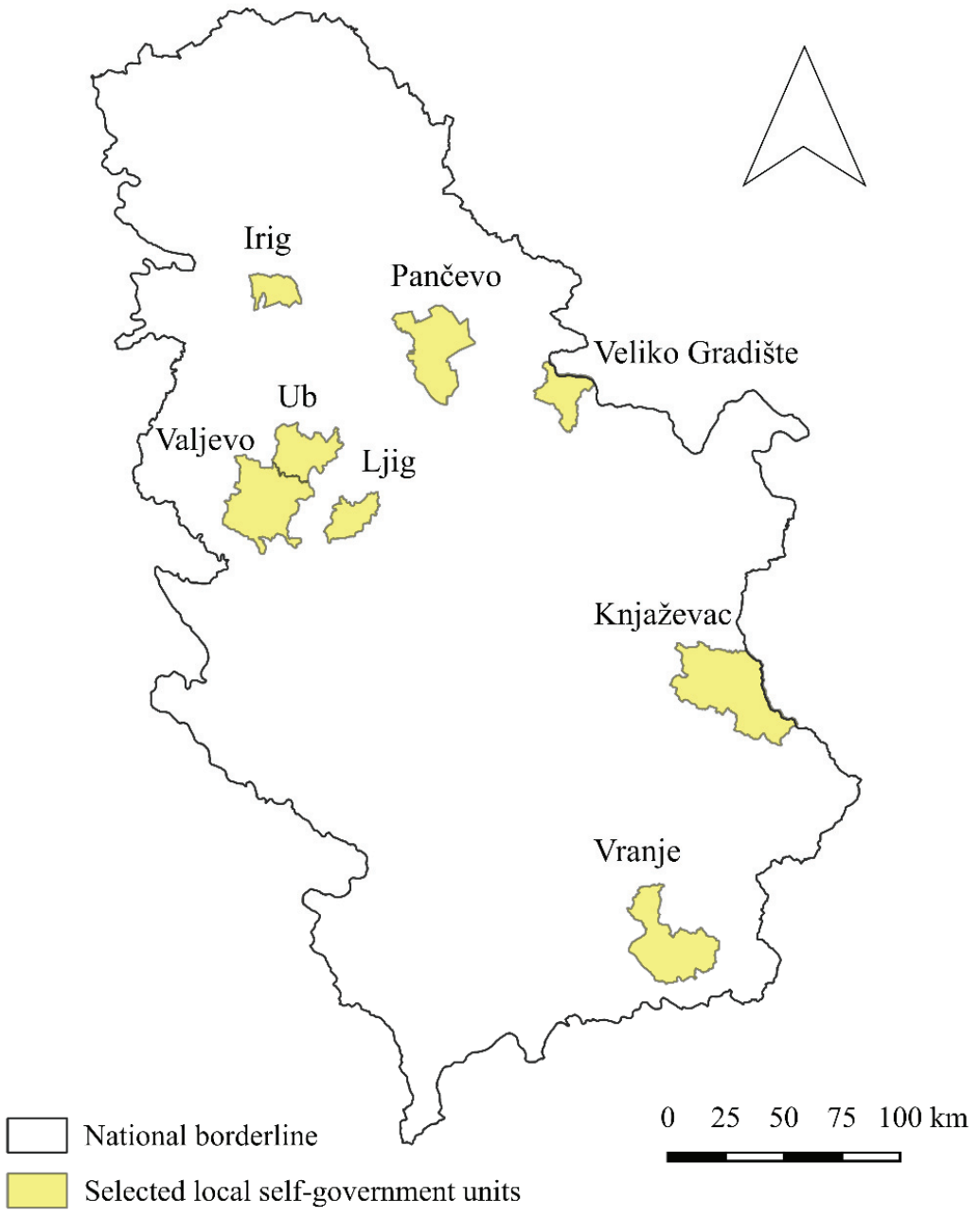

Figure 2. Analyzed sample of Spatial Plans of Local Self-Government Units
Source: Author's elaboration

According to the Rulebook on the Content, Method, and Procedure for the Preparation of Spatial and Urban Planning Documents (Official Gazette of the Republic of Serbia, No. 32/2019), in SPLSGUs the settlement network must be addressed within the planning solutions of the third planning area, entitled *Spatial Development, Distribution of Population, and Settlement Network and Public Services* (population; relationship between urban and rural settlements and functional integration of settlements and centers, organization of public services, etc.).

With the latest amendments to the Rulebook, the section concerning the analysis and assessment of the current situation was removed from the starting basis for the preparation of SPLSGUs. An analysis of several SPLSGUs shows that this section has generally been omitted in plans adopted after these amendments (Irig, Veliko Gradište, Ub). In the SPLSGU of Ljig, however, the analysis and assessment of the situation remain an integral part of the plan, even though it was prepared after the mentioned amendments to the Rulebook.

Table 2. Settlement Network in Spatial Plans of Local Self-Government Units

Contents of SPLSGUs related to the settlement network			SPLSGUs					
	1	2	3	4	5	6	7	8
ANALYSIS AND ASSESSMENT OF THE SITUATION								
Settlement network	+	-	+	-	+	+	+	-
Settlement size categories (by population) across the last three censuses	+	-	-	-	-	-	+	-
Spatial-functional organization of settlements	-	-	-	-	+	-	-	-
Functional determinants of the settlement network	-	-	-	-	+	-	-	-
Potentials and limitations	-	-	-	-	-	+	+	-
GOALS – settlement network	-	+	+	+	+	+	+	+
PLANNING SOLUTIONS – settlement network								
Relation between urban and rural settlements and functional integration of settlements and centers: hierarchy of centers	+	+	+	+	+	+	+	+
Coverage of village communities (Serbian: zajednice naselja)	+	+	+	+	-	+	+	-
IMPLEMENTATION – settlement network	-	-	-	-	+	+	+	+
Priority planning solutions, activities, and projects	-	+	-	-	+	+	+	+

Legend:
1– Ljig (Official Gazette of the Municipality of Ljig No. 4/2021), 2 – Irig (Official Gazette of the Municipality of Irig No. 39/2021), 3 – Vranje (Official Gazette of the City of Vranje No. 4/2016), 4 – Veliko Gradište (Official Gazette of the Municipality of Veliko Gradište No. 25/2021), 5 – Pančevo (Official Gazette of the City of Pančevo No. 22/2012), 6 – Valjevo (Official Gazette of the City of Valjevo No. 3/2013), 7 – Knjaževac (Official Gazette of the Municipality of Knjaževac No. 9/2011), 8 – Ub (Official Gazette of the Municipality of Ub No. 9/2012)
\+ exists
\- does not exist

Source: Authors' research

Within the planning solutions, the settlement network is most often addressed in the chapter entitled *The Relationship Between Urban and Rural Settlements and the Functional Integration of Settlements and Centers*. In addition, there is a wide range of chapter titles related to the settlement network: *Network and Function of Settlements* (Pančevo), *Settlement Network and Functional Zoning of the Municipality* (Veliko Gradište), *Development of the Settlement Network, Rural Settlements, and Areas* (Knjaževac), *Concept of Development and Organization of the System of Settlements and Centers* (Vranje), *Organization of the Settlement Network and Rural Areas* (Valjevo), etc.

Within chapters under these titles, a hierarchy of centers is defined, most often three-tiered (two-tiered in Veliko Gradište, four-tiered in Knjaževac, and single-tiered in Ljig). At the top of the hierarchy is the LSGU center, while at the bottom are the primary rural settlements. Between these two categories, different types of centers are defined:

- In the plan for Ljig, besides the municipal center to which all settlements gravitate, no other centers are identified.
- In the plan for Irig, in addition to the municipal center, the following levels are defined: First- and Second-Level Village Community Centers.
- In the plan for Vranje, apart from the municipal center, Village Community Centers and Rural Settlements with a Developed Center are distinguished.
- In the plan for Veliko Gradište, Sub-Municipal Centers are the only hierarchical tier between the municipal center and the primary rural settlements.
- In the plan for Pančevo, besides the LSGU center, Larger Local Centers and Local Centers are defined.
- In the plan for Valjevo, in addition to the LSGU center, Subcenters and Village Community Centers (or Micro-Development Centers) are distinguished. Furthermore, two categories of settlements are noted: more developed villages and settlements with specific functions.
- In the plan for Knjaževac, besides the municipal center, Sub-Municipal Centers, Local Centers, and Settlements with Tourist Functions are identified.

- In the plan for Ub, alongside the municipal center, two more types of centers are noted: Village Community Centers and Local Centers.

The analysis of local-level spatial plans unequivocally indicates the absence of consensus regarding the terminology for centers in rural areas that occupy hierarchical levels between the LSGU center and primary settlements, distinguished by a certain development of central functions. In addition to village community centers, which are most frequently included in local hierarchies, other terms are encountered, such as sub-municipal centers, subcenters, secondary centers, development centers, development nuclei, local centers, village centers, rural settlements with a developed center, etc.

Gravitational spheres, i.e., the settlements belonging to the zones of influence of centers identified in rural areas, are precisely defined in most SPLSGUs analyzed, with the exceptions of Pančevo and Ub.

Regarding the implementation of planning solutions in the area of settlement networks, this is generally expressed through priority planning solutions, activities, and/or projects. In some plans, the implementation section carries titles such as *Development and Organization of Centers in the Settlement Network* (Valjevo), *Functional Strengthening of the Municipal Center and Preservation and Transformation of Rural Settlements* (Knjaževac), or, in accordance with the planning part, *The Relationship Between Urban and Rural Settlements and the Functional Integration of Settlements and Centers*. However, in the plans for Ljig, Vranje, and Veliko Gradište, no priority planning solutions, activities, and/or projects related to the settlement network were defined.

Discussion

The analysis of the theoretical and planning framework for addressing the *settlement network* segment, as well as the content of selected spatial plans at different territorial levels, provides the basis for identifying and systematizing dilemmas and inconsistencies that are essential for improving the planning approach to this segment in the future.

Although the present analysis does not aim to provide a comprehensive evaluation of planning quality at each territorial level, the identified dilemmas point to several structural issues that may influence the coherence, transparency, and implementation capacity of spatial plans. These findings therefore provide an analytical basis for future research that could examine these implications in greater methodological depth.

Differences in the number and themes of subsegments in spatial plans (at different or within the same territorial levels)

The textual and tabular parts of the analysis clearly point to the absence of a basic consensus regarding the subject matter and structure of the *settlement network* segment in spatial plans, both across different territorial levels and within the same level. More specifically, apart from the definition of settlement hierarchy and the spheres of influence of central settlements (within which a pronounced terminological and methodological diversity is evident), none of the other subsegments of the analytical, conceptual, or implementation sections were identified as common to all analyzed spatial plans.

From the perspective of ensuring a minimum level of quality and content consistency in spatial plans, this situation raises the issue of the need to define a more uniform structure for this segment, one that would apply to all planning document developers in the Republic of Serbia. In other words, such variability in the number and thematic scope of subsegments may have several important implications for planning quality, coherence, and implementation. First, the lack of a more standardized structure reduces the comparability of spatial plans across territorial levels, which complicates vertical coordination within the planning system. Second, uneven analytical frameworks may lead to selective or incomplete consideration of key settlement network issues, thereby affecting the reliability of planning solutions. Third, differences in the treatment of conceptual and implementation subsegments may weaken the operational dimension of plans, resulting in documents that remain predominantly descriptive or strategic, without sufficiently defined instruments for implementation and monitoring. Ultimately, this heterogeneity may contribute to inconsistencies in decision-making, difficulties in evaluating plan effectiveness, and reduced transparency of the planning process.

The connection between segments in (strong) causal-sequential relations

The segments *population*, *settlement network*, and *public services*, although combined under a common chapter title, are in practice addressed as separate units. Moreover, the fact that they are often prepared by different experts (in some cases from multiple institutions) leads to insufficient integration, meaning that cause-and-effect relationships among them are

not considered to a significant degree. In the context of planning the development of the settlement network, this specifically implies a questionable grounding in demographic trends and the planned functional provision of settlements with public services. Since the establishment of the spatial-functional organization of the settlement network is practically a reflection of the existing or planned spatial organization of settlement functions (Popović, 2025), potential inconsistency is evident in terms of the unclear manner of linking future population dynamics (if included at all in a given spatial plan) with the planning of public service development (Živanović & Popović, 2024).

Insufficient integration between these causally interrelated segments may have particularly important implications for planning the development of the settlement network. If demographic trends and projections are not consistently aligned with the planning of public services, the resulting spatial-functional organization of settlements may be based on unstable or contradictory assumptions. This may lead to the designation of settlement hierarchies and spheres of influence that are not supported by realistic population dynamics or service capacities. Consequently, central settlements may be overburdened or underutilized, while smaller settlements may face further functional decline. In addition, the absence of clearly articulated causal linkages complicates the formulation of coherent settlement development strategies, as decisions regarding the strengthening, transformation, or specialization of settlements risk being made without a reliable demographic-functional foundation. During implementation, such inconsistencies may generate difficulties in prioritizing investments, aligning sectoral policies, and evaluating whether the planned settlement network structure corresponds to actual development processes. Ultimately, the fragmentation of these segments undermines the role of spatial plans as instruments for guiding balanced and functionally sustainable settlement network development.

Representation and approach to defining goals and concrete planning solutions

Similar to the situation in addressing the *public services* segment identified by Živanović and Popović (2024), in the case of the *settlement network* segment it can also be noted that greater emphasis is placed on the analytical part, that is, on the description of the existing situation and the developmental processes that led to it, while less attention is given to concretization in the form of defining adequate goals and spatially determined planning solutions.

Such an imbalance between analytical content and the definition of goals and concrete planning solutions may reduce the effectiveness of settlement network planning. When analytical insights are not translated into clearly articulated objectives and spatially explicit interventions, the strategic direction of settlement development remains ambiguous. This may weaken the rationale for defining settlement hierarchies and functional roles, while limiting the operationalization of concepts such as polycentric development or functional integration. In the implementation phase, insufficient concretization may lead to inconsistent interpretation of planning intentions, selective investment decisions, and difficulties in monitoring the achievement of development objectives. Ultimately, spatial plans risk functioning more as descriptive than as proactive instruments of settlement network transformation.

The relationship between the spatial organization of individual public services and the settlement network

The spatial organization of public service facility networks represents the basic determinant for defining the functional hierarchy of settlements and their spheres of influence. In order to maximize accessibility in line with the realistic possibilities of equipping settlements, the main idea of public service development is their concentration in a smaller number of settlements, which thereby gain greater hierarchical significance. Reference maps and accompanying textual descriptions are focused on highlighting these better-equipped, i.e., central settlements, and defining their predominant spheres of influence, without examining in detail the problems arising from differences in the spatial organization of individual public service facilities (Figure 3). In this context, as also emphasized by Živanović and Popović (2024), the open question is to what extent the different spatial organization of individual public services is taken into account in planning the spatial-functional organization of the settlement network. Consequently, a dilemma arises as to whether addressing this segment is substantively oriented toward solving concrete problems of service provision to the population.

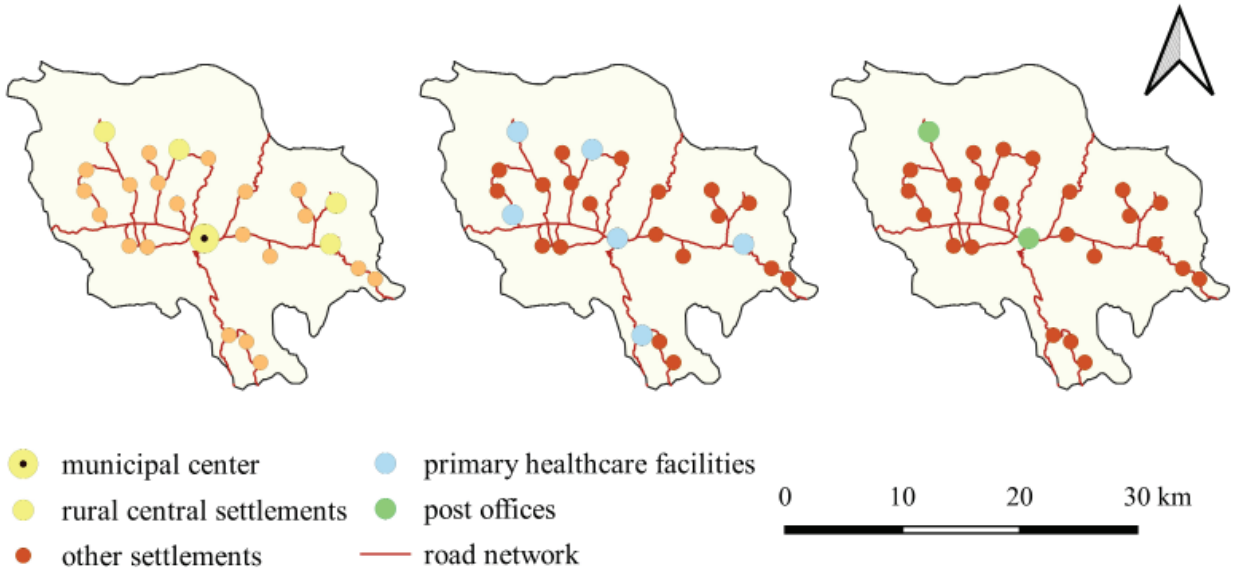

Figure 3. Differences in the spatial distribution of central settlements in relation to the spatial distribution of individual functions.
Data source: Spatial Plan of the Municipality of Sokobanja

Failure to adequately account for differences in the spatial organization of individual public services may significantly affect the validity of the planned settlement hierarchy and spheres of influence. If the functional significance of settlements is inferred from aggregated or simplified representations of service provision, important discrepancies between sectoral service networks may remain obscured. This may result in the designation of central settlements whose functional roles are not consistently supported across different service domains. In planning terms, such inconsistencies can weaken the reliability of spatial-functional models of the settlement network and reduce their capacity to reflect actual accessibility conditions. During implementation, this may contribute to uneven service availability, inefficient allocation of investments, and difficulties in coordinating sectoral policies. Ultimately, insufficient consideration of service-specific spatial patterns may limit the extent to which settlement network planning effectively addresses real problems of population service provision.

Consistency of methodology for establishing the spatial-functional organization of the settlement network

In practice, the spatial-functional organization of the settlement network entails establishing a functional hierarchy of settlements and defining the gravitational spheres of central settlements. Although spatial plans generally state that this is based on a set of relevant factors, most often including traditional ties between settlements, the spatial distribution of public facilities, characteristics of the transport network, and similar, methodologically it remains unclear how the integration of these factors leads to the concrete, spatially defined solutions that are proposed. When defining the functional hierarchy of settlements, although certain guidelines exist for distinguishing between different ranks of central settlements, methodological clarification is lacking on several precise issues: how the functional threshold for defining central settlements is determined in specific cases, how the number of settlement ranks is decided, how differences among settlements of the same rank are established, etc. Regarding the definition of spheres of influence, in addition to the previously mentioned dilemma concerning the relationship between individual public services and the settlements in which they are located, there is no clearly defined criterion for determining the boundaries of influence zones. Given this situation (while acknowledging the real impossibility of establishing an approach that could be entirely universally applicable across different regional/local contexts), the question arises whether this process is excessively left to the *discretionary judgment* of the plan developers.

Methodological ambiguity in establishing the spatial-functional organization of the settlement network may affect the robustness and credibility of planning solutions. Without sufficiently transparent procedures for defining settlement hierarchy, functional thresholds, and spheres of influence, resulting classifications may appear insufficiently justified. This can weaken the analytical foundation of the plan and reduce confidence in the proposed spatial-functional

model. In practice, inconsistent methodological approaches may produce variations in the identification of central settlements and the delineation of influence zones, complicating inter-territorial comparisons. During implementation, such uncertainties may hinder decision-making, coordination, and investment prioritization. Ultimately, excessive reliance on discretionary judgment may undermine the consistency and predictability of settlement network development.

Terminological consistency in planning the spatial-functional organization of the settlement network

Partly in connection with the previously mentioned methodological issues regarding the determination of the number and characteristics of specific settlement ranks, there is a pronounced diversity of terms used to designate them. The results of the conducted analyses indicate that this situation is particularly noticeable at the local level, where practically every one of the eight analyzed plans employs a different terminology for designating certain hierarchical ranks of settlements (as well as a different number of ranks themselves). The diversity in defining settlement ranks may have important implications for the coherence and practical application of settlement network planning. The use of inconsistent or non-standardized terminology can generate ambiguity in interpretation, hinder communication between planning levels, and complicate the comparison of planning solutions across territories. In methodological terms, differing labels for similar hierarchical categories may obscure substantive similarities or differences between settlements. During implementation, terminological inconsistency may contribute to misunderstandings among institutional actors, challenges in aligning sectoral policies, and reduced clarity in monitoring and evaluation processes. Ultimately, the absence of a more harmonized terminological framework may weaken the overall consistency of settlement network development policies.

Conclusion

From the presented theoretical framework and the analysis of selected spatial plans, it is evident that the *settlement network* segment is addressed in different ways depending on the territorial level, and within the same levels largely depending on the institution responsible for plan preparation. This diversity is reflected in the structure and content of planning documents, as well as in the methodological foundations and terminology used in defining categories and subsegments.

At the national level, as might be expected, there has been constant innovation in planning approaches to this segment. Each of these approaches reflected the dominant socio-economic circumstances of its time, with a clear effort to mitigate depopulation, encourage diversification of economic activities, and improve the socio-economic position of rural communities identified as the most vulnerable.

Regional spatial plans, as the intermediate level between national and local, display considerable heterogeneity. Differences are evident in the structure of the *settlement network* segment, in the number and content of subsegments, as well as in the methodology used to define the settlement hierarchy and their spheres of influence.

At the local level, i.e., in spatial plans of local self-government units, the diversity is even more pronounced. The analyzed examples show that there is practically no elementary consensus regarding uniform criteria, methodology, and terminology for the spatial-functional organization of local settlement networks. This situation can create confusion not only in the process of drafting documents but also in the actual implementation of planning solutions.

In general, a significant problem is the lack of a clearly defined methodology for determining the functional hierarchy and spheres of influence of settlements at all territorial levels. In addition, the analysis revealed limited integration of the segments population, settlement network, and public services. Although formally combined within the same chapter, in practice they are often prepared by different experts, which results in insufficient elaboration of cause-and-effect relationships. Without an integrated approach, this segment risks remaining at the level of general assessments and cartographic representations, without sufficient connection to the real needs of the population.

Importantly, the findings of this research do not imply the need for a rigidly uniform methodology applicable to all spatial plans regardless of scale or territorial context. Given that spatial plans form a hierarchical system addressing territories of varying size, complexity, and functional characteristics, a certain degree of methodological adaptation is both necessary and justified. Rather than advocating strict uniformity, this paper highlights the need for establishing a minimum level of methodological and terminological consensus. Such a framework would support comparability, improve coherence across planning levels, and enhance the transparency and practical applicability of planning solutions, while still allowing context-sensitive approaches. Strengthening this balance between consistency and flexibility would contribute to the

more effective planning and implementation of settlement network development policies.

With the adoption of the new Spatial Plan of the Republic of Serbia and the start of a new planning cycle, there is an opportunity to mitigate and potentially overcome the identified inconsistencies. The analysis of past experiences can serve as a foundation for more precise definition of methodological procedures and content, as well as for adopting a specific terminology whose applicability would be tested in practice. In this way, the quality of addressing the settlement network as a segment of fundamental importance for balanced spatial development and the quality of life of the population in Serbia would be enhanced.

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Air Temperature Fluctuations in Sarajevo and Climate Projections in the Context of Climate Change

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Abstract

When discussing climate change, we primarily refer to global warming, that is, the in-crease in air temperature which directly affects other climatic elements. The Sarajevo meteorological station has a homogeneous series of observations and measurements of this climatic element spanning 136 years (from 1888 to 2024) without interruption, which represents a highly representative period for monitoring changes in air temperature and its fluctuations in the study area. The main characteristic of the thermal regime in the Sarajevo area is warming. The mean annual temperature for the entire instrumental period is 9.8°C, with a linear warming trend of 1.7°C. In addition to the general analysis of air temperature and its fluctuations in Sarajevo over this long-term observational period, special attention will be devoted to projecting this climatic element up to the year 2100 under different climate scenarios.

Keywords: climate change; air temperature; climate scenarios; Sarajevo

Introduction

Climate change represents one of the most important challenges of the modern era faced by human society, significantly affecting natural processes on Earth. Several decades ago, climate change was discussed primarily within the scientific community, whereas today the processes of climate change and the associated natural phenomena are evident to the majority of the global population. It is noticeable that air temperatures are steadily increasing and that predicting weather conditions for any given month of the year has become increasingly difficult (Berdin et al., 2018), all as a result of intensified climate change processes. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "…any change in climate over time, whether due to natural variability or as a result of human activity."

The United Nations define climate change as long-term shifts in temperatures and weather patterns. They also emphasize that such changes may result from natural factors (e.g., periodic and secular perturbations of the Earth's orbit around the Sun, Earth's motion, large quantities of aerosols emitted during volcanic eruptions, wildfires, etc.) as well as anthropogenic factors, which have become increasingly pronounced in recent decades (Popović & Vuković, 2019; Hrelja & Drešković, 2025).

Human influence on climate is manifested through various forms of activities and interventions, including deforestation and the expansion of agricultural and urbanized areas. Through the consumption of fossil fuels

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(in energy production, transportation, agriculture, etc.), humans contribute to increased concentrations of carbon dioxide (CO_2) and other gases in the atmosphere, thereby intensifying the greenhouse effect and consequently global warming. The most important greenhouse gases naturally present in the atmosphere, which absorb longwave terrestrial radiation, include water vapor and carbon dioxide (CO_2), followed by methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Despite internationally defined obligations, atmospheric carbon dioxide concentrations continue to rise and, according to the World Meteorological Organization, reached record levels in 2019, being nearly 150% higher than in 1750 (Hrelja & Drešković, 2025). From this perspective, there is an urgent need to establish and implement mandatory policies aimed at reducing greenhouse gas emissions, particularly in the fossil fuel, waste, and agricultural sectors.

According to meteorological measurements, global temperatures have increased by 1.1 °C compared to the pre-industrial period. The global mean temperature between 2013 and 2023 was 1.19–1.22 °C warmer than the pre-industrial level, making this decade the warmest on record. However, regional differences in temperature increase are evident. Temperatures across the European continent rose even faster during this period, by 2.12–2.19 °C (Drešković & Hrelja, 2025b). Countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) have committed to limiting global temperature increase to well below 2 °C above pre-industrial levels, while striving to limit warming to 1.5 °C (Hrelja & Drešković, 2025).

The regional temperature of Southeast Europe increased during the second half of the 20th century. The period 1991–2020 is 0.5–1.0 °C warmer compared to the reference period 1990–1961, and warming will continue in the coming decades (Popov et al., 2018). The average temperature increase in the Western Balkans region is 1.2 °C compared to earlier climatic periods (Vuković & Vujadinović, 2018). By the end of the 21st century, further warming of between 1.7 and 4.0 °C is expected, depending on the influence of physical-geographical and socio-geographical factors. The Mediterranean region is warming approximately 20% faster than the global average and is considered one of the world's climate change hotspots. The average temperature increase in the Mediterranean has already reached 1.54 °C, and it is estimated to reach 2.2 °C by 2040 relative to the pre-industrial period. Consequently, Mediterranean countries are particularly exposed to the negative impacts of climate change (Vitali, 2021).

Regarding changes in precipitation, a generally balanced trend with pronounced regional variations is observed. In some areas, particularly northern regions, a slight increase in precipitation may occur, while southern areas, especially coastal zones, are expected to experience a decrease, leading to more frequent droughts, particularly during the summer months (Vuković & Vujadinović, 2018).

Bosnia and Herzegovina is located in the central part of the northern temperate climate zone and covers an area of 51,209 km², of which 51,179 km² is land and 12.2 km² is marine area (Drešković & Mirić, 2017a). The general climatic characteristics of Bosnia and Herzegovina are determined by the interaction between climatic factors and the quantitative and qualitative values of climatic elements. The most important climatic modifier is the country's orographic structure. The peripannonian region of Bosnia is widely open to the intrusion of cold continental air masses from the north and northeast, which penetrate deep into the mountainous–basin interior along the valleys of major rivers (Drina, Bosna, Vrbas, Sana, and Una). Nevertheless, despite the openness of the Pannonian Basin, the influence of these air masses is significantly reduced by the Alpine, Carpathian, and Balkan mountain systems surrounding the area from the north, northeast, and east (Drešković & Mirić, 2017a).

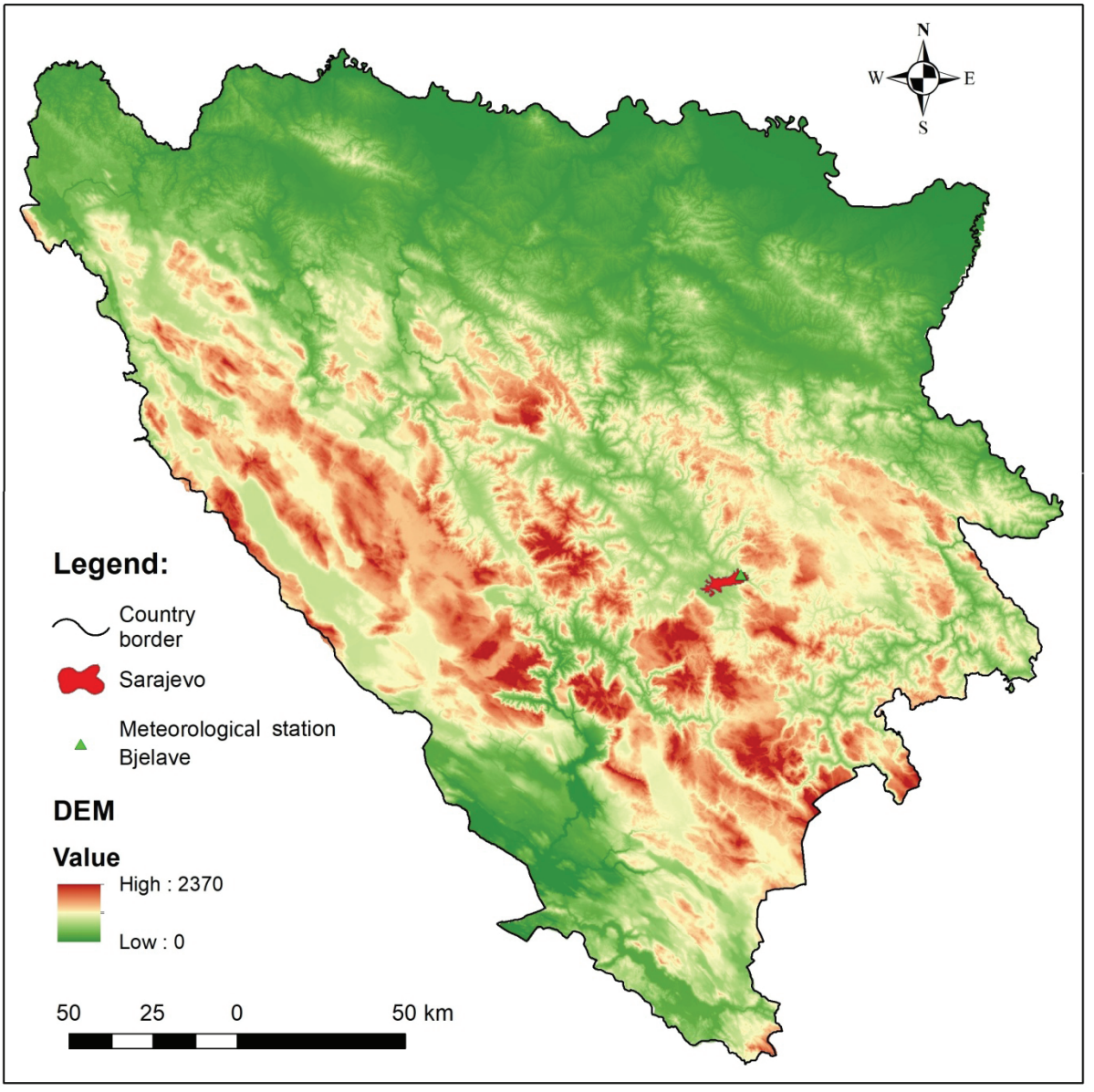

Figure 1. Geographical location of Sarajevo
Source: Authors, based on GIS data from the Department of Geography, University of Sarajevo.

At regional and local scales, orographic characteristics represent the most significant climatic factor. The Sarajevo Basin is located in an intramontane depression, with an average elevation of approximately 500 m, between the Bjelašnica and Igman massifs to the southwest and low- to mid-altitude mountainous terrain to the northeast. These physical-geographical characteristics, together with socio-geographical processes such as urbanization, land-cover changes, and the impact of construction on urban ventilation corridors, significantly influence the characteristics of the local climate in Sarajevo.

Research results show that a significant warming trend is present across the entire territory of Bosnia and Herzegovina. Both maximum and minimum temperatures have increased over the observed period. The rise in warm temperature extremes is particularly pronounced, while cold extremes show a decreasing trend (Popov et al., 2018). In Bosnia and Herzegovina, climate change has intensified over the past three decades (1995–2025), manifested through rising air temperatures, altered precipitation patterns, more frequent heatwaves, and changes in climate indices (Trbić et al., 2026). Research indicates that temperature increases in some of the largest urban centers in Bosnia and Herzegovina have exceeded the 2 °C threshold, accompanied by significant changes in precipitation regimes (Trbić, 2024). Based on data from the Bjelave meteorological station – the oldest in Bosnia and Herzegovina, with a homogeneous series of observa-

tions dating from 1888 to the present—the recorded temperature increase exceeds 1.5 °C. The dominant feature of the thermo-pluviometric regime of Bosnia and Herzegovina is warming, or humid stagnation, as linear trends in air temperature and precipitation amounts are positive (1.7 °C and 14 mm, respectively) (Drešković & Hrelja, 2025a). Climate models and projections for Bosnia and Herzegovina until the end of the 21st century indicate a rapid increase in air temperature, along with major changes in the precipitation regime, including an increase in intense rainfall events that contribute to fluvial, urban, and flash floods, as well as an increase in the number of dry days, which affects the occurrence of droughts and forest fires (Trbić, 2024). Furthermore, research results show that climate warming in Bosnia and Herzegovina is accompanied by a significant increase in the frequency and intensity of extreme heat events, including heatwaves (Trbić et al., 2022).

As a result of intensified climate change, high temperatures, increased air humidity, uneven precipitation distribution, and other associated phenomena contribute to making certain parts of the Earth increasingly unsuitable for human habitation. According to some estimates, more than 600 million people are directly or indirectly affected by the consequences of climate change (Schaeffer, 2025). Vulnerability assessments at the national level in Bosnia and Herzegovina indicate that the most sensitive sectors include agriculture, water resources (particularly droughts and floods), forestry and biodiversity, human health, and tourism (Žurovec et al., 2017; Ministry of Foreign Trade and Economic Relations of Bosnia and Herzegovina, 2020; UNDP, 2022).

In this context, it is essential to establish response plans and early warning systems to mitigate the negative spatial effects caused by climate change, with the aim of reducing damage to natural and socio-economic assets and minimizing human casualties. Scientific research plays a crucial role in climate change modeling. Through observation and analysis of climatic data, it is possible to derive relevant indicators of present climatic conditions, reconstruct past climate variability, and project future changes in climatic elements (Popović & Vuković, 2019).

Climate change assessments employ scenarios based on five socio-economic development pathways (Shared Socioeconomic Pathways – SSPs) and projected greenhouse gas concentrations in the atmosphere. According to the IPCC (2021), the only scenarios that project temperature increases remaining within the limits set by the Paris Agreement are those with projected warming of 1.0–1.8 °C, as well as scenarios with temperature ranges of 1.3–2.4 °C by the end of the 21st century compared to pre-industrial levels. These scenarios assume drastic emission reductions in the coming decades, achieving net-zero CO_2 emissions around 2050, followed by net-negative emissions. Without substantial efforts to reduce greenhouse gas emissions, global temperature increases will continue rapidly and may even accelerate. Under the most unfavorable scenario, temperature increases of 3.3–5.7 °C by the end of the 21st century are projected (Hrelja & Drešković, 2025).

The exposure of human society, natural assets, and critical infrastructure—systems essential for societal functioning—has become, and will continue to become, increasingly vulnerable due to the growing frequency of natural hazards driven by intensified climate change. Monitoring key climatic elements and modelling them through multicriteria analyses combined with physical-geographical and socio-geographical spatial factors, alongside the application of modern geoinformatics and artificial intelligence (AI) technologies, methods, and tools, can enhance the resilience of natural and socio-economic systems. These approaches support early risk detection, improved coordination, and more effective planning for climate change adaptation (Schaeffer, 2025). The implementation of such solutions may include predictive maintenance systems, simulations of extreme event scenarios, and automated adaptation and mitigation procedures addressing impacts caused by intensified climate change.

The analysis of climate change in Sarajevo has particular significance, given that the Sarajevo Basin is a true representative of the general climatic characteristics of the mountainous part of Southern Europe. In this regard, it can serve as a valuable complement for completing the overall picture of the scale of climate variability across the wider Western Balkan region.

The meteorological station at Bjelave has a homogeneous series of observations and measurements from 1888 to the present, which is highly representative for studying fluctuations in the main climatic elements, as well as for developing projections of climate change based on them. This research represents a continuation of previous studies on climatic elements and climate change in the territory of Bosnia and Herzegovina (Trbić et al., 2026; Drešković & Hrelja, 2025a; Drešković & Hrelja, 2025b; Drešković & Hrelja, 2025c; Trbić, 2024; Trbić et al., 2022; Popov et al., 2018). Previous research in the Sarajevo area has mainly focused on presenting the state of basic meteorological elements, namely temperature and precipitation. Earlier studies (Drešković & Hrelja, 2025a; Blažević et al., 2025; Drešković & Mirić, 2017b) addressed fluctuations in temperature and precipitation,

but were limited to shorter historical periods for which climatological data were available. However, this area is still insufficiently explored in terms of climate change trends. The main objective of this paper is to develop climate scenarios of annual air temperature change in the Sarajevo area based on IPCC climate scenarios. Given the existing lack of knowledge about climate change at the level of Sarajevo, as well as Bosnia and Herzegovina as a whole, the aim of this study is to provide baseline assumptions about future air temperature change scenarios in this area. This research can be of great importance for the wider community, as it may serve as a foundation for establishing timely plans for adaptation to climate change and related extreme events, with the goal of reducing their impacts on natural resources and material assets.

Data and Methods

The methodological framework for conducting the research was defined in accordance with the objectives and tasks of the study, which focus on analysing air temperature fluctuations and climate projections in the context of climate change in Bosnia and Herzegovina. In this context, the primary objective was to present changes in one of the key meteorological indicators—the thermal regime—during the recent climatic period and to model this climatic element up to the year 2100 under different climate scenarios.

The defined research tasks were carried out through several phases:

Phase 1: Collection of meteorological air temperature data for Sarajevo for the period from 1888 to 2024 from official statistical sources of the Federal Hydrometeorological Institute of Bosnia and Herzegovina (FHMZBiH, 2024).

These data were used to analyse changes in air temperature over the period 1888–2024 and to determine fluctuations of this meteorological element within the temporal framework from the establishment of the meteorological station network in Bosnia and Herzegovina to the present.

Phase 2: Analysis of air temperature changes in the study area under three different IPCC climate scenarios: SSP1-2.6 (low emissions, ambitious climate policies), SSP2-4.5 (moderate emissions, intermediate scenario), and SSP5-8.5 (the most pessimistic scenario, very high emissions). These three scenarios were selected to illustrate projected air temperature changes up to 2100 under conditions of very low, moderate, and high greenhouse gas emissions.

According to the IPCC Interactive Atlas (Regional Information – Advanced) and based on CMIP6 projection models, the aforementioned scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5—more detailed scenarios from the CMIP6 era that integrate socio-economic factors to provide robust climate projections) were analyzed for three time periods: 2021–2040 (near term), 2041–2060 (medium term), and 2081–2100 (long term), for the Mediterranean region, to which Sarajevo spatially belongs according to this projection.

The Mediterranean region was selected as the reference spatial framework for climate projections because, according to the classification of the Intergovernmental Panel on Climate Change (IPCC) and the IPCC Interactive Atlas, Bosnia and Herzegovina, including Sarajevo, belongs to the Mediterranean region. Although Sarajevo is geographically located in the interior of the Balkan Peninsula, its climatic characteristics represent a transitional type between continental and Mediterranean influences. While Sarajevo is not a typical Mediterranean area, its climate is significantly affected by Mediterranean processes, particularly in terms of seasonal warming and the distribution of precipitation. According to the Interactive Atlas, the region of Western and Central Europe, in comparison to the Mediterranean region, shows temperature values that are higher by approximately 0.2°C across all analyzed scenarios and periods. For this reason, the Mediterranean region was used as the reference area for applying regional climate scenarios and adapting them for local assessment in Sarajevo.

The Mediterranean is also recognized as one of the regions most sensitive to climate change, with a pronounced warming trend and an increased frequency of extreme climate events, making projections for this region relevant for assessing future temperatures in Sarajevo.

Table 1. Air temperature increase under SSP1-2.6, SSP2-4.5, and SSP5-8.5 climate scenarios for the Mediterranean region

Mean temperature (T) Change °C	Near Term (2021-2040)	Medium Term (2041-2060)	Long Term (2081-2100)
Scenario SSP1-2.6	0.9	1.1	1.3
Scenario SSP2-4.5	0.8	1.4	2.2
Scenario SSP5-8.5	1.0	2.1	4.6

Source: IPCC WGI Interactive Atlas, 2025.

The methodological projections of air temperature increase up to the year 2100 under the specified scenarios were based on measured air temperature values from the most recent 30-year climatic period. In accordance with these indicators, a quadratic function was developed to model the temporal evolution of air temperature increase:

$$T(t)= at^2+bt+c$$

- (t) – the number of years elapsed since the reference year from which the air temperature increase is calculated;

- (a,b,c) – coefficients representing the trend of the indicator increase over time.

The coefficients were determined using the least squares method, with the model fitted to the available data on average temperature and projections according to the scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The reference value was taken as the average temperature for Sarajevo for the period 1994–2024, while future values were defined based on projected temperature increases for the near-term (2021–2040), mid-term (2041–2060), and long-term period (2081–2100). This approach ensures that local data for Sarajevo are consistently aligned with regional scenarios.

A quadratic model was selected due to its simplicity and its ability to approximate the acceleration or deceleration of warming over the period up to 2100. The model used for projecting climate scenarios was tested using measured air temperature data for the past 100 years (1924–2024). The reference value was based on data from the first 30 years (average air temperature), after which the model was tested by projecting temperatures up to 2024. The actual average temperature for the entire observed period is 10.0°C, while the average projected air temperature is 9.9°C.

For the last 30 years (1994–2024), the average measured air temperature is 10.8°C, whereas the average projected air temperature is 11.1°C. These results (a small difference between the average actual and projected air temperatures) indicate that the model for projecting air temperature up to 2100 is fairly reliable and can be used to develop climate scenarios.

This phase of the study involved statistical processing of the collected digital meteorological data (air temperature), their modeling up to the defined period (2024–2100), as well as numerical and graphical analysis and systematic organization of the research results.

Results

Air temperature fluctuations in Sarajevo (1888-2024)

In the Sarajevo area, the mean annual air temperature over the entire instrumental period (1888–2024) is 9.8 °C. However, pronounced interannual variability is evident, with temperatures ranging from 7.71 °C in 1893 to 12.8 °C in 2024. Over the analyzed instrumental period of 137 years, a total of 74 years recorded mean annual temperatures above the long-term average (9.8 °C), while during 63 years the mean annual temperature was below this average value. The last 18 years have consistently exhibited mean annual temperatures higher than the long-term average. The overall trend in temperature change is best represented by a linear trend, which serves as a dynamic mean of the entire temperature series. Based on the linear trend, it was determined that the mean annual air temperature in the Sarajevo area increased by 1.7 °C over the full 137-year instrumental period.

Based on the analysis of general thermal characteristics, four predominant long-term periods can be distinguished, during which either an increasing or decreasing trend in average air temperature values prevailed, as best illustrated by the polynomial trend line.

The first characteristic period was recorded from 1888 to 1925, with reduced temperatures averaging 9.20 °C, approximately 0.60 °C below the established normal value. A prevailing increase in mean annual temperatures characterizes the second period (1926–1961), although several mostly single-year interruptions with lower temperature averages were observed. The period mean during this interval was 9.82 °C, 0.02 °C above the normal average temperature.

The next period (1962–1986) was marked by a renewed predominance of decreasing temperatures, with a period mean of 9.45 °C, i.e., 0.35 °C below the normal temperature, indicating a less pronounced cooling compared to the first period. The final fourth period, spanning 1987–2024, exhibits the most pronounced temperature increase, as indicated by a period mean of 10.62 °C, 0.82 °C above the long-term average air temperature.

To further illustrate air temperature fluctuations in Sarajevo, overlapping five-year and ten-year moving averages were analyzed. Compared to the actual mean annual temperatures, these moving averages significantly smooth out pronounced oscillations, making it easier to identify time intervals with distinct temperature trends.

The first such interval was recorded at the beginning of the instrumental period (1888–1895), with

markedly low temperatures (8.95 °C, 0.95 °C below the instrumental mean), a characteristic also observed across the European continent at the beginning of the 20th century.

From 1896 to 1905, temperatures increased slightly, with a period mean of 9.35 °C, still 0.45 °C below the long-term average. The period 1906–1913 was characterized by cooling, with the average overlapping mean temperature at 8.93 °C, 0.87 °C below the mean. A new phase of mild warming occurred from 1914 to 1924, with a period mean of 9.40 °C, followed by a six-year period (1924–1930) of more pronounced warming, reaching 9.91 °C, 0.11 °C above the instrumental mean.

During 1931–1943, interannual temperature variations were very pronounced, with one- to two-year intervals of alternating increases and decreases relative to the normal value. The period mean was 9.47 °C, 0.33 °C below the instrumental mean.

A subsequent warming phase occurred from 1944 to 1953, with a mean temperature of 10.27 °C, representing the second warmest interval in the entire instrumental record, 0.47 °C above the mean. This is confirmed by the exceptionally high mean annual temperature of 11.57 °C recorded in 1946, comparable to modern values.

Following this warming, an eight-year period (1953–1961) of slight temperature decline occurred, with an average of 9.63 °C. A further cooling trend defined the period 1962–1974, with an average temperature of 9.50 °C, although three single-year intervals exceeded the period mean. Similar thermal characteristics were observed during 1975–1986, although interannual variability was more pronounced, with the period mean at 9.47 °C.

The period 1987–2002 exhibited a marked warming trend, as all mean annual temperatures, except for two years, were above the instrumental mean. The average temperature was approximately 10.0 °C, representing one of the most pronounced 20th-century warming episodes (Drešković & Hrelja, 2025a).

From 2002 to 2024, the trend of significant warming continued, with an average temperature of approximately 10.9 °C, 1.1 °C above the long-term mean.

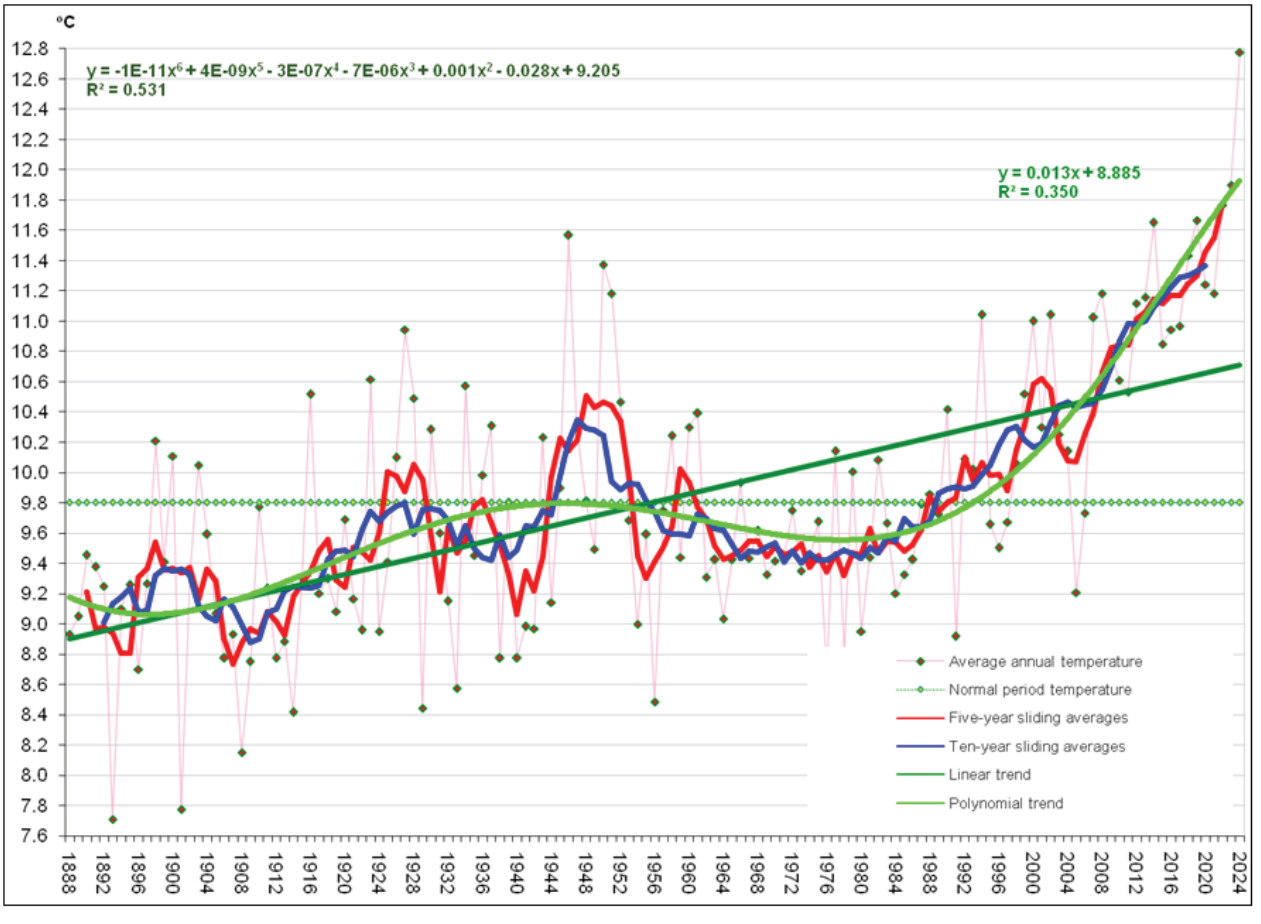

Figure 2. Air temperature fluctuations in Sarajevo for the period 1888–2024.
Source: Authors, based on data from the FHMZBiH

The trajectories of ten-year overlapping moving averages highlight long-term temperature trends. The first period (from the start of the instrumental record to 1906) shows a general warming trend, despite a shorter three-year interval of cooling. The period mean was 9.19 °C, 0.61 °C below the instrumental mean.

The period 1907–1914 was marked by a strong cooling trend, with a period mean of 9.05 °C, representing the most intense cooling within the entire instrumental record, 0.75 °C below the mean.

From 1915 to 1928, temperatures showed a renewed upward trend, with a period mean of 9.51 °C. The thermal regime from 1929 to 1936 was characterized by predominant stagnation of averaged temperatures around 9.65 °C. The subsequent shorter period (1937–1942) showed slight cooling, with a mean of 9.50 °C. This was followed by a period of intense warming from 1943 to 1951, with a mean temperature of 10.1 °C.

During the relatively long period 1952–1971, temperatures tended to decline, resulting in a mean of 9.66 °C, although several shorter intervals exhibited positive trends, notably a three-year warming at the end of this period (Drešković & Hrelja, 2025a).

From 1971 to 1986, averaged temperatures predominantly stagnated around 9.47 °C, with alternating short intervals of increases and decreases. The final period (1986–2024) is characterized by pronounced warming, with a high period mean of 10.4 °C.

Based on the graph, the continuation of the warming trend observed in the last period can also be expected, likely resulting in further increases in period mean temperatures.

Projections of air temperatures in Sarajevo (2024-2100)

In accordance with the established methodology, projections of air temperature in Sarajevo were made for three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5, across three periods: 2021–2040 (near-term), 2041–2060 (medium-term), and 2081–2100 (long-term).

Under all the scenarios, an increase in air temperature is observed up to 2100, with the magnitude of warming varying depending on the scenario considered.

Table 2. Climate scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 – projected air temperature increase for Sarajevo

Mean temperature (T) Change ºC	Near Term (2021-2040)	Medium Term (2041-2060)	Long Term (2081-2100)
Scenario SSP1-2.6	11.4	11.9	12.0
Scenario SSP2-4.5	11.4	12.1	12.9
Scenario SSP5-8.5	11.6	12.8	15.3

Source: Authors, based on FHMZBiH data and IPCC projections

According to the SSP1-2.6 climate scenario, the average air temperature in Sarajevo for the period 2024–2100 is projected to reach 11.7 °C, which represents an increase of 1.9 °C compared to the average air temperature over the previous 137 years (1888–2024).

Under this scenario, the projected average air temperatures would be 11.4 °C in 2040, 11.9 °C in 2060, and 12.0 °C in 2100.

According to the second, medium-emission scenario (SSP2-4.5), with moderate greenhouse gas emissions, the average air temperature in the period 2024–2100 is expected to reach 12.0 °C. Under this scenario, the projected average air temperatures for the near, medium, and long term would be slightly higher compared to the previously analyzed scenario. Specifically, the average air temperature would be 11.4 °C in 2040, 12.1 °C in 2060, and 12.9 °C in 2100.

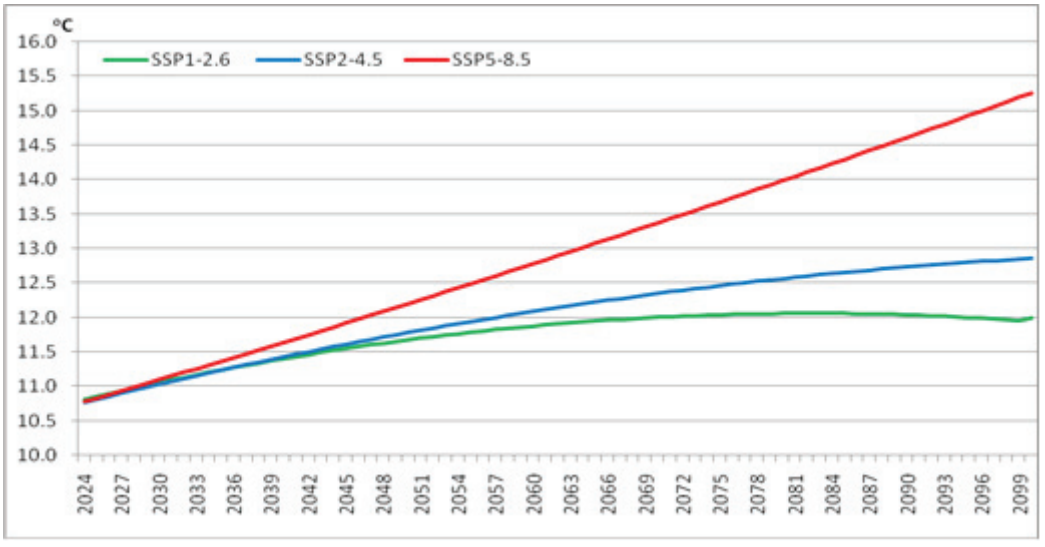

Figure 3. Climate scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 for the projected increase in air temperature in Sarajevo.
Source: Authors, based on FHMZBiH data and IPCC projections

The most pessimistic scenario, based on assumptions of very high greenhouse gas emissions (SSP5-8.5), projects that air temperatures in Sarajevo will reach significantly higher values than those projected under the previously analyzed scenario (SSP2-4.5). In the period 2024-2100, the average air temperature in Sarajevo under the SSP5-8.5 scenario is expected to be 12.9 °C, which would represent an increase of 3.1 °C compared to the previously analyzed period (1888–2024). According to this scenario, the average air temperature in 2040 will be 11.6 °C, in 2060 it will reach 12.8 °C, and by 2100 the average temperature is projected to rise to 15.3 °C.

Discussion

The results of this study clearly demonstrate a long-term warming trend in Sarajevo over the period 1888–2024, with a total increase of 1.7 °C in mean annual air temperature. This finding is directly supported by the results section, particularly the linear trend analysis and the persistence of above-average temperatures in the last two decades. The fact that the last 18 years all exceed the long-term mean (9.8 °C) indicates a clear shift toward a warmer climate regime rather than short-term variability.

The identified phases of warming and cooling further confirm that, although natural variability is present, the most recent period (1987–2024) is characterized by the strongest and most consistent warming. The mean temperature of 10.62 °C in this period (0.82 °C above the long-term average) highlights the acceleration of warming in recent decades. This result is consistent with previous studies for Bosnia and Herzegovina, which also report intensified warming since the late 20th century (Trbić et al., 2022; Drešković & Hrelja, 2025a).

When compared with regional studies, the warming trend observed in Sarajevo is in line with broader patterns across the Western Balkans and Southeast Europe. Previous research indicates temperature increases of approximately 1.0–1.2 °C in the region, while projections suggest continued warming throughout the 21st century (Popov et al., 2018; Vuković & Vujadinović, 2018). In this context, the warming of 1.7 °C recorded in Sarajevo appears slightly higher, which may be partly explained by local factors such as basin topography and urbanization effects. Similar behaviour has been observed in cities with comparable geographic settings, where limited air circulation and urban heat island effects contribute to higher temperature increases.

The projected temperature changes based on SSP scenarios indicate a continuation of the warming trend under all future pathways. However, these projections should be interpreted with caution. Climate scenarios are not predictions but plausible representations of future conditions based on different assumptions about greenhouse gas emissions and socio-economic development. Uncertainty arises from differences between climate models, emission pathways, and regional climate responses. Therefore, the projected values (e.g., up to 15.3 °C under SSP5-8.5) should be understood as potential outcomes within a range of possibilities rather than precise forecasts.

Despite these uncertainties, the differences between scenarios clearly illustrate the importance of emission pathways. The relatively moderate increase under SSP1-2.6 compared to the substantial warming

under SSP5-8.5 highlights the strong influence of mitigation policies on future temperature conditions.

Certain limitations of this study should also be acknowledged. First, the analysis is based on data from a single meteorological station (Bjelave), which, although homogeneous and long-term, may not fully capture spatial variability within the Sarajevo area. Second, the projections are derived using a simplified quadratic model, which may not fully represent the complexity of climate system dynamics. Third, the study focuses exclusively on air temperature and does not include other important climatic variables such as precipitation or extreme weather indices. Additionally, the influence of urbanization on temperature trends is not quantitatively assessed, although it is likely to play a role in the observed warming.

Overall, the results provide clear evidence of significant warming in Sarajevo and confirm that local temperature trends follow broader regional patterns. At the same time, the study contributes to a better understanding of long-term temperature dynamics in a geographically specific urban basin, highlighting the importance of both regional climate processes and local environmental factors.

Conclusion

Based on the results, the following general conclusions can be drawn:

- Global temperatures are continuously rising. Meteorological measurements indicate that the global temperature has increased by 1.1 °C compared to the pre-industrial period. The global mean temperature between 2013 and 2023 was 1.19–1.22 °C higher than the pre-industrial level, making it the warmest decade in recorded history.

- Temperatures in Europe are increasing faster than the global average. Over the same period, temperatures across the European continent rose by 2.1 °C.

- The basic characteristic of the thermal-precipitation regime in Bosnia and Herzegovina is warming or humid stagnation. In Sarajevo, where the longest meteorological measurements and observations have been conducted, linear trends for air temperature and precipitation show positive increases of 1.7 °C and 14 mm, respectively.

- Despite certain fluctuations (periods of rising and falling temperatures in Sarajevo), recent decades show a continuous increase in air temperature. This trend is projected to continue in the future. By 2100, all analyzed scenarios indicate a further rise in temperature. The projected average temperatures for the period 2024–2100 are: 11.7 °C according to SSP1-2.6, 12.0 °C according to SSP2-4.5, and 12.9 °C according to SSP5-8.5.

- Highlighted weather conditions contribute to the occurrence of climate-induced natural hazards such as droughts, floods, landslides, forest fires, and similar events, which have severe consequences for humans, natural systems, and material assets. The risks associated with these processes can be mitigated through the development of climate risk models, which can then inform responsible spatial planning, the establishment and enforcement of relevant legal frameworks, and the creation of protection and adaptation plans.

Based on these findings, there is a clear need for significantly increased efforts in the measurement and monitoring of climatic elements, as well as in modeling and forecasting climate-induced natural hazards across the entire territory of Bosnia and Herzegovina. Such monitoring and modeling are essential for guiding adaptation and mitigation strategies aimed at reducing the impacts of climate change on natural and social resources.

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Investigating the impact of El Niño Southern Oscillation and North Atlantic Oscillation on Temperature regime in the Republic of Azerbaijan

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Abstract

The study aims to investigate recent changes in the climate of Azerbaijan and climate drivers behind these changes. To reveal the combined influences of multiple climate oscillations, it was decided to employ regression models with climate teleconnections of North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO). Prior to these, Statistical analysis such as Mann – Kendall test and extreme value tests were applied to identify statistically significant trends. The findings revealed that temperature persistence dominates the local climate in the country. Overall, the impact of North Atlantic Oscillation is small, while El Nino – Southern Oscillation shows little to no impact.

Keywords: Azerbaijan; North Atlantic Oscillation; Climate Teleconnections; El Nino – Southern Oscillation; Climate Variability in Azerbaijan

Introduction

Climate change is a popular topic in the Republic of Azerbaijan for multiple reasons. Many are concerned with water resources, particularly glaciers as it is believed that it will add more challenges to already under stress water management sector (Huseynov et al., 2025a). Another concerning environmental issue is sea level change in Caspian Sea. There are different schools of thought on what is behind this trend. Some point out that hydroclimatic processes can be the main driver behind it (Jorissen et al., 2020). Others attribute this phenomenon to the anthropogenic influence (Ataei et al., 2018). Regardless of cause, it is expected that discussion around these matters will be even more frequent. Especially considering that countries located along the Caspian Sea are seeking ways to increase maritime transportation with the plans to establish middle corridor, such challenges remain to be main sources of discussion (Palu & Hilmola, 2023).

Several studies and reports from various international organizations note that Azerbaijan is among the countries that are most vulnerable to the climate change (World Bank Group, 2023). How the climate in Azerbaijan is changing has been the main subject of several studies. However, existing studies are mostly confined to analysing linear trend changes and frequently lack the application of robust methodologies. Accessibility to data, limited collaboration among data providers and academia remain to be constraining factor for elaborate studies (Blois, 2021). One way

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to get around the data scarcity problem is to rely on previously published materials or secondary datasets. Luckily, some local articles contain valuable station datasets (Mammadov, 2015). Secondary datasets like these can improve the depth and scope of the analysis in a scarce data environment. However, another important limitation of use of these datasets is that they along with methodological frameworks have mostly been pre-processed with the specific objectives in mind (Huseynov et al., 2025b). This can restrict their reusability and make it very hard for researchers to extract raw information suitable for independent analysis. Generally, by looking at literature related to climate change studies for Azerbaijan, several issues can be highlighted. First, the coverage of meteorological observation network is questionable, and temporally limited (Ebinger et al., 2010). Access to national dataset is very restricted if none existing. Although, law of the Republic of Azerbaijan on the right to obtain information is adopted in 2002, and constitute regulation on data sharing, yet mechanisms seem to be not working properly. State Hydrometeorological service does not have open-access online database which researchers can inquire about data for access. This hinders direct access and fast data access options for researchers. Furthermore, most of the physical studies exclude assessments for sectoral impact, keeping many aspects out of equation (World Bank Group, 2023). Last but not least important, the limited depth of literature focusing on how the climate forces, drivers, and conditions affect the local climate remains to be the main constraint. Caspian Sea in this sense remains an interesting case. It can be noted that ongoing sea level change amidst increased efforts to develop sea transport might have allured researchers to study Caspian Sea thoroughly. On the topic of climate dynamics, especially wind regime of Caspian Sea, and complex interlinkages with climate, more collaborative research is observed (Safarov et al., 2025).

The main objective of this research is to enhance the understanding of climate interlinkages affecting Azerbaijan. The conventional literature on Azerbaijan's climate mostly underlines the impact of the northern high-pressure (Siberia) systems, the soothing effect of the Caspian Sea, and Greater Caucasus (Khromov, 2005). Nonetheless, less attention has been given to understanding the possible role of large-scale atmospheric oscillations in contributing local climatic conditions. Most of the work have been done largely depict Azerbaijan's climate as being mainly confined by geographic factors, yet evidence from the literature focusing on other parts of world, demonstrates that the influence of external climate drivers are too strong to be disregarded (Velichkova et al., 2025). There are several atmospheric oscillations that can directly or indirectly affect regional climate variability. Among them the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO) are very influential and can be considered as predominant for climate of Caucasus too.

Even though NAO and ENSO originate far away from land, they still can substantially influence weather patterns across Europe, Mediterranean coast and the Caucasus. NAO is defined by the pressure difference between the Icelandic Low and the Azores High. It has multiple phases and any change in its phases can largely impact the winter weather in big parts of northern hemisphere. When it is in positive phase, a strong pressure gradient forms, and it strengthens westerly winds which steer warm, moist Atlantic air into Europe, resulting in green winter for the lands. Conversely, when it is in the negative phase, it weakens these winds and thus opportunity emerges for cold Arctic air to enter southward, bringing freezing temperatures and dry conditions to Northern Europe. However, due to the moderating effect of Mediterranean sea, winter becomes relatively colder in southern Europe and Caucasus.

ENSO on the other hand, is a complex form of ocean-atmosphere dynamics. Being one of the most dominant climate drivers, ENSO is a natural cycle in Pacific Ocean temperature, wind and cloud regimes. It is considered that influence of ENSO can be felt anywhere around the globe. ENSO has three phases, namely: La Nina, Neutral, and El Nino phases. During the neutral phase, steady trade winds blow across the tropical Pacific from the east to west. These winds accumulate warm water in the western part of Pacific. In exchange, the eastern part of pacific gets colder water through upwellings. Temperature gradient between east and west gets higher and thus rising air in the west move and descent in the east which creates cycle called Walker circulation. In this phase, west part of the ocean gets milder weather. In the case of La Nina, trade winds blow harder and western part of ocean gets warmer. Eastern part on the other hand gets colder and thus temperature gradient gets bigger. El Nino is completely opposite of La Nina. Trade winds get slower, allowing warmer water to drift back towards the east. This causes Walker circulation to break down, ending in multiple smaller circulations.

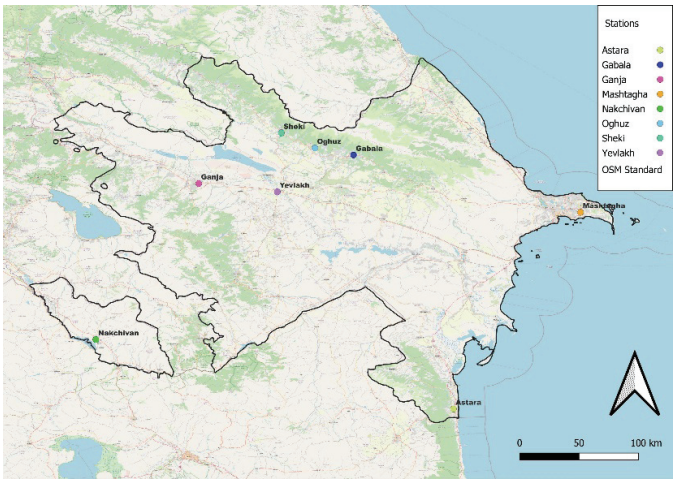

Figure 1. Map of the locations of stations

For our study, eight representative stations were selected from various climatic zones across Azerbaijan: Shaki, Oguz, Gabala, Astara, Nakhchivan, Mashtagha, Yevlakh, and Ganja (Figure 1). Sheki and Oguz both located in the north-west of Azerbaijan, on the southern slopes of the Greater Caucasus Mountains have similar climate types. They both experience a moderately humid climate with relatively cool conditions compared to lowland areas of Azerbaijan. Summers are warm, and winters are usually cold (temperatures usually vary around 0 °C in winter) and snowy. Gabala is neighboring city to Oguz, and its climate bears similarities with Sheki and Oguz's. But the city is located on relatively higher plateau, which results in relatively more snowfall. Astara, located on the southern Caspian Sea coast is distinctive with one of the most humid climates in Azerbaijan. It has humid subtropical climate and experiences more precipitation in autumn and winter. Its summers are warm, and winters are quite mild.

Nakhchivan has a strong continental and semi-arid climate. It holds both records of highest and lowest temperature in Azerbaijan. Mashtagha, located on Absheron peninsula, has a semi-arid climate with a strong maritime influence. Summers are very hot but moderated by sea breezes, with strong wind. Winters on the other hand are mild, rarely experience snowfall. Yevlakh is located in the Kura-Araz lowland, an extensive plain that cover more than half of Azerbaijan. It is mostly characterized by semi-arid climate. Summers are very hot, and winters are mild, with little precipitation. Ganja, located on the northern foothills of Lesser Caucasus Mountains has a continental climate. Summers are hot, and winters are cool.

Material and Methodology

Data used for this study comes from various sources. The data which is the main core of our study mostly acquired from State Hydrometeorological Service of Republic of Azerbaijan as it is the government body responsible for measurements of climate variables. But as we already discussed, access to the data for researchers is very challenging. For this reason, it becomes necessary to look for other sources. A portion of the data used in this study was obtained directly from this service, while other parts were extracted from international organizations. These external sources include the National Centers for Environmental Information (NCEI), World Meteorological Organization (WMO) and the U.S. National Oceanic and Atmospheric Administration (NOAA). It is important to note that this data was originally provided to these organizations by the National Hydrometeorological Service of Azerbaijan under international agreements and obligations. Another key resource is Climatic Research Unit TEMperature (CRUTEM), a global collection of station data created by the Climatic Research Unit at the University of East Anglia. The specific version we used for our research is CRUTEM 5.0.2.0 (Osborn, 2020). Combination of these datasets makes up our base climate data for analysis. For calculations related to teleconnections, other sources were used.

The Niño-3.4 sea surface temperature (SST) index, extracted from NOAA's Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) dataset, was employed to represent ENSO values (Huang et al., 2017). Another teleconnection that was used in this study, The North Atlantic Oscillation (NAO) is considered to be very important, heavily affecting the winter in northern hemisphere. It basically defines normalized pressure difference between a station on the Azores and one on Iceland. The index we used was obtained from the Climatic Research Unit (CRU), University of East Anglia (Jones et al., 1997). It is worth noting that all the datasets acquired for the study are monthly datasets.

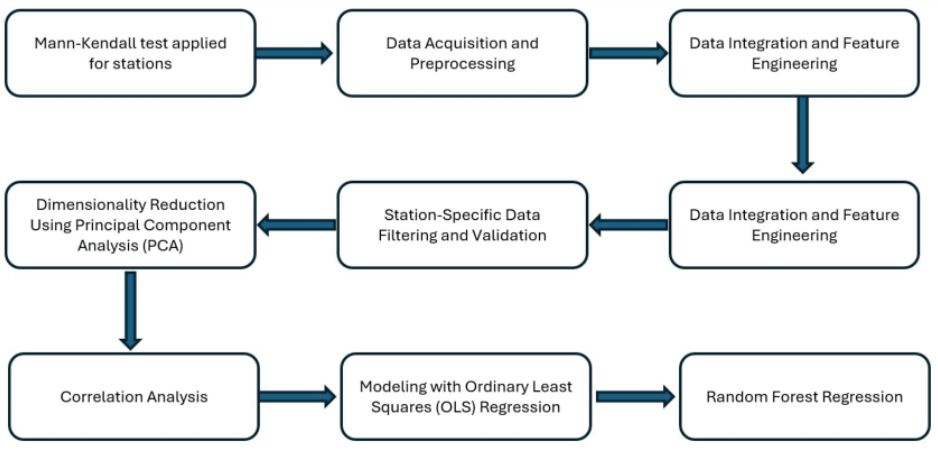

Figure 2. Workflow of methodological framework applied in this study

Figure 2 sums up what have been done for this study. But it does not reflect all the details. We have started our work with Mann-Kendall (MK) statistical test to identify trends that are statistically significant. MK test is a non-parametric test that is very popular in atmospheric and climate sciences. It is robust to outliers and can handle missing values which makes it very effective in identifying trends. In our research we applied MK prior to modelling steps because we wanted to identify trends before we examined relationship between temperature and indices. Teleconnections like NAO and ENSO often exhibit cycles of various timespans, short-term, long-term, etc. Prior studies identified NAO cycles around 7, 13, 20, 26, and 34 years (Seip et al., 2019). We can argue that any statistically significant trend can contain impact of these cycles. Similar things can be said about ENSO as well. Some studies showed strong ENSO teleconnection under warming trends identified by MK test (Vu Duy et al., 2022).

It should be noted that prior to each stage of analysis, preprocessing was conducted to ensure quality and uniformity. Only minimal preprocessing was required for the statistical analysis, specifically Mann-Kendall and Sen's Slope analysis as the temperature data were mostly complete with few occasional null values. The more extensive preprocessing was applied to the subsequent analysis which mostly involve data cleaning, structuring, and parsing. Data cleaning is a foundational step in any data analysis, involving detecting and correcting errors, inconsistencies, missing values, duplicates. Missing values were addressed using forward and backward filling. Additionally, disparate datasets were merged using a standardized date column to unify different time formats. Only after these preprocessing steps were completed were subsequent analysis conducted.

Then we created lagged values for temperature, NAO and ENSO. For time-series analysis using lagged features is very common and useful. For temperature analysis, effect of predictor is not directly reflected on temperature. Past states influence current temperatures. Due to delayed dynamics, introduction of lagged features became a necessity. After the basic diagnostics were performed, we moved on with next phase which is to apply Principal Component Analysis (PCA). PCA is a widely used statistical technique to reduce dimensionality of dataset. It transforms a set of variables that might be correlated into uncorrelated variables that are called principal components. Due to high temporal autocorrelation and persistent nature of ENSO, the values of ENSO, NAO, and temperature became highly multicollinear. That makes models fail to differentiate variables that are too similar to each other. Thus, to eliminate this problem PCA was applied. By applying PCA, we were able to reduce dimensionality through changing correlated variables into uncorrelated parts, therefore enhancing model stability and interpretability. We acquired various groups of PCA which expressed combination of drivers. After introducing PCA to our analysis we witnessed serious decrease in multicollinearity. To break down how each climate driver contribute to temperature variance, a Block Principal Component Analysis (Block PCA) was introduced. What it does differently than PCA is that it organizes predictors into theoretically defined blocks and applies dimensionality reduction within each block independently. To further assess multicollinearity among predictor blocks Variance Inflation Factor (VIF) was employed. With the help of VIF it is possible to quantify how much the variance of a regression coefficient is inflated because of linear relationship with other predictors. VIF values under 1 mean that there is complete independence from other predictors while VIF range 1 to 5 means modest to moderate correla-

tion. Any value above 10 indicate severe multicollinearity.

To investigate how different components relate to current temperatures at each station in Azerbaijan, regression analysis were employed. To have concise results we used two models: one that's straightforward (Ordinary Least Squares, or OLS), and another, named Random Forest is better suited for dealing complex, non-straight-line relationships. This machine learning technique creates decision trees from various samples of data and then averages their predictions to forecast monthly temperatures.

The primary linear model applied in this research is OLS regression. It was implemented using the statsmodels library in Python. For each station, the dependent variable is the observed monthly temperature values (y), with the independent variables consist of PCA components written and grouped as PC1, PC2, PC3 (PC4 for two stations) and the NAO features. A constant was added to the predictor matrix for each station. These were applied station by station along with diagnostic checks that include model summaries. To solve potential non-linearities, Random Forest regression is employed using scikit-learn's RandomForestRegressor with 100 estimators and a fixed random seed for reproducibility. The same predictor matrix which includes PCA components along with NAO features and observed temperature are used, enabling direct comparison possible.

Results

As mentioned in our workflow, we started our analysis with statistical tests. The ultimate purpose was to differentiate the stations with statistically significant trends. To accomplish this goal, we used pymannkendall library of Python programming language. We analyzed 8 stations, using monthly datasets gathered from various sources. With testing we identified P, Z, and Kendall tau values. Aside from these, we also uncovered Sen's slope values for our stations. Mann-Kendall values give us statistical significance of trends with percentage. We set alpha level (threshold) for significance as $p < 0.05$ (95% confidence level) since most of the time climate analysis employs this level.

Table 1. Results of Mann-Kendall test and Sen's Slope analysis

Station	Trend	P-value	Z-stat	Kendall Tau	Sen's Slope (°C/year)
Astara	no trend	0.056	1.913	0.07	0.007
Gabala	no trend	0.073	1.793	0.064	0.008
Ganja	increasing	0.007	2.699	0.099	0.012
Mashtagha	no trend	0.163	1.396	0.051	0.005
Nakchivan	no trend	0.245	1.163	0.043	0.006
Oguz	increasing	0.0	6.074	0.218	0.029
Sheki	increasing	0.0	6.104	0.22	0.029
Yevlakh	no trend	0.118	1.565	0.057	0.007

Looking at the results of Mann-Kendall test and Sen's Slope analysis (Table 1), we can see that only three stations have statistically significant trends. Those stations are Ganja, Oguz, Sheki. Sheki and Oguz located in same geography, and relatively close to each other showed very similar results. Interestingly, both stations illustrate increase of 0.030 °C per year, equal to ~1.5–3°C of warming over 50–100 years, which aligns with the global climate change predictions for the given time span (50–100 years). For other stations, we see that they also show increase in temperature though the trends are not statistically significant.

Next, the processes of data cleaning, structuring were applied to temperature, ENSO and NAO data. After preprocessing, further analysis were conducted to examine the relationships between monthly temperature data from selected weather stations and climatic teleconnection indices (ENSO and NAO). Along with lagged features, correlation matrixes were applied. The findings indicated high multicollinearity in the matrix (Figure 3).

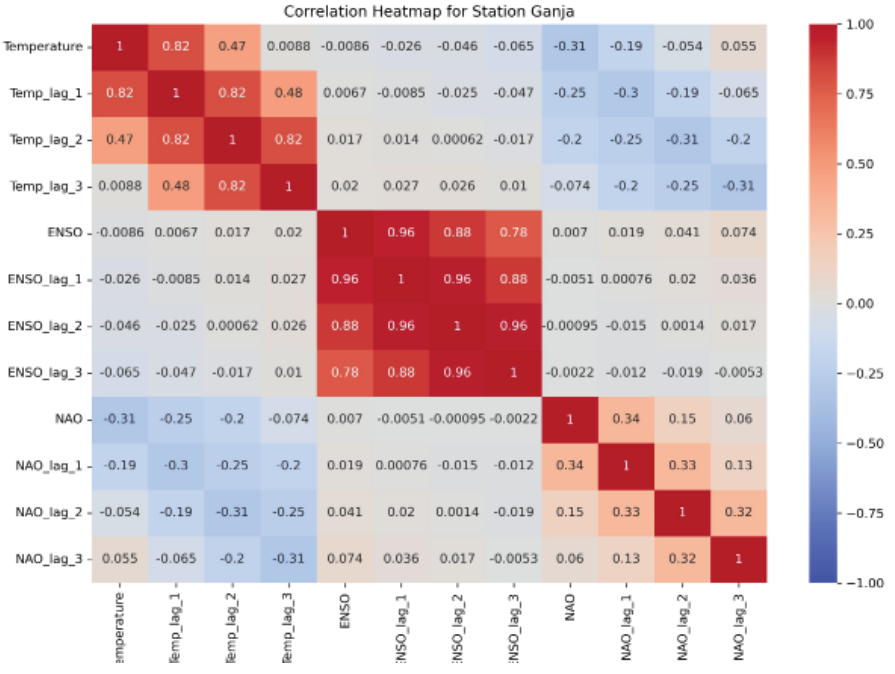

Figure 3. Correlation heatmap for Ganja station

In Figure 3 we see that multicollinearity of one of stations (Ganja) is substantially high and it is especially reflected among ENSO lags. Other stations also had same issue, showcasing high multicollinearity among lags. To solve multicollinearity and enhance our model, Principal Component Analysis were employed.Principal Component Analysis made a direct impact decreasing multicollinearity levels significantly (Figure 4).

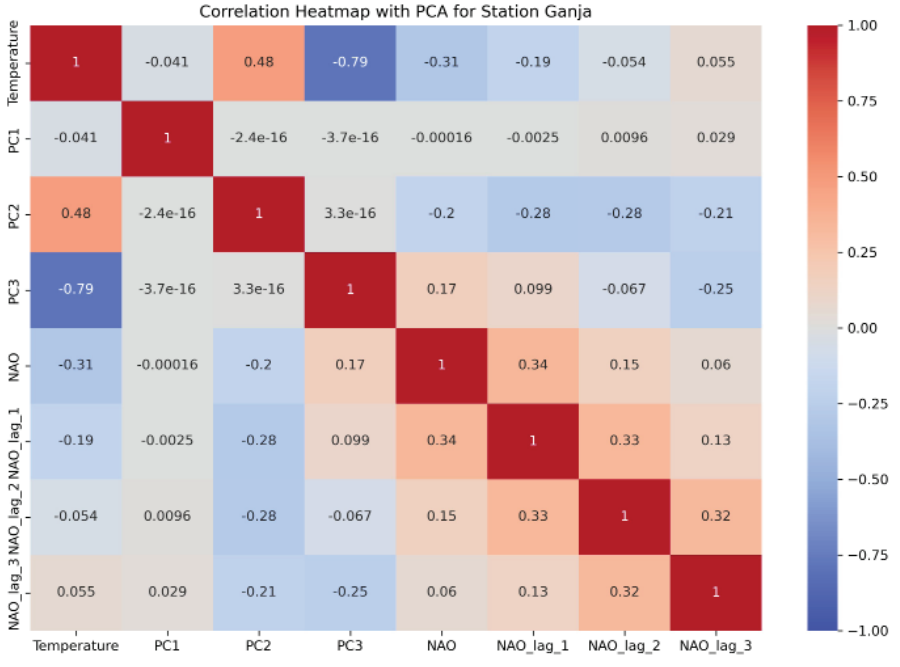

Figure 4. Correlation heatmap for Ganja station after the application of PCA

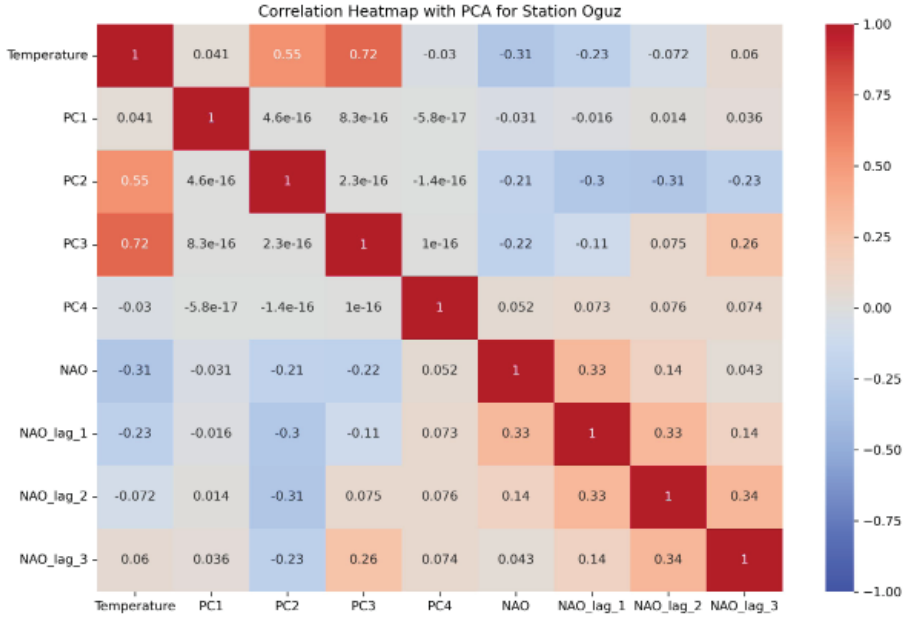

Figure 4b. Correlation heatmap for Oguz station after the application of PCA

Application of PCA showed that PC1 mostly correlated to ENSO and its lags while PC2 and PC3 mostly represented temperature lags. Some stations (Nakchivan, Oguz) appeared to have 4 PCs (Figure 4b). The variation in the number of PCs across stations is because of differences in variance of each station dataset. PC loadings from those stations with 4 PCs point out that PC4 mostly represent ENSO for those stations.

After the application of PCA, the application of Ordinary Least Square (OLS) regression models were introduced for each station. To avoid redundancy, outputs for a single representative station (Ganja) were showcased since there is consistency of results across stations. Results indicate relatively stable models for each station. Just to give an example, looking at OLS regression results of one of stations (Ganja), value of 0.868 for R-squared can be seen, which means OLS regression model for Ganja is very stable and explains 86.8% of the variance. The values for F-statistic and Prob (F-statistic) on the other hand are 191.3 and 3.06e-133 respectively. These values prove that the model is statistically significant and the relationship we found is not because of random chance. Durbin-Watson value of 2.306 is not an ideal value but it is generally accepted (Abdulhafedh, 2017). This value suggests that there is no major problem with autocorrelation. We got value of 9.021 for Kurtosis which indicates that our data has heavy outliers (Figure 5). Similar results were observed on the other stations too.

OLS Regression Results

Dep. Variable:	Temperature	R-squared:	0.868
Model:	OLS	Adj. R-squared:	0.864
Method:	Least Squares	F-statistic:	191.3
Date:	Fri, 06 Feb 2026	Prob (F-statistic):	3.06e-133
Time:	14:41:36	Log-Likelihood:	-841.62
No. Observations:	331	AIC:	1707.
Df Residuals:	319	BIC:	1753.
Df Model:	11		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	6.9722	0.442	15.787	0.000	6.103	7.841
Temp_lag_1	0.9792	0.046	21.232	0.000	0.888	1.070
Temp_lag_2	0.1193	0.071	1.683	0.093	-0.020	0.259
Temp_lag_3	-0.5616	0.046	-12.098	0.000	-0.653	-0.470
ENSO	-0.3123	0.864	-0.361	0.718	-2.012	1.388
ENSO_lag_1	0.1874	1.547	0.121	0.904	-2.857	3.232
ENSO_lag_2	0.8113	1.546	0.525	0.600	-2.231	3.854
ENSO_lag_3	-0.8103	0.873	-0.929	0.354	-2.527	0.906
NAO	-0.8231	0.177	-4.645	0.000	-1.172	-0.474
NAO_lag_1	0.3942	0.188	2.092	0.037	0.023	0.765
NAO_lag_2	0.3331	0.189	1.759	0.080	-0.040	0.706
NAO_lag_3	-0.3589	0.181	-1.980	0.049	-0.715	-0.002

Omnibus:	53.229	Durbin-Watson:	2.306
Prob(Omnibus):	0.000	Jarque-Bera (JB):	502.482
Skew:	0.210	Prob(JB):	7.71e-110
Kurtosis:	9.021	Cond. No.	366.

Figure 5. OLS Regression results for Ganja

In the coefficients section present in Figure 5, NAO values that look comparable in magnitude are observed. These values can be misleading because NAO and temperature persistence values operate on completely different scales. Temperature persistence values mostly vary by around 20 to 25 whereas NAO typically varies roughly between -3 and 3. To interpret physical impact of NAO in figure 5, one should consider the coefficient along with standard deviation. Since NAO has a much smaller range of variation, it requires a steep slope to produce a modest temperature effect.

This is where partial and semi partial correlations can be very helpful. To move beyond the raw coefficients and investigate contribution of drivers we introduced scale-free partial and semi-partial correlations (Figure 6).

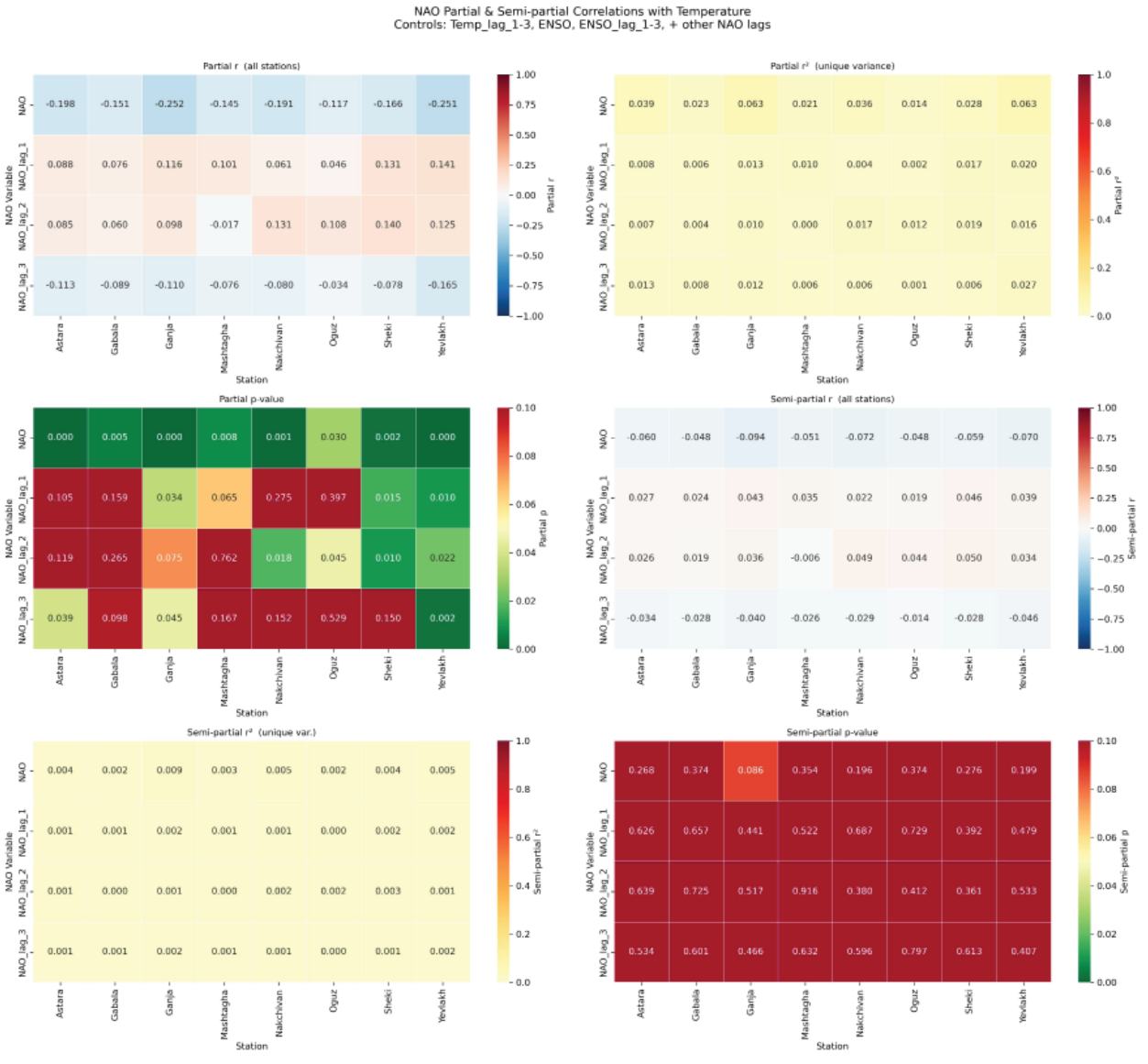

Figure 6. Partial and semi-partial correlations with temperature

Partial correlation basically strips away the effects of all the other predictors from both NAO and Temperature and what remains is the pure, isolated link between the two. The semi-partial correlation on the other hand only removes the effects of other predictors from NAO only, while temperature stays as it is. When squared, this value gets the exact percentage of total temperature variance that NAO only accounts for. Partial and semi-partial correlation analysis showed that among NAO terms, only the contemporaneous index (NAO) retained consistent independent significance across the stations. Others showed various results mostly indicating multicollinearity.

Figure 7 shows the OLS regression coefficients for our predictors across all the stations. According to the Figure 7, PC2 and PC3 are the largest coefficients across all stations, reflecting the dominant role of temperature persistence in temperature variability. By contrast, NAO lags and ENSO (PC1) display coefficients that are small and mostly non-significant.

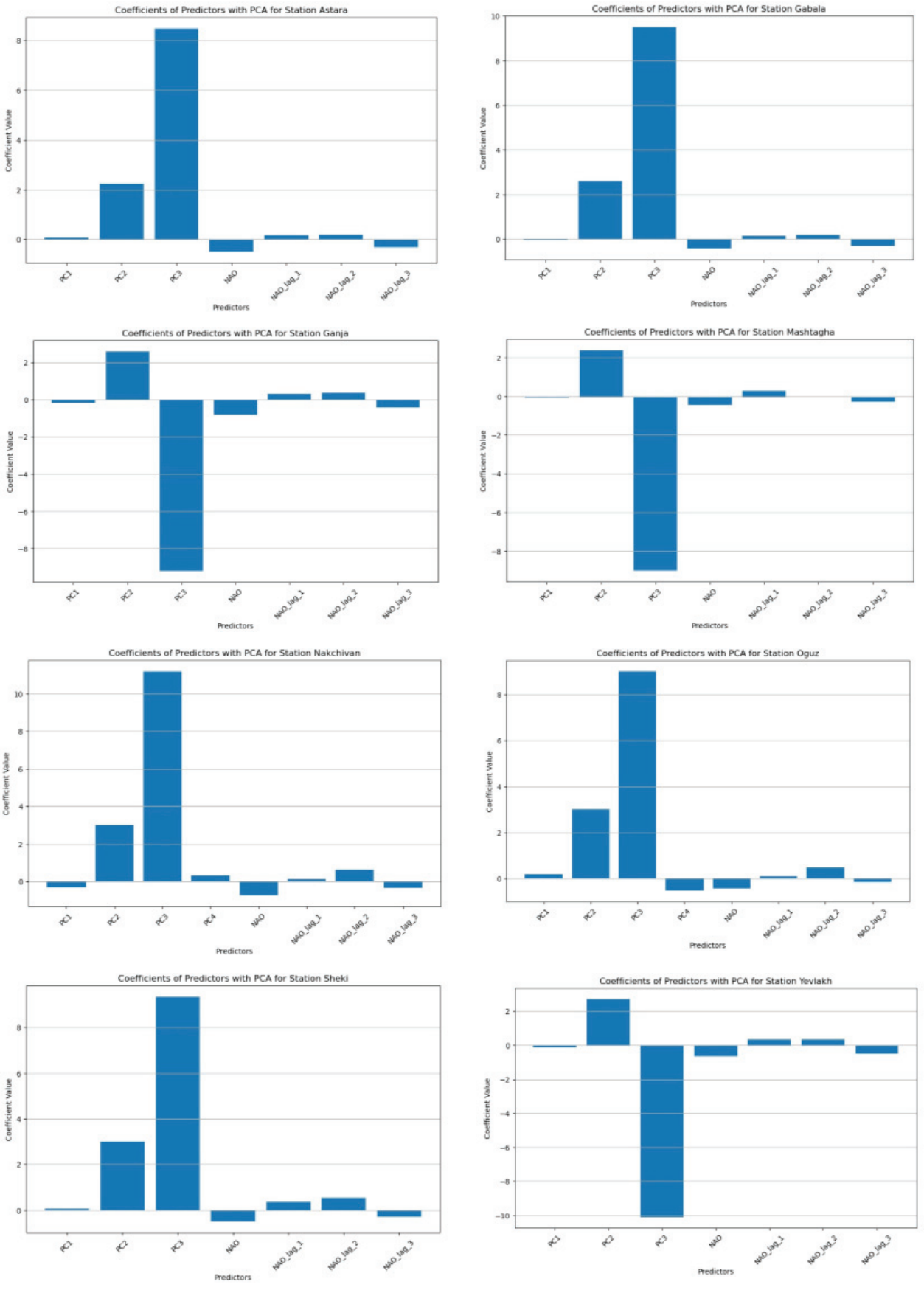

Figure 7. Coefficients of predictors with PCA for stations

Generally, all the stations show that PC3 is overwhelmingly stronger compared to other predictors (Figure 7). All of them indicate similar patterns with little differences. However, when comparing feature importances from Random Forest Regression models we see relatively bigger differences. There can be multiple reasons behind these differences. The divergence most probably stems from fundamental differences between OLS and RF modelling. The coefficients of predictors are extracted from OLS model. This means that they assume linear relationship between predictors and temperature. Minor differences can arise due to random noise and interactions with lags and PCs.

Table 2. Extracted feature importances for all the stations

STATIONS	TEMPERATURE P	NAO	ENSO
Astara	95.75%	2.51%	0.98%
Gabala	95.63%	2.78%	0.84%
Ganja	92.46%	6.44%	1.10%
Mashtagha	94.78%	4.34%	0.88%
Nakchivan	94.51%	3.73%	1.10%
Oguz	90.35%	6.42%	1.85%
Sheki	93.07%	5.69%	1.24%
Yevlakh	97.07%	2.31%	0.61%

RF importances show that among all the stations, only Ganja, Oguz, and Sheki experienced relatively higher values for NAO and ENSO (Table 2). These are also the only stations that have statistically significant trends according to Mann-Kendall non-parametric test.

To get an overview of relative strength of temperature persistence and teleconnections in explaining temperature variance, a variance decomposition analysis was conducted using a block principal component analysis (Block PCA) framework (Figure 8). These analyses do not just focus on whether each driver connects statistically to temperature, but it digs deeper, asking how much of the total temperature variance each driver accounts for on its own.

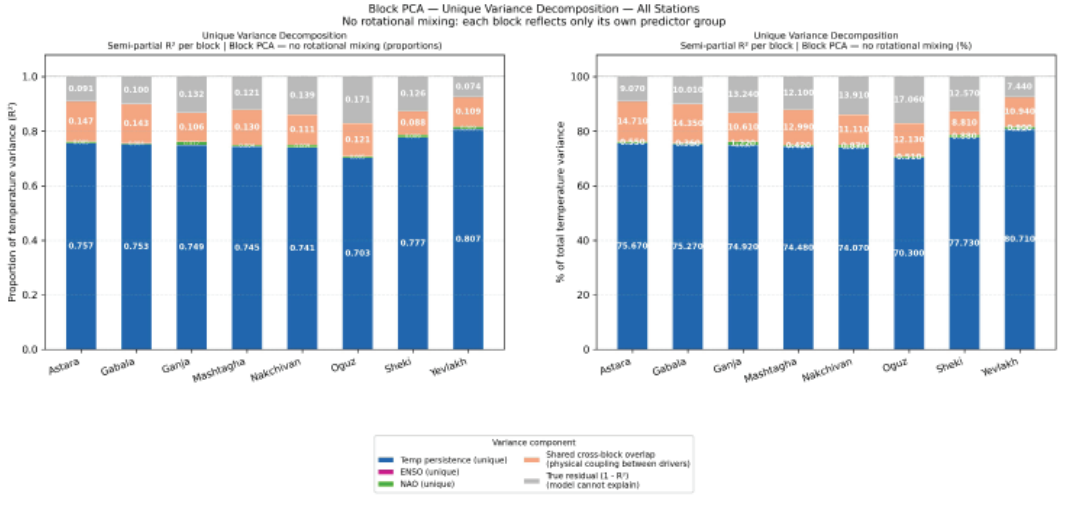

Figure 8. Unique variance decomposition for all stations

Figure 8 presents two panels. The left panel represents each driver's unique variance as a fraction of the total variance, demonstrating the relative dominance of temperature persistence, NAO, and ENSO among themselves. In this case the segments represented by bars add up to 1. The right panel on the other hand depicts each driver's contribution as a percentage of the total temperature variance. It should be noted that both panels take shared overlap and residuals into account.

One of the big methodological challenges in this type of analysis is multicollinearity. Multicollinearity can inflate regression coefficients and making it almost impossible to pin down the independent contribution of any single driver. To overcome this challenge, Variance Inflation Factor (VIF) diagnostics were applied to the blocks (Figure 9).

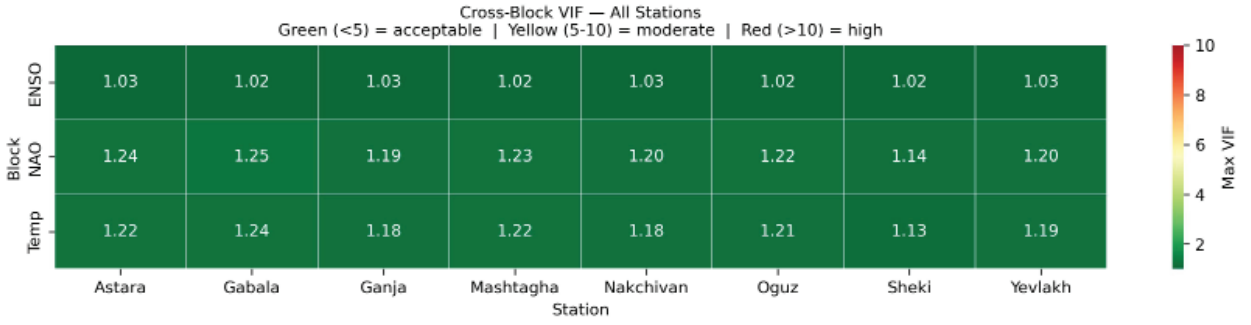

Figure 9. Cross-Block VIF diagnostics

A Variance Inflation Factor (VIF) of 1 usually means no correlation or no multicollinearity. Values between 1 and 5 indicate a moderate correlation. As Figure 9 indicates our values are well below the conventional threshold of 5. This indicate that our unique variance decomposition using block PCA (Figure 8) retains statistically significant predictors.

Another important finding was about the temporal changes occurred over the years. To examine whether the relative contributions of the three blocks (Temperature persistence, NAO, ENSO) changed or remained stable, unique variance decomposition using the Block PCAs was repeated independently for two time periods with the equal length: 1991–2004 and 2005–2018 (Figure 10).

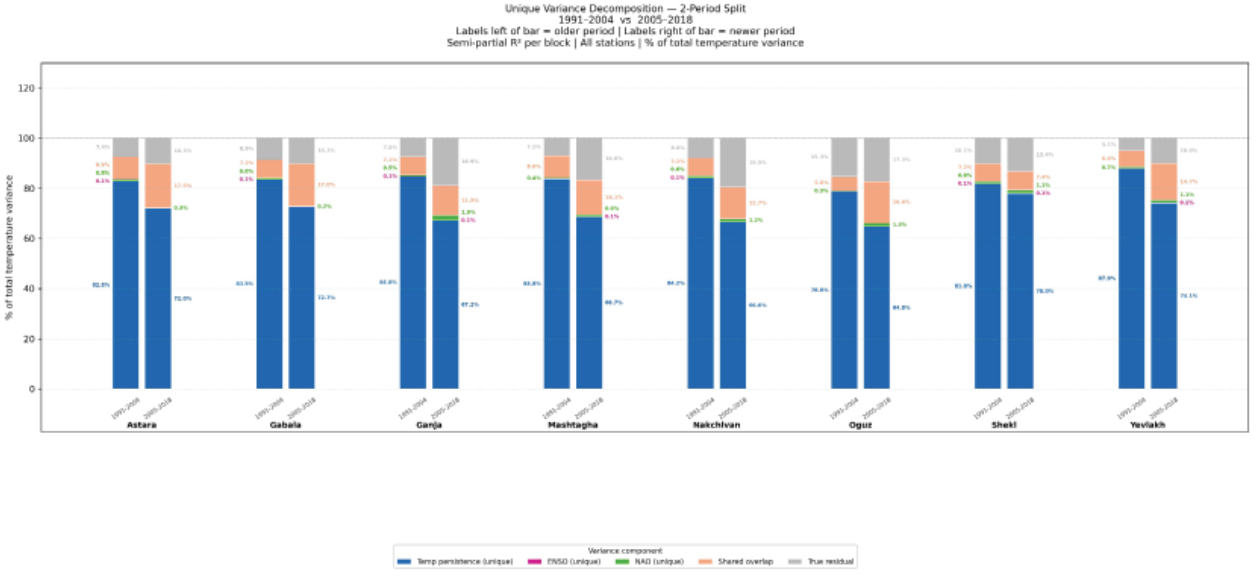

Figure 10. Temporal change of unique variance decomposition for all stations for two periods; 1991 – 2004 and 2005 – 2018.

With the approach given in Figure 10, the methodological consistency of analysis using block structure was preserved. Each period contains approximately 168 months of observations per station, making sure a statistically acceptable sample for reliable Block PCA estimation. Prior to application of unique variance decomposition, VIF diagnostics were recomputed and results ranged from 1.0 to 1.3.

To further analyse the changes, another unique variance decomposition using the Block PCAs was applied only this time with three time-periods: 1992 – 2000, 2001 – 2009 and 2010 – 2018 (Figure 11).

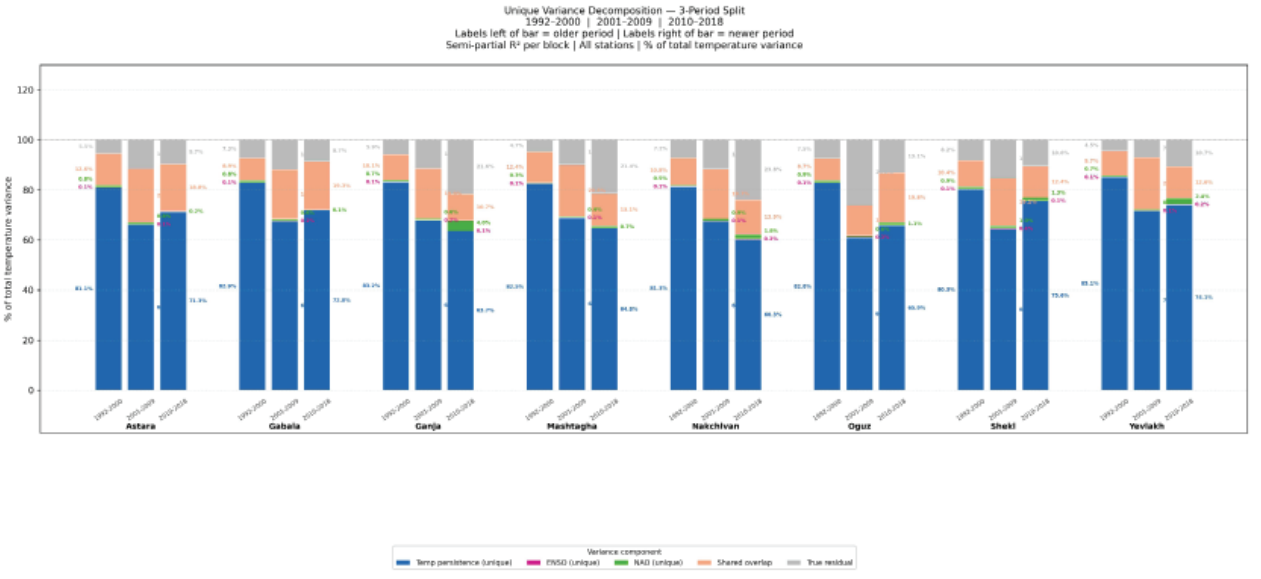

Figure 11. Temporal change of unique variance decomposition for all stations for three periods; 1992 – 2000, 2001 – 2009 and 2010 – 2018.

Figure 11 represents 3 time periods. The figure accounts for unique variance components of temperature persistence, NAO, ENSO along with shared cross block overlap and true residual. The three comparison points lets better scrutinization on the direction of trends and their consistency.

Discussion

The choice of applying the lag structure method was a deliberate one. Considering that climate drivers mostly do not show immediate impact and it takes some time to be reflected on temperature regime, it was decided to adopt lag structure to capture delayed effects.

Partial and semi-partial correlation analysis demonstrated that out of all the NAO terms, only the contemporaneous NAO contained significant, independent link with temperature across all the stations. The lags on the other hand exhibited unstable signs and yielded largely insignificant partial and semi-partial correlations. Figure 8 further revealed that temperature persistence is the dominant driver of month-to-month temperature variability across all eight stations in Azerbaijan. It accounts for 70.3% to 80.7% of total temperature variance and it does this independently of external climate forcing. The dominance of temperature persistence suggests that it is the local thermodynamic memory that governs interannual and seasonal temperature variability in the country. NAO, on the other hand, contributes a small but consistent unique share of temperature variance at every station, with values ranging from 0.360% to 1.220%. By contrast, ENSO barely contributes, confirming that ENSO's impact has been negligible in the given period. The shared cross block overlap accounts for values ranging from 8.8% to 14.7% at different stations. It represents portions that cannot be attributed to any single driver along with physical coupling between external forcing and temperature persistence.

Results of temporal change analysis offer different perspective on climate drivers. Figure 10 reveals striking findings about the temperature persistence. It shows sizable decline for the contribution of temperature persistence, a reduction of around 8 to 18 percentage across stations. Interestingly this decline was accompanied by increase in the shared cross-block overlap. This overlap explains joint variance of temperature persistence and other climate drivers. As demonstrated in Figure 6, there is significant overlap of NAO lags with temperature persistence. Therefore, we can assume that this shared overlap in Figure 10 include effects of NAO as well. This pattern points out an increasing physical entanglement among temperature persistence and external drivers. Although contribution of NAO still remains small, it showed a modest increase in 6 out of 8 stations. ENSO on the other hand remained as negligible over the years. Obvious increase in true model residual might be due to model's inability to capture growing temperature variability which is connected to more frequent extreme weather events in the second period.

While two period let us to see shift, it provides only single point comparison. To address this limitation, Block PCA decomposition with three time periods was employed (Figure 11). It offers better temporal resolution and easier tracking of changes. Figure 11 reveals that identified change across stations is not a gradual linear trend but rather a stepwise transition. The contribution of temperature persistence saw an

abrupt decrease in 2001 – 2009 while in third period, it fluctuated. Another important detail is the consistent and, in some stations, strong increase of NAO in the third period.

Initially negligible contribution of ENSO might seem inconsistent with few regional studies which highlights the significance of ENSO to Caspian Sea basin. Safarov et al. (2025) showed that Southern Oscillation Index (SOI) which is one of several indices used to measure ENSO has a stronger impact to Caspian Sea level changes than NAO does. However, ENSO influences the Caspian basin through wind patterns and evaporation rather than direct thermodynamic forcing on surface temperature. That is an important point because the index can convey a meaningful hydrological signal at the basin scale but barely leave a mark on local temperature especially in places like Azerbaijan where temperature persistence dominates variability as observed in the study. Thus, the findings of our study reinforce rather than contradict the work of Safarov et al. (2025), implying that the influence of ENSO and NAO in Azerbaijan works through dynamical pathways that are not reflected by direct temperature analysis at the station level.

To sum up our analysis revealed that changes in temperature persistence was abrupt one rather than being gradual, especially reflecting itself time period between 2001 and 2009. Second, over the years, we witnessed continuous growth in shared overlap and true residuals. This suggests that the regional climate has entered a phase of increased complexity which calls for deeper research with methods that can tackle changing patterns.

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Identification of Municipal Solid Waste Landfill Sites using the GIS and AHP Multicriteria decision analysis: A case of the urban municipality of Dédougou (Burkina Faso)

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Abstract

Sustainable management of municipal solid waste is a major challenge for developing countries, where rapid population growth and accelerated urbanization are increasing waste production and pressure on landfill sites. Selecting suitable landfill sites is a complex task that requires consideration of multiple environmental, geological, topographical and anthropogenic factors in order to minimize impacts on public health and the environment. This study focuses on the urban commune of Dédougou and proposes an approach combining GIS and the Analytic Hierarchy Process (AHP) to identify optimal municipal waste landfill sites. The data used includes groundwater depth, distance from built-up areas, distance from watercourses, slope, altitude, land use and cover, soil types, geological formations, and distance from road networks. Each factor was standardized, weighted according to Thomas L. Saaty's 1977 AHP scale, and integrated into the GIS to produce a landfill suitability map. The results indicate a classification of areas into five categories: very unfavorable (9.29%), unfavorable (23.55%), moderately favorable (27.25%), favorable (39.88%) and very favorable (0.06%). The weightings assigned reveal that groundwater depth (0.386), proximity to built-up areas (0.232) and distance from watercourses (0.131) are the most influential factors. The final map shows that suitable and very suitable sites are mainly located on the northern and north-western outskirts of the urban commune of Dédougou, while the central areas are largely unsuitable for landfills.

Keywords: Municipal Solid Waste management; Landfill site selection; Geographic Information System; Analytic Hierarchy Process; Dédougou (Burkina Faso)

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Introduction

One of the most common and serious problems facing developing countries is the lack of adequate space for waste disposal (Iskender, 2025; Armanuos et al., 2023)located in the middle of the Nile Delta in Egypt, suffers from random selection of sites for solid waste disposal, resulting in significant environmental challenges. The aim of this study is to determine optimal landfill locations within Al-Gharbia Governorate and validate the existing landfill sites. Four techniques of multi-criteria decision-making (MCDM. Rapid population growth, economic development and industrialisation have created numerous problems related to municipal solid waste management (MSWM) in developing countries (Yildirim et al., 2018). There is a direct correlation between population and the amount of waste (Othman et al., 2021).

The use of landfills has been hailed in the context of municipal solid waste management as an essential solution to open dumping and incineration (Oyedele et al., 2022). However, the process of disposing of municipal solid waste by landfill or sanitary landfill is one of the most common practices in various countries around the world. But selecting landfill sites and choosing the best site is not an easy process, as the identification and selection process involves strict rules and regulations (Abdel-razzaq et al., 2024). Selecting suitable landfill sites is challenging because it involves integrating numerous criteria into waste management and sustainability models without harming the environment (Oyedele et al., 2022). Municipal solid waste (MSW) management is essential to public health and quality of life in urban and rural environments (Ali et al., 2023). For urban planners, it is essential to carefully select landfills that have minimal impact on the environment (Antony et al., 2024).

Numerous studies have focused on the optimal selection of landfill sites using multi-criteria decision-making methods in conjunction with geographic information systems (Alkaradaghi et al., 2019). The use of multi-criteria decision-making (MCDA) approaches, which combine geographic information systems (GIS) and multi-criteria evaluation techniques such as the analytic hierarchy process (AHP), is currently considered a better approach (Asefa et al., 2021)a capital city of Harari regional state located in the eastern part of Ethiopia, covers an area of 19.5 km2 and has a total population of 270 000. Despite the fastest population growth of the city, it doesn't have a landfill site to accommodate the waste generated and open dumping is in full practice. As an integral part of a solid waste management plan, the construction of a landfill has been suggested by the city municipality. However, the multi-dimensional and conflicting aspect of landfill sitting, which involves environmental, social, technical, and economic considerations, challenges the location of a suitable landfill site. In the current study, we have applied geographic information system (GIS. GIS and MCDA software have improved the effectiveness and efficiency of selecting suitable sites; these are decision-making tools that help select appropriate sites for landfill disposal (Abdel-razzaq et al., 2024).

The overall objective of this study is to select suitable sites for the establishment of household waste landfills in Dédougou, by combining a Geographic Information System (GIS) with the Analytic Hierarchy Process (AHP). To achieve this objective, the study focuses on the following specific objectives:

- To identify and map the decision-making factors;
- To standardize and normalize the suitability criteria for landfill sites;
- To use the Analytic Hierarchy Process (AHP) to determine the relative importance of each criterion;
- Integrate the weighted criteria into a GIS-based multi-criteria evaluation model to generate a landfill suitability map.

Materials and Methods

Study area

The municipality of Dédougou is located in the province of Mouhoun and is one of seven municipalities that make up the province. The city of Dédougou is the capital of the municipality of the same name, the province of Mouhoun and the Boucle du Mouhoun region. It is located 230 km west of the political capital Ouagadougou and 176 km from Bobo-Dioulasso, the economic capital. Dédougou is connected to Ouagadougou by National Road N°. 14 and to Bobo-Dioulasso by National Road N°. 10. The access roads to both towns are paved and in good condition. The municipality of Dédougou covers an area of 1,352.56 km² or approximately 19.68% of the total area of Mouhoun Province. The municipality of Dédougou (Figure 1) shares its borders with the following municipalities:

- to the east with the municipality of Douroula;
- in the west, the municipalities of Sanaba and Bourasso;
- in the north, the municipalities of Sono and Gassan;
- in the south, the municipalities of Ouarkoye and Kona;
- to the south-east with the municipality of Safané.

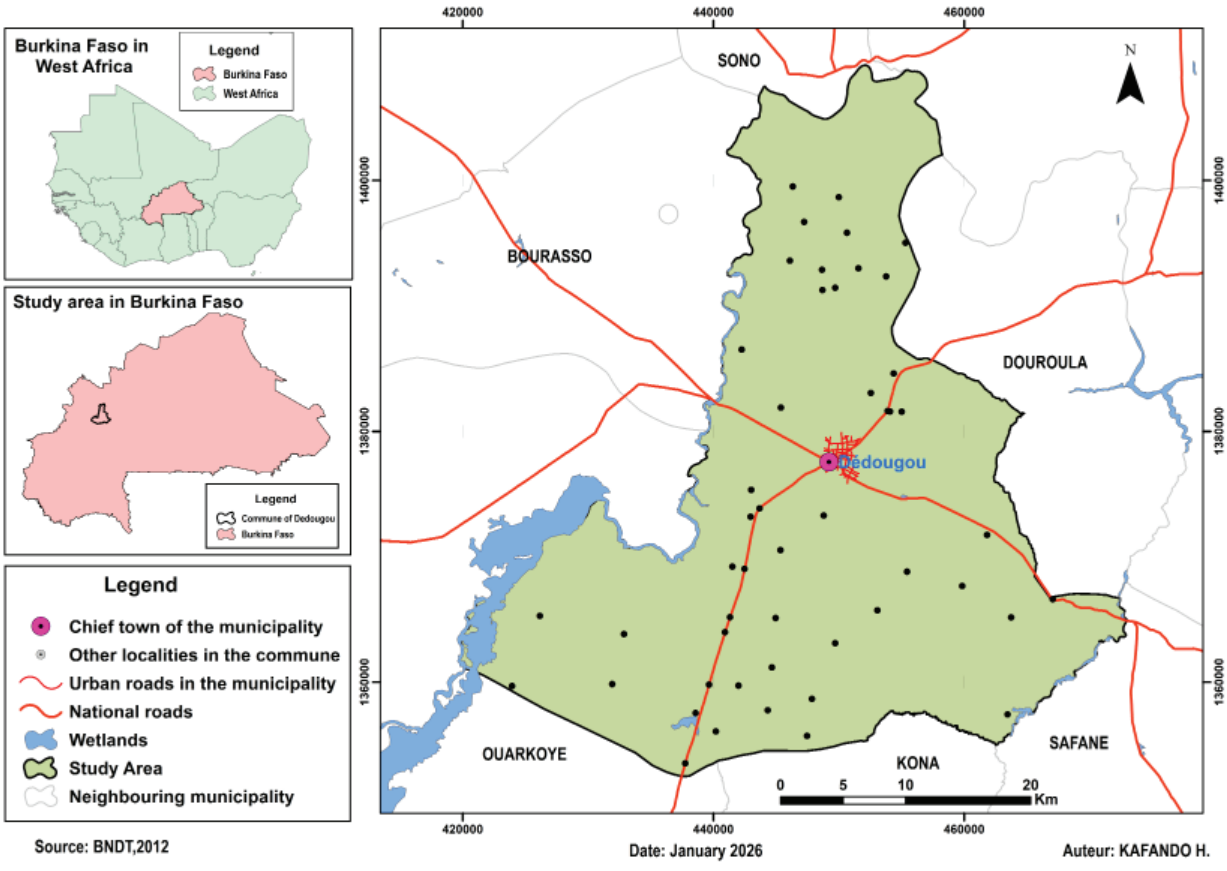

Figure 1. Study area Urban municipality of Dédougou

Data used in this study

The selection of potential sites for the establishment of a municipal landfill in the urban commune of Dédougou is based on the integration of several data sets. The main data used (Table 1) concern groundwater table, built-up areas, watercourse, types of soil, geological formations, land use/land cover, slope, roads, and, altitude factors that influence the location of landfill sites. These data were obtained from institutional sources, geomatics processing and field studies.

Table 1. Spatial data used for the selection of landfill sites in the urban municipality of Dédougou

N	Data	Acquisition
1	Groundwater depth	DGRE/DEIE, 2025
2	Built-up Areas	BNDT, 2012
3	Watercourse	BNDT, 2012
4	Types of soil	BUNASOLS, 2023
5	Geological formations	BUMIGEB, 2012
6	Land use/Land cover	Sentinel-2, 2025
7	Slope	STRM (NASA,2000)
8	Roads	BNDT, 2014
9	Altitude	STRM (NASA,2000)

Flowchart

To ensure a systematic and transparent selection of suitable municipal solid waste landfill sites, a structured methodological framework was developed. The approach integrates spatial analysis within a GIS environment and the Analytic Hierarchy Process (AHP) for multi-criteria decision-making. The framework includes the identification of the decision criteria based on literature review, local environmental context, following by criteria standardization, weighting, and overlay analysis. The Figure 2 present the overall methodological workflow adopted in this study.

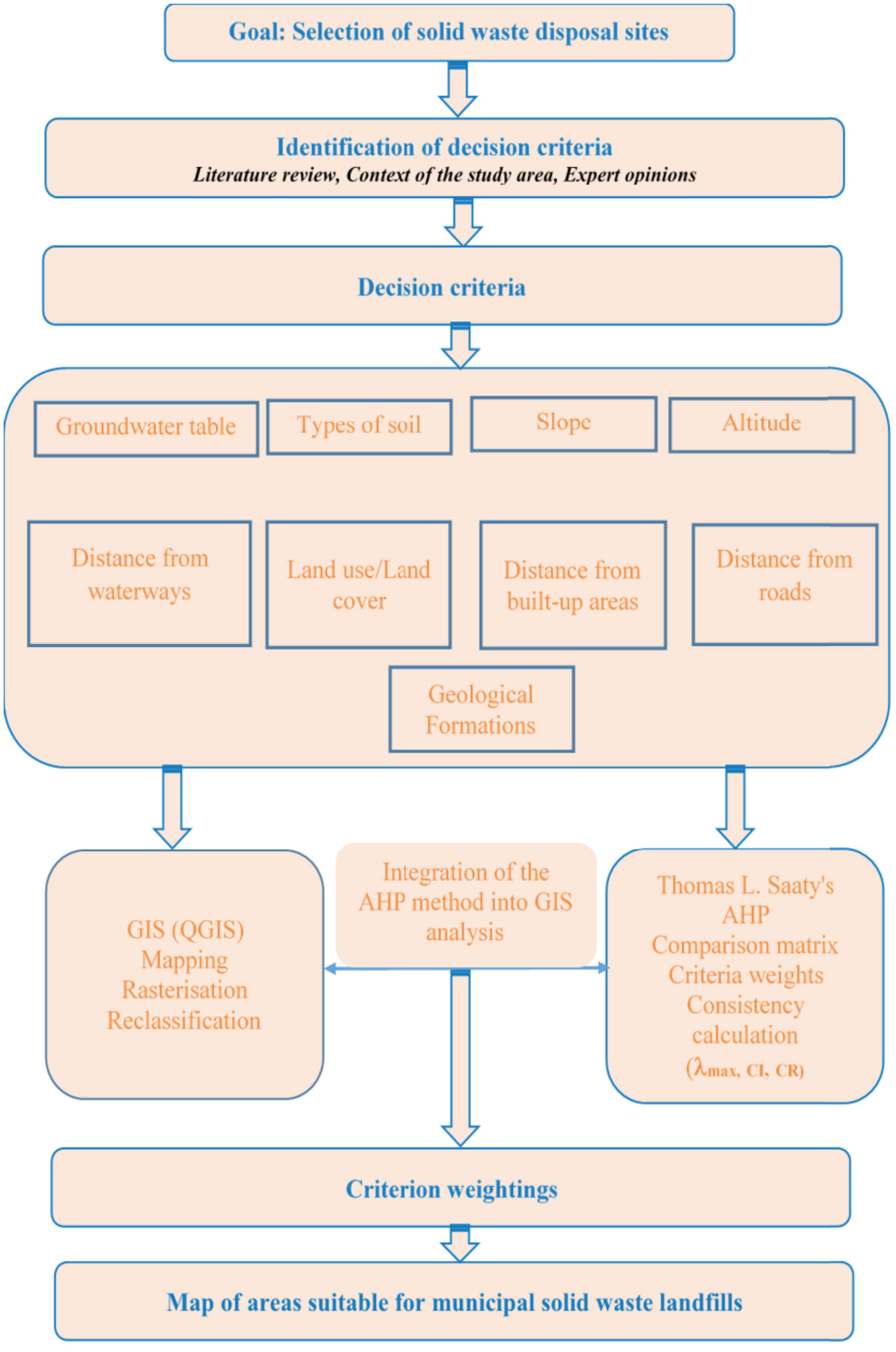

Figure 2. AHP-GIS integrated methodological workflow

Methods for integrating GIS and the AHP method

This study adopts an integrated framework combining Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) to identify suitable sites for the establishment of landfill sites. The selection of decision criteria was based on a depth review of the literature on GIS-based multi-criteria analysis for the selection of landfill sites. Furthermore, the choice of criteria takes into account the environmental and socio-economic conditions specific to the study area. The Table 2 presents the selected criteria, along with their justification and corresponding references.

Table 2. Selected criteria, justification and corresponding references

Criteria	Description/justification	Reference
Groundwater	Assess the distance from groundwater tables to prevent leachate from contaminating drinking water. Sites should be located sufficiently far from groundwater sources to ensure public health and environmental safety;	(Sisay et al., 2025; Mukomberanwa et al., 2025; Degefu & Asefa, 2024)
Built-up Areas	Avoid densely populated areas to minimize health risks, odor nuisance, and social conflicts. Sites located away from built-up areas are preferable to ensure social acceptance and operational safety;	(Degefu & Asefa, 2024; Kalisha & Munthali, 2024; Oluwanimifise & Anyaeche, 2024),
Watercourse	Maintain a safe distance from rivers, streams, or drainage channels to prevent contamination of surface water from runoff, and leachate. Buffer zones are essential for environmental protection ;	(Moumane et al., 2025; Mohammed, 2019; Audu et al., 2020; Aladenika, 2020)
Types of soil	Soils with low to moderate permeability should be selected in order to reduce the risk of leachate infiltration and ensure the geotechnical stability of landfills. Clay-rich soils are generally preferred due to their low permeability and high water-holding capacity;	(Elkhrachy et al., 2023; Salmana et al., 2024; Ali et al., 2023)
Geological formations	Geological characteristics must be taken into account to ensure the site's stability, its resistance to landslides, and its suitability for waste storage. Solid, low-permeability formations are preferred in order to minimize environmental risks;	(Soyaslan, 2025; Oguzhan et al., 2024; Armanuos et al., 2023)located in the middle of the Nile Delta in Egypt, suffers from random selection of sites for solid waste disposal, resulting in significant environmental challenges. The aim of this study is to determine optimal landfill locations within Al-Gharbia Governorate and validate the existing landfill sites. Four techniques of multi-criteria decision-making (MCDM
Land use/Land cover	Avoid sensitive areas (forests, wetlands, fertile farmland) and prioritize degraded or low-yield land in order to minimize environmental and social impacts. Land use planning ensures sustainable site selection;	(Moumane et al., 2025; Okin et al., 2024; Bhusal et al., 2023 ; Tafti et al., 2026)
Slope	Preference is given to gently sloping areas in order to minimize soil erosion, rapid surface runoff and construction difficulties. Steep slopes increase environmental and technical risks, as well as costs;	(Kalisha & Munthali, 2024; Degefu & Asefa, 2024)
Distance from roads	Assess the proximity of roads to ensure accessibility whilst minimizing traffic in residential areas. An optimal distance helps to reduce operating costs and environmental impact;	(Audu et al., 2020; Khalifa, 2015)
Altitude	Moderate elevations are generally preferred in order to avoid flood-prone areas, facilitate construction and ensure accessibility. Extremely low or high elevations can increase risks or costs.	(Tafti et al., 2026; Bhusal et al., 2023)

Decision criteria mapping

a. Distance from roads

Distance from roads is an essential criterion when choosing a landfill site. It affects accessibility for waste transport while minimizing the impact on residential areas. This factor (Figure 3) therefore helps to identify sites that are both accessible and safe (Molla, 2024; Rimal & Gurung, 2026).

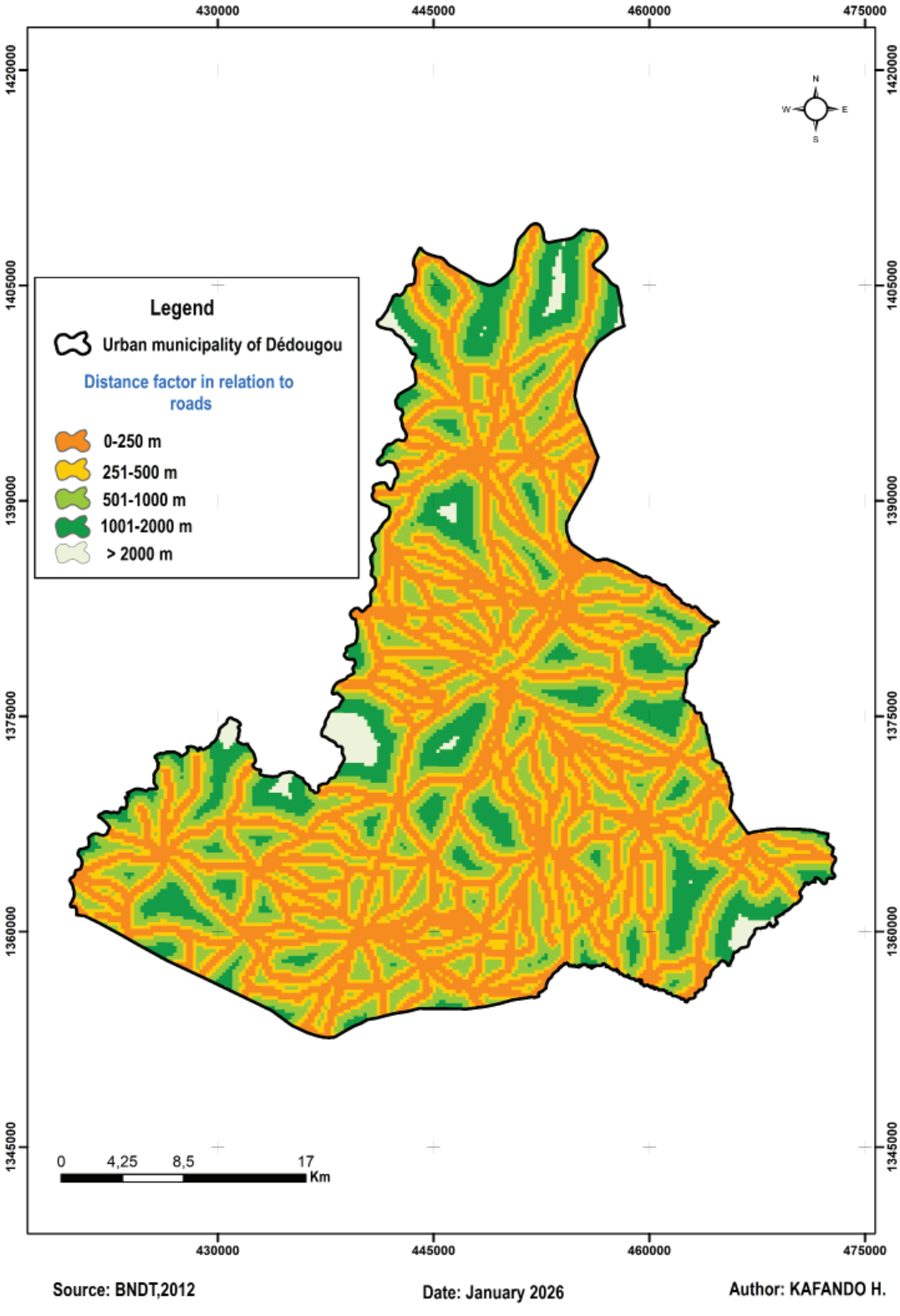

Figure 3. Distance from roads map in the urban municipality of Dédougou

b. Distance from watercourses

Distance from waterways is an essential criterion in choosing a landfill site. It helps protect water resources from contamination and maintain safety buffer zones along rivers and streams. This factor (Figure 4) thus minimizes environmental and health impacts (Chandel et al., 2024; S. Kumar et al., 2024; Tella et al., 2025).

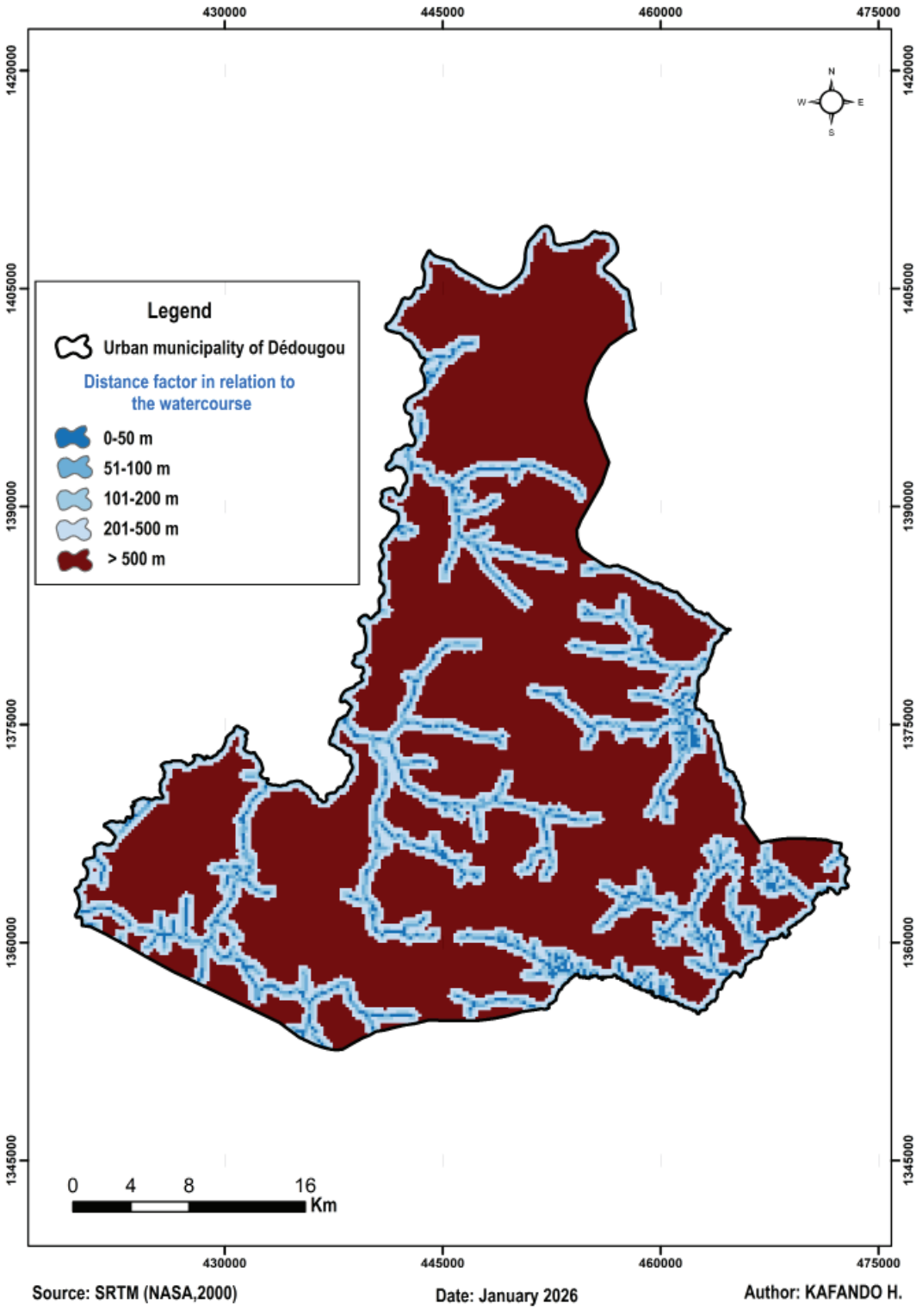

Figure 4. Distance from watercourses map in the urban municipality of Dédougou

c. Geological formations

Geological formations (Figure 5) influence the stability of a landfill site and the infiltration of waste into the soil. Permeable rocks or sediments can increase the risk of groundwater contamination, while impermeable formations offer better protection for the environment. This factor is therefore essential to ensure site safety and minimize impacts on soil and water resources (Alam et al., 2024; Wang et al., 2025).

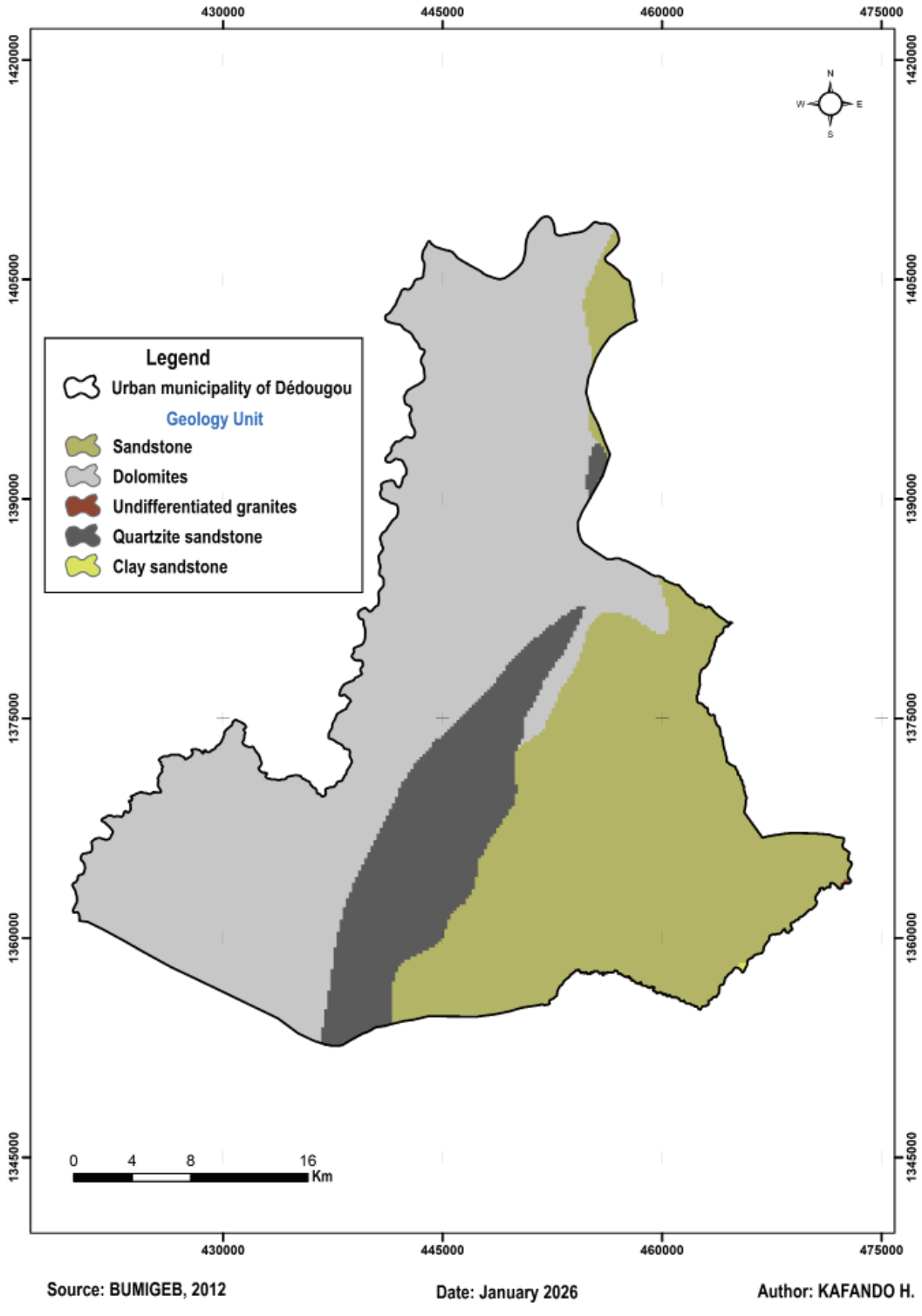

Figure 5. Geological formations map in the urban municipality of Dédougou

d. Altitude

The factor altitude (Figure 6) influences natural drainage and the risk of flooding at the site. Sites located at higher altitudes are less prone to flooding and allow surface water to drain away by gravity, reducing environmental and health risks. This factor therefore contributes to the safety and sustainability of the landfill site (Gebremichael et al., 2025"mendeley":{"formatedCitation":"(Gebremichael et al., 2025; Copăcean & Cojocariu, 2025).

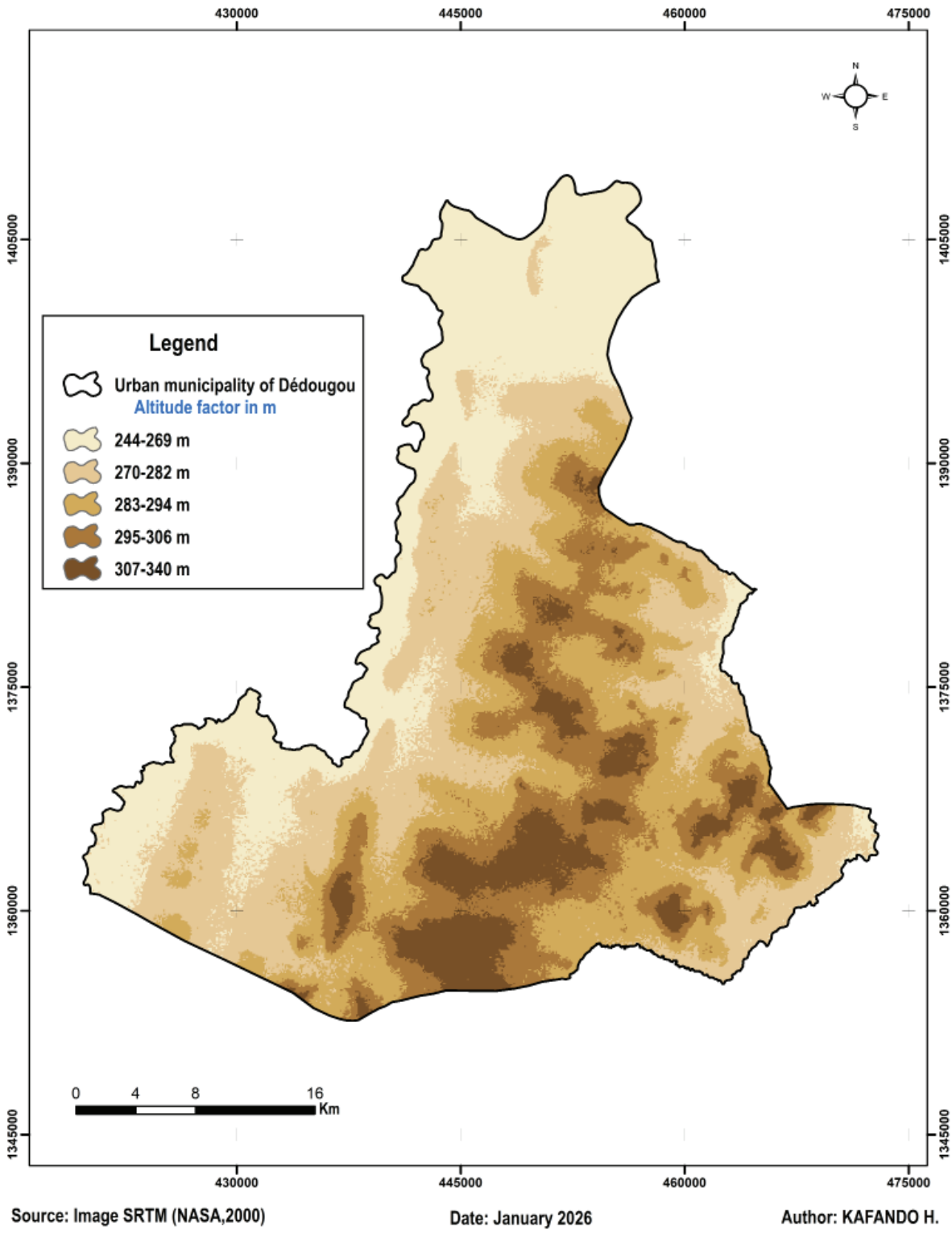

Figure 6. Altitude map in the urban municipality of Dédougou

e. Slope

The factor slope (Figure 7) influences site stability and surface water drainage. Steep slopes can cause erosion and rapid leachate runoff, while gentle slopes can lead to water accumulation and soil saturation. This factor is therefore crucial to ensuring safety, sustainability and effective waste management in landfills (Inegbedion & Orobosa, 2023; Sisay et al., 2025; Chandel et al., 2024).

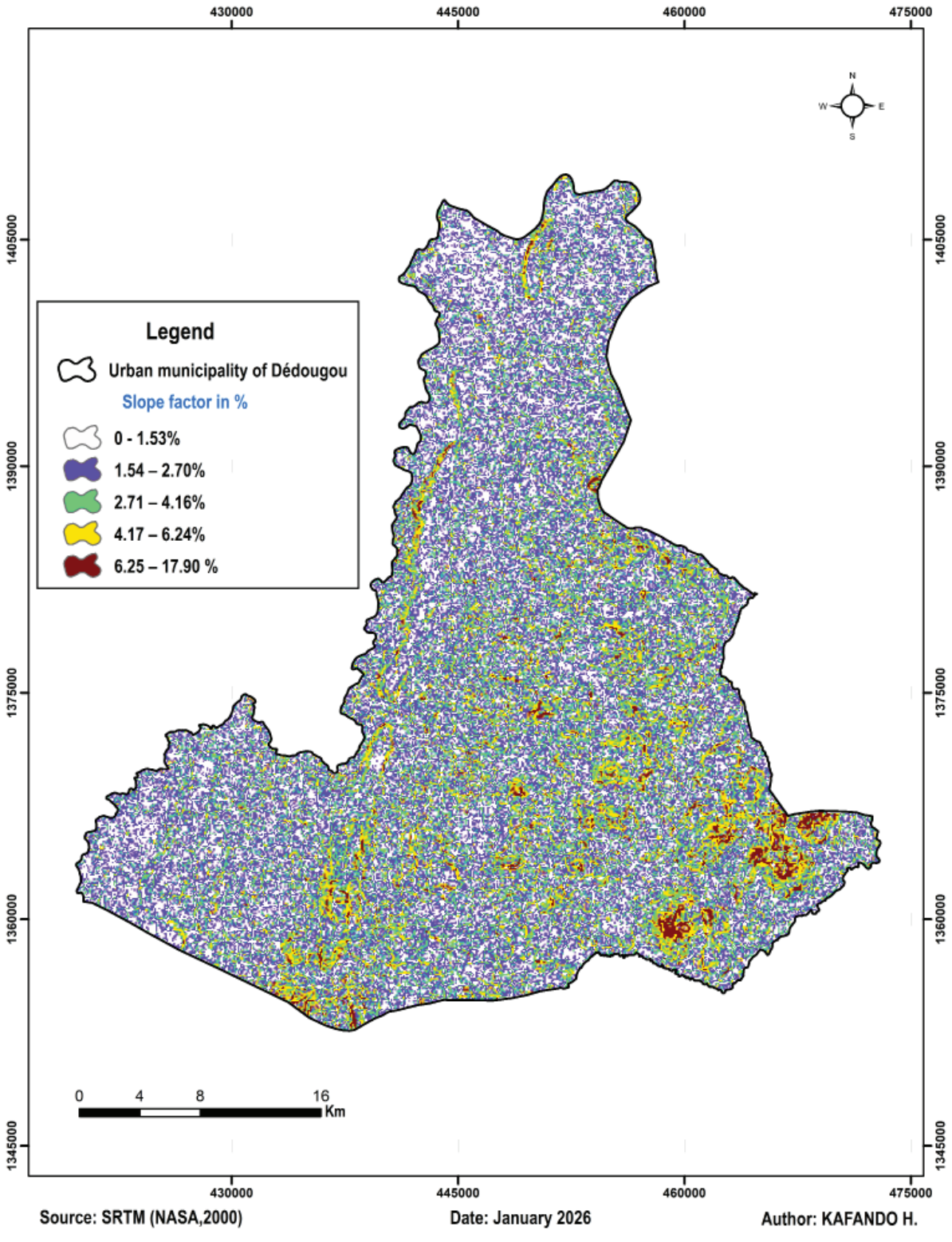

Figure 7. Slope map in the urban municipality of Dédougou

f. Soil type

The soil types (Figure 8) influence the stability, drainage and leachate containment of a landfill site. Clay soils, which are less permeable, help prevent leachate from seeping into groundwater, while sandy or highly permeable soils increase the risk of contamination. This factor is therefore essential for environmental protection and the long-term safety of the site (Kalisha & Munthali, 2024; Wamyil et al., 2026).

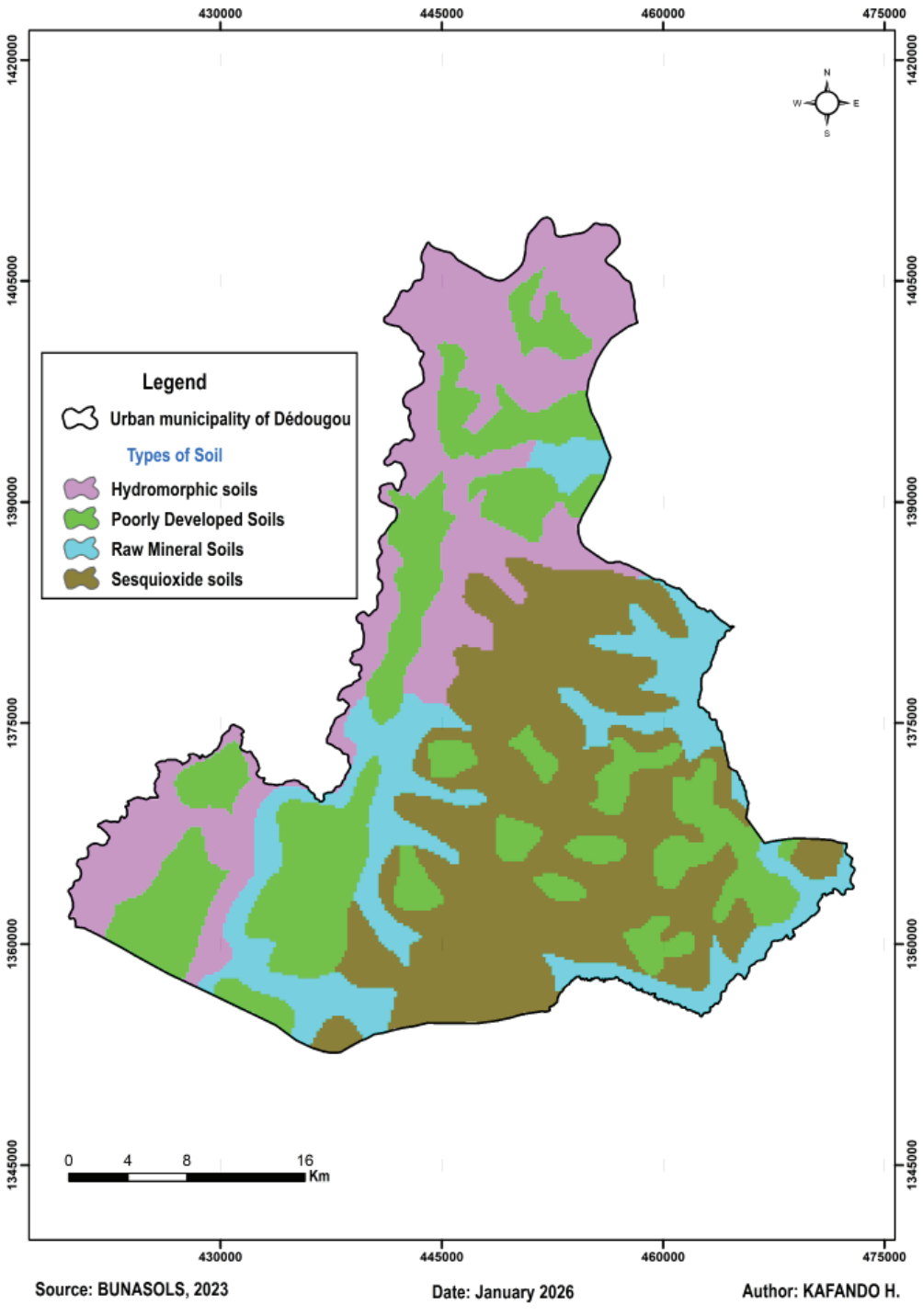

Figure 8. Soil type map in the urban municipality of Dédougou

g. Build up area

Distance from urban areas (Figure 9) is an essential criterion in landfill site selection, as it minimizes health risks, odours, and other nuisances affecting nearby populations (A. Kumar et al., 2024). Maintaining sufficient distance from inhabited areas also helps to reduce social conflicts. In addition, increasing this distance helps to limit conflicts associated with the Not In My Backyard (NIMBY) syndrome, where local communities oppose the siting of waste facilities near their living areas (Holm et al., 2021; Bao et al., 2023) . Furthermore, environmental regulations and planning guidelines recommend buffer distances between landfill sites and residential areas to ensure public health and environmental protection (UNEP & UNITAR, 2013; WHO, 2024).

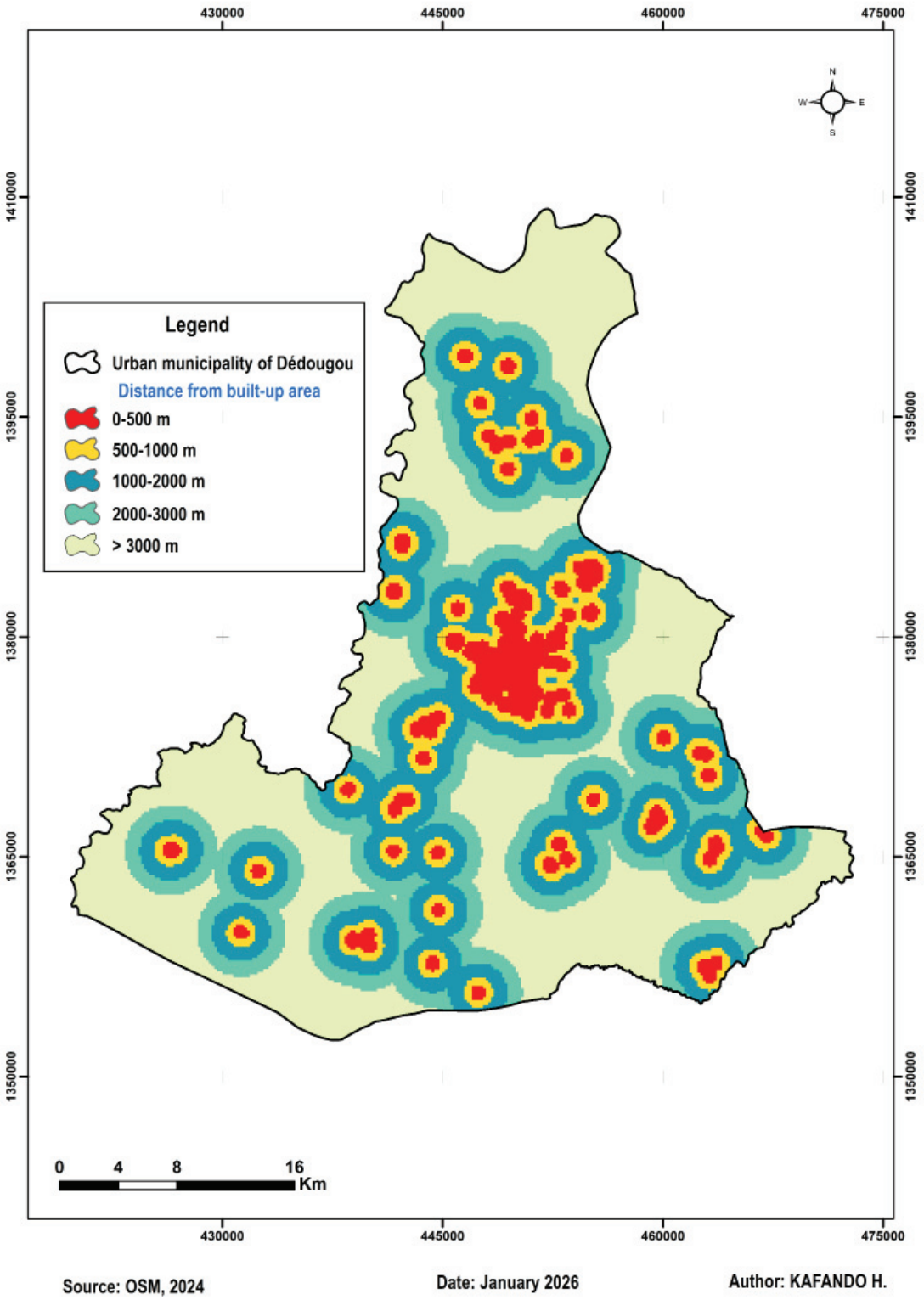

Figure 9. Distance from urban areas map in the urban municipality of Dédougou

h. Land use/Land cover

Land use and land cover (Figure 10) influence the choice of landfill sites based on human activities and vegetation cover. Densely populated or cultivated areas are generally avoided in order to reduce social and environmental impacts, while underused or undeveloped land is preferred. This factor thus contributes to balancing accessibility, safety and environmental protection (Tafti et al., 2026; Sisay et al., 2025; S. Kumar et al., 2024; Chandel et al., 2024).

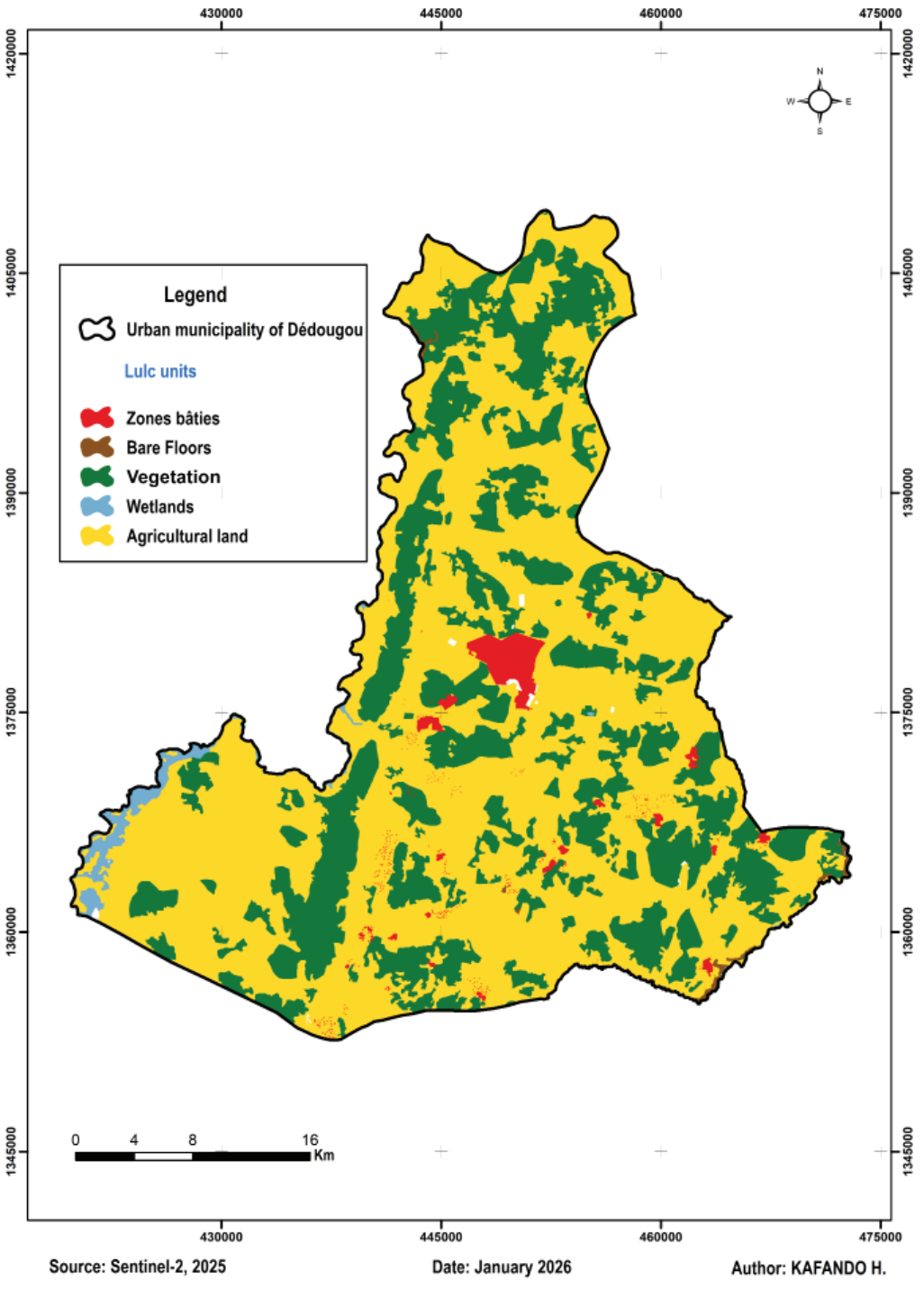

Figure 10. Land use/Land cover map in the urban municipality of Dédougou

i. Groundwater depth

The groundwater depth (Figure 11) is a determining factor in the selection of waste disposal sites, as it determines the vulnerability of groundwater to pollution (Sisay et al., 2025; Al-Fares, 2024; Armanuos et al., 2023)located in the middle of the Nile Delta in Egypt, suffers from random selection of sites for solid waste disposal, resulting in significant environmental challenges. The aim of this study is to determine optimal landfill locations within Al-Gharbia Governorate and validate the existing landfill sites. Four techniques of multi-criteria decision-making (MCDM. Highlighting areas with shallow groundwater level that are more vulnerable to contamination and therefore less suitable for landfill site selection.

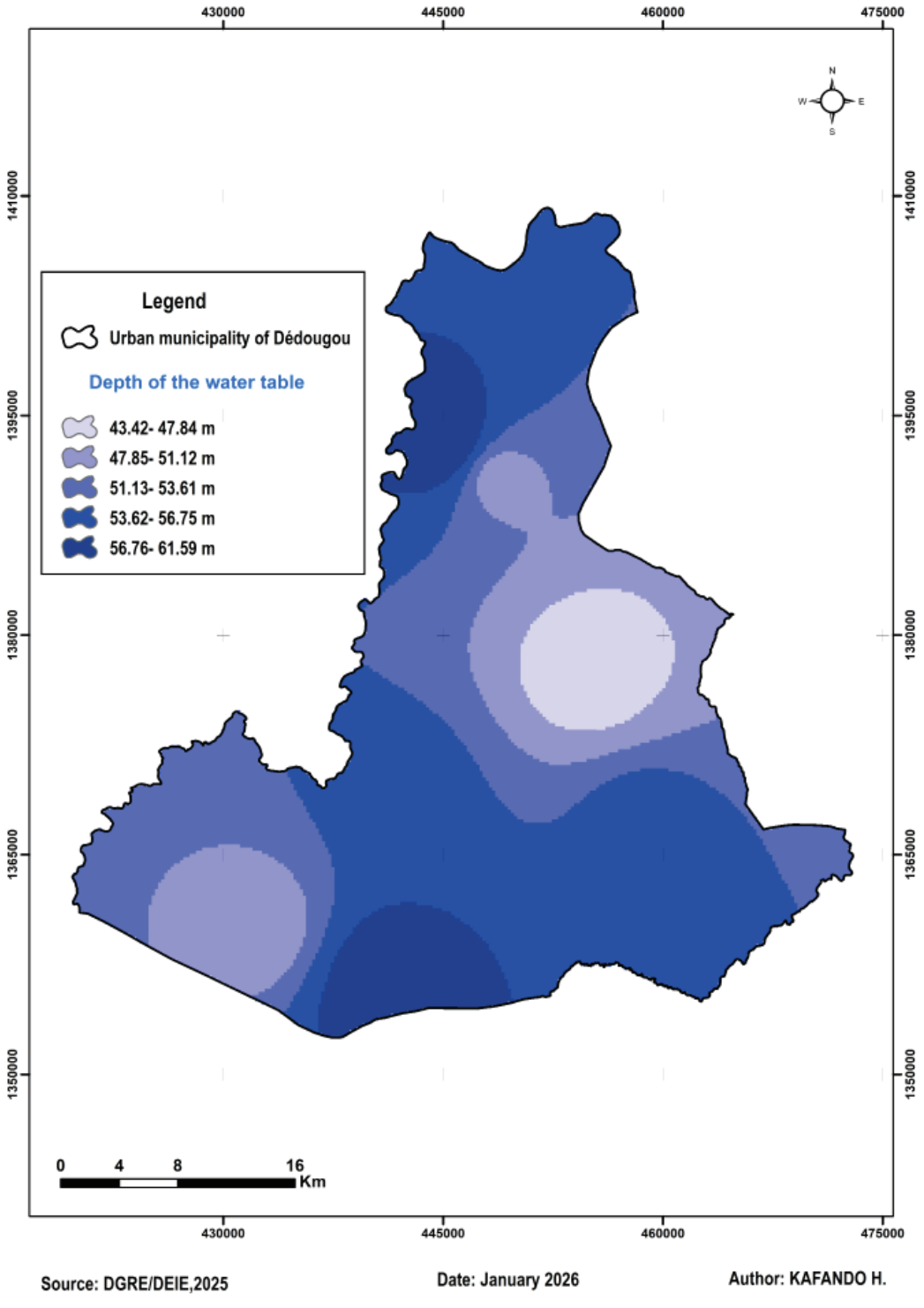

Figure 11. Spatial distribution of groundwater depth (m) in the urban municipality of Dédougou

Standardization and normalization of decision criteria

Before integrating the decision criteria into the weighted superimposition analysis, all spatial layers were normalized to ensure comparability and consistency within the multi-criteria evaluation framework. As the selected criteria were in different units of measurement (m, %, etc.), a reclassification process was applied to convert them to a common suitability scale ranging from 1, which means very low suitability, to 5, which means very high suitability. The normalization system adopted in this study is presented in Table 3.

Table 3. Standardization and normalization of decision criteria

Criteria selected	Sub-criteria	Units	Aptitude classes	Aptitude score
Distance from roads	0-250	m	Very low	1
	251-500		Low	2
	501-1000		Medium	3
	1001-2000		High	4
	> 2000		Very high	5
Distance from watercourse	0-50	m	Very low	1
	51-100		Low	2
	101-200		Medium	3
	201-500		High	4
	> 500		Very high	5
Land use/land cover	Built-up areas	Occupation unit	Very low	1
	Wetlands		Very low	1
	Agricultural land		Low	2
	Vegetation		Medium	3
	Bare floors		Very high	5
Slope	0-1.53	%	Very low	1
	1.54-2.70		Low	2
	2.71-4.16		Medium	3
	4.17-6.24		High	4
	6.25-17.90		Very high	5
Altitude	244-269	m	Very low	1
	270-282		Low	2
	283-294		Medium	3
	295-306		High	4
	307-340		Very high	5
Types of soil	Hydromorphic soils	Soils unit	Very low	1
	Slightly evolved soils		Low	2
	Raw mineral soils		Medium	3
	Sesquioxide soils		Very High	5
Distance from urban areas	0-500	m	Very low	1
	501-1000		Low	2
	1001-2000		Medium	3
	2001-3000		High	4
	> 3000		Very high	5
Geological formations	Dolomites	Geological units	Very low	1
	Sandstone		Low	2
	Quartzite sandstone		Medium	3
	Clay sandstone		High	4
	Undifferentiated granites		Very high	5
Groundwater depth	43.42- 47.84	m	Very low	1
	47.85- 51.12		Low	2
	51.13- 53.61		Medium	3
	53.62- 56.75		High	4
	56.76- 61.59		Very high	5

Source: Authors

Analytic Hierarchy Process scale (Thomas L. Saaty 1980)

The Analytic Hierarchy Process developed by Saaty L. Thomas, employs a fundamental scale of pairwise comparison to assess the relative important between two criteria. The table 4 present the fundamental AHP scale.

Table 4. AHP Scale

Value	Meaning
1	Equal importance
3	Moderate importance
5	High importance
7	Very high importance
9	Absolute importance
2.4.6	Intermediate value

Results

Pairwise comparison matrix

The Table 5 is our pairwise comparison matrix for comparing the importance of each decision criterion. The values in this table are based on Saaty's scale. Where 1 = equal importance and 9 = absolute importance of one criterion over another.

Table 5. Pairwise comparison matrix of decision criteria

Criteria	Gt	Ba	Wc	St	Gf	Lulc	Sl	R	Al
Gt	1	3	5	7	7	9	9	9	9
Ba	1/3	1	3	5	5	7	7	7	7
Wc	1/5	1/3	1	3	3	5	5	5	5
St	1/7	1/5	1/3	1	3	3	3	3	3
Gf	1/7	1/5	1/3	1/3	1	3	3	3	3
Lulc	1/9	1/7	1/5	1/3	1/3	1	2	2	2
Sl	1/9	1/7	1/5	1/3	1/3	1/2	1	2	2
R	1/9	1/7	1/5	1/3	1/3	1/2	1/2	1	2
Al	1/9	1/7	1/5	1/3	1/3	1/2	1/2	1/2	1

Legend of the table: R = Roads, Wc = Watercourse, Lulc = Land use/land cover, Sl =Slope, Al =Altitude, St=Soil type, Ba = Built-up area, Gf = Geological formations, G t= Groundwater table.

Criterion weighting and justification

The decision criteria were weighted using the Analytic Hierarchy Process (AHP) following a structured and transparent procedure. The pairwise comparison matrix for this study was developed by the authors based on an in-depth analysis of the scientific literature on landfill site selection using GIS-AHP methods.

Initially, the relative importance of each criterion was determined by analyzing previous studies conducted in similar environmental and socio-economic contexts (Sisay et al., 2025; Elkhrachy et al., 2023; Armanuos et al., 2023)located in the middle of the Nile Delta in Egypt, suffers from random selection of sites for solid waste disposal, resulting in significant environmental challenges. The aim of this study is to determine optimal landfill locations within Al-Gharbia Governorate and validate the existing landfill sites. Four techniques of multi-criteria decision-making (MCDM. Particular attention was given to both the frequency of use of each criterion and the level of importance attributed to it in these studies. Criteria consistently identified as critical for environmental protection and public health, such as groundwater depth, distance from built-up areas, and distance from watercourses, were therefore assigned higher relative importance.

Secondly, based on this literature review, pairwise comparisons between the criteria were performed using Saaty's fundamental scale (Saaty, 1980). To ensure transparency and reproducibility, the assignment of pairwise comparison values followed a structured decision rule. Criteria directly related to environmental protection and public health (e.g., groundwater, water-

courses, built-up areas) were systematically assigned higher importance values (5-9), whereas criteria with a secondary influence (e.g. altitude, roads) were assigned moderate to low values (1-5). These judgments were guided by both the frequency of occurrence and the relative importance of criteria reported in previous studies conducted in comparable contexts. Each comparison reflects a reasoned judgment regarding the relative importance of one criterion over another within the specific context of Dédougou. For example, groundwater protection was considered significantly more important than accessibility factors due to the high risk of groundwater contamination in the absence of adequately engineered landfill systems.

Thirdly, the pairwise comparison matrix was normalized and the criterion weights were derived from the principal eigenvector. To assess the reliability of the judgments, the Consistency Ratio (CR) was calculated. The obtained value (CR = 0.055) is below the acceptable threshold of 0.1 indicating a satisfactory level of consistency in the comparisons.

The resulting weights (Table 6) reflect a logical prioritization of environmental protection criteria over technical and accessibility factors. Groundwater depth (0.386) received the highest weight due to its critical role in preventing contamination. Distance from built-up areas (0.232) and distance from watercourses (0.131) were also assigned high weights, as they directly influence risks to public health and environmental safety. In contrast, criteria such as altitude (0.022) and distance from roads (0.026) were assigned lower weights, as their impact is considered secondary within the specific geographical context of the study area. The final weights assigned to each criterion are presented in Table 6.

Table 6. Weight of each Criteria

Nº	Criteria	Weighting of criteria
1	Groundwater depth	0.386
2	Buil up area	0.232
3	Watercourse	0.131
4	Types of soil	0.077
5	Geological formations	0.059
6	Land use/Land cover	0.035
7	Slope	0.030
8	Roads	0.026
9	Altitude	0.022
Total		1

Consistency calculation

a. Maximum eigenvalue (λ_{max})

The maximum eigenvalue was calculated to verify the consistency of the decision criteria judgements. The calculation formula is:

$$\lambda\mathbf{max} = Aij\,\frac{\mathrm{wi}}{\mathrm{wj}}$$

A is the pairwise comparison matrix (Table 6)
Wi is the weight of criterion i
Wj is the number of criteria
The maximum eigenvalue calculated for our study λmax is equal to: 9.643

b. Consistency index (CI)

To validate the judgements, we calculated the consistency index. The calculation formula is :

$$CI = \frac{(\lambda\mathrm{max}-\mathrm{n})}{(n-1)}$$

CI=0.080

CI=is the consistency index

c. Consistency ratio (CR)

To verify the validity and acceptability of the matrix, we calculated the consistency ratio.

$$CR = \frac{CI}{AI}$$

CR= **0.055**
CR=is the random index
Integration of the AHP method into GIS analysis

a. Standardization of criteria

Each decision factor has been reclassified (Table 7) into five levels. This reclassification allows for compatibility of the factors to be aggregated in the GIS software.

Table 7. Reclassification of decision factors for landfill site selection

Reclassified value	Site suitability
1	Very unfavorable site
2	Unfavorable site
3	Moderately unfavorable site
4	Favorable site
5	Very favorable site

b. Weighting of factors in the GIS

The final map is obtained by the weighted sum of the factors. The following equation is used to determine suitable sites for municipal solid waste disposal in the urban municipality of Dédougou

Sites suitable = ("Groundwater depth* 0.386) + ("Built-up area" * 0.232) + ("watercourse" * 0.131) + ("Soils type" * 0.077) + ("Geological formations" * 0.059) + ("Land use/Land cover" * 0.035) + ("Slope" * 0.030) + ("Roads" * 0.026) + ("Altitude" * 0.022)

c. Map of sites suitable for municipal waste disposal

The Figure 12 shows the spatial distribution of areas suitable for the establishment of municipal solid waste landfills in the urban municipality of Dédougou.

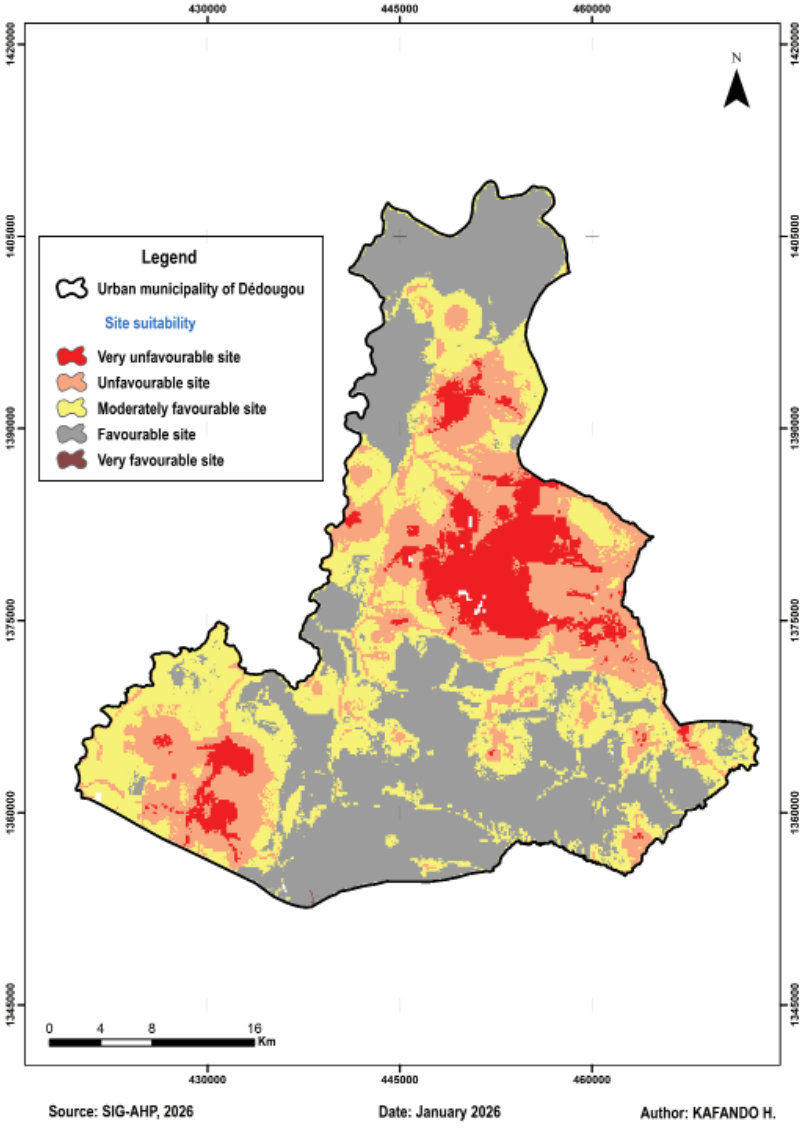

Figure 12. Sites suitable for municipal waste disposal

Discussion

Analysis of the results of mapping the suitability of municipal solid waste landfill sites in the urban commune of Dédougou, produced by combining GIS and the AHP method, shows that the study area is structured into five levels of suitability, with a clear spatial differentiation between central urban areas and peripheral zones. This result highlights the strong influence of urbanization and environmental constraints on site selection. The resulting map shows that the most suitable areas are mainly located in the peripheral zones, while central areas are largely unsuitable due to high population density and land use constraints. This spatial pattern confirms findings from previous studies, particularly those conducted in Hossana and Gimba Town in Ethiopia (Wanore et al., 2023; Sisay et al., 2025), where suitable landfill sites were also identified in peripheral areas. However, unlike some studies that report large continuous suitable zones, the results in Dédougou indicate a more fragmented distribution of suitable areas. This difference can be explained by the spatial organization of the municipality, where land use is increasingly constrained by agricultural activities and scattered settlements, limiting the availability of large homogeneous zones. Similarly, the classification into five suitability classes is consistent with the study conducted in the Najran region of Saudi Arabia (Elkhrachy et al., 2023). Nevertheless, the relative importance of certain criteria appears to differ, particularly regarding topographic factors. While slope was identified as a key determinant in studies such as that conducted in Turkey (Soyaslan, 2025), its influence in Dédougou seems to be less significant, which can be attributed to the relatively low topographic variability of the study area. The weighting of criteria using the AHP method played a central role in the results obtained. Although this method has been criticized for its subjectivity, the consistency of the spatial distribution observed in this study suggests that the weighting remains coherent with local environmental realities. This finding is in line with the study conducted in Nepal (Subedi, 2025).

However, the present study did not incorporate advanced approaches such as Fuzzy AHP, which could reduce uncertainties related to pairwise comparisons. Future research could therefore integrate such methods, as suggested by recent reviews (S. Kumar et al., 2024), to improve the robustness of decision-making. Finally, the mapping produced confirms that locating landfill sites away from densely populated areas is essential for minimizing health and environmental risks. However, these results remain theoretical and require field validation to assess their practical feasibility. In addition, the integration of temporal dynamics, such as urban growth and future waste production trends, would significantly improve long-term planning and sustainability of landfill site selection. The mapping produced for solid waste disposal sites in the urban municipality of Dédougou confirms that the most suitable areas are located on the outskirts of inhabited areas, which is important for minimizing health risks. However, additional field validation is necessary to confirm the practical feasibility of the proposed sites. In addition, the integration of temporal data in this case projections of urban growth and future trends in waste production should be considered in future studies in order to anticipate long-term needs.

Conclusion

This study addressed the crucial issue of sustainable solid waste management by identifying potential sites suitable for waste disposal in the urban municipality of Dédougou. The final map shows that 0.06 km² of the municipal territory is highly suitable and 536.08 km² is suitable for municipal solid waste disposal. These sites are located on the outskirts of the municipality, mainly to the north and north-west. 124.98 km² of the municipality are very unfavourable areas and 316.63 km² are unfavourable. They are located in the centre of the municipal territory. Moderately favourable areas, covering 27.25 km², occupy the areas above the favourable areas. Thanks to the GIS-AHP approach. We have transformed the complex issue of solid waste into a valuable decision-making tool. The multi-criteria GIS-AHP approach has proven effective in integrating both natural constraints (topography, waterways, soil) and anthropogenic constraints (proximity to roads, built-up areas and land use). Ultimately, the GIS-AHP approach applied to solid waste in the municipality of Dédougou provides an operational tool for sustainable waste planning and management.

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