Original Scientific Paper/Originalni naučni rad UDC/UDK: 551.583:355.525(497.17)"20"
Paper Submitted/Rad primljen: 10.04.2025. 355/359:623]:001.895(497.17)"20"
Paper Accepted/Rad prihvaćen: 15.05.2025.
DOI: 10.5937/SJEM2502012R

Klimatske promene i njihov uticaj na vojni poligon Krivolak u 21. veku: izazovi, prilagođavanje i uloga pametnih vojnih tehnologija

Rexhep Mustafovski[1], Aleksandar Petrovski[2], Marko Radovanović[3]*

[1] Ss. Cyril and Methodius University, Faculty of Electrical Engineering and Information Technologies, Skopje, North Macedonia, rexhepmustafovski@gmail.com
[2] Goce Delcev University, Military Academy "General Mihailo Apostolski", Skopje, North Macedonia, aleksandar.petrovski@ugd.edu.mk
[3] University of Defence, Military Academy, Belgrade, markoradovanovicgdb@yahoo.com

Apstrakt: Klimatske promene predstavljaju sve veći izazov za vojnu infrastrukturu, posebno u regionima podložnim ekstremnim vremenskim uslovima i ekološkim transformacijama. Ovaj rad analizira uticaj klimatskih promena na vojni poligon Krivolak u Severnoj Makedoniji. Integracijom podataka o životnoj sredini, vojne doktrine i novonastalih tehnologija, istraživanje sagledava kako se ova značajna obučna zona transformiše u pogledu upotrebljivosti terena, operativne spremnosti i logističkog planiranja. Rad predstavlja procenu zasnovanu na scenarijima, uz vizualizovane rezultate koji prikazuju operativne posledice klimatskih promena. Pored toga, predstavljeno je kako pametne tehnologije, poput geoprostornog monitoringa, prediktivnog modeliranja i adaptivnih sistema za obuku, mogu unaprediti otpornost. Ovi nalazi ukazuju na širu potrebu za integracijom svesti o klimatskim promenama i tehnološkog prilagođavanja u vojno planiranje i projektovanje infrastrukture.

Ključne reči: Poligon Krivolak, otpornost na klimatske promene, vojna spremnost, tehnološko prilagođavanje

Climate Change and Its Impact on the Krivolak Military Training Area in the 21st Century: Challenges, Adaptation, and the Role of Smart Military Technologies

Abstract in English: Climate change presents increasing challenges for military infrastructure, especially in regions prone to extreme weather and environmental transformation. This paper examines how climate change is affecting the Krivolak Military Training Area in North Macedonia. By integrating environmental data, military doctrine, and emerging technologies, the study explores how this vital training site is being reshaped in terms of terrain usability, training readiness, and logistical planning. The paper presents a scenario-based assessment and includes visualized results to demonstrate the operational consequences of climate change. Moreover, it introduces how smart technologies such as geospatial monitoring, predictive modelling, and adaptive training systems can improve resilience. These findings reflect a broader need to integrate climate awareness and technological adaptation into military planning and infrastructure design.

Keywords: Krivolak Training Area, Climate Resilience, Military Readiness, Technological Adaptation

1. Introduction

Across the globe, climate change is beginning to influence military decision-making, training logistics, and infrastructure planning. Armed forces are not only affected by rising temperatures, extreme precipitation, and environmental degradation, but also expected to operate effectively within these evolving conditions. In the Balkan region, the Krivolak Military Training Area represents one of the largest and most strategically significant defense zones. Located in a semi-arid landscape, Krivolak is increasingly exposed to temperature rise, unpredictable rainfall, soil erosion, and seasonal shifts, all of which have operational consequences on land usability, exercise schedules, and environmental safety (Tavares da Costa and Krausmann, 2021; European Commission, 2021; ICS Europe, 2022; Glavinov and Kamchev, 2023).

Numerous global defense strategies now identify climate change as a risk to readiness and mission continuity (Palazzo, 2022; NATO, 2022; CNA Corporation,2007). These effects include both direct consequences: such as heat-related training restrictions or erosion of maneuver terrain and indirect risks such as infrastructure degradation and energy supply instability. The European Defence Agency and other institutions stress the urgency of adopting site-specific climate resilience measures, including the use of renewable energy systems, integrated environmental monitoring, and digital scenario modeling (Naumann, et al., 2021; Bellasio et al., 2021).

This paper focuses on Krivolak as a critical case study. It reviews historical climate patterns and current environmental stressors, followed by a detailed table of site characteristics. It then presents a simulation-based scenario demonstrating how climate variables impact military use of the training area. Finally, the paper proposes adaptation strategies that incorporate geospatial tools, autonomous surveillance platforms, and data-driven energy management. The conclusions drawn offer guidance for policymakers, defense planners, and environmental engineers concerned with the future of military infrastructure under changing climate conditions (European Space Agency, 2020).

2. Overview of the Krivolak Military Training Area

The Krivolak Military Training Area is the largest and most strategically important training site in North Macedonia, covering approximately 22,500 hectares of primarily arid, rugged, and semi- mountainous terrain. Situated in the central-southern part of the country, Krivolak serves as a key facility for national military preparedness, NATO interoperability exercises, and international defense cooperation. The site includes live-fire zones, maneuver corridors, UAV testing fields, and simulated urban environments, making it a multi-domain training platform.

In recent years, Krivolak has experienced significant environmental pressure linked to climate variability. Increasing annual temperatures, changing precipitation patterns, and dry season expansion have led to more frequent soil erosion, vegetation loss, and the degradation of surface stability, which is essential for maneuver operations and infrastructure preservation. According to climate risk assessments across the Balkan region, the combination of heat extremes, sudden flooding, and water scarcity is expected to continue shaping Krivolak‘s usability and readiness conditions in the coming decades.

Several defense institutions have already begun integrating environmental and climate metrics into their training site assessments and modernization efforts. For Krivolak, the adoption of real-time climate monitoring tools, terrain-responsive infrastructure, and predictive modeling platforms is becoming increasingly relevant, especially as joint international exercises grow in frequency and complexity (Tavares da Costa and Krausmann, 2021).

Figure 1: Aerial View of the Krivolak Training Area

(Source: *https://mod.gov.mk/at-krivolak-we-continue-to-develop-our-military-skills-a-joint-exercise-of-cadets-from-the-military-academy-with-members-of-the-army-of-montenegro/?__cf_chl_tk=usfFJAxx0vJpB6OuY4IGBT97QE3GtVAZSiMDgVTEvAE-1748788564-1.0.1.1-OrpljwT76FO_gbvSHyckXgzmKcE8O0fElkfpPx8lzCI****)***

This aerial image captures a section of the Krivolak Training Area during a rotary-wing training exercise. The terrain visible here is indicative of the arid and semi-arid landscape that dominates the region and is increasingly affected by climate-induced soil erosion, vegetation stress, and seasonal surface instability.

Figure 2: Map View of Krivolak and Surrounding Infrastructure

(Source: *https://www.google.com/maps/place/Krivolak/@41.5276923,22.1098246,15z/data=!3m1!4b1!4m6!3m5!1s0x1356714a1bbffe8d:0x47ee944159df8069!8m2!3d41.5284194!4d22.1206661!16s%2Fm%2F04mxmrw?entry=ttu&g_ep=EgoyMDI1MDUyOC4wIKXMDSoASAFQAw%3D%3D****)***

This map highlights the geographic boundaries of the Krivolak Military Training Area in relation to nearby civilian settlements, road networks, and natural features such as the Vardar River. It provides context for the strategic location of the site and its logistical accessibility, both of which are increasingly influenced by seasonal climate variations and infrastructure exposure risks.

Table 1: Key Features of the Krivolak Military Training Area

Feature	Details
Location	Central-Southern North Macedonia
Total Area	Approx. 22,500 hectares
Elevation Range	230–950 meters
Climate Zone	Semi-arid to Mediterranean transition
Training Functions	Live fire, maneuver, UAV testing, NBC drills
Infrastructure Components	Shooting ranges, control towers, command zones
Vegetation Cover	Sparse grassland and shrubland
Average Summer Temperature	34°C (rising trend)
NATO Usage	Used in multinational joint exercises
Environmental Challenges	Soil erosion, heat stress, flood risk

Table 1 summarizes the essential physical, operational, and environmental characteristics of the Krivolak Military Training Area. These attributes define the site's strategic value and also indicate the environmental sensitivities that make it increasingly vulnerable to climate-related stress. The elevation range and semi-arid to Mediterranean transition climate shape the types of exercises that can be performed throughout the year. The site‘s sparse vegetation and open terrain provide ideal conditions for live-fire and maneuver operations, while also increasing susceptibility to erosion and dust propagation during dry seasons. The average summer temperature already reaches above 34°C and continues to rise annually, placing additional pressure on infrastructure and personnel endurance. Furthermore, Krivolak's frequent use in NATO-aligned training and multinational exercises underlines the importance of maintaining its operational readiness, which depends heavily on terrain stability, resource access, and adaptability to climate variability. These factors form the foundation for the scenario-based analysis and climate impact projections discussed in the next section.

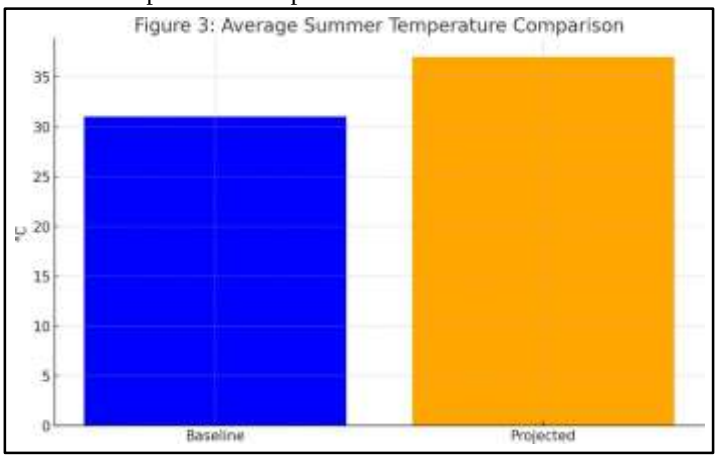
3. Scenario-Based Climate Impact Analysis

To better understand how climate change is affecting the operational value of the Krivolak Military Training Area, a comparative scenario was developed using baseline historical data and projected environmental conditions. This scenario models three critical indicators: average summer temperature, usable training days per year, and surface erosion risk. The aim is to quantify how ongoing climate trends may degrade the availability, safety, and sustainability of the training environment. These projections are informed by regionally observed climate patterns and defense-related environmental assessments (Palazzo, 2022). The figures below present a side-by-side comparison of historical conditions (baseline) and anticipated impacts by mid-century if no mitigation strategies are implemented.

3.1. Average Summer Temperature

The average summer temperature at Krivolak is expected to rise from approximately 31°C to 37°C. This increase will elevate the frequency of heat-related training cancellations and impose greater physiological strain on personnel, particularly during live-fire and extended field operations. Elevated temperatures also accelerate ground surface hardening, reducing maneuverability and increasing fire hazard risk.

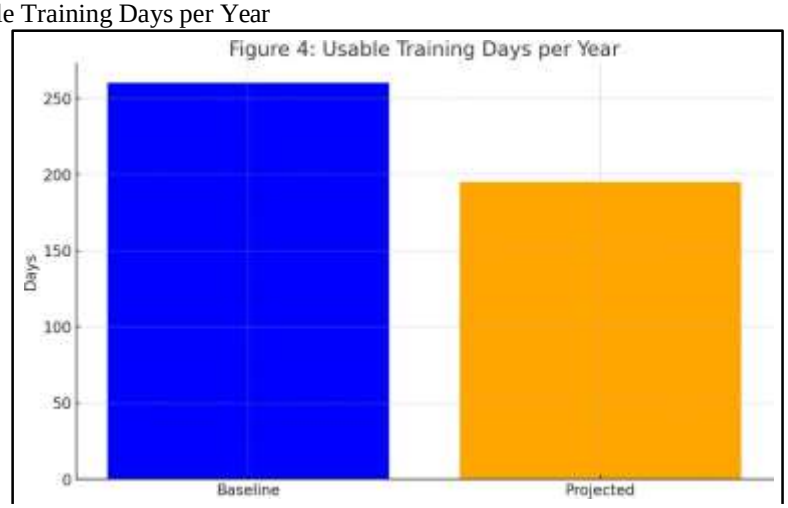
Figure 3: Average Summer Temperature Comparison



3.2. Usable Training Days per Year

Training availability is projected to drop from 260 usable days per year to around 195. This decline is attributed to heat stress thresholds, heavy rainfall episodes, and wind-induced dust storms, which can disrupt visibility and degrade sensor performance. Reduced scheduling flexibility could affect readiness cycles and coordination with allied exercises, especially during NATO seasonal rotations.

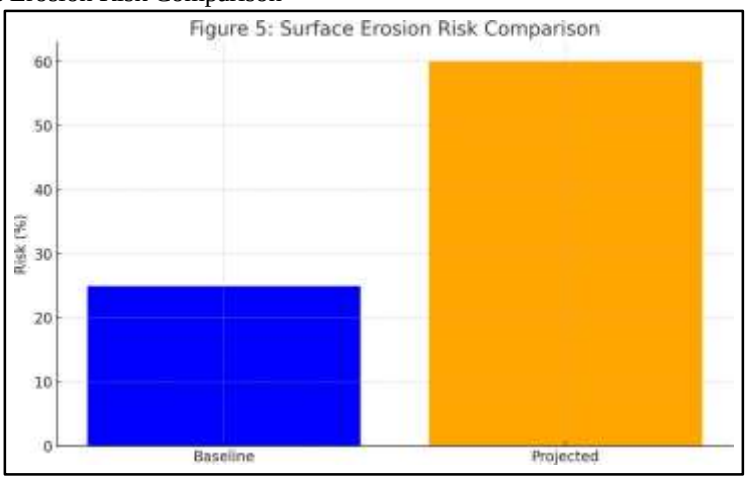
Figure 4: Usable Training Days per Year



3.3. Surface Erosion Risk

Erosion risk is expected to more than double, from 25 percent to over 60 percent, due to intensified rainfall variability and vegetation decline. Surface instability poses direct threats to a range of infrastructure such as roads, bunkers, and observation points. It also impacts environmental compliance and could lead to training area closures for remediation and restoration efforts (European Space Agency, 2020).

Figure 5: Surface Erosion Risk Comparison



These scenario-based insights demonstrate that climate change is not only an environmental issue but a direct factor in training readiness, mission assurance, and long-term military planning. The results underscore the urgent need for climate adaptation policies at Krivolak, including infrastructure reinforcement, predictive monitoring systems, and seasonal training strategy revisions (Bellasio et al., 2021).

4. Adaptation Strategies and Technological Integration

The observed and projected climate impacts at the Krivolak Military Training Area demand a proactive approach grounded in both environmental resilience and technological modernization. As climate conditions increasingly influence training availability and infrastructure durability, it becomes critical to integrate adaptive strategies that preserve operational continuity and improve long-term sustainability.

One of the primary areas for adaptation lies in infrastructure design and material resilience. Roads, firing positions, and observation structures must be reinforced with erosion-resistant materials and drainage systems that respond to shifting rainfall patterns and seasonal runoff. Elevated summer temperatures also necessitate shade structures, heat-resistant pavements, and cooling shelters to protect personnel and sensitive equipment during prolonged exposure.

In parallel, technology can play a central role in climate adaptation. Installing real-time environmental monitoring stations throughout Krivolak would enable commanders to track temperature, soil moisture, and wind conditions, improving decision-making related to exercise planning and safety thresholds. Satellite-based terrain monitoring, combined with UAV surveillance, could identify areas undergoing rapid erosion or vegetation loss, allowing for timely remediation (ICS Europe, 2022). These data systems also support predictive modeling, helping planners forecast periods of reduced usability and adjust logistics accordingly.

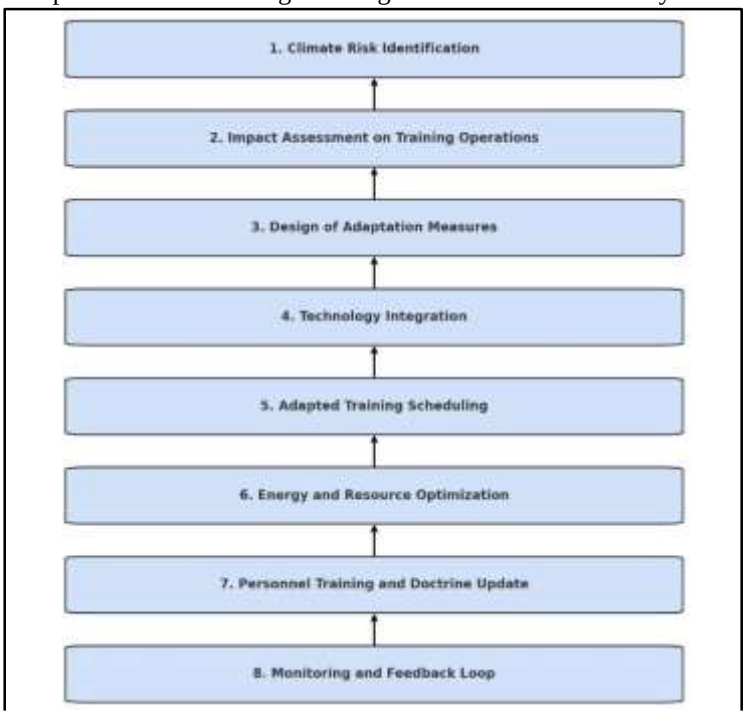
Another essential element is the development of a seasonally adaptive training calendar. With a projected loss of up to 65 training days per year, military planners may need to redesign the training cycle to optimize exercises in early spring and late autumn, when temperatures and erosion risk are lower (Naumann, et al., 2021). This change would be supported by artificial lighting systems and modular training stations, enabling nighttime and low-visibility scenarios that take advantage of cooler conditions.

Krivolak could also benefit from the integration of energy-efficient technologies, such as solar- powered observation posts and battery-backed command points, which reduce reliance on fuel logistics and improve environmental compatibility. This aligns with broader NATO and EU defense sustainability goals, which emphasize green defense infrastructure and climate-conscious military planning.

Finally, adaptation should extend to training doctrine and personnel awareness. Updating operational manuals to include climate risk protocols, first-aid procedures for heat injuries, and environmental restoration guidelines will enhance both preparedness and safety. Joint exercises can incorporate environmental risk management as a key training component, ensuring that climate resilience becomes a core skill for field commanders and logistics teams.

By integrating these measures, Krivolak can transition into a model for climate-resilient military training in the Balkans. The convergence of modern technology, adaptive logistics, and environmental science is no longer a theoretical consideration, it is a practical necessity for maintaining mission effectiveness under changing global conditions.

Figure 6: Climate Adaptation and Technological Integration at Krivolak Military Training Area



5. Conclusion and Strategic Implications

The findings presented in this paper confirm that climate change is not only an environmental or logistical concern, but a significant strategic factor for military training infrastructure. The Krivolak Military Training Area, as a core asset in the defense posture of North Macedonia and a key site for NATO-aligned exercises, faces increasing vulnerability from rising temperatures, variable precipitation, and terrain degradation. These changes directly affect the usability, safety, and operational readiness of the training zone.

The scenario-based analysis clearly illustrates the operational consequences of inaction. A projected reduction in usable training days, a steep rise in erosion risk, and intensified summer heat will all require immediate attention from military planners. Without structural and procedural adaptation, the long-term viability of Krivolak as a multi-domain training facility could be compromised.

However, this study also demonstrates that the integration of adaptive strategies ranging from real-time environmental monitoring to training schedule reform, can significantly mitigate the anticipated disruptions. Technological solutions, when matched with appropriate planning and infrastructure resilience, offer a path forward.

More importantly, the eight-step workflow developed in this paper offers a transferable model that can guide climate adaptation in similar military zones throughout the Balkans and beyond.

Ultimately, military readiness in the 21st century will depend not only on tactical capability, but on strategic environmental foresight. Krivolak can serve as a pioneering example of how armed forces can operate smarter, sustainably, and more securely in an era shaped by climate transformation.

Literature

1. Glavinov, A. and Kamchev, G. (2016).The Impact of Climate Change on Military Activities.*Contemporary Macedonian Defence Journal*, 16(31),67-78.https://eprints.ugd.edu.mk/21873/1/31_SMO-za-web-EN.pdf%20samo%20TRUD.pdf
2. Palazzo, A. (2022).Climate Change and the Military: The Implications for Force Readiness and Security. *Centre for Australian Army Leadership and US Army War College.*https://www.govinfo.gov/content/pkg/GOVPUB-D110-PURL-gpo216189/pdf/GOVPUB-D110-PURL-gpo216189.pdf
3. ICS Europe (2022). *Integrated Country Strategy – North Macedonia*, U.S. Department of State and U.S. Embassy Skopje.
4. Tavares da Costa, S. and Krausmann, E. (2021).Impacts of Natural Hazards and Climate Change on EU Security and Defence.*Publications Office of the European Union*, Luxembourg.doi:10.2760/244397
5. European Commission (2021).*Assessing Climate Change Risks on Critical Infrastructure in the EU*, JRC Science for Policy Report, European Union, Brussels.
6. NATO (2022).*Climate Change and Security Impact Assessment*, North Atlantic Treaty Organization, Brussels.
7. CNA Corporation (2007).*National Security and the Threat of Climate Change*, Center for Naval Analyses, Arlington, VA, USA.https://biotech.law.lsu.edu/climate/docs/SecurityandClimate_Final.pdf
8. Naumann, G., Mentaschi, L., Cammalleri, C. and Feyen, L. (2021).Increased Economic Drought Impacts in Europe with Anthropogenic Warming.*Nature Climate Change*, 11(6), pp. 485–491.https://eartharxiv.org/repository/object/242/download/475/
9. European Space Agency (2020).*Climate Risk and Resilience in the Defence Sector: Strategic Analysis*, ESA, Brussels.https://www.eeas.europa.eu/eeas/enhancing-climate-security-and-defence_en
10. Bellasio, J., Ecola, L., and Morgan Jones, M. (2021).Climate Resilience in Defence Planning.*RAND Europe*, Cambridge, United Kingdom.https://eda.europa.eu/docs/default-source/consultation-forum/studies/navigating-climate-change-in-defence-climate-risk-management-guide-for-chiefs-of-defence-staff.pdf