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[*Plenary lecture*]

Linking Climate Stress, Land-Use Change and River-System Sustainability: A GIS-Based Ecological Equilibrium Index for Serbia

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Abstract: River systems are increasingly exposed to interacting pressures from land-use change, urbanization and climate extremes. This study presents a GIS-based Ecological Equilibrium Index (EEI) for national-scale screening of river-system sustainability in Serbia. The operational index integrates land-use/land-cover ecological support, normalized river-network density and land-use pressure on a harmonized 100 × 100 m grid, while climate, demographic and water-related hazards are used as supporting layers for interpretation. The national mean EEI is 0.149, indicating a slightly positive but transitional condition, with low and very low values concentrated along major urban-industrial river corridors. River-network reductions of 20% in Belgrade, 18% in Novi Sad, 15% in Niš and 13% in Pančevo coincide with intensified land transformation. Climate stress can further amplify these pressures through drought, reduced dilution, intense runoff and flood hazards, highlighting the need for integrated spatial planning, river restoration and climate adaptation.

Keywords: climate change; ecological equilibrium index; river systems; land-use change; GIS

Introduction

River systems are among the most sensitive interfaces between climate, land use and society. Changes in temperature and

precipitation regimes alter runoff, low-flow conditions, flood frequency, erosion and pollutant transport, while urban expansion, agricultural intensification and infrastructure development modify drainage connectivity, riparian zones and floodplains. These processes rarely act independently. Climate stress can magnify the effects of land transformation, particularly where water demand, wastewater generation and impervious surfaces are concentrated along major river corridors (Fussmann et al., 2014; Zhou, 2014). For this reason, river sustainability requires spatially explicit approaches able to connect ecological support, hydrological structure and anthropogenic pressure within a common analytical framework.

Serbia provides a suitable national-scale case because its major development axes overlap with the Danube, Sava, Tisza, Drina, Velika Morava and Nišava river systems, while southern and eastern regions are additionally exposed to drought, flood hazards, water scarcity and infrastructure limitations (Milovanović et al., 2022). The objective of this invited lecture is to demonstrate how a transparent GIS-based Ecological Equilibrium Index (EEI) can be used as a screening tool for river-system sustainability and how climate-related stress can be incorporated as an interpretative and planning layer without obscuring the operational structure of the index. The broader aim is to bridge geospatial environmental assessment with climate adaptation and practical water-management decisions.

Methods and data

The EEI was calculated on a harmonized 100 × 100 m raster grid in WGS 84 / UTM Zone 34N (EPSG:32634). ESA WorldCover at 10 m resolution provided the primary land-use/land-cover (LULC) information. SRTM elevation data, national hydrographic layers and historical topographic maps were used to derive and verify river-network structure, while Sentinel-2, Landsat and CORINE data supported interpretation of land-cover change. Population, settlement, urban-industrial, climate, hazard and water-quality datasets were used as independent supporting evidence rather than

as direct mathematical components of the simplified index. This separation keeps the EEI reproducible while allowing climate and societal pressures to be analysed alongside it (Valjarević, 2024; Chatrabhuj et al., 2024).

LULC classes were reclassified into ecological-support and pressure coefficients. River density was calculated using an approximately 5-km-radius circular moving window and normalized to a 0–1 range. The EEI equation presented in this study is an original formulation conceived and developed by Aleksandar Valjarević; it builds on his GIS-based research on river-network sustainability and ecological vulnerability (Valjarević, 2026a; Valjarević, 2026b). The operational formulation is:

$$EEI = [(LULC_{positive} + RD_{norm}) / 2] - LULC_{pressure}$$

where $LULC_{positive}$ represents ecological support from vegetation, wetlands and water-related land cover, RD_{norm} represents normalized local river-network density, and $LULC_{pressure}$ represents mapped pressure associated mainly with built-up and intensively transformed land. The theoretical EEI range is –1 to +1. Negative values indicate dominance of mapped pressure, values near zero indicate transitional balance, and positive values indicate stronger ecological support. Buffer zones of 0–2 km, 2–5 km and >5 km around major river and urban-industrial corridors were used to evaluate proximity effects. Historical changes between 2002 and 2022 and a 2050 trend-continuation scenario were used to assess emerging spatial pressure. Climate information was interpreted as a stress multiplier, particularly for drought, low-flow, intense runoff and flood-prone regions; GIS-based drought assessment provides a complementary framework for this interpretation (Penny et al., 2023).

Results and discussion

The national mean EEI was 0.149 (approximately 0.15), with values from –1.000 to approximately 0.56 and a standard deviation of 0.421. This indicates a slightly positive but vulnerable transitional condition at national scale, while also revealing strong spatial contrasts. High

EEL values were associated mainly with forest-dominated, wetland, water-related and less urbanized landscapes. Low and very low classes covered 31.364% of the valid classified area and were concentrated along major urban-industrial and river-development corridors. The Danube–Sava corridor, the broader Belgrade–Novi Sad region, the Velika Morava development axis and the Niš urban-industrial area emerged as principal cumulative-pressure hotspots.

Mapped river-network reductions between 2002 and 2022 reached approximately 20% in Belgrade, 18% in Novi Sad, 15% in Niš and 13% in Pančevo. Urbanization intensity showed a strong inverse association with river-network density (Spearman $\rho = -0.78$, $p < 0.05$). The strongest direct concentration of land sealing, infrastructure development, floodplain occupation and channel modification occurred within 2 km of urban-industrial zones. These results show that national population decline does not necessarily reduce environmental pressure, because people, infrastructure and investment can become increasingly concentrated in a limited number of river corridors.

Climate change adds a second dimension of vulnerability. Drought and prolonged low-flow periods can reduce dilution capacity and increase water-temperature and water-quality stress, whereas intense precipitation can accelerate runoff, erosion, sediment transport and contaminant delivery. Southern and eastern Serbia therefore require attention even where urbanization is lower, because climate-sensitive catchments may combine drought, flood hazards, water scarcity and limited infrastructure. The 2050 planning scenario further suggests that continued development along the northern Serbia–Belgrade–Velika Morava–Niš axis may increase pressure on floodplains, riparian vegetation, drainage connectivity and groundwater-recharge areas.

For climate adaptation, the EEL should be interpreted as a spatial screening layer rather than a regulatory water-quality index. Low EEL areas can guide denser field monitoring, wastewater-control priorities, riparian restoration, sustainable urban drainage, green-blue

infrastructure and floodplain protection. High-value areas should be protected by maintaining forest cover, wetlands, headwater channels and hydrological connectivity. The approach also demonstrates how GIS can connect climate science with societal decision-making by translating heterogeneous environmental information into a transparent map of where intervention is most urgent.

Conclusions

The GIS-based EEI provides a transparent and transferable framework for screening river-system sustainability under land-use and urban-development pressure. Its application to Serbia demonstrates that a slightly positive national mean can conceal extensive local hotspots, particularly along major development corridors. Climate change does not need to be embedded directly in the operational index to be relevant: climate stress can be overlaid as an independent layer that explains where low-flow, drought, intense rainfall and flood conditions may amplify existing anthropogenic pressure. This distinction preserves methodological transparency while strengthening the value of the EEI for climate adaptation and strategic spatial planning.

The principal management message is that land-use planning, river restoration, wastewater management and climate adaptation should be treated together. Repeated EEI calculations, combined with climate projections and field observations, can support early warning, scenario comparison and prioritization of interventions. The framework is particularly useful for national or basin-scale assessment where monitoring networks are incomplete but consistent geospatial data are available.

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