Chemia Naissensis, Vol 8, Issue 1, RESEARCH ARTICLE, 52-7,
https://doi.org/10.46793/ChemN8.1.52DJ

Urbanization and Industrialization in the Nišava District: A GIS Analysis of River Network Change (1983–2050)

Running title: Urbanization Impacts on River Networks in the Nišava District

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ABSTRACT

Urbanization and industrialization have significantly transformed the hydrological systems of southern Serbia, especially in the Nišava and South Morava basins and the city of Niš. Over the past decades, rapid urban growth and industrial activity have altered river morphology, reduced the permanence of tributaries, and reshaped drainage networks. Using GIS and Remote Sensing methods, including high-resolution DEMs, census data, and cartographic archives, this study analyzes urban–river interactions from 1983 to 2023, with projections to 2050.Results show that Niš, strategically located along the Nišava and South Morava corridors, has experienced substantial urban expansion, leading to increased surface runoff, erosion risks, and degradation of riparian ecosystems. The Nišava River has undergone fragmentation of its natural dendritic system, while the South Morava has become a central axis of metropolitan and industrial development. Projections to 2050 highlight intensified risks of floodplain encroachment, declining groundwater recharge, and further deterioration of water quality. The findings emphasize the urgent need for integrated basin management and sustainable urban planning in Niš and its surrounding river valleys. Balancing economic growth with ecological resilience is essential to preserve hydrological stability and ensure long-term sustainability in the region.

Keywords: South Morava River, Nišava River, Niš, Urbanization, GIS analysis, Pollution

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Introduction

Urbanization and industrialization represent two of the most powerful agents of landscape transformation, fundamentally altering hydrological systems and reshaping ecological processes across the globe. Their influence extends beyond built-up environments to encompass entire river basins, where land-cover transitions, increased imperviousness, and intensified anthropogenic activity interact to redefine runoff dynamics, channel morphology, and ecosystem functioning. In transitional economies such as Serbia, these processes are highly concentrated along river corridors, where settlements, industries, and transport routes converge to form critical axes of development (Tomsett and Leyland, 2019; Grill et al., 2015; Shen and Wang, 2023). The Nišava District in southern Serbia epitomizes this interaction: strategically located at the intersection of the Nišava and South Morava valleys and anchored by the city of Niš, it functions as a vital economic, demographic, and ecological corridor linking Central Europe with the Aegean basin. Over the past four decades, this district has experienced rapid urban growth, industrial intensification, and infrastructural expansion, producing far-reaching consequences for river morphology, drainage density, and long-term hydrological resilience.

River networks serve not only as carriers of water, sediments, and nutrients but also as ecological lifelines that sustain biodiversity, agricultural productivity, and groundwater recharge. However, in areas undergoing accelerated land-use change, these networks become vulnerable to fragmentation, simplification, and hydromorphological instability. In the Nišava District, urban expansion has reduced tributary permanence, narrowed riparian zones, and intensified surface runoff, while industrial operations have reshaped sediment loads, modified channel beds, and heightened local flood risks (Du et al., 2019; Zhao et al., 2020; Andersen et al., 2021). Such patterns echo global observations where urban corridors increasingly overlap with ecologically fragile basins, raising concerns about the sustainability of water resources and the capacity of rivers to maintain their natural resilience under sustained anthropogenic pressure. Projections to 2050 indicate that without proactive conservation and regulation, urban encroachment into floodplains and secondary valleys of the Nišava and South Morava will heighten ecological degradation, accelerate channel incision or aggradation, and further constrain groundwater recharge (Redman et al., 2004; Fourqurean et al., 1999).

Previous national-scale studies have emphasized the role of industrial-urban corridors along the main Danube–Sava–Morava axis, where heavy industries, metropolitan expansion, and hydropower development collectively reshape river systems (Chen et al., 2023). Yet, the Nišava District, a dynamic zone connecting the Balkans' northern and southern hydrological systems, remains comparatively underexplored. Its dual identity as both a southern industrial hub and a hydrologically sensitive region makes it particularly vulnerable to cumulative impacts. Niš, as Serbia's third-largest city, illustrates the tensions between economic growth and ecological vulnerability. Situated directly on the Nišava River and intimately linked to the South Morava basin, Niš has expanded longitudinally along valley corridors, reinforcing its role as a transportation and industrial center. This expansion, however, has increased exposure to erosion, urban flooding, riparian degradation, and disruption of natural hydrological pathways.

Climatic variability further compounds these challenges. Between 2000 and 2023, Serbia experienced multiple severe droughts, accompanied by declining river discharges and shifting seasonal hydrological regimes in key basins such as the Drina and South Morava (Durlević et al., 2024; Valjarević et al., 2020a). In Niš, summer water demand frequently exceeds sustainable extraction thresholds, with per capita consumption surpassing 1,700 m^3 during the warm season compared to recommended sustainable levels of approximately 1,300 m^3. Such imbalances exert pressure on existing supply systems, particularly suburban settlements dependent on shallow aquifers and riverbed springs. Intensifying hydrometeorological extremes, flash floods, heatwaves, droughts, and sudden high-intensity rainfall events underscore the vulnerability of the Nišava and South Morava basins to compounded natural and anthropogenic stressors.

Adding to this complexity is Serbia's chronically insufficient water management infrastructure. More than 85% of the country's wastewater is discharged untreated into river systems, and even major cities lack fully operational wastewater treatment facilities (Takić et al., 2017; Urošev et al., 2022). Niš and its surrounding municipalities face similar deficiencies, with untreated municipal and industrial effluents contributing to deteriorating water quality, altered nutrient balances, and exacerbation of eutrophication in downstream sections of the Nišava. These trends mirror conditions observed in other Balkan and Eastern European basins, where urban and industrial pollution, combined with insufficient environmental governance, heighten the risk to freshwater ecosystems.

To address these urgent challenges, this study integrates Geographic Information Systems (GIS) and Remote Sensing (RS) to examine urban–river interactions in the Nišava District from 1983 to 2023, with projections to 2050. High-resolution Digital Elevation Models (DEMs), digitized topographic archives, census datasets, CORINE land-cover layers, and hydrological models are combined to reconstruct long-term changes in drainage density, tributary permanence, riparian continuity, and basin morphology. Advanced analytical tools zonal statistics, Kernel Density Estimation (KDE), stream order analysis, landscape fragmentation indices, and Multi-Criteria Decision Analysis (MCDA) are applied to identify spatial hotspots of hydrological disruption, quantify tributary loss, evaluate fragmentation severity, and detect correlations between industrial expansion and river connectivity decline (Yu et al., 2023). Together, these methods provide an integrated spatial temporal framework for understanding basin evolution under sustained anthropogenic pressures and for forecasting future vulnerabilities under scenarios of continued demographic, industrial, and infrastructural development.

By focusing on Niš and its surrounding river basins, this research contributes to broader regional and international debates on sustainable urban planning, watershed governance, and ecological resilience in rapidly changing environments. It positions the Nišava District as both a microcosm of Serbia's industrial hydrological dilemmas and a critical test case for integrated basin-scale decision-making. The findings underscore the necessity of balancing economic development with ecological protection, enforcing stricter wastewater and land-use regulations, restoring riparian buffers, and fostering regional cooperation for transboundary water governance (Zwarteveen et al., 2017). Ultimately, the future hydrological stability of the Nišava and South Morava basins will depend on reconciling urban expansion with ecological sustainability ensuring that southern Serbia's rivers continue to serve not only as economic lifelines but also as essential ecological safeguards.

The Nišava District is located in southeastern Serbia and covers an area of approximately 2,729 km². It borders the Pirot, Toplica, Jablanica, and Zaječar districts and extends eastward toward the Bulgarian frontier. The district lies within the South Morava basin, with the Nišava River as its dominant hydrological feature. The city of Niš, one of Serbia's largest urban and industrial centers, is situated at the confluence of the Nišava and the South Morava rivers, making this district a crucial node in regional hydrological, economic, and transport networks. The strategic location along the international Corridor X, connecting Central Europe with the Aegean, further emphasizes the Nišava District's importance as both a transit hub and an area of concentrated urban–industrial development (Dimić et al. 2018; Fig. 1).

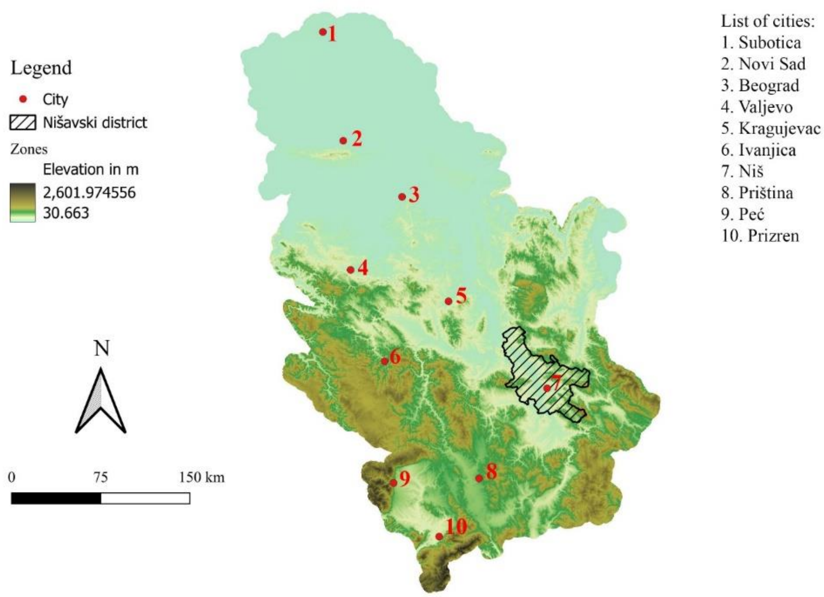

Figure 1. Location of the Nišava District with major urban centers and key physiographic features

This map illustrates the administrative boundaries of the Nišava District in southern Serbia, highlighting its principal urban settlements, major transportation corridors, and the regional river network. The figure provides essential spatial context for understanding the district's role as a strategic corridor for ecological, demographic, and infrastructural connectivity.

Relief is diverse, with elevations ranging from broad alluvial plains in the Nišava and South Morava valleys (180–250 m) to the surrounding mountains, including Suva Planina (1,810 m), the Svrljig Mountains (1,334 m), and Jastrebac (1,491 m). This topographic diversity generates significant spatial contrasts in hydrological regimes. The valley floors accommodate dense urban and industrial activity, while upland zones maintain fragmented rural settlements and forest cover. The climate is predominantly temperate-continental, with hot summers (average July temperatures of 22–24 °C) and moderately cold winters (average January temperatures around 0 °C). Annual precipitation ranges from 600–800 mm in the valleys to over 1,000 mm in mountainous areas. These climatic and geomorphological factors strongly influence runoff, erosion potential, and the vulnerability of local river networks to anthropogenic pressures (Menković et al. 2018; Ilies et al. 2022).

The Nišava River is the main hydrological axis of the district. Originating in western Bulgaria, it flows westward through Dimitrovgrad, Pirot, and Niš before joining the South Morava River. Major tributaries include the Jerma, Temska, and Kutinska rivers, which drain the mountainous terrain and contribute to the basin's dendritic structure. Urban expansion along the Nišava corridor, particularly around the city of Niš, has fragmented the natural fluvial system, altering the permanence of tributaries and increasing surface runoff. The South Morava, into which the Nišava discharges, acts as a collector of industrial effluents and urban wastewater, magnifying cumulative impacts downstream (Kovačević-Majkić and Urošev, 2014).

The Nišava District has experienced accelerated urban growth since the late 20th century, with Niš emerging as the third-largest city in Serbia. Industrial activities include machinery production, electronics, textiles, food processing, and construction materials, much of which is concentrated along river valleys for access to water and transport. The clustering of settlements and factories along the Nišava corridor has produced distinct urban–industrial belts. These belts have increased impervious surfaces, reduced infiltration capacity, and heightened the frequency of flash floods and water quality deterioration. Projections to 2050 suggest further expansion of the Nišava–South Morava urban corridor, reinforcing its role as a metropolitan-industrial hub while simultaneously amplifying hydrological risks (Živanović et al. 2019).

The main environmental challenges in the Nišava District stem from untreated wastewater, riverbank modification, gravel extraction, and deforestation of upland catchments. More than 80% of municipal and industrial wastewater is discharged untreated into rivers, degrading water quality and threatening aquatic biodiversity. Hydropower projects and channelization efforts have also altered natural flow regimes, while climate change intensifies extremes such as droughts, heatwaves, and sudden high-intensity rainfall events. These pressures highlight the Nišava District as both an engine of economic growth and a hydrologically vulnerable region in need of integrated management strategies (Stamenković et al. 2013).

Materials and methods

The methodological framework integrates multi-temporal cartographic, demographic, and remote sensing datasets to analyze the influence of urbanization and industrialization on the river networks of the Nišava District. Historical topographic maps (1:25,000 and 1:50,000 scale) from the Military Geographical Institute were digitized and georeferenced to provide reference conditions for the years 1983, 2000, and 2023. High-resolution Digital Elevation Models (DEMs) derived from the Shuttle Radar Topography Mission (SRTM, 30 m resolution) and Sentinel-1/2 satellite imagery were used to delineate watersheds, extract drainage networks, and identify land-use/land-cover dynamics. Population census data for 1981, 2002, 2011, and 2022 from the Statistical Office of Serbia were rasterized into density surfaces to capture urban expansion trends across the district's municipalities, with emphasis on Niš as the main urban-industrial hub.Industrial activity was mapped from spatial records of major factories, industrial zones, and energy facilities, including historical data on metallurgical, textile, and chemical plants in Niš, Bela Palanka, and Svrljig. These datasets were supplemented with national spatial plans and municipal development strategies to track the spatial evolution of industrial corridors (Zhao et al. 2022).

GIS and Remote Sensing Processing

Hydrological modeling was performed using QGIS 3.28.6 and SAGA GIS. DEMs were preprocessed (sink filling, flow accumulation, and flow direction algorithms) to delineate watersheds, extract stream networks, and calculate slope, aspect, and flow length. The derived hydrographic networks were classified according to Strahler stream order to detect changes in drainage typology, tributary permanence, and fragmentation over time (Valjarević 2025a; Valjarević 2025b)

To assess the interaction between anthropogenic activities and river systems, a buffer analysis was conducted at 500 m, 1 km, and 2 km distances from industrial sites and urban centers. Zonal statistics were applied within these buffers to summarize hydrological attributes such as stream length, drainage density, and slope gradients, enabling a quantitative evaluation of industrial and urban proximity effects.
Kernel Density Estimation (KDE) was used to visualize hydrological "hotspots" where tributary loss, drainage simplification, or river fragmentation coincided with clusters of industrial activity and urban expansion. These heat maps allowed spatial identification of areas most exposed to anthropogenic hydrological stress.

Graduated symbols, choropleth maps, and proportional symbology were used to visualize hydrological change and urban-industrial expansion. Comparative mapping of 1983, 2000, and 2023 allowed temporal tracking of river network modification. Spearman's rank correlation was applied to test the statistical relationship between urban-industrial growth and drainage density decline. Projection scenarios to 2050 were developed using a cellular automata–Markov chain model within SAGA GIS to simulate future land-use dynamics and their potential hydrological implications.

Results and discussion

Between 1983 and 2023, the Nišava District experienced marked urban growth concentrated around the city of Niš. Population density maps derived from census data revealed that Niš expanded from a compact urban core into a sprawling metropolitan area, stretching along the Nišava and South Morava valleys. Secondary centers such as Bela Palanka, Svrljig, and Gadžin Han showed modest demographic increases, though their growth was dwarfed by the metropolitan dominance of Niš. Overall, urban land cover increased by more than 65% across the district, with the most rapid expansion occurring between 2002 and 2022 (Badach et al. 2020).

Industrial zones in the Nišava District followed the same longitudinal corridors as settlement growth. By overlaying industrial site geolocations with buffer analyses, three major industrial clusters were identified:

1. **Niš Industrial Core** – encompassing metallurgy, electronics, textile, and food-processing plants;
2. **Bela Palanka Corridor** – with smaller-scale manufacturing and quarrying;
3. **Svrljig Zone –** characterized by agro-industrial activity and emerging energy facilities.

The buffer analysis demonstrated that 72% of industrial activity lies within 2 km of permanent watercourses, underscoring industries' dependence on rivers for water supply and waste discharge.

Hydrological modeling revealed significant transformations in the Nišava District's drainage systems. In 1983, the Nišava River and its tributaries displayed a predominantly dendritic network with high drainage density and perennial flow in most second- and third-order streams. By 2023, this structure had undergone fragmentation, with drainage density decreasing by 14% across the district and perennial tributaries diminishing by 11%, many downgraded to intermittent or ephemeral streams, particularly near urbanized zones. Stream order simplification was observed in the Nišava Valley east of Niš, where formerly branching tributaries were replaced by parallelized and shortened streams. Kernel Density Estimation (KDE) heat maps further highlighted hydrological "hotspots" around Niš and Bela Palanka, where tributary loss and stream discontinuities strongly overlapped with industrial and settlement expansion zones, emphasizing the profound impacts of urbanization and industrialization on the region's river network (Okabe et al. 2009; Fig. 2).

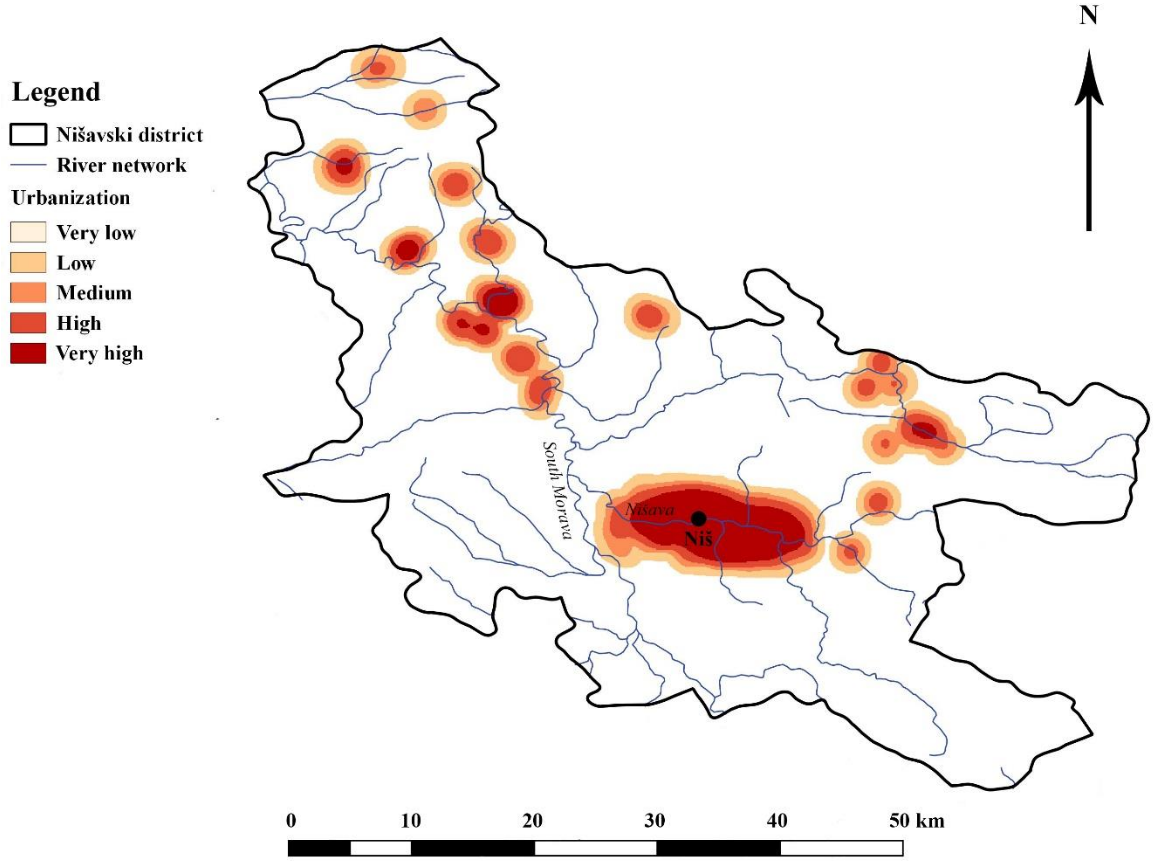

Figure 2. Urbanization patterns and river network configuration in the Nišava District in 1983

This figure shows the spatial distribution of urbanized areas and the structure of the river network during 1983, reflecting the early phase of settlement expansion and landscape transformation. It provides a historical baseline for analyzing subsequent urban growth, hydrological modifications, and long-term environmental change in the district.

The Multi-Criteria Layer Analysis (MCLA) revealed clear spatial patterns of hydrological vulnerability across the Nišava District. High-risk zones were concentrated in the Niš urban-industrial belt, where tributary loss exceeded 20% over the past four decades, in the lower Nišava Valley near Bela Palanka, where quarrying and transport infrastructure drove drainage simplification in small catchments, and at the South Morava confluence, and urban runoff and industrial wastewater jointly reshaped natural flow regimes. Medium-risk zones were mapped in the municipalities of Svrljig and Gadžin Han, where smaller settlements and localized industrial activity are exerting growing pressure on the fluvial system. By contrast, low-risk areas were confined to the surrounding mountainous terrain, where hydrographic networks remain well preserved and urban encroachment is minimal, highlighting the spatial contrasts between disturbed valley zones and more resilient upland catchments (Fig. 3).

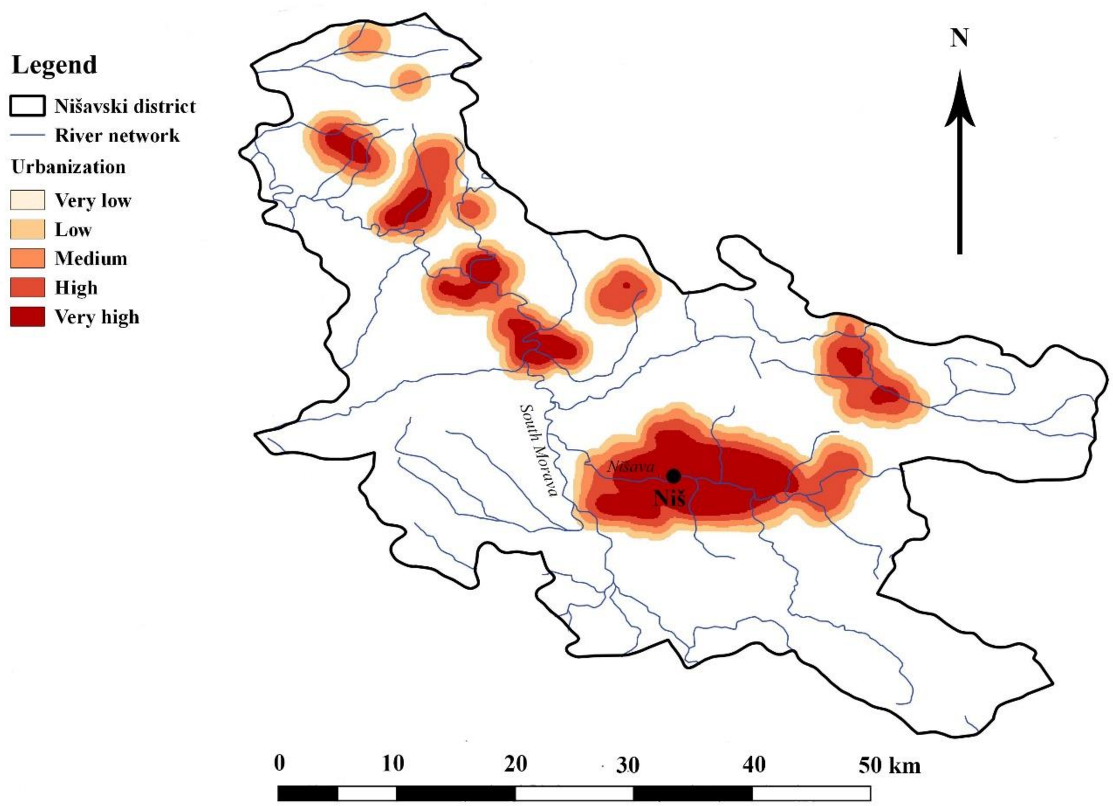

Figure 3. Urbanization patterns and river network configuration in the Nišava District in 2023.

This figure presents the contemporary extent of urban development alongside the current river network, illustrating four decades of spatial expansion, infrastructural growth, and hydrological alteration since 1983. It serves as a key reference for assessing the magnitude and direction of urban-driven landscape and drainage changes within the district.

Simulation modeling using the cellular automata–Markov chain approach projected further hydrological stress by mid-century. If current trends continue, urban expansion in Niš is expected to merge with peri-urban belts along the South Morava corridor, while industrial zones will intensify near transportation hubs. By 2050, drainage density could decline by an additional 8–10%, with perennial tributaries reduced by up to 20% relative to 1983 baselines. The Nišava District is therefore on track to develop into a consolidated urban-industrial corridor with pronounced hydrological instability unless sustainable management measures are adopted (Baykal et al. 2022; Fig.4).

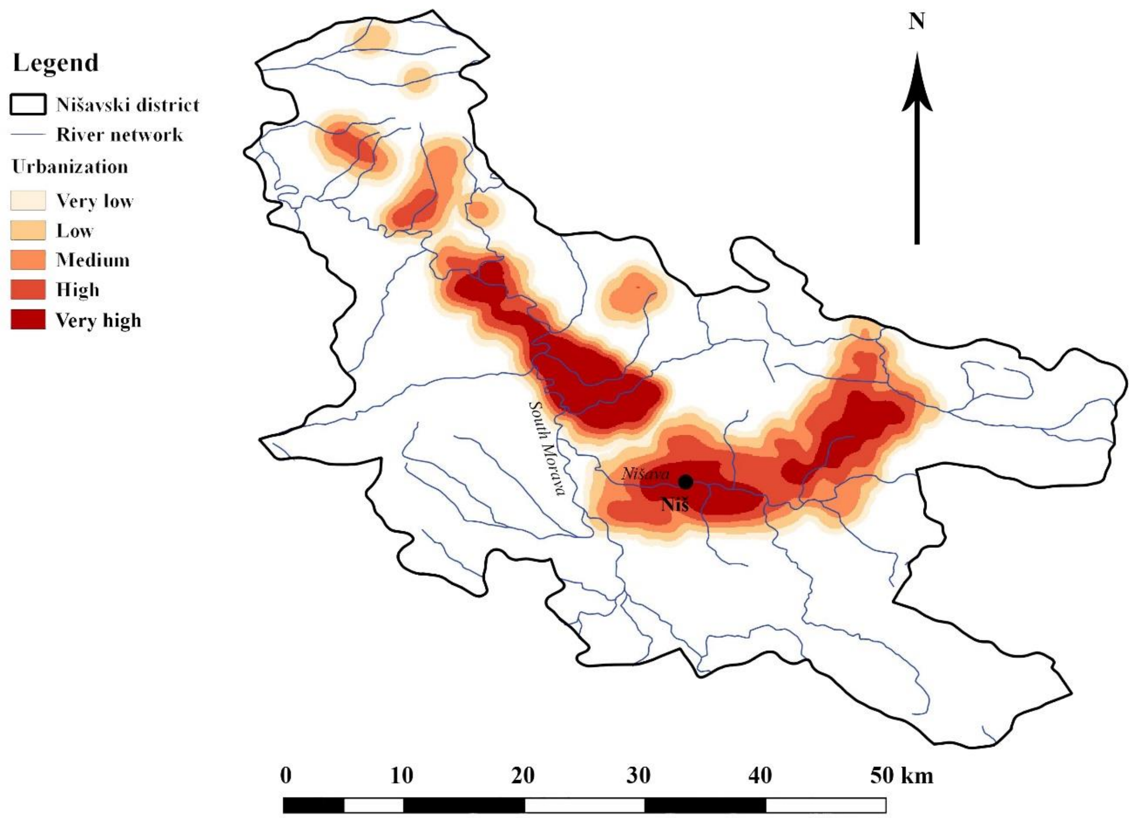

Figure 4. Projected urbanization in the Nišava District and anticipated impacts on the river network by 2050

This figure illustrates modeled urban expansion and the expected spatial reconfiguration of the river network under future development scenarios. It highlights zones of potential hydrological disturbance, increased channel modification, and landscape fragmentation, providing a forward-looking assessment of how continued urban growth may influence drainage patterns and environmental stability by mid-century.

Table 1. Industrial facilities by proximity to rivers in the Nišava District

Municipality	0–500 m	500–2000 m	>2000 m
Niš	18	25	12
Bela Palanka	7	10	5
Svrljig	3	6	4
Gadžin Han	2	4	3

Table 2. Vulnerability index of municipalities in the Nišava District

Municipality	Tributary loss (%)	Drainage density decline (%)	Vulnerability class
Niš	22	18	High
Bela Palanka	15	12	High
Svrljig	9	7	Medium
Gadžin Han	6	5	Medium
Mountain areas	3	2	Low

The results demonstrate that the Nišava District has undergone profound transformations in its hydrological systems due to concentrated urban and industrial development, particularly around Niš. Similar to findings at the national scale the river corridors of the Nišava and South Morava act as both attractors of population growth and as recipients of industrial pressures. The documented reduction in drainage density and tributary permanence highlights how urban sprawl and industrial wastewater discharge collectively erode the resilience of river systems. These changes parallel global observations where rapid urbanization accelerates river fragmentation, alters natural flow regimes, and increases surface runoff (Grill et al., 2015; Du et al., 2019).

The Multi-Criteria Layer Analysis (MCLA) identified Niš and Bela Palanka as high-risk zones, confirming that industrial clustering near rivers magnifies hydrological stress (Valjarević et al. 2020b). Peripheral municipalities such as Svrljig and Gadžin Han remain moderately affected but display emerging vulnerabilities. This spatial polarization reflects broader Serbian patterns, where metropolitan-industrial corridors concentrate growth and risks, while mountainous peripheries preserve ecological stability (Valjarević, 2024). The vulnerability gradient underscores the importance of integrating watershed-scale governance into spatial planning, rather than relying solely on administrative boundaries.

The Nišava case aligns with regional analyses showing that urban-industrial expansion reduces tributary density and increases hydrological simplification (Nawar et al., 2025; Shahid & Mustafa, 2020). However, unlike larger rivers such as the Danube or Sava, the Nišava and its tributaries possess limited self-purification capacity, making them highly sensitive to contamination from industrial effluents and urban runoff. This supports the argument that small- to medium-sized river basins require more stringent protection than large, high-capacity systems.

The projection to 2050 suggests the emergence of a consolidated urban-industrial corridor linking Niš with the South Morava Valley. Such development may enhance regional connectivity but will likely intensify hydrological instability unless sustainable measures are implemented. Without adequate intervention, tributary loss could exceed 20% relative to baseline conditions, further reducing biodiversity, groundwater recharge, and flood-regulation capacity. This scenario reflects the paradox observed across Southeast Europe: economic efficiency is gained at the expense of cumulative ecological

The findings emphasize the urgent need for:

1. **Expansion of wastewater treatment infrastructure** – Serbia currently operates far fewer facilities than required, and the Nišava District is particularly under-served.
2. **River buffer protection zones** – strict enforcement of 500–1000 m protective belts could mitigate industrial and urban encroachment.
3. **Integration of vulnerability mapping into planning** – MCLA-based tools should be adopted for regional decision-making to prioritize areas for intervention.
4. **Restoration of degraded tributaries** – ecological engineering, reforestation, and river rehabilitation programs are critical for restoring drainage density.

The Nišava District represents a microcosm of the wider Serbian and Balkan dilemma: balancing economic modernization with ecological sustainability. The district's experience shows that uncontrolled urban-industrial expansion in hydrologically sensitive valleys leads to structural degradation of rivers. However, the same corridors could become models for sustainable development if integrated basin management, clean technologies, and ecological restoration are prioritized.

The projected scenarios for 2050 further emphasize the urgency of intervention. If current urbanization trends persist, the Nišava District is likely to evolve into a continuous urban–industrial corridor connecting Niš with the wider South Morava basin. Such a configuration may support economic growth and regional connectivity but will likely exacerbate hydrological instability, reduce groundwater recharge, intensify flood risk, and accelerate the simplification of the drainage network. The cellular automata–Markov chain model suggests that tributary loss may reach up to 20% relative to 1983, a threshold associated with significant ecological impairment in comparable European basins.

Climate variability adds another layer of complexity. Increased heatwaves, droughts, and flash-flood events reported in Serbia since 2000 enhance the sensitivity of the Nišava basin to both natural and anthropogenic stressors. Reduced baseflows during summer months, combined with increased surface runoff from expanding urban areas, may alter seasonal river regimes and reduce water availability for both ecosystems and human consumption.

Importantly, the results point toward several actionable strategies. First, expanding wastewater treatment infrastructure must be prioritized, as untreated discharges remain a major driver of ecological degradation. Second, enforcing protective riparian buffer zones—particularly the 500–1,000 m belts identified in the analysis could substantially reduce tributary fragmentation and preserve floodplain function. Third, the MCLA-based vulnerability maps produced in this study should be integrated into municipal planning processes to guide zoning, industrial expansion, and ecological restoration. Finally, tributary rehabilitation through reforestation, reconnection of cut-off channels, and bank stabilization could help restore drainage density and enhance basin resilience.

Comparable dynamics are evident in Central Europe. The urban-industrial expansion in the Upper Silesian Coal Basin (Poland-Czech Republic) has long been associated with extensive hydrological alteration, including the diversion of smaller tributaries, depression of the groundwater table, and increased sediment transport from excavated areas. These examples reinforce the findings from the Nišava District, where quarrying, transport infrastructure, and industrial clustering have produced visible impacts on drainage structure and hydrological connectivity (Grizzetti et al., 2017).

Western European experience further illustrates the long-term consequences of unregulated industrial–urban growth. In northern Italy's Po Valley, decades of intensive development along river corridors led to the simplification of fluvial networks and a decline in ecological integrity, prompting widespread restoration initiatives, including re-meandering, riparian reforestation, and floodplain reconnection. Similar interventions may eventually be required in the Nišava basin if current trajectories persist, especially given the projected decline in tributary permanence by 2050.

A key difference, however, is that many Western European basins benefit from stronger wastewater management systems and more mature regulatory frameworks. In contrast, as highlighted in this study, over 80% of the wastewater in the Nišava District remains untreated, placing local tributaries under significantly greater ecological stress than their counterparts in countries with advanced environmental governance. This comparison underscores the need for Serbia and other Western Balkan nations to accelerate the development of wastewater infrastructure and adopt integrated watershed-management principles aligned with EU Water Framework Directive standards.

Overall, the Nišava District represents a microcosm of the broader challenges facing Southern and Eastern European basins where rapid urban and industrial development intersect with fragile hydrological systems. This study contributes valuable empirical evidence demonstrating how spatially concentrated human activities can compromise river basin sustainability. At the same time, it highlights clear opportunities for implementing integrated watershed management strategies that balance economic priorities with ecological protection and long-term hydrological stability (Valjarević, 2025d).

Despite its comprehensive GIS-based framework, this study has several limitations. First, the resolution of available DEMs (30 m SRTM) may underestimate micro-scale tributary networks, especially in mountainous areas. Second, industrial pollution datasets were incomplete, with some smaller facilities lacking publicly accessible discharge records, limiting the precision of water quality correlations. Third, census data were available only at decadal intervals, making it difficult to fully capture short-term fluctuations in urban growth and migration. Finally, while the cellular automata Markov chain model provides robust projection scenarios, its accuracy depends on the assumption that past trends will continue, which may not account for abrupt policy shifts or major infrastructure projects. Addressing these constraints in future research will require higher-resolution satellite products, continuous hydrological monitoring, and integration of field-based ecological assessments.

Future research on the Nišava District should build upon the methodological framework and empirical findings of this study by integrating higher-resolution datasets, advanced modeling techniques, and interdisciplinary approaches. Several key directions can substantially strengthen future understanding of urban-river interactions and support the development of sustainable basin management strategies. First, hydrological monitoring should be enhanced by using high-resolution Digital Elevation Models (DEMs), such as LiDAR and TanDEM-X, which can capture micro-tributaries, subtle channel changes, and erosion processes that remain undetectable in 30 m-resolution products. These data would improve the accuracy of stream-order classification, drainage density measurements, and hydrological connectivity assessments, particularly in narrow valleys and steep upland segments where current models likely underestimate tributary complexity.

Second, future studies should incorporate continuous water quality monitoring and improved pollution datasets, including real-time sensors, industrial discharge registries, and in situ sampling campaigns. The current lack of detailed wastewater data limits the ability to quantify relationships between industrial activity and ecological degradation. Enhanced datasets would allow researchers to integrate nutrient loads, heavy metals, and dissolved oxygen into spatial models, enabling basin-wide assessments of ecological health and biogeochemical resilience.

Third, climate hydrology integration should be deepened by coupling regional climate models (RCMs) with hydrological forecasting tools to evaluate long-term effects of droughts, heatwaves, extreme rainfall, and seasonal regime shifts. Ensemble projections combining CORDEX, ERA5-Land, and local meteorological observations could help identify future thresholds of flood risk, groundwater recharge decline, and ecosystem stress. Such modeling is essential given the documented increase in hydrometeorological extremes and anticipated climatic variability in southern Serbia.

Fourth, socio-ecological and governance dimensions should be expanded in future analyses. Urban growth patterns in Niš, Bela Palanka, and smaller municipalities are strongly shaped by demographic trends, economic transitions, and spatial planning practices. Incorporating household water use data, economic indicators, and land-market dynamics could clarify how social drivers interact with hydrological processes. Additionally, stakeholder-based research involving municipalities, industries, and local communities can illuminate governance barriers to implementing riparian buffer protections, wastewater infrastructure, and integrated basin management.

Fifth, future research should examine restoration potential and ecological rehabilitation scenarios. Modeling the effects of reforestation, riparian buffer expansion, wetland reconstruction, and sustainable urban drainage systems (SUDS) could identify cost-effective strategies for restoring tributary permanence, improving water quality, and reducing flood vulnerability. These nature-based solutions are increasingly relevant as the Nišava basin transitions into a consolidated urban-industrial corridor.

Sixth, machine learning and artificial intelligence (AI) approaches offer valuable new tools for predicting hydrological disruption and land-use change. Deep-learning models such as U-Net, Random Forest, and LSTM networks can improve future urban growth simulations, classify river fragmentation hotspots more precisely, and integrate multi-source datasets from satellite imagery to socioeconomic variables into unified predictive frameworks.

Finally, a priority for future work is the creation of a long-term, integrated river-basin observatory for the Nišava and South Morava valleys. Such a platform would combine hydrological sensors, remote-sensing products, ecological surveys, urban planning data, and historical archives, enabling real-time monitoring and supporting adaptive management strategies. Establishing this observatory would allow researchers and policymakers to track hydrological changes continuously, evaluate the effectiveness of interventions, and build a comprehensive evidence base for sustainable regional development.

Conclusion

This study revealed that the Nišava District, and particularly the urban-industrial hub of Niš, has experienced profound hydrological transformations over the past four decades. Using GIS and Remote Sensing techniques, we demonstrated that rapid urbanization and industrial clustering have directly contributed to tributary loss, drainage density decline, and stream network simplification. These changes underscore the critical role of anthropogenic pressures in reshaping small and medium-sized river systems, which lack the buffering capacity of larger basins.

The spatial analysis highlighted three primary hotspots of hydrological stress: the Niš metropolitan zone, the Bela Palanka corridor, and the South Morava confluence. In these areas, industrial activities, urban sprawl, and inadequate wastewater management collectively intensified river fragmentation and ecological vulnerability. By contrast, mountainous peripheries such as Svrljig and Gadžin Han retained relatively stable hydrographic structures, though signs of emerging risk are already visible.

Projections to 2050 indicate that without intervention, the Nišava District will evolve into a consolidated urban-industrial corridor with further reductions in tributary permanence and a loss of ecological services such as groundwater recharge, biodiversity support, and flood regulation. This trajectory mirrors broader patterns across Serbia and Southeast Europe, where economic integration along river corridors comes at the cost of hydrological resilience.

To reverse these trends, integrated basin-scale governance is essential. Expanding wastewater treatment infrastructure, enforcing protective river buffers, restoring degraded tributaries, and embedding vulnerability maps into spatial planning should be treated as urgent priorities. The Nišava District thus exemplifies both the risks of unmanaged urban-industrial growth and the opportunities for sustainable transformation. If guided by evidence-based policies, the region could transition from a corridor of hydrological stress into a model of balanced development that safeguards rivers as vital ecological and economic lifelines.

Acknowledgment

The study was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract number 451-03-137/2025-03/200091).

Conflict-of-Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Andersen, L. M., Carstensen, J., Conley, D. J., & Hasler, B. (2021). Urban and agricultural pressures on aquatic ecosystems in Europe: Increasing nutrient loads and decreasing resilience. *Ambio*, 50(2), 273–287. https://doi.org/10.1007/s13280-020-01337-2

Badach, J., Voordeckers, D., Nyka, L., & Van Acker, M. (2020). A framework for air quality management zones – useful GIS-based tool for urban planning: Case studies in Antwerp and Gdańsk. *Building and Environment*, 174, 106743. https://doi.org/10.1016/j.buildenv.2020.106743

Baykal, T. M., Colak, H. E., & Kılınc, C. (2022). Forecasting future climate boundary maps (2021–2060) using exponential smoothing method and GIS. *Sci Total Environ*, 848, 157633. https://doi.org/10.1016/j.scitotenv.2022.157633

Chen, J., & Tang, X. (2023). Towards sustainable cities: Studying evaluation index of water environment carrying capacity. *Water Resour Manage*, 37, 5919–5938. https://doi.org/10.1007/s11269-023-03635-5

Dimić, V., Milošević, M., Milošević, D., & Stević, D. (2018). Adjustable model of renewable energy projects for sustainable development: A case study of the Nišava District in Serbia. *Sustainability*, 10(3), 775. https://doi.org/10.3390/su10030775

Du, Y., Cai, W., Xu, Y., Wang, Y., & Zhang, X. (2019). Urban expansion and its impact on surface runoff in the Yangtze River Delta. *Land Use Policy*, 86, 366–377. https://doi.org/10.1016/j.landusepol.2019.05.010

Durlević, U., Valjarević, A., Novković, I., Vujović, F., Josifov, N., Krušić, J., & Ivanović, M. (2024). Universal snow avalanche modeling index based on SAFI–Flow-R approach in poorly-gauged regions. *ISPRS Int J Geo-Inf*, 13(9), 315. https://doi.org/10.3390/ijgi13090315

Fourqurean, J. W., & Robblee, M. B. (1999). Florida Bay: A history of recent ecological changes. *Estuaries*, 22, 345–357. https://doi.org/10.2307/1353203.

Grizzetti, B., Pistocchi, A., Liquete, C., & others. (2017). Human pressures and ecological status of European rivers. Sci Rep, 7, 205. https://doi.org/10.1038/s41598-017-00324-3.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., & Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, 569(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Ilies, G., Ilies, M., Hotea, M., Bumbak, S. V., Hodor, N., Ilies, D. C., & Vasić, P. (2022). Integrating forest windthrow assessment data in the process of windscape reconstruction: Case of the extratropical storms downscaled for the Gutai Mountains (Romania). *Front Environ Sci*, 10, 926430. https://doi.org/10.3389/fenvs.2022.926430

Menković, L., Košćal, M., Milivojević, M., & Đokić, M. (2018). Morphostructure relations on the territory of the Republic of Serbia. *Glasnik Srpskog geografskog društva*, 98(2), 1–28. https://doi.org/10.2298/GSGD1802001M

Okabe, A., Satoh, T., & Sugihara, K. (2009). A kernel density estimation method for networks, its computational method and a GIS-based tool. *Int J Geogr Inf Sci*, 23(1), 7–32. https://doi.org/10.1080/13658810802475491

Redman, C., Grove, J., & Kuby, L. (2004). Integrating social science into the Long-Term Ecological Research (LTER) network: Social dimensions of ecological change and ecological dimensions of social change. *Ecosystems*, 7, 161–171. https://doi.org/10.1007/s10021-003-0215-z

Shen, J., & Wang, Y. (2023). An improved method for the identification and setting of ecological corridors in urbanized areas. *Urban Ecosyst*, 26, 141–160. https://doi.org/10.1007/s11252-022-01298-5

Stamenković, S. M., Ristić, S. S., Djekic, T. L., Mitrovic, T. U., & Baošić, R. (2013). Air quality indication in Blace (Southeastern Serbia) using lichens as bioindicators. *Arch Biol Sci*, 65(3), 893–897. https://doi.org/10.2298/ABS1303893S

Takić, L., Mladenović-Ranisavljević, I., Vasović, D., & Đorđević, L. (2017). The assessment of the Danube River water pollution in Serbia. *Water Air Soil Pollut*, 228(10), 380. https://doi.org/10.1007/s11270-017-3551-x

Tomsett, C., & Leyland, J. (2019). Remote sensing of river corridors: A review of current trends and future directions. *River Res Appl*, 35, 779–803. https://doi.org/10.1002/rra.3479

Urošev, M., Milanović Pešić, A., Kovačević–Majkić, J., & Štrbac, D. (2022). Hydrological characteristics of Serbia. In Manić, E., Nikitović, V., & Djurović, P. (Eds.), *The geography of Serbia* (pp. 145–164). Springer. https://doi.org/10.1007/978-3-030-74701-5_6

Valjarević, A. (2025b). Ecological impact of oil fields on Venezuela's river systems: Water stress and environmental challenges. *J South Am Earth Sci*, 105675. https://doi.org/10.1016/j.jsames.2025.105675.

Valjarević, A. (2024). GIS-based methods for identifying river networks types and changing river basins. *Water Resour Manage*, 38, 5323–5341. https://doi.org/10.1007/s11269-024-03916-7

Valjarević, A., Filipović, D., & Milanović, M. (2020b). New updated world maps of sea-surface salinity. *Pure Appl Geophys*, 177, 2977–2992. https://doi.org/10.1007/s00024-019-02404-z

Valjarević, A., Filipović, D., Valjarević, D., et al. (2020a). GIS and remote sensing techniques for the estimation of dew volume in the Republic of Serbia. *Meteorol Appl*, 27, e1930. https://doi.org/10.1002/met.1930

Valjarević, A., Morar, C., Brasanac-Bosanac, L., Cirkovic-Mitrovic, T., Djekic, T., Mihajlović, M., & Kaplan, G. (2025c). Sustainable land use in Moldova: GIS & remote sensing of forests and crops. *Land Use Policy*, 152, 107515. https://doi.org/10.1016/j.landusepol.2025.107515

Valjarević, A., Šiljeg, A., Šiljeg, S., Vujović, F., & Sahay, A. (2025a). GIS-based water stress analysis in North African drylands. *J Arid Environ*, 230, 105427. https://doi.org/10.1016/j.jaridenv.2025.105427

Valjarević, A. (2025d). GIS and remote sensing methods in predicting the dissipation time of rural settlements under the influence of climate change in the Republic of Serbia. *J Urban Manag*, 14(2), 500–511. https://doi.org/10.1016/j.jum.2024.12.002.

Yu, Z., Lu, M., Xu, Y., Wang, Q., Lin, Z., & Luo, S. (2023). Network structure and stability of the river connectivity in a rapidly urbanizing region. *Sci Total Environ*, 894, 165021. https://doi.org/10.1016/j.scitotenv.2023.165021

Zhao, Q., Yu, L., Du, Z., Peng, D., Hao, P., Zhang, Y., & Gong, P. (2022). An overview of the applications of earth observation satellite data: Impacts and future trends. *Remote Sens*, 14(8), 1863. https://doi.org/10.3390/rs14081863

Zhao, Y., Zhang, R., Jiang, W., & Hu, M. (2020). Influence of land use and urbanization on runoff characteristics in the Beijing metropolitan area. *Water*, 12(10), 2821. https://doi.org/10.3390/w12102821

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., Biza, A., Boakye-Ansah, A., Faber, S., Cabrera Flamini, A., Cuadrado-Quesada, G., Fantini, E., Gupta, J., Hasan, S., ter Horst, R., Jamali, H., Jaspers, F., Obani, P., Schwartz, K., Shubber, Z., Smit, H., Torio, P., Tutusaus, M., & Wesselink, A. (2017). Engaging with the politics of water governance. *WIREs Water*, 4, e1245. https://doi.org/10.1002/wat2.1245