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Article

GIS-Driven Mapping of Urbanization and Industrialization Pressures on River Basins and Environmental Degradation

Aleksandar Valjarević [1,2]

(1) University of Belgrade, Faculty of Geography, Studentski Trg 3/III, 11000 Belgrade, Serbia

(2) Faculty of Education, University of East Sarajevo, Bosnia and Herzegovina, Semberskih ratara 1E, Bjeljina, Bosnia and Herzegovina

Correspondence: aleksandar.valjarevic@gef.bg.ac.rs

Abstract: This study uses an integrated GIS and remote sensing framework to evaluate how these combined drivers influence river systems and surrounding environmental quality over the period 1983–2025. A multi-temporal geodatabase was compiled to capture urban expansion patterns, industrial and mining site distribution, land-use change, and hydrological characteristics of river networks. Hydrological analysis focused on drainage density, tributary persistence, and network connectivity as indicators of the functional capacity of river basins to convey, dilute, and naturally attenuate pollutants. The spatial results indicate a broad tendency toward simplified river morphology and reduced network complexity in several basins, expressed through declining drainage density and contraction of smaller tributaries. These changes are environmentally important because the loss of headwater channels and minor streams weakens dispersion and retention processes, increasing the likelihood that contaminants remain concentrated within main channels and propagate downstream during both low-flow and high-runoff events. Pollution pressure is associated with multiple sources, including heavy metals and suspended solids linked to mining and metallurgy, petrochemical and industrial residues near production zones, untreated or insufficiently treated municipal wastewater, and diffuse agricultural runoff carrying nutrients and pesticides. Hotspot screening and spatial overlay identify persistent clusters of elevated environmental stress in the Danube–Sava–Morava corridor, where dense urban-industrial infrastructure coincides with hydrologically sensitive river reaches, and in the Nišava–Timok region, where mining legacies amplify local contamination risk. remote sensing indicators further suggest riparian stress in selected reaches, consistent with cumulative pollution exposure and altered hydrological conditions. The findings support a basin-scale management response that combines infrastructure upgrades and stricter regulation with continuous spatial monitoring. Priority measures include expanding wastewater collection and treatment capacity, enforcing industrial discharge limits, improving containment and remediation of mine waste, and integrating routine field sampling with GIS-based risk mapping. The results provide practical guidance for identifying priority river basins where urban industrial pressures require immediate management intervention. The findings also support the use of GIS-based monitoring as a decision-support tool for improving river basin planning, pollution control, and sustainable water resource management. By linking sources, pathways, and changing river-network capacity, the approach provides practical evidence base for targeted interventions and more sustainable river basin governance.

Keywords: GIS; remote sensing; industrialization; river basin degradation; Serbia; urbanization; water quality hotspots

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Introduction

Environmental pollution is now widely recognized as a multidimensional challenge with far-reaching implications for ecosystem functioning and sustainable development. As cities expand, industries intensify production, and land use becomes increasingly transformed, pressures accumulate across key environmental compartments—air, water, soils, and biodiversity—often exceeding the capacity of local systems to absorb disturbance. These impacts are not distributed evenly: they tend to be strongest in regions where economic change is rapid but environmental governance, enforcement, and monitoring infrastructure evolve more slowly. In such contexts, industrial growth, urban sprawl, and intensified agriculture can generate pollution burdens that escalate faster than institutional responses, amplifying degradation at the landscape scale (Black, 1997). This imbalance is particularly visible in countries experiencing post-socialist transition, where long periods of industrial restructuring, legacy pollution, aging infrastructure, and uneven spatial development have reshaped environmental risks. Serbia provides a clear example, given the long-term concentration of industrial and urban functions along major river valleys, especially within the Danube–Sava–Morava corridor, which historically offered advantages for transport, water supply, and settlement expansion. Today, these same corridors represent some of the most environmentally stressed and hydrologically sensitive zones in the Western Balkans, where cumulative pressures converge on river basins and associated ecosystems (Wang et al, 2022; Valjarević et al, 2025a).

Two recent GIS-based investigations provide an empirical foundation for understanding how these pressures interact with river systems: (1) analyses of urbanization and industrialization dynamics and their influence on river networks in Serbia, and (2) a GIS and regression-based assessment of urbanization and industrialization impacts on river network stability in south-east Serbia. Together, these studies describe a spatially explicit and temporally progressive transformation of riverine landscapes driven by decades of anthropogenic activity. They document how industrial expansion, settlement growth, channel modification, hydrotechnical interventions, and land conversion collectively reshape river morphology, reduce drainage density, weaken tributary persistence, and increase susceptibility to water quality deterioration. Such hydrological changes reflect broader socio-environmental processes that undermine ecological integrity and water security (Rafiee et al, 2024; Valjarević et al, 2025b).

Building on these findings, the present synthesis links river-network change with the broader environmental pathways through which pollution accumulates and spreads. When river networks lose complexity, natural buffering capacity declines: watersheds become less able to dilute, retain, and attenuate contaminants, while transport through simplified channels can become faster and more direct. Consequently, pollutants may move more efficiently across the basin, influencing surface waters, groundwater interactions, floodplain sediments, irrigated soils, and downstream aquatic habitats (Habersack et al, 2016).

An integrated methodological framework combining GIS, remote sensing, hydrological modeling, and statistical analysis offers a robust basis for diagnosing these processes. GIS supports hotspot detection, exposure gradient mapping, and pathway modeling; remote sensing contributes multi-temporal evidence of land-cover change, surface-water dynamics, and environmental stress; hydrological modeling clarifies how network restructuring alters connectivity and contaminant mobility. Taken together, the two GIS-based studies highlight the urgency of coordinated monitoring and management to support evidence-based policy, sustainable watershed planning, and long-term ecological resilience in Serbia amid ongoing development pressures and environmental change (Habersack et al, 2016; Valjarević et al, 2025b).

Accordingly, the main aim of this study is to quantify and spatially map the extent to which combined urbanization and industrialization pressures have reshaped river network structures, intensified environmental degradation across major river basins in Serbia during the period 1983–2025, using an integrated GIS, remote sensing, and hydrological modeling framework. The research is based on the hypothesis that increased urban–industrial intensity leads to measurable simplification of river networks, expressed through reduced drainage density, altered connectivity, and loss of tributary persistence, while basins experiencing stronger network simplification simultaneously exhibit higher concentrations and spatial clustering of pollution and environmental stress indicators. Guided by this premise, the study addresses three key research questions: (i) where the dominant urban and industrial pressure hotspots are located, how their spatial patterns have evolved over time, (ii) how fundamental river network metrics have changed across Serbia's river basins over the last four decades, (iii) to what extent observed modifications in river network capacity and structure are associated with the spatial distribution of environmental degradation, pollution-risk corridors (Kumar et al, 2018). Rapid population growth and intensive industrial development have significantly increased water demand, resulting in greater dependence on groundwater resources instead of surface water. Consequently, groundwater quality has deteriorated due to industrial effluent discharge and other anthropogenic activities. In this study, GIS mapping was applied to illustrate the spatial distribution of groundwater quality, while water quality indices and health risk assessments based on physicochemical parameters were used to evaluate potential risks to human health (Gani et al, 2025).

Materials and Methods

In this study, Kernel Density Estimation (KDE) is emphasized as a practical spatial modeling tool for detecting and visualizing pollution hotspots and the populations most likely to be exposed by transforming discrete point sources (e.g., industrial plants, mines, landfills, and traffic corridors) into continuous surfaces of probable influence, thereby distinguishing core exposure zones from broader impact gradients. In parallel, zonal statistics are used to summarize hotspot intensity and related environmental indicators within meaningful spatial units (e.g., river sub-basins, municipal boundaries, census tracts, or buffer zones), enabling clear comparisons across areas, identification of priority zones, and transparent reporting of mean, maximum, and percentile-based exposure metrics. When KDE outputs are coupled with proximity buffers, time-sensitive indicators, and zonal summaries, the combined approach provides a robust screening-level basis for risk mapping, targeting field verification, and prioritizing monitoring locations and mitigation measures. The methodological flowchart clearly illustrates all procedures and methods applied in the study (Figure 1).

For validation purposes, historical topographic maps from earlier periods were used as independent reference data to assess the accuracy and reliability of the input datasets and derived model outputs. These maps enabled cross-checking of river network geometry, tributary persistence, and terrain features, providing temporal and spatial verification of GIS- and remote-sensing-based results. The integration of historical cartographic sources strengthened the robustness of the analysis by reducing uncertainties 136 associated with model-driven interpretations and long-term landscape change detection (Figure 2).

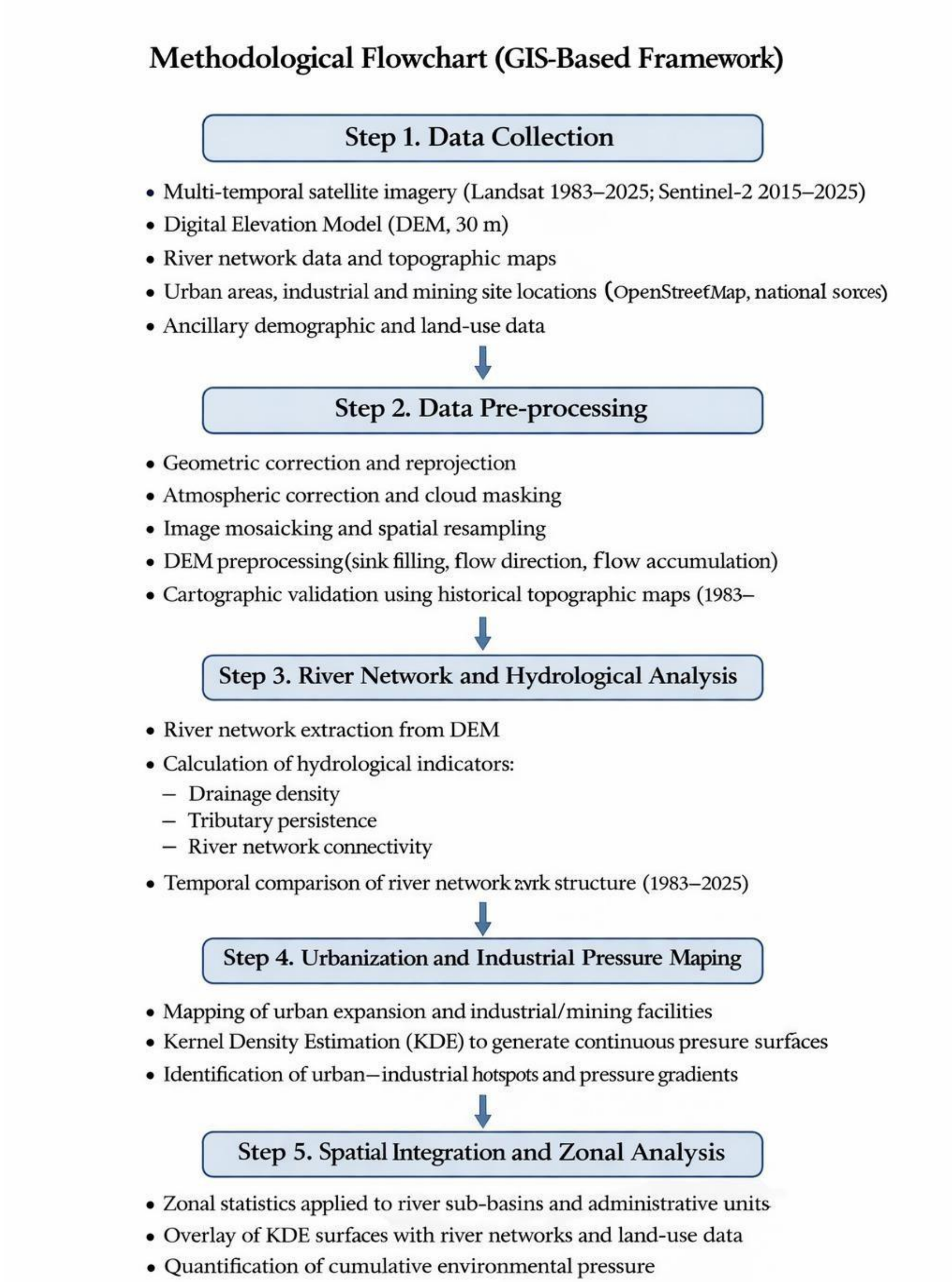

Figure 1. Flowchart of the main methods and methodological steps used in this study

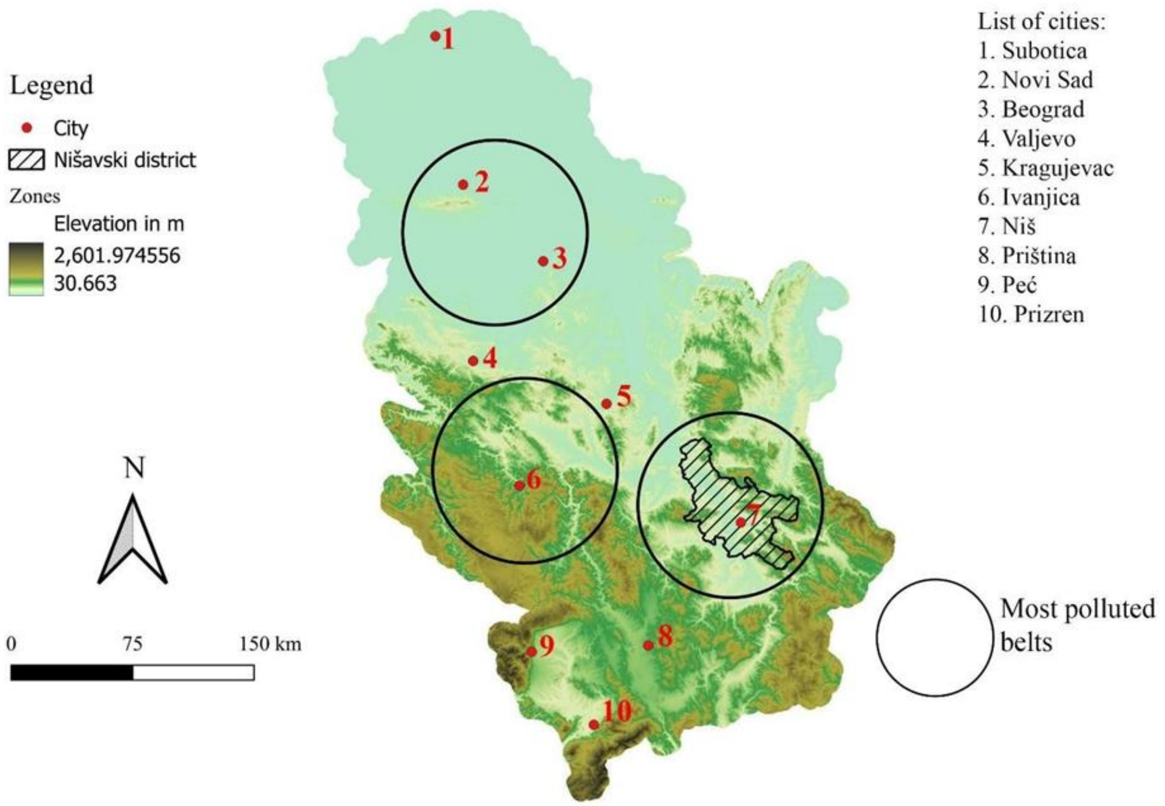

Figure 2. The position of most polluted areas in the Republic of Serbia.

The methodology was designed to provide a transparent, reproducible, and spatially consistent assessment of urbanization- and industrialization-driven pressures on river basins across Serbia. The analysis integrated open-access remote sensing data, including multi-temporal Landsat imagery (30 m spatial resolution; 1983146 2025) and Sentinel-2 imagery (10 m spatial resolution; 2015–2025), with digital elevation model (DEM) data (30 m), topographic maps, and vector layers representing river networks, settlement and urban expansion, and industrial–mining facilities obtained from OpenStreetMap and relevant national geospatial sources. All datasets were harmonized through geometric correction, reprojection to a common coordinate reference system, atmospheric correction and cloud masking (for satellite imagery), mosaicking where necessary, and resampling to a uniform spatial resolution to enable robust cross-temporal comparison. DEM and topographic map preprocessing included sink filling, flow direction, and flow accumulation modelling, as well as cartographic verification of river courses and terrain features, to support drainage network extraction and the calculation of hydrological indicators, including drainage density, tributary persistence, and river network connectivity. The criteria used to represent environmental pressure and degradation were selected based on their established relevance to river system functioning and contaminant transport, and classification thresholds were defined using data-driven approaches to delineate zones of low, moderate, and high impact. Kernel Density Estimation was applied to transform discrete industrial and mining point sources into continuous pressure surfaces and to identify persistent hotspot clusters, while spatial overlay and multi-criteria integration were used to quantify cumulative pressures and relate them to observed changes in river network structure and spatial patterns of environmental stress over the study period (Omar et al, 2024).

A major strength of GIS-based integration is that it does not treat exposure as purely distance-based. By coupling industrial locations with wind regimes (prevailing directions, gust frequency, stagnation episodes), elevation and terrain roughness (which shape dispersion and inversion potential), land cover, and settlement morphology, spatial models can approximate where pollutants are most likely to accumulate and who is most likely to be affected. Overlaying these layers with settlement distribution and demographic attributes (population density, age structure, socioeconomic status, health access, mobility constraints) enables a more realistic representation of vulnerability, highlighting, for example, small rural communities downwind of industrial sources, or low-income urban neighborhoods situated near major road corridors and valley-bottom in version zones. This approach directly supports environmental justice frameworks because it makes inequities visible in geographic terms: not only where pollution is high, but where high pollution intersects with limited adaptive capacity and constrained access to healthcare or clean-water alternatives (Chatrabhuj et al, 2024). The resulting outputs ranked hotspot zones, exposure corridors, and priority intervention maps can be used to guide targeted air and water monitoring, optimize placement of sensors, inform zoning and permitting decisions, and design public health interventions such as early-warning advisories, school protection measures, and community-level mitigation projects. In short, GIS-based spatial modeling links environmental processes with human geography in a way that strengthens both risk governance and evidence-based public health action (Winsemius & Braaten, 2024).

Environmental pollution influences population health through multiple, interlinked exposure pathways, with water, air, and soil acting as the primary vectors by which contaminants enter human physiological systems, and these pathways often reinforce one another such that exposure in one medium can amplify risks associated with another; in river-dominated landscapes such as Serbia where settlements, industrial zones, transport routes, and agricultural areas are densely aligned with hydrological networks—water pollution is particularly critical because communities depend on rivers for drinking water supply, irrigation, recreation, and ecosystem services, making any decline in water quality a direct driver of vulnerability (Baker et al, 2007). In this setting, a major structural problem is the widespread discharge of insufficiently treated wastewater into rivers, which elevates microbial risks and increases the likelihood of exposure to pathogens (e.g., *Escherichia coli*, Enterococcus, Giardia, and hepatitis A virus), while untreated industrial effluents contribute toxic loads of heavy metals (lead, arsenic, cadmium, mercury, chromium) that accumulate in sediments and aquatic food chains and are associated with neurological impairment, renal damage, carcinogenic outcomes, and developmental disorders, particularly among children; at the same time, nutrient-enriched discharges accelerate eutrophication, promoting algal blooms and hypoxia that degrade aquatic ecosystems and reduce fisheries productivity, and many industrial processes also introduce endocrine-disrupting chemicals (EDCs) such as phenols, phthalates, and solvents that may disrupt hormonal balance and reproductive health across generations. Air pollution remains another major and escalating concern in Serbia, driven by large industrial emitters, aging energy infrastructure, inefficient household heating, and increasing traffic, producing persistently elevated concentrations of $PM_{2.5}/PM_{10}$, SO_2, NO_x, O_3, benzene, and other volatile organic compounds; long-term exposure to these pollutants is linked to higher burdens of asthma, COPD, cardiovascular disease, stroke, lung cancer, adverse pregnancy outcomes, cognitive decline, and mental health effects, and Serbia is frequently highlighted among European countries with high air-pollution-related mortality and PM2.5 levels that exceed WHO guidance by large margins (Valjarević, 2024a). Emissions are also spatially uneven: Bor's copper smelting is associated with arsenic-rich dust and SO_2, Pančevo's petrochemical complex with hazardous hydrocarbons (benzene, toluene, xylene), Smederevo's steel production with particulate metals, and Obrenovac's lignite power plants with substantial SO_2 and particulate releases, which can disperse regionally under prevailing winds and basin topography (Valjarević, 2024b). Soil pollution represents a slower but persistent pathway because it enters the food chain and undermines agricultural productivity, with mining and industrial hotspots (e.g., Bor, Majdanpek, Kolubara) showing elevated metal loads that can transfer into crops, livestock, and human diets, contributing to chronic risks such as cancer, neurodegenerative disease, endocrine dysfunction, immune suppression, and childhood developmental impacts, while also reducing yields and intensifying rural vulnerability (Prodanova et al, 2024). In this context, GIS and remote sensing provide indispensable, spatially explicit tools for moving beyond isolated measurements toward integrated environmental assessment: by combining satellite time series, DEMs, land-use layers, industrial inventories, and hydrological models, researchers can map sources, model contaminant pathways, detect trends, delineate exposure zones, and evaluate vulnerability under alternative development scenarios, while advanced geospatial analytics (zonal statistics, Kernel Density Estimation, MCDA, and machine learning) support hotspot identification, composite risk mapping, and predictive modeling of future pressure patterns, thereby strengthening the evidence base for targeted interventions and policy decisions in rapidly transforming settings such as Serbia (Do, 2025).

Results

Industrialization and Urbanization Drivers of Hydrological Degradation in Serbia's River Basins

Serbia's hydrological systems have been substantially reshaped over recent decades as industrial growth, expanding urban footprints, infrastructure modernization, demographic shifts, and climate variability have acted together to reconfigure river-basin processes and river-network structure. Watersheds that were once defined by high connectivity, dense tributary patterns, and relatively stable ecological functioning, especially within the Danube–Sava–Morava system, are increasingly characterized by altered morphology, constrained dynamics, and reduced resilience under persistent human pressure. The spatial concentration of industry and settlements along river corridors has progressively modified drainage networks, adjusted stream patterns, and weakened the hydrological balance that historically supported ecosystem integrity, agriculture, and regional water security (Valjarević, 2024b).

Major valleys such as the Velika Morava, Južna Morava, Zapadna Morava, Drina, Kolubara, and Nišava have long served as ecological corridors connecting upland source areas with lowland plains, enabling sediment transfer, seasonal inundation, and groundwater recharge. Since the late twentieth century, however, metallurgy, mining, petrochemical production, energy generation, and manufacturing have increasingly clustered in these riverine zones because of water availability, favorable terrain, and transport accessibility. This clustering has intensified pollutant pressures and accelerated hydromorphological interventions, including channel straightening, bank reinforcement, embankment construction, dredging, and, in some cases, the removal, diversion, or functional isolation of smaller tributaries.

Urban expansion has further amplified hydrological stress. As Belgrade, Novi Sad, Niš, Kragujevac, Smederevo, and Pančevo have extended outward along riverbanks, floodplains have often been converted into residential, commercial, and industrial land. The growth of impervious surfaces—roads, roofs, parking areas, and industrial platforms has increased runoff, reduced infiltration, and heightened flash-flood potential during extreme precipitation. These shifts disrupt longitudinal and lateral connectivity, disturb sediment regimes, and may accelerate channel incision or aggradation depending on local geomorphic controls.

Evidence from the study on urbanization and industrialization dynamics in Serbia demonstrates that these pressures are accompanied by measurable, long-term changes in river-network properties. Using digitized historical cartography, DEM-based hydrological modeling, and multi-decadal GIS analysis, the research identifies declining drainage density, loss of perennial tributaries, simplification of branching river structures, and fragmentation of minor watercourses across multiple basins, with 1983–2025 emerging as a particularly dynamic interval shaped by economic transition, industrial restructuring, and rapid urban growth. Reported patterns include reduced drainage density linked to land-use change and channelization, lower network complexity due to flood-control infrastructure and urban encroachment, decreased tributary permanence influenced by both climate-related flow shifts and water abstraction, increased fragmentation near major industrial zones (e.g., Pančevo, Bor, Smederevo, Kolubara), and growth of artificial hydrographic features such as accumulation lakes, retention basins, drainage canals, and modified channels.

At the national scale, GIS results indicate that industrial–urban corridors have expanded along the Danube– Sava–Morava axis, forming broad zones where natural river behavior is increasingly constrained by regulation, infrastructure, and wastewater discharge. Additional hydrological destabilization is associated with the spread of small hydropower facilities in parts of southern and western Serbia, where altered flow regimes, disrupted sediment transport, and habitat fragmentation can further reduce river-system integrity (Liu et al, 2022).

Looking forward, projections to 2050 suggest that if current trajectories continue, Serbia may face further contraction of natural drainage networks, rising vulnerability under more frequent droughts and high-intensity rainfall, growth of interconnected industrial corridors linking major cities, worsening downstream water-quality conditions where treatment capacity remains insufficient, and higher flood exposure as floodplains become more urbanized and hydrological buffering capacity declines. Predictive scenarios also indicate intensified urban development along existing valleys, potentially forming near-continuous metropolitan belts from Subotica to Belgrade and from Belgrade toward Niš, with implications for biodiversity, agriculture, regional water security, and transboundary cooperation within the Danube Basin.

Overall, the documented transformation of river networks from 1983–2025 and the risks implied by projections through 2050 underscore the need for integrated watershed management, stronger environmental regulation, expanded green infrastructure, and sustained GIS-based monitoring that support development while safeguarding Serbia's critical water resources (Liu et al, 2022; Valjarević, 2024b) (Figure 3).

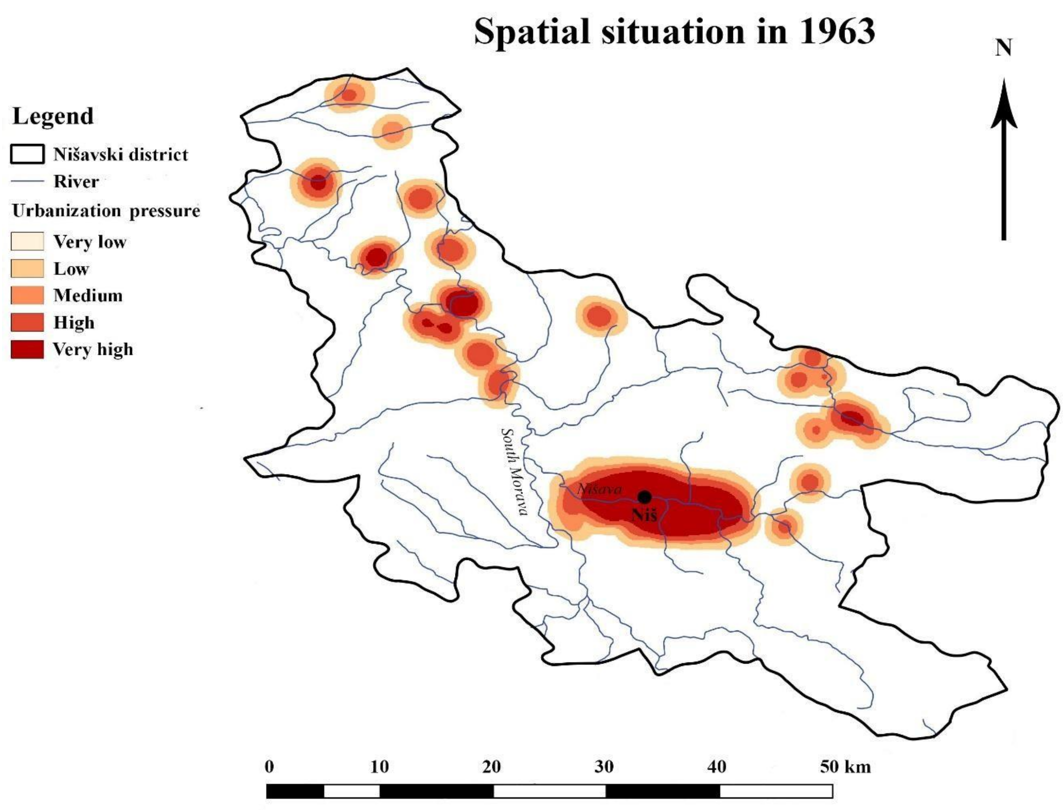

Figure 3. The spatial situation in 1963 and its influence on rivers.

The map of the spatial situation in 1963 indicates that urbanization pressure in the Nišava District was highly concentrated and strongly aligned with major river valleys. The highest intensity is clearly observed in the city of Niš, along the Nišava River and near its confluence with the South Morava, reflecting the early concentration of population, infrastructure, and economic activities along river corridors. Outside this main urban core, several smaller but distinct local hotspots of medium to high intensity appear along secondary streams and valley floors. At the same time, mountainous and peripheral areas are predominantly characterized by very low to low urbanization pressure. This spatial pattern highlights the crucial role of river systems in shaping early regional development. It indicates that river corridors were already the most exposed zones to anthropogenic pressures by the early 1960s, forming the foundation for subsequent degradation of river corridors. At the scale of south-eastern Serbia, this pattern reflects a broader regional structure in which urban growth and socio-economic activities were historically concentrated in river valleys, while upland and mountainous areas remained sparsely populated and functionally peripheral. Major river corridors such as the Nišava and South Morava acted as natural axes of connectivity, enabling transportation, trade, and industrial development, but simultaneously increasing pressure on fluvial systems. As a result, south-eastern Serbia already exhibited a pronounced spatial imbalance by the 1960s, with rivers serving both as drivers of regional development and as the most vulnerable components of the landscape to cumulative anthropogenic impacts.

Expansion of Industrial Corridors Along River Networks

Industrial activity in Serbia is highly concentrated along major river corridors, where reliable water supplies, transport links, and energy infrastructure create favorable conditions for production. The Danube–Sava–Morava system represents the country's principal industrial spine, operating as a strategic multi-river corridor that has long supported heavy manufacturing, logistics, and power generation. Along this axis are some of Serbia's most important industrial nodes, including the petrochemical and refinery complex in Pančevo, the Smederevo steelworks, the Bor copper mining and smelting district, and the Kolubara lignite basin, which underpins much of the national thermal-energy supply. Because these activities require substantial volumes of river water for cooling, processing, conveyance, and effluent management, their location near waterways is economically efficient but environmentally sensitive (Milovanović et al, 2007).

Additional industrial clusters extend through the Nišava and Timok valleys, where manufacturing, mining, and agro-processing are concentrated in urban centers such as Niš, Pirot, Bela Palanka, and Zaječar. These valley corridors remain strongly shaped by river-dependent infrastructure and accessibility, reinforcing a persistent pattern of river-oriented industrial geography. Beyond the main corridors, smaller basins in the Kolubara, Ibar, and Drina regions support further groupings of food processing, construction materials production, extractive activities, and light industry.

This spatial concentration, however, intensifies hydrological vulnerability. The manuscript notes that more than 70% of industrial facilities in southeastern Serbia are situated within 2 km of major rivers, forming exposure hotspots where contaminants can rapidly enter river systems. Proximity to riverbanks increases the probability of accidental spills and long-term pressures such as untreated or insufficiently treated wastewater discharge, heavy-metal accumulation, and thermal pollution. At the same time, associated infrastructure channel regulation, embankments, water withdrawals, and riverbank reinforcement—alters natural flow regimes and sediment dynamics, contributing to tributary disconnection and persistent changes in river morphology. Such interventions reduce floodplain buffering capacity and weaken self-purification processes, ultimately amplifying pollution transport and downstream impacts on ecosystems and communities (Valjarević et al, 2018).

GIS-based hydrological modeling indicates significant reductions in the complexity of river networks across Serbia. From 1983 to 2023, the number of perennial tributaries decreased by over 10%, while drainage density dropped by 8–15% across various basins. This decline can be attributed to urban growth, river channel modifications, the construction of small hydropower plants, and industrial water extraction.

The Nišava District shows similar trends: GIS regression analysis reveals an 8.3% decrease in drainage density and a 10.8% reduction in tributaries between 1983 and 2023. These changes are driven by extensive land-use shifts, infrastructure expansion, and rising surface imperviousness, particularly in the growing Niš metropolitan area (Valjarević et al, 2020; Murayama et al, 2021) (see Figure 4).

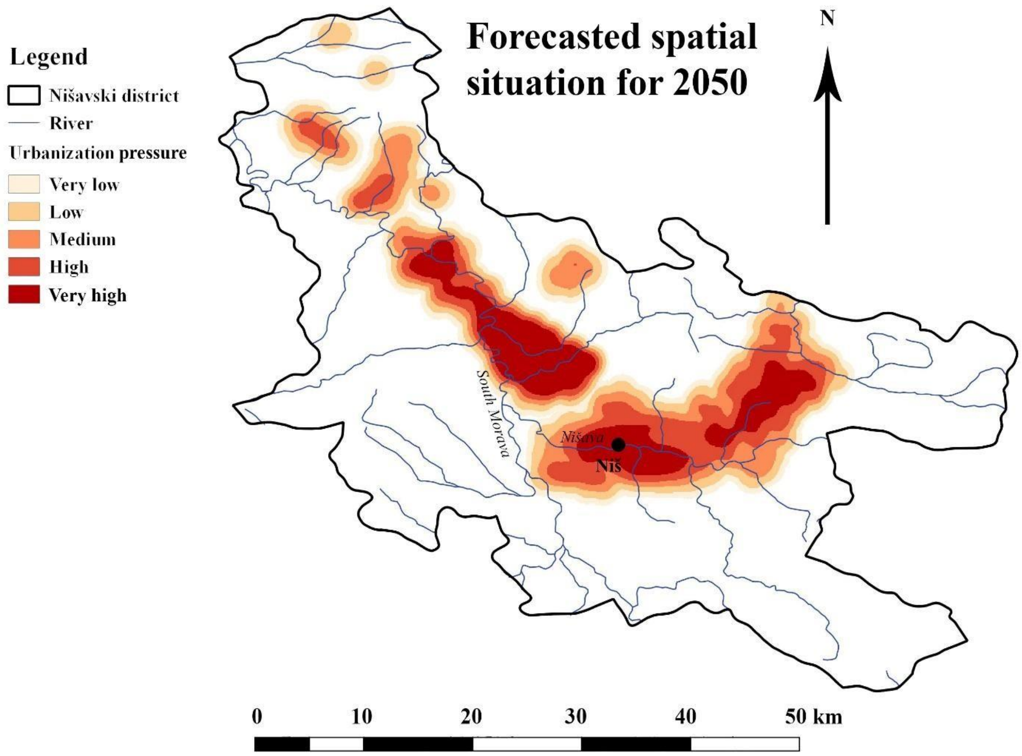

Figure 4. Forecasted spatial situation and its influence on rivers in 2050.

The forecasted spatial situation for 2050 reveals a pronounced intensification and spatial expansion of urbanization pressure across the Nišava District, with a clear tendency toward the formation of continuous high- to very-high-pressure zones along major river corridors. Unlike the more localized pattern observed in 1963, urban influence in 2050 is projected to spread longitudinally along the Nišava and South Morava valleys, creating an almost uninterrupted urban–industrial belt centered on Niš and extending toward secondary urban nodes. Medium- and high-intensity hotspots also become more frequent along tributaries, indicating growing pressure on smaller river systems and their surrounding floodplains. Peripheral and mountainous areas remain relatively less affected, but even these zones show signs of increasing low- to medium-pressure development, suggesting gradual spatial diffusion of development. Overall, the map highlights a future scenario in which river corridors in south-eastern Serbia are expected to experience cumulative and amplified anthropogenic stress, substantially increasing their vulnerability to hydromorphological alteration, pollution, and ecological degradation if integrated spatial and water management measures are not implemented.

Reduced drainage density limits the ecological resilience of river systems by decreasing natural buffering capacities, reducing groundwater recharge, and accelerating pollutant transport downstream. Simplified networks also intensify flooding risks, as water accumulates more rapidly during heavy rainfall events an increasingly frequent occurrence under climate change.

Industrial wastewater, heavy metals, oils, organic pollutants, and thermal discharges enter river networks more quickly when the hydraulic complexity is diminished. This accelerates the spread of contaminants and increases human exposure through drinking water systems, irrigation, and fisheries (Newson et al, 2000).

Water pollution remains one of Serbia's most widespread public health pressures. The ongoing degradation of river networks, together with inadequate wastewater collection and treatment, creates multiple, intersecting health risks that affect both urban and rural communities.

Mining basins such as Bor and Majdanpek are widely recognized as pollution hotspots in Southeast Europe, with elevated concentrations of copper, arsenic, cadmium, and lead reported in nearby rivers and soils. Prolonged exposure to these heavy metals is associated with serious health outcomes, including neurological impairment, kidney damage, reduced cognitive development in children, reproductive disorders, increased cancer risk, and immune-system suppression.

In the Nišava District, industrial clusters located close to river channels can release chemicals that enter the Nišava and South Morava rivers and are transported downstream. Over time, these pollutants may accumulate in agricultural soils and potentially transfer into locally consumed and nationwide food crops, potentially leading to chronic dietary exposure and long-term public health risks.

Estimates indicate that over 85% of wastewater in Serbia is discharged without adequate treatment, increasing exposure to waterborne pathogens such as *E. coli*, Salmonella, and Enterococcus. Rural communities that rely on private wells and shallow aquifers are often at higher risk because microbial contamination can spread quickly through poorly protected groundwater. As a result, gastrointestinal infections, including hepatitis A and recurrent diarrheal illnesses, tend to be more prevalent in areas where water and sanitation infrastructure is degraded or incomplete.

Major urban centers including Belgrade, Novi Sad, Niš, and Kragujevac, continue to face significant gaps in wastewater treatment capacity. Belgrade is frequently cited as having no fully operational citywide wastewater treatment system, meaning that large volumes of organic and microbial loads enter the Danube and Sava each year, with downstream consequences for ecosystems, recreation, irrigation, and public health.

Climate change is creating additional pathways for pollution-related health risks by amplifying hydrological extremes. Flood events can remobilize legacy industrial waste, untreated sewage, and agrochemicals, rapidly spreading contaminants across floodplains, agricultural land, and nearby settlements. Serbia's severe floods in 2014 illustrated how quickly pollutants can be redistributed during extreme runoff and inundation, increasing the likelihood of acute exposure and longer-term contamination of soils and water sources.

Looking ahead, the projected intensification of extreme rainfall across Serbia and the wider Balkans adds uncertainty to public health protection and water-quality management. These conditions strengthen the case for denser environmental monitoring networks, risk-based land-use planning in flood-prone zones, and early-warning systems that integrate hydro-meteorological forecasts with pollution surveillance.

The results of this study demonstrate that long-term urbanization and industrialization have substantially altered river network structure and environmental conditions across Serbia between 1983 and 2025. GIS- and remote sensing–based analyses reveal a consistent decline in drainage density, loss of minor tributaries, and simplification of river-network connectivity, particularly within major industrial–urban corridors such as the Danube–Sava–Morava system and the Nišava–Timok region. These hydromorphological changes coincide spatially with persistent pollution hotspots associated with mining, heavy industry, petrochemical facilities, and densely populated urban areas. Kernel Density Estimation and multi-criteria spatial integration indicate that reduced network complexity weakens natural buffering and self-purification capacity, facilitating faster downstream transport and accumulation of pollutants. Overall, the findings highlight a strong spatial linkage between intensified urban industrial pressure, river network degradation, and increased environmental vulnerability, underscoring the need for basin-scale management and continuous GIS-based monitoring to support sustainable water resource planning.

Discussion

The integrated GIS-based analysis in this manuscript shows that Serbia's industrialization and urbanization have generated persistent, cumulative, and spatially clustered pressures on environmental quality and population health. The findings indicate that hydrological degradation, pollution dispersion, and public health vulnerability are not separate phenomena, but interconnected pathways shaped by the geography of industry, uneven wastewater infrastructure, land-use change, and broader socio-economic dynamics. By combining multi-temporal geospatial datasets with hydrological modeling and environmental-health indicators, the study offers an evidence-based view of how concentrated industrial corridors continue to transform Serbia's ecological conditions and exposure landscape.

A key result is that river-network restructuring, as expressed in reduced drainage density, tributary loss, and simplified hydromorphology facilitates faster and wider pollutant transport. As buffering capacity declines, contaminants such as heavy metals, hydrocarbons, nutrient-enriched effluents, and microbial pathogens can move more efficiently through watersheds, increasing exposure potential for downstream communities. This risk is especially pronounced in major basins and corridors, including the Danube–Sava– Morava system, the Nišava corridor, and the Timok valley, where industrial activity and settlement density frequently overlap. These hydrological pressures are further amplified by climate change, which can intensify flood-driven mobilization of stored contaminants, modify seasonal runoff regimes, and increase thermal stress within river systems.

Industrial emissions add a parallel layer of environmental-health burden. Major point-source regions—mining districts (Bor, Majdanpek), steel production (Smederevo), petrochemical facilities (Pančevo), and lignite-based power generation (Obrenovac, Kostolac) are associated with degraded air quality and elevated chronic exposure risks. Spatial clustering in GIS highlights that these sources often coincide with densely populated settlements and sensitive demographic groups, reinforcing concerns related to respiratory and cardiovascular disease, long-term carcinogenic exposure, and reduced life expectancy. Importantly, the analysis emphasizes that air, water, and soil contamination can operate synergistically, producing multipathway exposure profiles that are frequently underestimated in single-medium environmental assessments (Zehe and Sivapalan, 2009).

The manuscript also draws attention to structural infrastructural constraints. With more than 80–85% of wastewater discharged without adequate treatment, untreated effluents can reach rivers with limited control, while agricultural runoff and industrial discharges contribute additional contaminant loads. Together, these processes form "pollution corridors" in which contaminants accumulate across water, soils, and biota, potentially entering into groundwater resources, food chains, and urban water supplies. The limited wastewater treatment capacity in major cities, including Belgrade, Niš, and Kragujevac, further reinforces these systemic pressures.

Methodologically, the study demonstrates the practical value of GIS and remote sensing for environmental-health research and policy support. Approaches such as Kernel Density Estimation (KDE), multi-criteria decision analysis (MCDA), zonal statistics, and DEM-based hydrological modeling enable detailed mapping of pollution gradients, identification of priority risk zones, and development of forward-looking vulnerability scenarios. Overall, the Discussion argues that Serbia's environmental-health challenges are rooted in the spatial logic and infrastructure deficits of its development trajectory; without coordinated action across water management, emissions control, land-use planning, and public health, pollution-related risks are likely to intensify under continued urbanization and climate change.

While this study relies primarily on GIS-based modeling and multi-temporal remote sensing analyses, the results should be interpreted in the context of available validation constraints. To strengthen the robustness of the findings, model outputs were cross-checked using independent historical topographic maps and cartographic sources, which provided an external reference for river network geometry, tributary persistence, and long-term landscape change. This approach allowed partial validation of hydrological indicators derived from DEM-based modeling and reduced uncertainties associated with purely model-driven interpretations. Nevertheless, the lack of systematic, long-term field-based water-quality measurements across all basins is a limitation that should be addressed in future research. Integrating targeted field sampling, continuous monitoring stations, and in situ physicochemical measurements with GIS-based spatial modeling would further enhance the reliability of pollution assessments and support more precise quantification of exposure pathways. Despite these limitations, the consistency of spatial patterns across independent datasets and time periods suggests that the identified hotspots and degradation trends reflect persistent and structurally embedded pressures rather than short-term or model-induced artifacts.

Conclusions and Recommendations

This study delivers an integrated GIS-based evaluation of how industrialization and urban growth have transformed Serbia's hydrological systems, environmental conditions, and public health context over the last four decades. The results indicate that river-network degradation, limited wastewater treatment, heavy-metal pollution, deteriorating air quality, and climate-related extremes interact to produce a layered and cumulative risk landscape. Spatial concentration of industry along key river corridors, most notably the Danube–Sava–Morava axis and the Nišava–Timok region, strengthens exposure pathways and facilitates the movement of contaminants into surface waters, soils, and the atmosphere.

Hydrological modeling identifies marked reductions in drainage density and tributary persistence, trends that weaken ecological resilience and enable faster pollutant transfer across basins. In parallel, air-quality evidence suggests that industrial emissions remain a major health stressor, contributing to higher burdens of respiratory and cardiovascular illness and long-term carcinogenic risks. Soil contamination and potential food-chain transfer further extend these impacts, particularly in agricultural communities located near mining districts and industrial sites (Cressie, 1988).

The synthesis highlights the strategic value of GIS and remote sensing as decision-support instruments for environmental governance. By integrating multi-temporal datasets with geostatistical methods and vulnerability mapping, the study produces policy-relevant outputs that can guide risk reduction, spatial planning, and targeted monitoring. The findings support the need for urgent investments in wastewater treatment, tighter control of industrial discharges and emissions, restoration of natural hydrological functions, and strengthened environmental-health surveillance.

Ultimately, Serbia's transition toward sustainable development depends on coordinated action that links environmental science, hydrology, spatial planning, and public health policy. The evidence suggests that without integrated interventions, ongoing industrial expansion and urbanization will continue to degrade ecosystems, widen health inequalities, and erode long-term resilience. In this context, GIS-based research functions not only as a diagnostic framework, but also as a practical foundation for designing safer, healthier, and more sustainable river-basin systems across Serbia (Valjarević, 2025).

Limitations

Despite the comprehensive spatial and temporal scope of this study, several limitations should be acknowledged. First, the analysis relies primarily on GIS-based modeling, remote sensing indicators, and secondary geospatial datasets, which, although powerful for large-scale and long-term assessments, cannot fully substitute for systematic field-based measurements. The limited availability of continuous in situ water-quality, sediment, and groundwater monitoring data across all river basins constrained the ability to directly validatemodeled pollution patterns and exposure gradients.

Second, the spatial resolution of remote sensing data, particularly Landsat imagery (30 m), may limit the detection of fine-scale hydromorphological changes and localized pollution sources, especially in small tributaries and narrow river corridors. While Sentinel-2 data (10 m) partially mitigate this issue for recent years, subtle or short-lived disturbances may remain underrepresented in the multi-decadal analysis.

Third, industrial and urban pressure indicators were derived from available inventories and open-source datasets, such as OpenStreetMap, which may contain positional uncertainties, temporal inconsistencies, or incomplete records, particularly for legacy industrial sites and informal pollution sources. Although cross-referencing with historical maps and ancillary data reduced these uncertainties, some level of underestimation or spatial generalization is unavoidable.

Finally, the study focuses on structural and spatial indicators of environmental degradation and does not explicitly model pollutant transport dynamics, chemical transformations, or biological responses within river systems. Consequently, the results should be interpreted as a screening-level assessment of cumulative pressure and vulnerability rather than as a detailed process-based water-quality model. Future research would benefit from integrating field sampling, continuous sensor networks, and coupled hydrological–biogeochemical models to refine risk estimates further and strengthen causal inference.

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