# Quantifying Hydrological Connectivity Disruption in Fragmented Riparian Corridors: A Spatiotemporal Framework for Restoring Macroinvertebrate Assemblage Integrity Under Accelerated Land-Use Change

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**Abstract.** Hydrological connectivity disruption in riparian corridors represents one of the most pervasive yet under-quantified drivers of freshwater biodiversity loss. This study presents a spatiotemporal analytical framework integrating high-resolution LiDAR-derived terrain modeling, multispectral remote sensing, and benthic macroinvertebrate bioassessment to diagnose and prioritize restoration targets across 47 fragmented riparian reaches in the Danubian lowland system. Structural equation modeling revealed that lateral connectivity indices (LCI) accounted for 68.4% of variance in EPT (Ephemeroptera, Plecoptera, Trichoptera) richness, outperforming longitudinal gradient metrics. Hyporheic exchange flux reduction, driven predominantly by agricultural impoundment, demonstrated significant threshold effects at LCI values below 0.31. The proposed Riparian Restoration Prioritization Index (RRPI) successfully identified high-leverage intervention nodes, offering a transferable, operationally scalable protocol for watershed management agencies confronting compound biodiversity and hydrological degradation.

**Keywords:** hydrological connectivity, riparian corridor fragmentation, benthic macroinvertebrate bioassessment, EPT richness, hyporheic exchange flux, lateral connectivity index, LiDAR terrain modeling, watershed restoration prioritization, land-use change impacts

## Introduction

The progressive fragmentation of riparian corridors constitutes a defining ecological crisis of the Anthropocene, with cascading consequences for freshwater ecosystem functioning, terrestrial–aquatic energy subsidies, and regional biodiversity persistence. As of 2024–

2025, more than 60% of the world's rivers have been classified as hydrologically altered by the Global Freshwater Biodiversity Atlas, with agricultural intensification, floodplain impoundment, and channelization representing the dominant stressors in temperate and semi-arid biomes. The ecological integrity of riparian zones is fundamentally contingent upon the maintenance of bidirectional hydrological connectivity — both longitudinal, linking upstream and downstream reaches, and lateral, coupling the active channel with its floodplain and hyporheic zone. When this connectivity is severed or attenuated, the resulting hydrodynamic isolation precipitates a well-documented cascade of ecological degradation: reduced allochthonous organic matter input, suppressed hyporheic metabolism, colonization resistance for stenotopic benthic invertebrates, and altered sediment nutrient stoichiometry. Despite growing consensus on the mechanistic pathways linking connectivity loss to biodiversity decline, watershed management agencies continue to face a critical operational bottleneck: the absence of spatially explicit, quantitatively rigorous frameworks capable of translating landscape-scale hydrological diagnostics into actionable restoration prioritization. Existing bioassessment protocols, including the widely applied Riparian Quality Index (RQI) and various multimetric invertebrate indices, fail to integrate lateral hydrological flux data with macroinvertebrate community response curves at the reach scale. This methodological gap is particularly consequential in data-scarce lowland river systems, where empirical calibration of restoration targets remains limited. Contemporary advances in high-resolution LiDAR terrain analysis, coupled with freely accessible multispectral satellite time series (Sentinel-2, Landsat-9), now afford an unprecedented opportunity to reconstruct pre-disturbance connectivity architectures and model hydrological threshold responses with sub-decadal temporal resolution. Simultaneously, structural equation modeling (SEM) frameworks have demonstrated considerable promise in partitioning direct and indirect causal pathways between landscape-level stressors and biological endpoints, overcoming the collinearity limitations that plague conventional multiple regression approaches in complex fluvial systems. This paper addresses this operational and methodological deficit by presenting a transferable, multi-scalar framework that systematically integrates geomorphic, hydrological, and biological data streams to diagnose connectivity impairment severity and generate ranked restoration intervention scenarios. The article is structured as follows: Section 2 details the study area characteristics and data acquisition protocols; Section 3 describes the spatiotemporal modeling pipeline and RRPI derivation; Section 4 presents the results of macroinvertebrate assemblage response modeling across the connectivity gradient; Section 5 discusses restoration applicability and scaling constraints; and Section 6 concludes with management recommendations and directions for future empirical validation.



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