

RESEARCH ARTICLE

Identification of urban water system ecological networks and ecological corridors based on multisource data modeling

Li Hong*, Wanci Wang, Panru Li

College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, Heilongjiang, China.

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Urban water systems are fundamental components of ecological security. However, ecological patch fragmentation and compounded flood risks have increasingly threatened the structural integrity and functional stability of urban water systems. This study performed a spatial overlay analysis to Jilin City, Jilin, China and clarified the spatial pattern and coupling characteristics of the overlaid hydrological and ecological networks. Based on digital elevation model (DEM) data, ArcGIS hydrological tools, and the soil conservation service curve number (SCS-CN) model, the study identified main water flow paths and runoff-sensitive areas across Jilin City. The hydrological network presented a differentiated spatial distribution pattern of “riverine aggregation and strong topographic coupling”. The morphological spatial pattern analysis (MSPA) and the delta probability of connectivity (dPC) index results showed that 18 core ecological sources were delineated, covering 347.91 km² that accounted for 74.58% of the total aquatic area. The aquatic ecological network was characterized by “intact large patches, patch isolation, and vulnerable connectivity”. Coupled with minimum cumulative resistance (MCR) and gravity models, a comprehensive resistance surface was constructed to identify 153 potential ecological corridors whose combined length reached 1,892.3 km. Further, by overlaying hydrological and ecological network data, 33 high importance corridors were obtained, 87.6% of which were in moderate and high runoff zones. Notably, the hydrological and ecological corridors of Jilin City were spatially overlapped with key ecological wetlands including the main stem of the Songhua River and the Songhua Lake. This study demonstrated a strong spatial coupling between hydrological and ecological networks, providing a scientific basis for integrated water system management, ecological connectivity enhancement, and flood risk mitigation in urban areas.

Keywords: urban; water system; ecological network; ecological corridors; multisource data.

*Corresponding author: Li Hong, College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, Heilongjiang 150030, China. Email: hongli@neau.edu.cn.

Introduction

Urban water systems are a fundamental element that underpins ecological security in a region, serving as critical spatial substrates for biological migration and diffusion, stormwater retention, landscape optimization, and environmental improvement. However, rapid urbanization has

caused numerous challenges including river channelization, shoreline hardening, wetland shrinkage, streams blockages, and blue-green space fragmentation. These disturbances have collectively degraded ecological connectivity and hydrological regulation capacities of urban water systems [1]. The traditional hydrological paradigm based on natural cycle assumptions has

become inadequate under intensifying human activities [2]. Engineering oriented methods have largely overlooked landscape ecological integration [3]. Fragmented sectoral governance has hindered systematic solutions to compound water challenges [4].

Recent studies have advanced the understanding of water system spatial patterns and ecological network structures. The water system ecological network is characterized by strong processability, corridor function and risk coupling. Its spatial structure not only encompasses the landscape layout, but is also closely linked to confluence pathways, terrain gradients, surface runoff, and flood sensitive areas [5]. Identifying the water system ecological network solely from landscape layout cannot reveal the complex coupling between hydrological and ecological processes as it overlooks the resistance of surface features like water bodies and human disturbances [6]. Nor does it support integrated spatial analysis of ecological connectivity and stormwater retention. Therefore, systematic ecological network construction using integrated spatial models is needed to enhance connectivity [7]. Existing studies mainly focus separately on flood risks or landscape ecological evaluation, lacking systematic spatial analysis integrating “hydrological process-ecological structure-spatial pattern”. Consequently, adopting an ecological network perspective to coordinate spatial restoration and pattern optimization within water systems is emerging as a pivotal research direction for watershed governance and urban land spatial planning. Jilin City is situated in the central-eastern part of Jilin Province, China and acts as a critical node in the upper reaches of the Songhua River. The urban core is traversed by the Songhua River, imposing hydrological pressure during the summer rainstorm seasons. In particular, the region suffers from fragile ecological corridor connectivity and spatial overlap between flood-sensitive and ecologically vulnerable areas.

This study aimed to clarify the spatial pattern and coupling characteristics of hydrological and

ecological networks in Jilin City through an integrated multisource data modeling approach. By integrating ArcGIS hydrological analysis into the construction of ecological networks, this research leveraged multisource data such as the digital elevation model (DEM) and incorporated the soil conservation service curve number (SCS-CN) model to delineate hydrological risks in Jilin City [8]. Morphological spatial pattern analysis (MSPA), landscape connectivity metrics using delta probability of connectivity (dPC), the minimum cumulative resistance (MCR) model, and gravity models were used to identify ecological sources and corridors and analyze the spatial pattern of potential corridors [9]. This study identified crucial water system connectivity spaces along river valleys, low lying areas, and tributary junctions, unveiled the spatial coupling relationship between hydrological and ecological networks, and evaluated the practical applicability of governance methods, which provided methodological insights for ecological restoration and spatial regulation of urban water systems in cold climate riverine cities.

Materials and methods

Overview of the study area

The study area was Jilin City, located in central eastern Jilin Province, China between 121°38′–131°19′ E and 40°52′–46°18′ N. It is a critical node in the upper Songhua River with a temperate continental monsoon climate and precipitation concentrated in summer. The terrain descends from the southeast mountainous areas to the northwest plains, creating diverse hydrological and ecological conditions that make Jilin City a representative case for studying the coupling between hydrological processes and ecological networks in cold-climate riverine cities.

Data sources and processing

This study used basic datasets including DEM data from Shuttle Radar Topography Mission 1-Arc-Second Global Digital Elevation Model (SRTMGL1, 30 m) (<https://earthexplorer.usgs.gov/>), land use data from China 30 m Land Cover

Dataset (CLCD) (<https://www.resdc.cn/>), soil type data from Harmonized World Soil Database (HWSD) v1.2 (<https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>), transportation infrastructure data from OpenStreetMap (OSM) (<https://download.geofabrik.de/>), rainfall records from Jilin City Meteorological Station (http://www.jlcity.gov.cn/zt/ztzt/jl_sqxxzx/xq_jcqxfw/202407/t20240727_1218606.html). Hydrological networks were extracted from the SRTMGL1 DEM using GIS-based hydrological analysis tools. To ensure that spatial consistency for unified analysis, all multisource data were projected to the WGS 1984 UTM Zone 52N (EPSG:32652) coordinate system based on the WGS84 datum, (<https://epsg.io/32652>). Following reprojection, all data were preprocessed *via* clipping, resampling, rasterization, and attribute reclassification. According to the requirements of hydrological analysis and ecological network construction, these data were further generated to form thematic data layers including slope gradients, flow accumulation, flow direction, sub catchment delineations, land use resistance factors, hydrological soil groups, and traffic disturbance factors. Given that the water system ecological network stresses the coordination between ecological processes and spatial structures, data processing considered both hydrological simulation and ecological identification. DEM, rainfall, soil, and land use data were used to simulate rainfall runoff and confluence processes to identify the watershed relationships and potential flooding prone areas, while aquatic habitats and associated blue-green patches were extracted and analyzed to underpin MSPA, landscape connectivity assessment, and resistance surface formulation. To minimize error propagations caused by inconsistent spatial resolution, all spatial analyses were conducted at a unified raster scale. ArcGIS Desktop (Esri, Redlands, CA, USA) was used for spatial analysis. D8 flow direction algorithm and Strahler stream order classification were applied for hydrological network extraction. SCS-CN model was implemented following the USDA-NRCS technical

manual (<https://www.nrcs.usda.gov>). MSPA was performed using GuidosToolbox (<https://forest.irc.ec.europa.eu/en/activities/lpa/guidos/>). dPC indices were computed using Conefor Sensinode (<https://www.conefor.org>). MCR modeling was conducted *via* the cost-distance tool in ArcGIS.

Extraction of hydrological corridors based on ArcGIS

Hydrological corridors constitute the essence of watershed hydrological processes and serve as the natural framework of the water system ecological network. Based on DEM data as the foundational input, five steps were employed to delineate these corridors including sink filling, flow direction calculation using the D8 algorithm, flow accumulation computation, river network extraction with a threshold greater than 5,000, and subdivision of the watershed into sub-basins *via* the Strahler stream order classification. This systematic framework delineated precise hydrological spatial units, which were essential for subsequent runoff simulation, risk identification, and coupled hydrological and ecological network analysis [10, 11].

Construction of the SCS-CN model

SCS-CN model (Natural Resources Conservation Service, Department of Agriculture, USA) is an event rainfall surface runoff empirical model that calculates the runoff depth based on land use/land cover (LULC), hydrologic soil groups (HSG), and antecedent moisture conditions (AMC). It is suitable for regional scale stormwater response simulations, owing to fewer required parameters, wide applicability, and seamless integration with GIS spatial analyses. It has been widely adopted to estimate the watershed runoff, identify flood risks, and construct hydrological resistance surface [12, 13]. The basic assumption of this model lay in water balance principles and an initial abstraction ratio $\lambda = 0.2$. The model's core equations were as follows.

$$S = \frac{25400}{CN} - 254 \quad (1)$$

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (P > 0.2S) \quad (2)$$

$$Q=0 \text{ (} P \leq 0.2S \text{)} \quad (3)$$

where P was the total precipitation (mm). Q was the actual runoff (mm). CN was the curve number, a pivotal integrative parameter that directly determined the runoff potential. A higher CN value brought about a smaller S and thus greater runoff Q [14]. In this model, different rainfall responses across diverse land surfaces were transformed into comparative hydrological risks to identify high runoff and flooding prone areas. Based on the data of CLCD and HWSO v1.2, the single rainfall depth was substituted into SCS-CN runoff generation formula, and then substituted into the corrected CN value under AMC III, a saturation-based classification standard proposed by the USDA-NRCS, Washington D.C., USA to characterize soil moisture status prior to rainfall events with empirical equations provided for converting CN II to CN III. The surface runoff depth Q was calculated pixel by pixel. The runoff depth values were classified using the natural breaks (Jenks) method on the spatial distribution map. By overlaying these results with the hydrological network, the final output could be obtained.

Identification of ecological sources using MSPA

In this study, water bodies and associated ecological patches were taken as foreground elements, while the other land uses served as the background to extract the spatial structural characteristics of the aquatic landscape in the study area. Using MSPA model, the aquatic ecological space was classified into seven structural types including core, bridge, edge, isthmus, branch, islet, and perforation, which helped identify ecological core patches and structural connectivity corridors. To avoid subjective selection bias, dPC index was used to quantify patch importance and identify key ecological sources that served as network nodes for subsequent ecological corridor extraction and optimization [15]. The dPC was calculated as follows.

$$dPC = \frac{PC_{total} - PC_i}{PC_{total}} \times 100\% \quad (4)$$

where PC_{total} was the overall network connectivity with all patches present. PC_i was the connectivity after removal of patch i. The higher the dPC value was, the more important the patch was to the maintaining of the network connectivity. Considering the scale of the study area and the distribution of aquatic characteristics, patches with an area greater than 120 hectares and a dPC greater than 0.3 were selected as core ecological sources. This process was implemented using Conefor software to calculate PC and dPC indices and then combined with ArcGIS to realize the spatial visualization of patch importance.

Extraction of potential ecological corridors

MCR model was employed to compute the least cost pathways across resistance surfaces between ecological sources, which could effectively delineate potential ecological corridors. Taking the selected core ecological sources as the source and the target, the optimal connectivity paths were extracted based on a composite resistance surface, forming the potential ecological corridor network across the study area. Six resistance factors were selected including land use type, elevation, slope, distance to roads, distance to water bodies, and distance to flood risk zones. Resistance values were assigned on a scale of 1 to 1,000 with lower values indicating better ecological connectivity. The core formula was as follows.

$$MCR = f_{\min} \sum_{j=n}^{i=m} (R_i \times D_{ij}) \quad (5)$$

where MCR was the minimum cumulative resistance from the source to the target. R_i was the resistance coefficient of landscape unit i to species movement. D_{ij} was the distance traversed from landscape unit i to j. $f_{\min}$ was the function of selecting the minimal value.

Importance evaluation of potential ecological corridors

To identify corridors that needed priority restoration and protection, this study applied a gravity model integrating source patch size, connectivity contribution, and relative resistance

to quantitatively assess and rank the importance of ecological corridors. High importance corridors connected ecologically valuable core patches or served as principal conduits for ecological flows, constituting indispensable components of a resilient ecological network. The gravity model was expressed as below.

$$G_{ij} = \frac{L_{\max}^2 \times \ln(S_i) \times \ln(S_j)}{L_{ij}^2 P_i P_j} \quad (6)$$

where G_{ij} was the interaction strength between ecological sources i and j . $L_{\max}$ was the maximum resistance across all corridors in the study area. L_{ij} was the cumulative resistance between sources i and j . S_i and S_j were the areas of ecological sources i and j , respectively; and P_i and P_j were their respective resistance values [16]. Corridors with a gravity value exceeding 0.5 were deemed as being highly important.

Results and discussion

Extraction of hydrological corridors

ArcGIS hydrological analysis tools were used to delineate the hydrological corridors in Jilin City. The results indicated that the city's river network exhibited a prototypical dendritic structure as densely distributed in the southeast and sparsely spread in the northwest, which was highly aligned with the local topography and geomorphology (Figure 1). Main runoff confluence areas were in the mountainous and hilly areas of the southeast, where the confluence paths were distributed in a reticular pattern. In contrast, in the northwest plains, the river network had low density with slow confluence velocity and high water retention and flooding risk. According to Strahler stream ordering, high order streams predominantly were distributed along the main channel of the Songhua River, while lower order tributaries were extensively distributed throughout the southeastern mountains. It formed such a hydrological pattern where main stems guide flow supplemented by tributaries in a hierarchical convergence. Thirteen sub-

watersheds were delineated, all of which had distinct boundaries, well-defined flow paths, and relatively homogeneous hydrological response characteristics. The sub catchments covered the entire study area without overlapping. This finding provided precise spatial units for SCS-CN runoff simulation and flood risk identification, significantly enhancing the model's computational accuracy and result reliability.

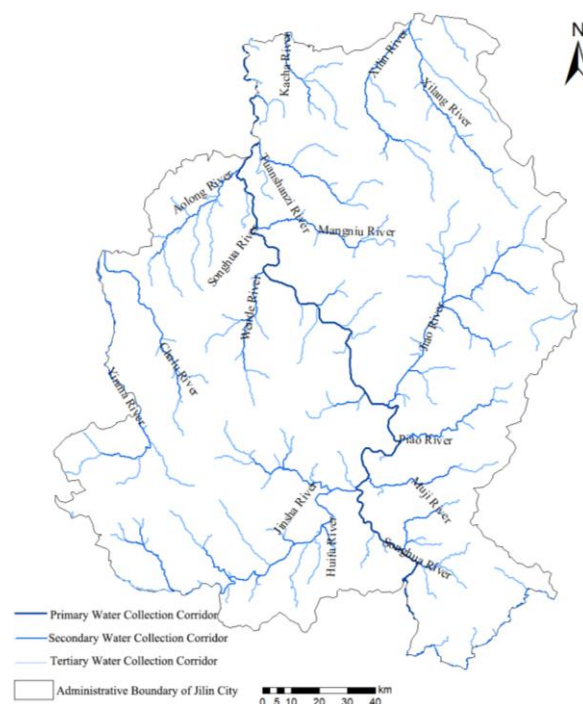


Figure 1. River network classification results of Jilin City.

Runoff depth and potential flooding risk analysis

The hydrological network presented a differentiated pattern of “clustering along watercourses and strong coupling with the underlying terrain” (Figure 2). High runoff areas (56 – 71 mm) primarily clustered around the Songhua River valley plain, the main urban district, and the down streams of the Wende River. These areas were also the concentrated area of aquatic ecological corridors, presenting high risks for flooding. In these areas, the conflict between hydrological stress and ecological preservation was the most prominent. Medium runoff areas (24 – 56 mm) were distributed

throughout suburban gentle slopes and transitional hilly zones by which ecological corridors predominantly traversed, serving as buffer and transitional zones. Low runoff areas (< 24 mm) concentrated in southeastern mountainous forest zones and the core region of Songhua Lake. They functioned as a pivotal urban water conservation area and an ecological security barrier, as well as crucial spaces for flood regulation and ecological source protection areas.

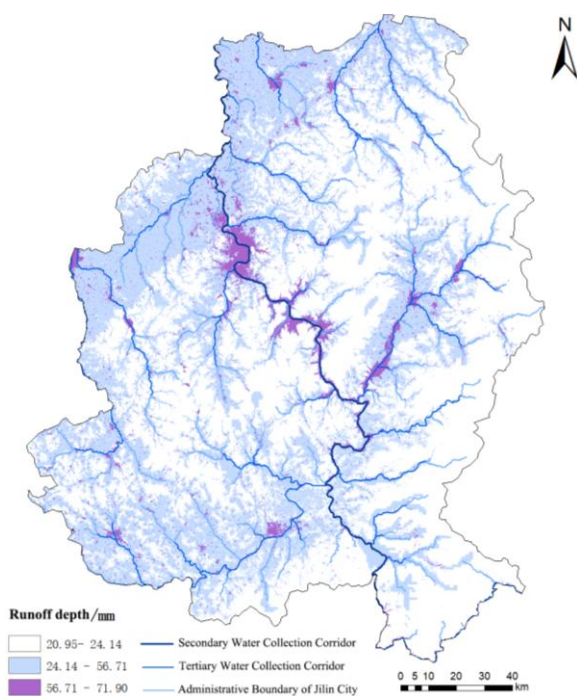


Figure 2. Spatial distribution of runoff depth in Jilin City.

Simulation outcomes from the SCS-CN model revealed that, under typical rainfall conditions, runoff depth in Jilin City presented distinct spatial heterogeneity, characterized by a general pattern of higher runoff in the northwest and lower runoff in the southeast (Figure 3). Potential flood risk zones were distributed along major rivers, hydrological corridors, and depressions, which showed that current hydrological processes displayed significant spatial clustering. There was a notable spatial superposition

between flood risks and areas with intense anthropogenic activities.

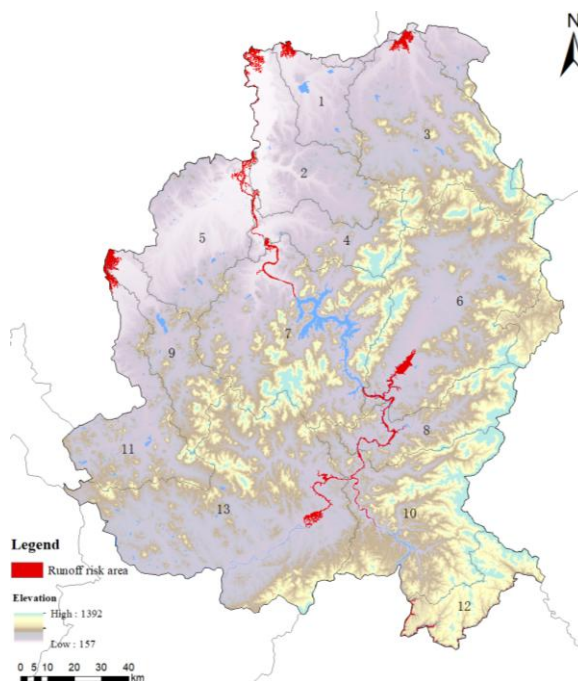


Figure 3. Spatial distribution characteristics of stormwater flooded areas.

Landscape pattern characteristics of aquatic areas based on MSPA

The MSPA results revealed that the total aquatic landscape area within Jilin City totaled 466.52 km², among which 347.91 km² or 74.58% were core areas, which indicated that Jilin City boasted an intact aquatic ecological foundation with sufficiently large ecological patches that provided a sound basis for constructing an ecological network (Figure 4). However, structural connectivity components were severely lacking. Bridging zones accounted for merely 1.20%, and loop zones constituted only 1.04%. The results indicated insufficient effective ecological connectivity among aquatic patches, which impeded ecological flow transmission. The landscape thus exhibited such a pattern that large patches remained intact but were fragmented and isolated in small patches with fragile ecological connectivity. Edge zones constituted 17.02%, posing high protective

pressure on ecological buffers, whereas isolated patches such as islets and branches remained small in proportion. These findings suggested that the sole reliance on the natural continuity of existing water bodies was insufficient to ensure the overall network resilience. Therefore, corridor reinforcement and node optimization were required to enhance lateral connectivity.

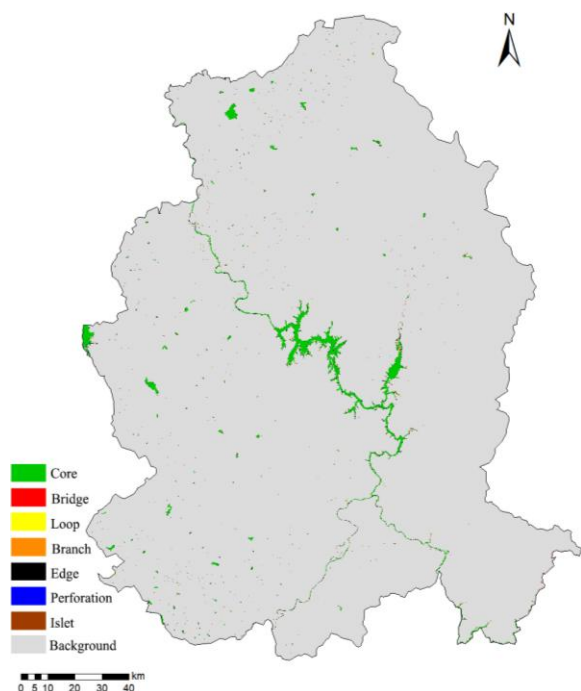


Figure 4. Distribution map of aquatic landscape types in Jilin City based on MSPA.

Selection of core ecological sources

More than 120 hm^2 areas with a dPC value exceeding 0.3 were selected in this study to obtain eighteen core ecological sources that were conducive to forming a stable ecological framework to play a decisive role in sustaining regional landscape connectivity and underpinning the configuration of ecological corridors. The total source areas covered 28,018.71 hm^2 , in which Songhua Lake (source 1) occupied 20,404.80 hm^2 , accounting for 72.8% of the total with a dPC value of 95.046. It presented itself as the keystone of the city's ecological network, fulfilling critical functions such as water

conservation, wildlife habitat provision, flood regulation, and climate moderation. Large and medium sized reservoirs including the Songhua River urban section, Hongshi Lake, and Baishan Lake were also large in areas with relatively high dPC values. They were part of the network's backbone and facilitated cross-regional ecological connectivity. Conversely, smaller reservoirs in suburban and hilly zones occupied smaller areas with lower dPC values. They were scattered primarily around towns and agricultural landscapes, fulfilling the function of local ecological connectivity, rainwater retention, and microhabitat protection (Figure 5).

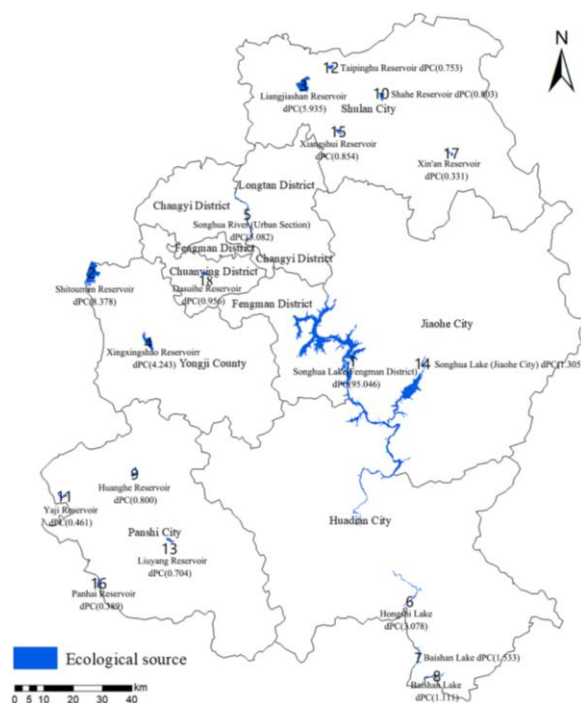


Figure 5. Distribution map of ecological sources in the study area.

Comprehensive resistance surface characterization

Analytic hierarchy process (AHP) was employed to determine the relative importance of each resistance factor. Twenty domain experts were invited to compare the importance of every two factors to construct the judgment matrix and calculate factor weights. After the consistency test, the consistency ratio (CR) was found to be

of 0.0065 (< 0.1), demonstrating acceptable consistency. The weighting results showed that land use had the highest weight of 0.28 followed by distance to flood risk zone of 0.21 and distance to river network of 0.18, while slope (0.12), elevation (0.11), and distance to roads (0.10) contributed relatively less to the overall resistance. These factors were standardized and applied to weighted overlay analysis in ArcGIS to generate the comprehensive ecological resistance surface of the entire region (Figure 6). Low-resistance areas were primarily distributed along the main stem of Songhua River and adjacent lake and reservoir margins, standing for preferred spatial corridors for connectivity. Medium resistance areas were mainly found in suburban transitional areas and some agricultural landscapes, where ecological permeability remained relatively strong despite that moderate anthropogenic disturbance existed. High resistance areas were distributed across high density built-up land and major traffic intersections.

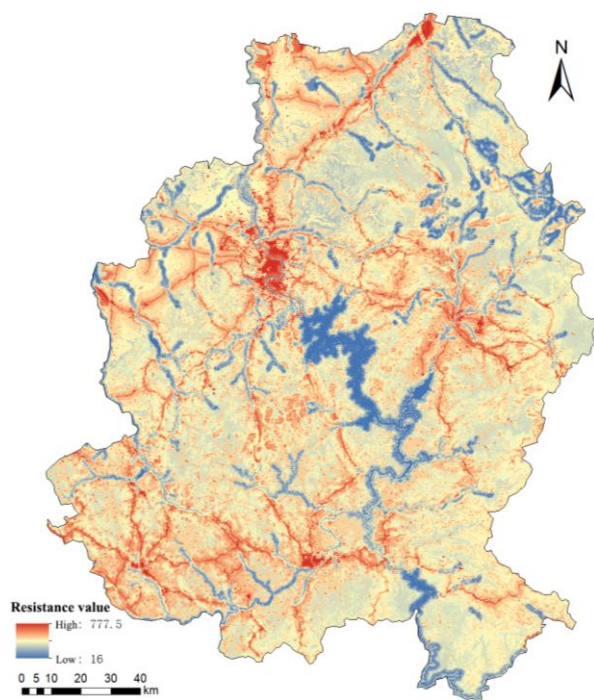


Figure 6. Integrated spatial resistance surface analysis of the Jilin City water system.

Extraction of potential ecological corridors and hierarchical importance classification

According to the integrated resistance surface and MCR model, a total of 153 potential ecological corridors were extracted with an aggregate length of 1,892.3 km and an average corridor length of 12.4 km (Figure 7A). The spatial distributions of these corridors exhibited pronounced aggregation along low-resistance areas and demonstrated a strong coupling with runoff areas. Notably, 87.6% of the corridors lay in medium and high runoff areas, which indicated that the optimal ecological diffusion paths were highly consistent with hydrological confluence channels. The gravity model was employed to quantitatively evaluate and systemically analyze the interaction intensity among the eighteen ecological sources. The threshold for gravity was set as 0.5. After threshold screening, 33 high importance ecological corridors were ultimately identified (Figure 7B). These corridors were designated as core research objects for studying follow up aquatic ecological network optimization and ecological restoration. There was a significant coupling relationship between the high importance corridors and the hydrological processes, which indicated that the hydrological confluence paths were highly aligned with pathways of minimal ecological resistance. Consequently, positioning corridors along principal runoff channels was conducive to simultaneously enhancing ecological connectivity and augmenting rainstorm runoff regulation capacities.

Comparative spatial pattern analysis of hydrological and ecological networks

A spatial overlay comparison was conducted between the river network extracted *via* ArcGIS hydrological analysis and the potential ecological corridors derived from MCR model. The results revealed that these two types of networks presented evident commonalities and divergences. The hydrological and ecological corridors were highly convergent along key areas such as the main stem of the Songhua River, the Songhua Lake reservoir area, surrounding large and medium reservoirs, and mid-to-lower

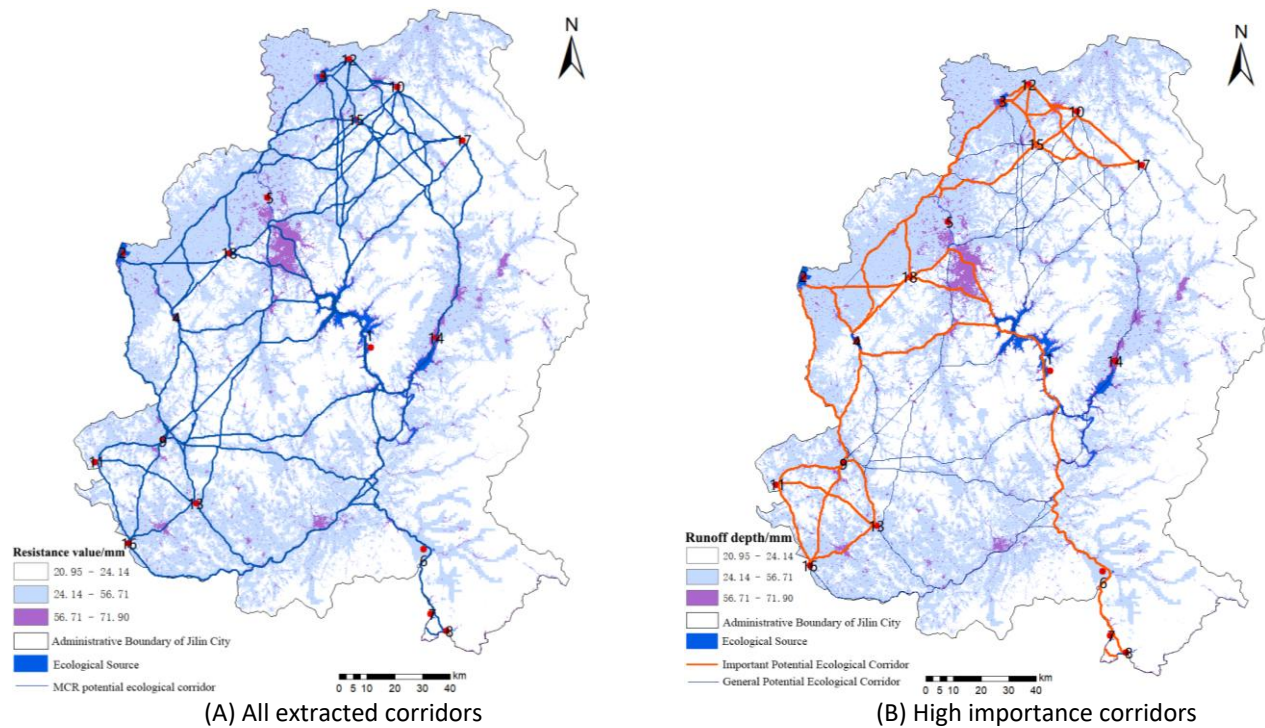


Figure 7. Extraction and classification of potential ecological corridors in Jilin City.

reaches of principal tributaries. These areas concurrently served as primary channels for runoff aggregation and conveyance, as well as preferential space for low resistance diffusion of ecological flows, thus forming a core dual connectivity backbone interlinking hydrological and ecological networks. In these areas, mutual reinforcement between networks was apparent. The hydrological process provided natural channels that facilitated ecological connectivity, while ecological patches furnished buffering space that was conducive to hydrological regulation. The comparison of these two networks accounted for the pattern of “main stem coupling with localized divergence” (Figure 8). The findings offered tangible scientific foundations for further zoned governance, corridor restoration, and spatial management.

Conclusion

This study integrated hydrological corridors, hydrological process, and flood risks into the

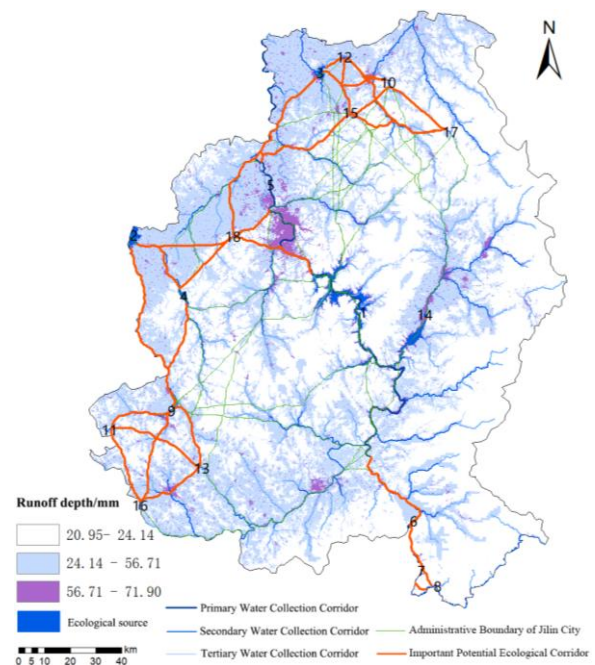


Figure 8. Comparison of the spatial patterns of hydrological and ecological network overlays.

spatial pattern analysis of ecological networks, overcoming the limitations of traditional

research that emphasized landscape connectivity while ignoring hydrological constraints. An integrated framework of “hydrological identification-ecological extraction-spatial coupling” was established to characterize the intricate interactions inherent in urban water systems. The hydrological and ecological networks were highly synergistic along the principal river trunks, whereas the spatial divergence was evident near tributary terminus and built-up areas, which revealed a spatial pattern characterized by main channel coupling and local divergence. Compared with single network analysis, the coupled hydrological-ecological identification framework could balance the dual goals of ecological connectivity and flood regulation, comprehensively revealing the composite spatial characteristics of urban water systems. Future research should introduce time series datasets to dynamically simulate hydrological processes, explore freeze–thaw mechanisms, and conduct multiscale refined analysis. All these would aim to enhance the practical applicability and robustness of the findings.

Acknowledgements

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