Connectivity of hydrology between lotic and lentic systems: consequences for integrated watershed management

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Abstract

River Corridors (RC) provide a significant share of freshwater for human and ecological requirements. The functions of flowing (lotic) rivers and creeks and ponded (lentic) waterbodies like reservoirs or lakes are extensively researched; their aggregate functions remain less comprehended. This compilation presents nationally uniform RC statistics to delineate the effects of lotic and lentic characteristics and to assess alterations over centuries prior. High-Resolution (HR) records detailing waterbodies throughout 10 million miles of the synonymous U.S. (CONUS) river network were categorized by waterway type and beginning (historic versus anthropogenic or extensively handled), area of coverage, and level of interaction, as inferred from alterations in water residence timescale within river passageways. Four decades of human disruption resulted in significant fluctuations in RC composition, with a shift towards more lotic ecosystems due to beaver disappearance and the demise of waterwheel mill lakes by the end of the 18th century. The 20th century experienced a significant increase (49%) in river passage area due to developing and maintaining small ponds and reservoirs for purposes such as hydration, hydroelectricity, water supply, livestock grazing, and stormwater drainage. The residence time of water in waterways doubled or tripled in extensive regions, and even more in particular sites, throughout the last century due to the expanded presence of shelters and monitored small lakes. Despite dams and lakes currently prevailing in the RC top areas, the findings indicate that the increasing prevalence of small ponds affects a larger segment of the system length due to their effect on headwater rivers, where most water and chemical pollution reaches the river sector. The research concludes with a framework for the integrated modelling of the tangible, biogeochemical, and biological determinants of RC operations, change paths, and governance prospects.

Keywords: Hydrology, Lotic and lentic, Watershed, Water

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Introduction

River Corridors (RC) (Han *et al.,* 2022) constitute a minor fraction of the terrain, approximately one percent, yet they play a disproportionately significant role in fulfilling the freshwater requirements of both humans and wildlife. They retain and transmit substantial volumes of clean water that sustain healthy and diversified aquatic environments while fulfilling societal demands for drinking and industrial applications, irrigation, animals, energy generation, and additional purposes. The resilience of RC to alterations in flow, heightened chemical runoff, elevated temperatures, and intensified water extraction is partially attributed to their fundamental roles (Gandhi, Prakruthi and Vijaya, 2024; Cavallini *et al.,* 2024). RC facilitates the interchange of water among the primary channel and the deeper, more stagnant ponded regions, as well as subterranean areas inside the bed, financial institutions, wetlands, and Floodplains (FP) (Jayapriya, 2021; Bonet *et al.,* 2022). The storage areas in RC are crucial for retaining water and gradual release, which mitigates the impacts of floods and droughts. Extended relationships with shallow regions and soils enhance ecological well-being and water quality by facilitating the filtration of fine particles and the transformation of substances and pollutants in hyporheic zones. Water treatment in waterways is improved; excessive storage duration promotes harmful algae blooms and hypoxia (Graziano, Deguire and Surasinghe, 2022; Wohl, 2021). Healthy RC maintains an equilibrium in water residence time, nutrient transport, water column dimensions, temperatures, light, and benthic exchange, fostering optimal metabolism that processes carbon and cycles nutrients in quantities that sustain effective food chains, different fauna, and associated ecological services for the community (Ranjan and Bhagat, 2024).

Relatively scant studies have been devoted to the significance of lotic structures within RC, such as tiny ponds, dams, and islands. Flowing waters and rivers primarily facilitate the downstream transport of water and minerals within river systems, whereas lotic waterbodies predominantly govern water retention in these systems (Monica Nandini, 2024). The characteristics of RC transition to broader, further, and more languid lentic waters as river and river valleys suddenly expand and/or decrease in gradient. Geological obstacles, including glacial mountains, debris flows, fallen logs, and biologically modified structures such as squirrel dams, impose limits on lotic waters in river channels (Comte *et al.*, 2022). Engineered structures, including earthen foundations, culverts, bridges, undercrossings, low-water bridges, and reservoirs of various dimensions, are becoming more significant elements linked to human disruption of river pathways (Farfoura *et al.,* 2023). The function of lotic water bodies inside canals of rivers is posited to fluctuate along an infinite number of hydrogeomorphic, climatic, biological, and anthropogenic slopes, as per the serial discontinuities idea. Examining those concepts has predominantly been confined to localized investigations (Robles *et al.*, 2015).

Lentic waterbodies within RC induce seasonal variations in the trends and determinants of primary efficiency and the rates of fertilizer and silt removal and storage processes (Lan *et al.*, 2024; Sahu and Kumar, 2024). Their significant biogeochemical impacts stem from their extensive surface area, increased solar energy input, prolonged water residency duration, and restricted horizontal mixing that encourages classification, resulting in bed deposits that could be light-limited or oxygen-depleted in contrast to water bodies. Artificial lakes under mountain sources reduce the flow rate in river valleys and diminish the downward movement of solutes and particles during springtime snowfall (Agarwal and Yadhav, 2023). Increased summer autotrophic growth in lakes can enhance the pulse of liquid organic matter that flows downward through the RC. Lentic waters significantly affect organic carbon cycles in river basins. Lentic flows can modify downstream constituent burdens by holding small particles and organic matter while intermittently releasing these elements to downstream river segments after extended storage durations (Ghosh and Chatterjee, 2023; Pandey and Gupta, 2024).

The research examined trends in the dimensions and network positioning of approximately two billion lentic waterways throughout 10 million km of RC throughout the Contiguous United States (CONUS) (Singh and Yadav, 2024), utilizing High-Resolution (HR) imagery encompassing lentic waterways as little as 0.0002km². The investigation evaluated the contributions of lotic and lentic systems to the surface region encompassing river passageways, hydraulic loads, and water retention timescales (Carter and Zhang, 2025). The measures are comprehensively delineated in the RC measures portion, and the research measured them across scales from tiny waterways to extensive basins of rivers to the whole United States (Reddy and Verma, 2024; Akyol and Capape, 2024). The study evaluated temporal alterations in RC by classifying lentic waterways as either formerly extant or constructed or extensively handled in the past centuries, alongside less definitive assessments of variations in beaver pond areas and mill ponds linked to waterwheel-operated grain silos (Sujatha, 2024).

Materials and Methods

Data Sources and Analysis of RC

The research utilized publicly accessible HR datasets for the CONUS to consider the impacts of approximately 90k lakes, 34k dams, 12 million km of waterways, and 1.8 million tiny ponds. The dimensions, network placements, and densities of lotic and lentic systems nationwide were measured to elucidate local trends in the role of lentic waterway types in the areal protection, hydraulic loads, and water retention timeframe of RC. The assessment of RC measures is the first to integrate recently accessible HR statistics on small ponds and streams with information regarding larger waterways, dams, and reservoirs in a CONUS-wide assessment.

To ensure information accuracy and coherence, the research limited the study to the time-averaged surface-water manifestations of RC, including perennial or periodic streams, river channels, and associated ponds, dams, and lakes. This research omits significant RC features, including riparian wetland areas, FPs, and subterranean hyporheic zones. Despite advancements in the national-scale calculation of several RC properties, the research determined that essential components were either absent for a coherent CONUS-scale study or for a temporal assessment. This examination excludes upland lakes and wetland areas that are physically separated from the river valley (i.e., lacking a mapped surface water conjunction), even though these watershed features are recognized to possess significant underlying or fleeting exterior (i.e., sporadic fill-and-spill) relationships that evacuate onto the river valley. The research foresees future evaluations of terrestrial-aquatic links that will integrate all permanent and periodic watershed characteristics in the higher ground and river valley.

Investigation of RC Networks and Taxonomy of Waterbodies

The research commenced by integrating the Medium-Resolution (MR) National Hydrography Dataset (NHD) with the recently accessible HR NHD, encompassing many tiny ponds and rivers. During the study, the HR NHD was available without all the properties of the MR NHD; hence, the research adopted the strategy of augmenting the MR NHD to incorporate the HR data.

This "merged" methodology allows for utilizing the comprehensive existing NHDPlus features. It circumvents the significant work required to create HR characteristics and inputs for models across the NHD. Those technological hurdles will be surmounted; in the interim, integrating medium and HR databases can yield a robust, precise, and beneficial hydrologic research and water quality modelling methodology.

MR NHD delineates surfaces for lentic waterways often exceeding 1 ha (0.02 km^2), with a minority of small lakes (12% of MR lentic waterways) possessing surface sizes as diminutive as 0.2 ha (0.002 km^2). The NHD includes mean annual cubic discharge projections, drainage regions for MR streams, and various features across most of the CONUS. Tiny ponds are typically defined by their surface spans of 1 hectare (0.02 km^2) or less, accounting for almost 92% of the recently recorded lentic waterways in the HR NHD, down to dimensions comparable to a standard beaver pond, approximately 0.02 hectares (0.0002 km^2). Integrating data from HR NHD augmented the count of lentic waterways by an average of 12 compared to those identified in MR NHD. A small fraction of the MR waterways is replicated in the HR collection; hence, the research removed duplicates containing minor inaccuracies from the final database before the analysis. HR NHD encompasses supplementary coverage of smaller streams with greater resolution, as well as the primary rivers and creeks documented in MR NHD.

Lentic streams were categorized into four distinct categories: (i) lakes, (ii) dams, (iii) historic tiny lakes that have functioned simply without extensive oversight for the past centuries, and (iv) handled small lakes established for water supply, agricultural usage, or other purposes, which are maintained in accordance. Lakes and tiny ponds are thus regarded as enduring characteristics that existed over 150 years ago and are minimally handled for human utilization. Controlled waterways, including reservoirs and tiny lakes, are understood to have been formed through the digging of canals, the building of canals, or other significant modifications of what have once been a natural waterway, or they represent entirely newly developed ponded water features.

The study categorized ponds as any MR lentic waterway in the NHD that is not classified as a reservoir. The 34k dams were recognized as waterways classified by the National Identification of Dams (NID), already featured in the MR NHD. The research recognized small controlled ponds as the supplementary 13k minor reservoirs in the NID that were less than 0.02 km^2; these ponds were represented in the MR NHD and appeared in the HR NHD, necessitating meticulous elimination of repetitions. Almost all of the 1.8 million tiny lakes in the HR database are neither classified as gated reservoirs in the NHD nor replicated in the MR NHD. The research categorized waterways as controlled, little lakes, or historical, small ponds based on local markers of anthropogenic disturbance (e.g., vegetation categorization), as detailed in the subsequent section.

Contemporary and Historical Examination

The research assessed temporal variations in RC lake surface areal weights, water occupancy timeframes, and hydraulic stresses by contrasting present circumstances with estimated conditions from around 150 years ago. The contemporary RC encompasses the current database of rivers, dams, historical small ponds, controlled small ponds, and waterways. For these reasons, the beginning of the twentieth century RC is characterized by surviving lakes, ancient, tiny lakes, and contemporary waterways. The projected river and stream lengths shifted by the building of dams or the creation of small lakes are given. The surface regions with relocated rivers and river lengths were estimated utilizing the flowline distance from the NHD that crosses the relevant lentic waterway, an approximation of stream speed, a width estimation, and the current discharge estimation. Calculations of RC from the present time and the beginning of the twentieth century rely on the exact mean yearly departure, which remains unclear but serves as a pragmatic approximation for these objectives. The early 20th century river hallway predicts that the establishment of stores and small ponds invariably supplanted a stream or river, potentially leading to an overestimation of the rise in river hallway surface areas in instances where lakes or historical small pools were enlarged through the building of dams to form a larger reservoir. To the understanding, no extensive pre-1900 information is available to assess the areas of old water bodies that were enlarged by reservoir building; therefore, the research presumes that only waterways and streams were substituted.

Results and Discussions

Connection within the FP

Between 2010 and 2025, the Santa Fe Port gauge reported maximum and minimum hydrometric readings of 6.5 m and 1.7 m, respectively. The connectivity changes examined from 2.2 to 6.5 meters in the tributary river deltas approximate the study timeframe. The lotic ecosystems comprise 95 hectares, constituting 5% of the area. This result consistently remained inferior to the amount of FP lakes associated with the lotic habitats (at 2.4 m, the lentic habitats linked to the lotic ones encompass 115 ha).

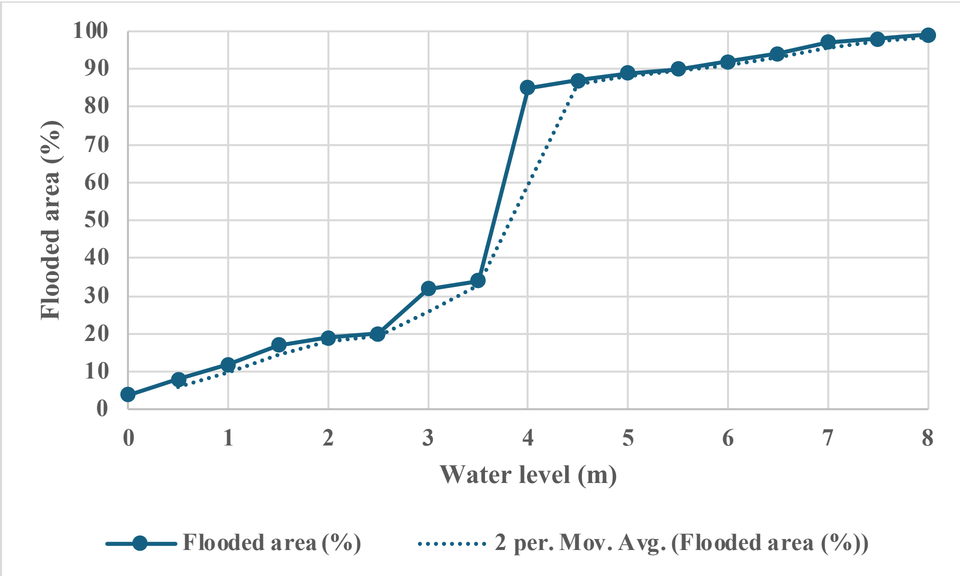

Figure 1: Flooded area analysis.

Through quantitative assessment of inundated regions at various water levels, the research can identify three primary connection patterns within the research area:

- From 2.1 to 3.4 m: minimal connection alterations; the interconnections among lotic and lentic ecosystems gradually expand (flooded regions fluctuate from roughly 7.0% to 10.6% of the total area).
- Between 3.4 and 4.4 m: substantial alterations in interaction; around 3.6 m, the initial significant transformation occurred, characterized by a pronounced influx of water into the desolate avenues of the FP (lower sections of the plain), enhancing the interconnections among FP water bodies and lotic systems (from 10.6% to 21.3% of the FPs is interconnected between 3.5 and 3.7 m, with 32 lakes linked).
- At an average depth of 4.2 meters, certain channel banks overflow in the FPs' lower sections; once reaching 4.4 meters, the inundated regions encompass 80% of the total surface.
- Exceeding 4.4 m: overflow occurs; most channel walls are submerged, the FP is nearly entirely flooded, and all waterways are interconnected.

Alteration of Water Composition

Water quality predominantly fluctuated throughout the period based on seasonal variations and FP connection (Figure 1). It exhibited a pronounced seasonal correlation; it was markedly reduced during summer collections compared to winter ($p < .002$), while T demonstrated an inverse trend ($p < .002$). Variations in pH, K, Tr, and Total Dissolved Solids (TDS) were predominantly associated with the extent of FP connection; Tr was much lower at poor connection compared to high connection ($p = .05$) and at low connection compared to overflow ($p = .008$). K and TDS exhibit a correlation, with both demonstrating considerably elevated values at low connections compared to high connections ($p = .003$) and at low connections versus overflow ($p < .002$). Additionally, pH is considerably higher at low connection than overflowing ($p = .006$).

Trends of Heightened Similarity in Lotic/Lentic Ecosystems at Diminished FP Connection

The disparity in diversity of species among lotic and lentic ecosystems increased with rising water levels in the study area. This pattern was not statistically significant ($p = .09$) but approached the relevance threshold established in this investigation. The three sampling conducted during the reduced FP connection exhibited greater similarity across lotic and lentic areas, indicating a substantial presence of identical species in both ecosystems. Conversely, increased connection typically resulted in fewer species shared across lotic and lentic ecosystems (e.g., merely four species were common to both ecosystems at the two elevated water levels).

The 15 prevalent species account for 68% of the overall fish population. For most migrants, abundance was significantly greater at lotic areas with poor connection, averaging 15 fish captured at poor connections compared to two at elevated overflowing levels. FP inhabitants (stationary fish or animals exhibiting brief excursions within FP ecosystems) exhibited a pattern analogous to that of migrants. The mean frequency of every kind was greater in lotic areas with poor connection than in those with higher connection and overflowing rates.

Conclusion

Our research expands upon the foundational work that established a structure for measuring RC characteristics and activities extensively. The study utilized new sources of information to enhance the precision of surface water regions. The research combined this with examining water residency timeframes separately and collectively for river routes' lotic and lentic elements. The temporal analysis of change reviewed the impact of human activity on the significant alterations in the physical characteristics of river channels. Several centuries ago, a resurgence of lotic characteristics in tiny streams occurred throughout the 20th century due to increased runoff maxima from tiled crops, roadside canals, and urban impermeable surfaces. The mid-twentieth century marked the zenith of the massive building of dams on medium and large rivers, enhancing water supplies and the generation of hydropower, alongside the establishment of tiny ponds that facilitated pastures for cattle in the arid western plains. In the latter part of the 20th century, mindful engineering and legislation prompted substantial expenditures in constructing small ponds for rainwater storage in towns and countryside.

The analysis revealed a net effect of human problems in waterways throughout the 20th century that was characterized by a 49 percent rise in the areal protection of CONUS river passageways and a doubling to quadrupling of water citizenship timescales, primarily due to the building of dams and managed tiny lakes. Retention wetlands currently predominate in the upper area of the river basin. Tiny ponds encompass a larger stream kilometers than reservoirs, with a total of 175k km for small lakes as opposed to 82k km for dams. The total area of tiny ponds is growing more rapidly than dams, and their cumulative impact on water remains predominant over that of lentic waterbodies in the rivers, where most water and chemical additions occur.

The findings establish a foundation for tackling emerging challenges using models and analytical tools that encompass the entire spectrum of river hallway characteristics and functions throughout the 10 million miles of CONUS river passageways, including water retention and cleansing, habitat provision, and resiliency to imbalanced ecosystem phenomena such as hypoxia and damaging algal blooms. The next emphasis will be on enhanced prediction capacities that predict potential issues and prioritize actions to maintain or reconstruct RC functioning.

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