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Review

Anthropogenic Modifications and River Ecosystem Services: A Landscape Perspective

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Abstract: The process of development has led to the modification of river landscapes. This has created imbalances between ecological, economic, and socio-cultural uses of ecosystem services (ESs), threatening the biotic and social integrity of rivers. Anthropogenic modifications influence river landscapes on multiple scales, which impact river-flow regimes and thus the production of river ESs. Despite progress in developing approaches for the valuation ecosystem goods and services, the ecosystem service research fails to acknowledge the biophysical structure of river landscape where ecosystem services are generated. Therefore, the purpose of this review is to synthesize the literature to develop the understanding of the biocomplexity of river landscapes and its importance in ecosystem service research. The review is limited to anthropogenic modifications from catchment to reach scale which includes inter-basin water transfer, change in land-use pattern, sub-surface modifications, groundwater abstractions, stream channelization, dams, and sand mining. Using 86 studies, the paper demonstrates that river ESs largely depend on the effective functioning of biophysical processes, which are linked with the geomorphological, ecological, and hydrological characteristics of river landscapes. Further, the ESs are linked with the economic, ecological, and socio-cultural aspect. The papers show that almost all anthropogenic modifications have positive impact on economic value of ESs. The ecological and socio-cultural values are negatively impacted by anthropogenic modifications such as dams, inter-basin water transfer, change in land-use pattern, and sand mining. The socio-cultural impact of ground-water abstraction and sub-surface modifications are not found in the literature examined here. Further, the ecological and socio-cultural aspects of ecosystem services from stakeholders' perspective are discussed. We advocate for linking ecosystem service assessment with landscape signatures considering the socio-ecological interactions.

Keywords: river landscape; anthropogenic modifications; hydrological alterations; ecosystem services; ecosystem functions

1. Introduction

River landscapes are interconnected, complex, dynamic, interacting social–ecological systems [1,2]. From headwaters to deltas, healthy rivers provide all the basic necessities for the survival and developmental needs of mankind [3]. In recent decades, the survival of many rivers is at stake due to huge water diversions for human needs. Significant hydrological alterations are results of large investments in water technologies and infrastructures for irrigation and hydro-power across the globe as well as land-use change [4]. Modifications to a river landscape are the result of divergent preferences and the choices of different stakeholders. Anthropogenic use of land and water, while benefiting human development, has damaged the delivery of ecosystem services (ESs) [5–10]. These modifications either directly impact ecosystem functions or accelerate natural processes that affect river-flow regimes and thus ES production. Ecosystem loss as a consequence of hydrological alterations because of flow-magnitude and -timing changes is well-documented [11,12]. Many water-resource managers consider artificial impoundments as a significant cause of hydrological alterations [11,13,14]. Large dams are not the only causes of hydrological alterations. For example, land-cover changes can lead to changes in how a catchment partitions rainfall into evaporation and runoff [15]. The diversion of water by the exploitation of aquifers, changes in land-use patterns, subsurface modifications, and inter-basin water transfer are examples of the forms of anthropogenic modification that cause hydrological alterations [5,12,16–18]. The addition of contaminants and nutrient enrichment in rivers on the river-segment scale can modify the natural flow regime [5,19]. At reach level, sand mining and stream channelization cause geomorphic and hydrological changes. When human-induced drivers change the dynamics and complexity of a river ecosystem, they cause large-scale environmental problems that diminish ecological functions in the lower river reach, resulting in a decline in ecosystem services provided by rivers.

Consequently, the benefits derived from river ecosystems services are not only consumed in a place where they are produced but often consumed elsewhere. For example, hydro-power is generated along a river, but it is transported far from the river to benefit people across the river landscape, including urban areas, and beyond. Services like water supply is either used for fulfilling basic needs (e.g., drinking) or for economic needs (e.g., industrial use of water) between upstream and downstream users. These spatiotemporal connections emerge from the typology of a river network and utilization of water according to human preferences [20,21]. Therefore the use, or abuse, of water or land resources in one part of the basin can influence water availability and provisioning of services in other regions because river ecosystems are complex systems linked dynamically across spatial and temporal scales of interactions [22]. For example, land-use and land-management decisions [23], which are sometimes dependent on water needs of associated activities [22], often lead to alterations of the river flow, evaporation, and transpiration regimes [23], thereby altering diverse ecosystem services within the basin and beyond.

Acknowledging the interconnectedness between various biophysical and social systems of a river landscape, we undertook an interdisciplinary review to understand how anthropogenic activities propagate through the landscape to influence and impact ES production. To narrow down the scope of the review, we focused only on the following seven types of anthropogenic modifications: (1) dams, (2) stream channelization (3) inter-catchment water transfer, (4) sand mining, (5) groundwater abstraction, (6) changes in land-use patterns, and (7) subsurface modifications.

This review aims to synthesize knowledge on changes in ecosystem processes and functions concerning anthropogenic landscape modifications (Figure 1). Through various examples, we advance our understanding of how river ESs largely depend on the effective functioning of biophysical processes that are linked with geomorphological, ecological, and hydrological characteristics of the river landscape, and how anthropogenic modifications of river landscapes cause imbalances between social, economic, and cultural uses of ESs, making river landscapes more vulnerable and less resilient.

The rest of this paper is organized as follows. The importance of linking landscape features with ecosystem services is discussed in Section 3. Then, we review the potential anthropogenic modifications and classify the diverse mechanisms that affect various biophysical processes of interest to ES production in Section 4. We also provide an overview of anthropogenic modifications and their influence on economic, ecological, and socio-cultural aspects of ecosystem services (Section 5). Further, emergent challenges are discussed in Section 6 followed by the conclusion (Section 7). This will help to better understand the role of spatiotemporal connections of the river landscape in ecosystem service assessment and to develop long-run strategies to promote the resilience and sustainable management of river-basin resources.

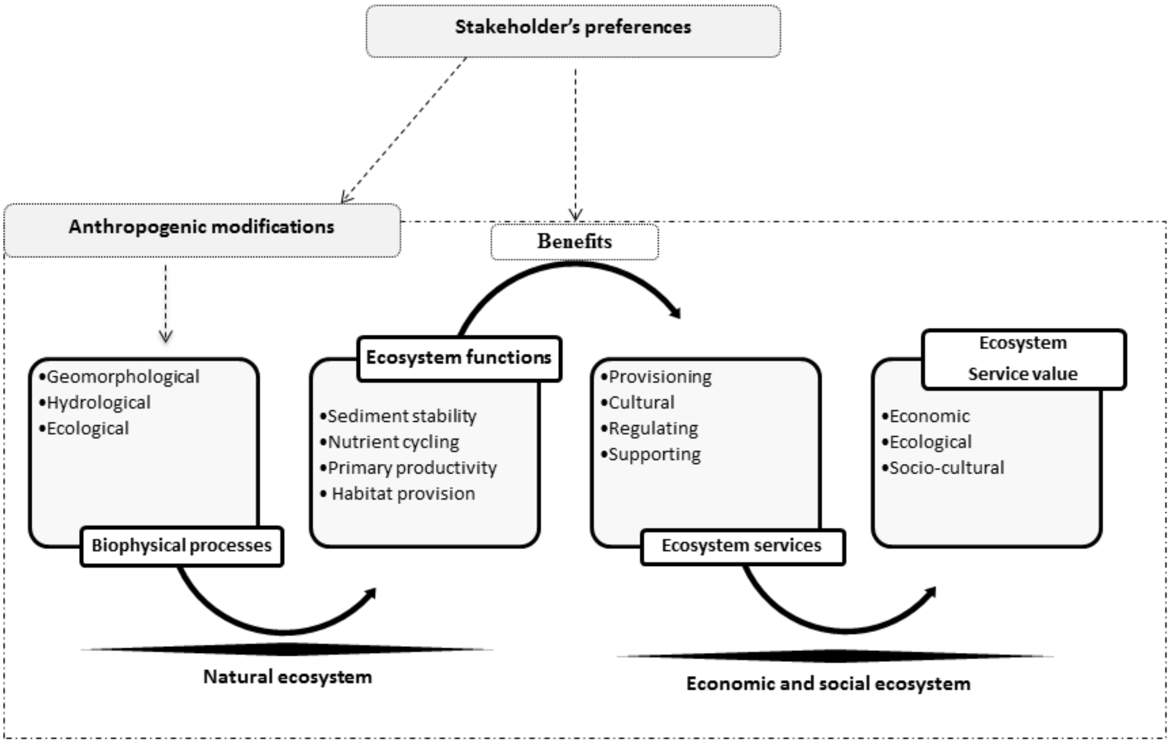

Figure 1. An overview of anthropogenic modifications on river ecosystem services (ESs).

2. Review Approach

2.1. Literature Search

We performed a systematic search of the peer-reviewed literature following the PRISMA method [24] to identify evidence of the impact of anthropogenic modifications on river landscapes that impact ESs. On the basis of the anthropogenic drivers selected for study, we searched the electronic database Scopus with keywords such as "river", "basin/catchment/watershed", and "ecosystem services" against each type of anthropogenic modification (Table 1). On the basis of this search, 1092 references were retrieved. Duplication were removed and only peer-reviewed articles written in English were selected for the review (n = 915). We then scrutinized the title and abstract of each publication to fit references with the aim of our search, and to include references related with anthropogenic modifications for further analysis (n = 667). For this subsample, articles were scrutinized on the basis of the following criteria: (1) specific reference to ecosystem services, ecosystem processes, or functions; and (2) papers specifying evidence of hydrological, ecological, and geomorphological components of the impact on river landscapes.

Table 1. Different keyword combinations for the literature search before inclusion criteria were applied.

Impact Type	Different Keyword Combinations with 'Ecosystem Services' and 'Impact'	No. of Papers
Dams	Dam, damming	255
Stream channelization	Channelization, drying of swamps, canals, wetland drainage	202
Inter-catchment water transfer	Inter-catchment water transfer or inter-basin water transfer	16
Sand mining	Sand mining	18
Groundwater abstraction	water abstraction	33
Change in land-use pattern	urbanization, deforestation, agricultural practices	538
Subsurface modifications	mining, metro rail, urban karst	30

2.2. Assessment Criteria

A total of 86 references were selected to map the evidence of the impact of anthropogenic modifications on river ecosystem services Figure 2. An overview of the number of papers under each type of modification is given in Figure 3. Subsequently, we cataloged and classified papers indicating the ecohydrological or geomorphological changes in river ecosystems in connection with ecosystem responses. Not all studies explicitly referred to the classification of ESs. For example, exotic species are an indicator of species diversity, contributing to supporting services. Therefore, we used ESs classified by [3], and the Common International Classification of Ecosystem Services (CICES) by [25] to establish connections between ecosystem responses and ESs (Table 2).

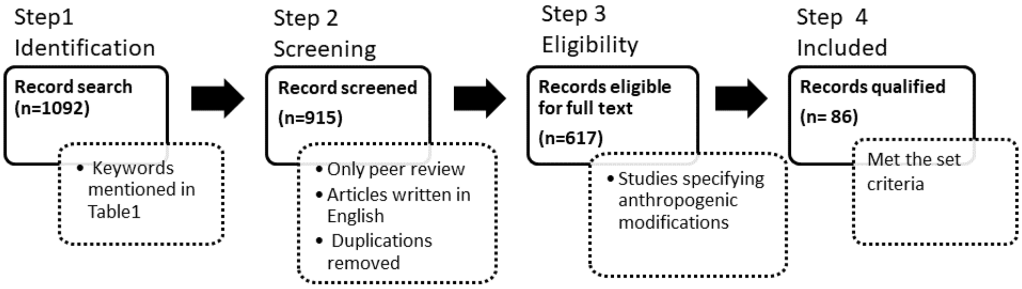

Figure 2. Flow diagram of review approach following the PRISMA method.

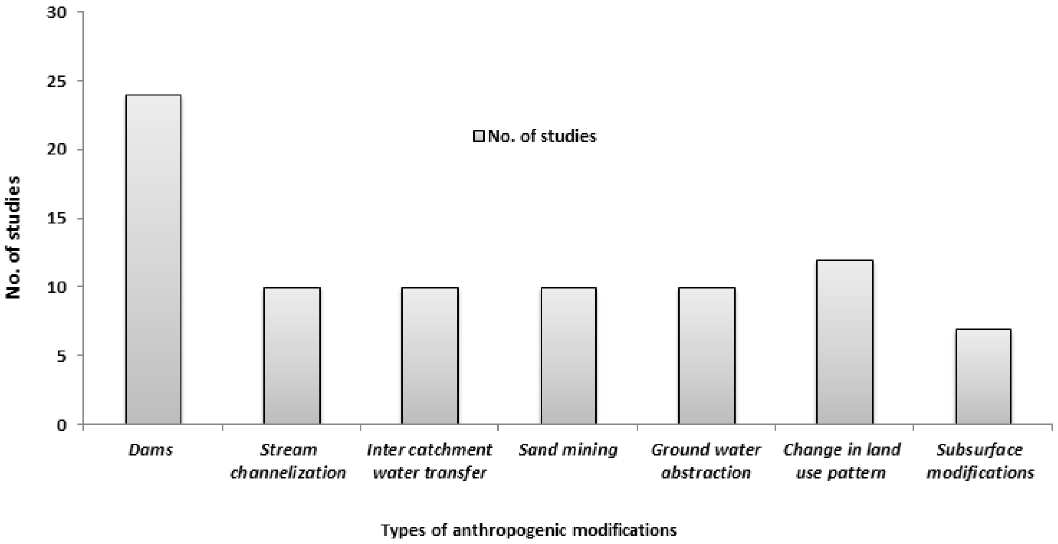

Figure 3. Number of studies reported under each anthropogenic-modification type after inclusion criteria were applied.

Table 2. List of ecosystem services compiled from [3,25].

Provisioning Services	Regulating Services	Cultural Services	Supporting Services
Food production	Carbon sequestration	Educational values	Soil retention
Water yield	Water purification	Cultural heritage values	Soil formation
Genetic Resources	Flood control	Ecotourism Recreation	Primary production
Fuel Raw materials	Disease regulation	Inspiration	Photosynthesis
Natural medicines	Air quality regulation	Spiritual and religious values	Habitat provision
	Erosion control	Aesthetic values	

3. Linking Ecosystem Services with River Landscape Features

"In every respect, valley rules the stream" [26]. Stream ecologists have long acknowledged the significance of river landscape on the river flow regime [26–28]. However, the notion that river landscapes act as "biophysical templates" [29] that produce most of the ecosystem services has often been overlooked. No doubt, flow regimes are important in this regard [30] but the flow regime itself is influenced by many biotic and abiotic factors and interactions within a river landscape [9,28]. Primarily, landscapes are the result of co-evolution of climate, topography, vegetation, and geology [9,31–33] and are considered a prominent feature of river basins [31,32,34–36].

To understand the interactive processes by which patterns of climate, topography, vegetation, and geology, including soils, are coupled in landscape arrangements and dynamics [31], due consideration needs to be given to geomorphological, hydrological, and ecological characteristics of the river basin within a hierarchy of spatial and temporal scales. Given the complexity of riverine ecosystems, the hierarchical structures of the geomorphological, hydrological, and ecological components [37] help to understand the linkages of various biophysical processes in a river ecosystem and production of ecosystem services.

The geomorphic subsystems provide the structural basis to a river landscape. The functional aspects consist of hydrological and ecological functioning of the system. Abiotic or biotic agents act as drivers and carriers of this functioning. Various ecological processes respond to these drivers, leading to a set of ecosystem functions [38]. From headwater to the delta, the physical variables within a river system present a continuous physical-geomorphic gradient for ecosystem functions [29,39,40]. The model of river ecosystem synthesis proposed by Thorp et al. [41] and Thorp [42] suggests that levels of ecosystem services provided by riverine landscapes depend on hierarchically arranged hydrogeomorphic patches from the valley to reach scales, known as functional process zones. At each level of spatial scale, the geomorphic structures such as channel width, instream cover, and channel depth, form landform attributes associated with habitat and niche complexity of river systems and processes [38]. These structures influence the habitat template of rivers and thus the number of functional micro- and macro-habitats [43]. These habitat templates assimilate the biota, and biological interactions, including physical and chemical processes, that collectively determine production of ecosystem services like species diversity, climate regulation, and food production [41,44,45]. An overview of linkage between ecosystem services and landscape features is given in Table 3.

At catchment and landscape scale, the river ecosystem is interconnected by blue water (liquid water) and green water (water vapor) flows which contribute to the biophysical processes that generate ecosystem services [46,47]. Both blue and green water contribute to the consumptive use of water. The consumptive use of blue water withdrawn from reservoirs, river streams, or groundwater in the form of irrigation, water supply for domestic and industrial use is always highlighted as provisioning services in ecosystem service research. The consumptive use of green water, which flows back to the atmosphere in vapor form, contributes towards ecosystem resilience and the generation of ecosystem services in the long run and at large spatial scales [22]. The ability of ecosystem processes to modify the available water flow is essential to produce ecosystem services [22]. The interconnections between climate, topography, vegetation, and soils lead to the spatial distributions of soil moisture, evapotranspiration, and vegetation within the basin [31]. Patterns of plant rooting depth bear a strong topographic and hydrologic signature at landscape to global scales [48], which control the distribution of the total soil water content and soil losses, including leakage and runoff [31]. Therefore, water plays a crucial link between hydrological and biogeochemical processes through its controlling influence on regulating ecosystem functions like transpiration, runoff generation, carbon assimilation, and nutrient absorption by plants.

The capacity of ecosystem functions to provide ecosystem services is thus a result of interactions between various geomorphological, hydrological, and ecological processes over multiple spatial and temporal scales [44]. It may be physical (e.g., bioremediation), chemical (e.g., mineralization, calcification), or biological (e.g., photosynthesis, larval dispersal). For example, the ecosystem functions of primary productivity help in maintaining species diversity, which in turn provides provisioning services of food and raw materials. Similarly, the sediment stability functions of ecosystems support sediment transfers in river channels from upstream to downstream. This sustains soil productivity and food productivity for human beings.

Table 3. The matrix linking ecosystem services with river landscape features. Source: adapted from Keele et al. [45].

Riverscape Feature/ Land Cover	**Provisioning**			**Regulating**			**Supporting Services**			**Cultural Services**		
	Water supply	Agriculture	Timber production	Flood mitigation	Climate regulation	Water quality	Soil formation	Habitat provision	Species diversity	Aesthetic	Inspirational/recreation	Educational
River width	🟩 ***							🟩 **	🟩 **			
Waterfalls										🟩 **	🟩 ***	🟩 *
Morphology				🟩 *			🟩 ***	🟩 ***	🟩 ***	🟩 *	🟩 *	🟩 ***
Weirs	🟩 ***							🟩 ***	🟩 ***			
Channelization and embankments				🟧 ***								
Land cover types												
Flood plain forest	🟩 *		🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***	🟩 ***
Riparian buffer		🟩		🟩 **		🟩 ***		🟩 ***	🟩 ***	🟩 **	🟩 **	🟩 *
Agricultural land		🟩 *			🟧						🟩	🟩
Urban areas	🟩				🟧 **	🟧		🟧	🟩		🟩 ***	🟩 **
Dams and reservoir units	🟩 ***				🟧 **	🟧 ***		🟧 ***	🟩 ***	🟧	🟧	🟧
Urban areas	🟧 *					🟧 ***				🟧 *	🟧 **	🟧
Cultural heritage feature												

*** Strong evidence supporting linkages. ** moderate evidence supporting linkages. * weak evidence supporting linkages. 🟧 Negatively contribute to ecosystem service capacity. 🟩 Positively contribute to ecosystem service capacity.

4. Impact on Ecosystem Services

The anthropogenic modification of a river landscape on multiple spatial scales impacts the supply of ESs, posing a threat to human well being. Hydrological alterations that result from the provision of water to developmental activities have changed the ecosystem structures and processes of river flows [49]. The social and ecological impacts of hydrological alterations caused by dams were widely reported [11,13,14,50]. The remainder of this section investigates ecohydrological or geomorphological changes in connection with ecosystem responses to anthropogenic modifications of river landscapes on various scales, and how this affects ES production (Table 4).

4.1. Inter-Basin Water Transfer

On a catchment level, there are numerous examples of global anthropogenic modifications in the form of inter-basin water transfers, especially in Australia [51], the USA [51], Asia [52], and South Africa [53]. Inter-basin water transfers redistribute water resources from water-abundant regions (donors) to water-short regions (recipients) to alleviate water shortages and facilitate developmental activities in the recipient basin [54,55]. Vast engineering structures on both sides of the conveying channel system cause changes in geomorphological features e.g., channel geometry, channel width, and sedimentation and siltation problems [56]. This further causes stream-flow reduction in both donor and recipient streams, which decreases water availability [57], negatively impacting the riverine ecology and fisheries [58,59]. It modifies habitat environments and provides pathways for the invasion and establishment of exotic species [60]. For example, the number of migratory salmon was reduced after the implementation of the central valley project in the United States as it blocks the downstream movement of fish. [51].

4.2. Changes in Land-Use Patterns

Change in land use and land cover due to urbanization, deforestation, and agricultural practices have impacted the water balance. Expanded impervious surfaces, compaction, and soil modification resulting from urban development such as parking lots, roofs, sidewalks, and driveways can have enormous repercussions on the hydrologic cycle and corresponding water quality [61,62]. Deforestation is also one of the most evident forms of anthropogenic impact on land surfaces [63]. It affects the microclimate on a regional level, impacting precipitation and evaporation, therefore altering runoff patterns [15]. The impact of land-use/land-cover changes may not be visible in the short term, but long-term impact has been observed [64] to decrease the value of regulating services [65].

4.3. Subsurface Modification and Tunneling Work

Impact-assessment studies on subsurface anthropogenic modifications and tunneling work on aquifer hydrogeology are limited, but have gained much attention [66–68]. Subsurface modifications include mining activities, tunnel excavation for metro lines, underground thermal-energy storage (UTES), and gas pipes, and create hydrogeological barriers to natural groundwater flows [66,69,70]. Human-made, highly connected subsurface pathways like sewer pipes, potable water pipes, and stormwater infiltration channels [71,72], known as "urban karsts", impact groundwater hydro-geomorphological processes that deteriorate groundwater quality by contaminating adjacent surface and groundwater bodies [72–74].

4.4. Groundwater Abstraction

Another important type of subsurface modification is groundwater abstraction. Globally, around 38% of irrigated areas are groundwater based [75]. The excessive abstraction of groundwater results in widespread decline in groundwater storage, which not only affects the water supply, but also accelerates saltwater intrusion and causes land subsidence [76,77], impacting water availability in the long run. Abandoned open-cast mines alter hydrological watershed processes by decreasing annual surface flow and water yield because of surface-soil disturbance and the accumulation of surface runoff in large depressions [78,79].

Table 4. Impact of anthropogenic modifications on ecosystem response concerning ecosystem services (ESs).

Modification Types	Eco-Hydro-Geomorphological Changes	Ecosystem Response	Affected ES
Catchment scale			
Inter-basin water transfer	Change in channel and width River erosion and land inundation,	Stream-flow reduction [56,57]	Water availability
	Exchange of aquatic species	Reduction of native species [51,60,80] Loss of aquatic diversity [55,58,59,81] Homogenization and bioinvasion [82]	Species diversity
Landscape unit scale			
Land-use impact	Low evapotranspiration and precipitation	Altered runoff patterns[15,83,84]	Micro climate regulations
	Surface-soil erosion and increased surface runoff	Reduced infiltration and base flow [77,85–87]	Groundwater recharge
	Discharge of agricultural contaminants	Stream-flow contamination [88]	Water quality
	Loss of riparian zones	Reduction of wetland areas [89]	Wetland productivity
	Loss of swamps and marshy areas	Loss of habitats [90,91]	Species diversity
	Loss of forest areas	Altered surface runoff[61]	Soil formation
Subsurface modification	Hydrological barriers to natural flows	Decreased infiltration[67,68]	Groundwater recharge
	Subsurface-soil disturbance and runoff accumulation in large depressions	Altered annual surface flow [78,79]	Microclimate regulations
	Discharge of urban-karst contaminants	Water contamination [72,73]	Water quality
Groundwater abstraction	Increase in saltwater intrusion	Decreased water productivity[92–94]	Water supply
	Land subsidence	Water unavailability [76,95,96]	Water supply
	Flow reduction in natural springs	Impact on groundwater terrestrial ecosystems [97]	Species diversity
	Reduced stream flow	Fish assemblage and habitat availability [98–100]	Species diversity
Segment scale			
Stream channelization	Bank erosion and changes in nutrient concentration	Decreased water productivity [101–104]	Water supply
	Heterogeneity of river-bed substrates	Impact on aquatic organisms[105–107]	Species diversity
	Changes in flow velocity and hydropeaking	Impact on riparian micro invertebrates [79,106,107]	Species diversity
Damming	Changes in flow regimes	Decline in fish abundance [108–110]	Species diversity
		Decrease in aquatic flora and fauna[111–113]	Species diversity

Table 4. *Cont.*

Modification Types	Eco-Hydro-Geomorphological Changes	Ecosystem Response	Affected ES
	Conversion of lotic to lentic environment	Growth of exotic species [30,114]	Species diversity
	Salinization and water logging	Water quality[48,115]	Species diversity
	Fragmented habitats	Phytoplankton composition [116]	Species diversity
		Zooplankton diversity [117]	
	Change in sediment transportation	Nutrient fluxes and biogeochemical cycle [118,119]	Microclimate regulations
		Greenhouse gases (GHGs) [120]	
	Loss of connectivity with deltaic and riparian zones	Loss of riparian and aquatic vegetation[121,122]	Species diversity
		Reduction in agricultural productivity [114]	Food production
		Obstructed fish migration [123]	Species diversity
		Aquatic food webs [86,124]	Species diversity
		Aquatic breeding habitats [125–127]	
Reach scale			
Sand mining	River-bed stability and bank erosion	Loss of productive cultivation areas [92,128]	Food production
	Sediment deposition	Loss of deep pools [129,130]	Species diversity
		Impact on food webs [131,132]	Species diversity
	Changes in sediment composition	Impact on benthic communities [133]	Species diversity
	Bathymetric changes	Changes in water levels [134,135]	Water availability

4.5. Damming

On the segment scale, the construction of a dam across a river converts a river segment of a natural watercourse into stagnant water [30]. The lacustrine environment of impoundments reduces the habitat availability of species dependent on riverine-forest and riparian ecosystems [122]. Changing water levels upstream creates unstable habitat conditions that disturb the life cycle and reduce the growth rate of aquatic species [136]. Consequently, species diversity is altered, which impacts provisioning services. Sediment depositions downstream directly impact channel morphology in the form of width narrowing, channel deepening, and arresting flow within the channel [137]. This further impacts the water quality and composition of biotic communities, which influences supporting and regulating services. River damming also impacts the functions of the nutrient and biogeochemical cycle by changing the composition of silica and carbon cycles [118].

4.6. Stream Channelization

Similar to damming, stream channelization alters the landscape by cutting and dredging sediments. Small streams are widened and straightened for agriculture and water conveyance, whereas large rivers are modified for navigation, flood control, and floodplain development. Stream channelization impacts the fluvial geomorphology, energy conditions, and sediment-transport potential of rivers, making the modified channel unstable, which aggravates bank erosion [138,139]. It also alters the nutrient dynamics of river-flow regimes by decreasing nutrient concentrations and other biologically reactive solutes that regulate ESs by stimulating primary production, thereby affecting water quality and ecosystem health [101,140].

4.7. Sand Mining

Urban expansion and infrastructure development have led to increased mining activities [141,142]. The indiscriminate mining of sand and gravel from river beds, inland dunes, and floodplain areas has caused extreme damage to river-basin environments and their ecodiversity [141]. In channel sand mining significantly impacts channel morphology [18,143,144]. On the reach scale, sand and gravel mining over the deposition rate results in low infiltration and excessive riverbank erosion, which affects sediment transportation [144]. The rapid extraction of sand and gravel from riverbeds also influences hydrological processes by increasing evaporation rate and reducing groundwater recharge, leading to the failure of irrigation wells in surrounding areas [144]. Thinner superficial fluvial layers in mining areas, as a result, often lead to lower longitudinal and lateral hydrologic connectivities [145]. Extensive sand mining places enormous burdens on fish habitats, migratory pathways, ecological communities, and food webs [131,132,141].

5. The Ecological and Socio-Cultural aspect of Ecosystem Services and Human Well Being

Many landscape modifications simultaneously interact, making it difficult to separately determine the impact of each. Such modifications have multiple effects on ES and human well being [141]. Landscape modifications cause multifaceted and overlapping forms of impact on hydrological, ecological, and geomorphological components of the river basin, bringing complex changes in ecosystem processes, and affecting ecosystem functions. These drivers can impact one or more ES, and lead to interactions between ESs [146,147]. For example, damming destroys ecological and social habitats upstream due to submergence; downstream, it impacts habitats by reducing flow towards wetlands and floodplains. Consequently, it leads to a decrease in floodplain productivity affecting food and raw-material supply to people [114].

Likewise, land-use/land-cover changes associated with agricultural practices [148], deforestation, and urbanization tend to decrease the infiltration rate of the land surface, which minimizes groundwater recharge and increases surface runoff. Simultaneously, such changes in land use reduce evapotranspiration, which affects microclimate regulation. Changes in land-use patterns accelerate the impact of climate change on ESs [149,150]. The combined effect of climate change and land use has significant inhibitory impact on ecosystem functions, like water retention, nitrogen export, and phosphorus export [150,151], which weaken ES production. The relative importance and combined influences of landscape modification also depend on spatial scale and landscape composition [150]. When regulating and supporting services are affected, this slowly influences the availability of provisioning and cultural services [152].

These interactions result in tradeoffs and synergies between ESs [147,153]. Tradeoffs between stakeholders on a spatiotemporal scale for river ESs are not independent, but instead exhibit complex interactions that depend on the nature of irreversibility of the ecosystem [146,154]. This creates imbalances between economic, ecological, and social–cultural ES uses, threatening the ecological and social integrity of the catchment in the long run (Table 5). For example, a study by [155] on tradeoffs between water use, food-security supply, and energy production for hydro-power projects in the lower Mekong basin concluded that the ecological cost (sediment/nutrients), social cost (loss of capture fisheries), and other mitigation costs were greater than the benefits from electricity generation, improved irrigation, and flood control, which are mainly economic-benefit-oriented (see also [104]). The high demand for provisioning services such as water supply, irrigation, and hydro-power deteriorates the integrity of ecological processes that affect river-basin regulatory and supporting services.

Table 5. Influence of river-landscape modifications on economic, ecological, and socio-cultural ES aspects. The signs (+) and (−) indicate positive and negative influence on ecosystem services, respectively.

Anthropogenic Modifications	**Ecosystem Services**		
	Economic	**Ecological**	**Socio-Cultural**
Inter-basin water transfer	Uninterrupted water supply for irrigation (+) Navigation (+)	Species diversity (−) Habitat provision (−)	Displacement (−) Livelihood (−) Tourism (±) Aesthetics (−)
Change in LULC	Urbanization (+) Living space (+) Agricultural use (+)	Microclimate regulation (−) Groundwater recharge (−) Floodplain connectivity (−) Habitat provision (−) Species diversity (−)	Livelihood (−) Aesthetics (−) Tourism (−)
Subsurface modifications	Urbanization (+) Living space (+) Transportation (+)	Groundwater recharge (−)	–
Groundwater abstraction	Water supply for industrial, domestic, and agricultural use (+)	Groundwater recharge (−) Saltwater intrusion (−)	–
Stream channelization	Irrigation (+)	Ag. productivity (−) Water logging (−)	–
Damming	Hydro-power (+) Irrigation (+) Water supply (+) Fisheries(±)	Fish migration (−) Sediment flow (−) Water logging (−) Water quality (−) Ag. productivity (−) Species diversity (−) Floodplain connectivity (−)	Flood control (+) Displacement (−) Livelihood (−) Tourism (±) Aesthetics (−)
Sand mining	Input material for construction (+)	River-bed instability (−) Bank erosion (−) Soil formation (−) Groundwater recharge (−) Species diversity (−)	Aesthetic (−)

Landscapes are the signatures of ecological, economic, social, and cultural interactions [156,157]. The modification of river landscape impacts the landscape features having prime importance in the life of the indigenous people and riparian population [156,157]. The religious belief, folklore, customs, and traditions of these people are closely entwined and are influenced by riverine landscapes.

The power matrix of the stakeholders plays an important role in utilization of ecosystem services. Grimble and Wellard [158] define stakeholders as all those who affect or are affected by the policies, decisions, and actions of the system. They can be individual, communities, social groups, or institutions of any size, aggregation, or level in a society (Figure 4). Some stakeholders, which include institutions, government agencies, and policy makers, have more power to carry out modifications on river landscape compared to stakeholders having low power in the matrix (e.g., fishers, indigenous people, local people). River water diverted by influential stakeholders may obstruct the freely accessible benefits (e.g., livelihood, tradition, and aesthetics) of less powerful people [159]. Power asymmetries among stakeholders create social conflict and can affect stakeholders' well being. For example, the construction of dams for harvesting water for irrigation and hydro-power has resulted in the displacement of many people, especially marginal farmers, forest dwellers, riparian, and indigenous communities [50,160]. The livelihood support gradually declines due to displacement by dams resulting in shifting of the occupation and migration of the community [160]. Similarly, stream channelization and water diversion create conflicts between different upstream and downstream users [161]. Therefore, ecosystem service research should be informed with detailed understanding of linkages of ecosystem services with landscape signatures including socio-ecological interaction between them.

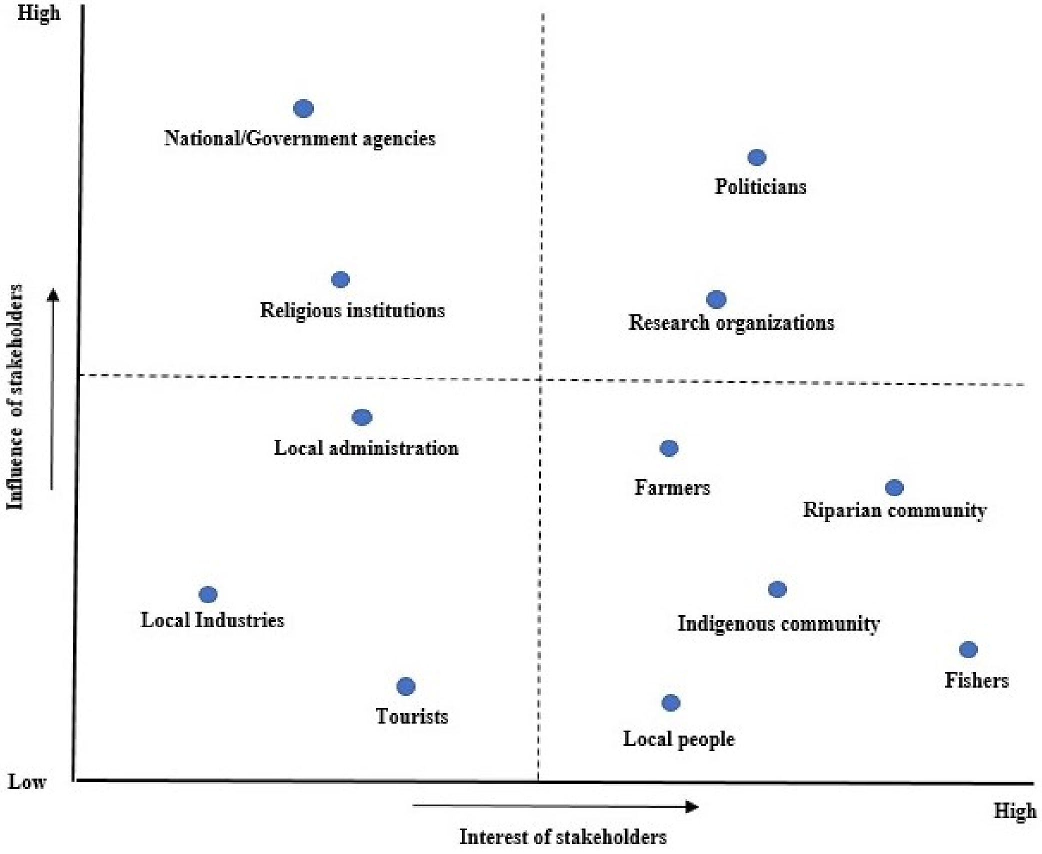

Figure 4. The influence–interest matrix of riverine stakeholders.

6. Emergent Challenges for Ecosystem Service Valuation

Anthropogenic modifications on river landscape are the result of divergent human preferences and choices by different stakeholders. The paper fills some knowledge gaps of biophysical linkages of river landscape and its importance in the delivery of ecosystem services. Understanding the critical linkages between river landscape and ecosystem delivery is crucial for ecosystem service assessment and can foster restoration strategies. Linking anthropogenic pressure, ecological status, and ecosystem services is important for holistic management of river ecosystem service [9,162]. In a monetary-based economy, so far, ecosystem service valuation acted as an important tool for ecosystem service assessment, but the framework is not able to quantify the ecological and social value of ecosystem services [21]. Therefore, further research needs to explore the value of ecosystem services not only based on monetary value but also the ecological and socio-cultural values should be given due consideration. Moreover, the trade-offs and synergies among river ecosystem services at spatial and temporal scales need to be investigated in detail. Ecosystem services are considered as a part of socio-ecological system; therefore, knowledge of relationships among ecosystem service at the landscape level is important to avoid unwanted tradeoff and to exploit synergies [146]. The goal of future direction in ecosystem service assessment should be to consider ecosystem services from the landscape perspective. It requires integration of various disciplines to understand landscape complexity and system response. Furthermore, the incorporation of stakeholders' participation, local knowledge, and locally spatial characteristics needs to be assimilated into the process of ecosystem service assessment in river basins.

7. Conclusions

Human interventions in the landscape are evident across river basins. Landscapes are experiencing significant changes challenging the ecological and social integrity of rivers. Our review demonstrated that ES quality and quantity largely depend on the effective functioning of biophysical processes, which are again linked with the geomorphological, ecological, and hydrological characteristics of river basins. The critical challenge is a more holistic representation of the river landscape in ecosystem service research which is constrained by the understanding of ecosystem structure and functions, and its relationship with ecological, economic, and socio-cultural values of ecosystem services contributing towards ecosystem resilience and sustainability [2,163]. This paper shows that ecosystem service research should be considered from a holistic landscape perspective. Ecosystem service assessment with greater sensitivity to the responses and the interaction between biophysical and socio-economic processes could help water managers and researchers striving for a welfare-maximizing equilibrium between demands for river-based ESs and modifications of river landscapes without damaging the structural and functional connectivities of the river basin.

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