

Review

Application of Ecological Restoration Technologies for the Improvement of Biodiversity and Ecosystem in the River

Pushuang Li ¹, Dan Li ^{2,3,*} , Xiaoqing Sun ¹, Zhaosheng Chu ³, Ting Xia ² and Binghui Zheng ^{3,*} 

¹ College of New Energy and Environment, Jilin University, Changchun 130021, China; lips8541@163.com (P.L.); sunxq13@jlu.edu.cn (X.S.)

² College of Urban Construction, Nanjing Tech University, Nanjing 211816, China; xiating@njtech.edu.cn

³ Environmental Standards Institute of Ministry of Ecology and Environment of the People's Republic of China, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; zhaoshengchucraes@163.com

* Correspondence: lidan01@njtech.edu.cn (D.L.); zhengbinghui@craes.org.cn (B.Z.);
Tel.: +86-182-171-912-62 (D.L.)

Abstract: With global warming, urbanization, and the intensification of human activities, great pressures on river ecosystems have caused ecosystem degradation, the decline in habitats and biodiversity, and the loss of function. Ecological restoration technologies (ERTs) in rivers are effective measures for improving habitat and biodiversity, which has the advantage of recovering ecosystems and biodiversity and promoting the formation of healthy rivers. Several applications of ERTs, including ecological water transfer, fish passage construction, dam removal/retrofit, channel reconfiguration, river geomorphological restoration, natural shoreline restoration, floodplain reconnection, revegetation, etc., are summarized. The classifications of ERTs are highlighted, aiming to distinguish the difference and relationship between structure and the processes of hydrology, physics, geography, and biology. The pros and cons of these technologies are discussed to identify the applicability and limitations on the river ecosystem. In the dynamic processes in the river, these interact with each other to keep ecosystem balance. ERTs are more helpful in promoting the restoration of the natural function of the river, which contribute to the management of river ecological health. Some proposals on river management are suggested. Establishing a unified river health evaluation system will help promote positive feedback on rivers and the further development of ERTs.

Keywords: ecological restoration technologies; function; biodiversity; ecosystem; habitat



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1. Introduction

Global climate changes, urbanization, and environmental pollution have caused tremendous pressure on river ecosystems [1]. Increasing water scarcity and water pollution have led to shrinking river habitats, declining biodiversity, and deteriorating ecosystems. Consequently, the degradation, damage, and destruction of the structure, functions, and biotic integrity of river ecosystems increase the health risks to the water security [2–5]. Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed [6]. Technologies referred to the ecological restoration in the river are imperative to improve river habitat and biodiversity, and recover river ecosystem functions [7,8].

As a “four-dimensional” comprehensive ecological system in vertical, horizontal, spatial, and temporal aspects, the river system has various functions (Figure 1), such as self-purification, rainwater storage, flood regulation, and shipping [9,10]. The river ecosystem contains many processes and can provide substances, energy, and ecosystem values for human beings. As a geographic landscape, the river changes with history and can derive ecological service value, social service value, leisure value, cultural value, and aesthetic value. The resilience of its ecosystem depends on several processes such as hydrology, geomorphology, biogeochemistry, biology, ecology, and the corresponding

circulation processes of water source, substances, and ecology in the catchment [11,12]. Biogeochemical processes affect substance circulation and then change the water quality. The interrelationships present synergistic effects among influencing factors, including climate, river geomorphology, hydrological conditions, hydraulic characteristics, biogeochemistry, etc. The climatic and hydrological conditions mainly affect the ecological processes, the structure, and function of the river system on the river basin scale, while the river geomorphology, the hydraulic characteristics, and the biogeochemistry have a significant impact on the ecosystem diversity and integrity of small-scale river sections and corridors [13–15]. The geochemical properties of rivers make different processes have spatial effects on different scales.

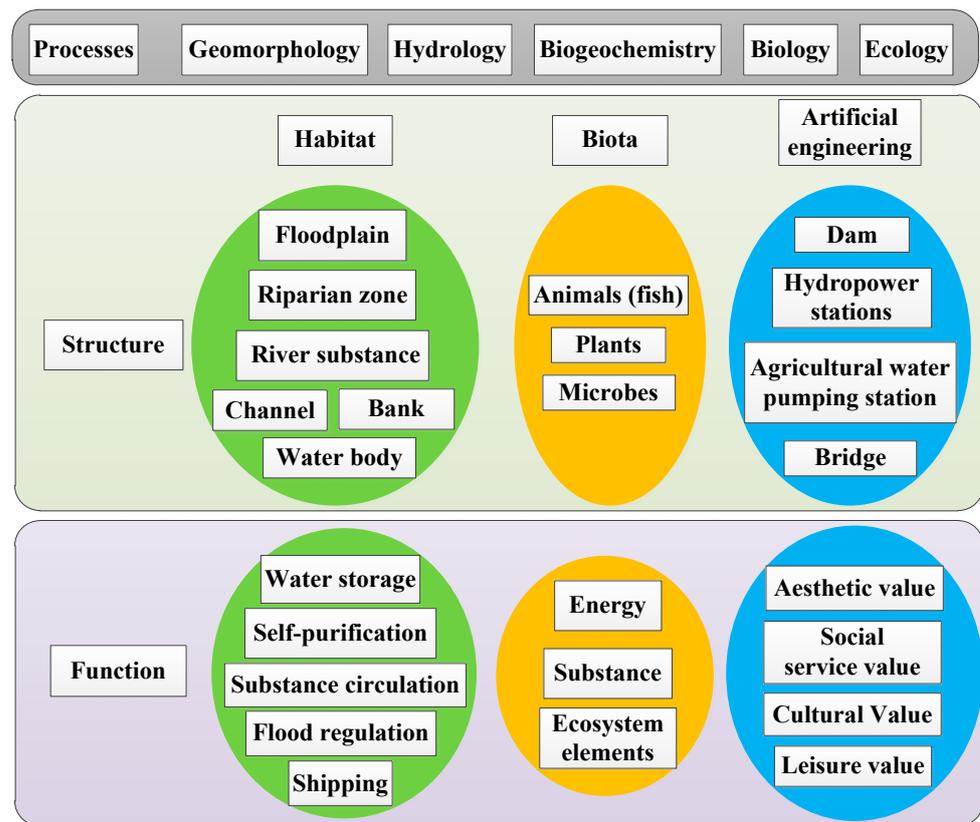


Figure 1. Processes, structures, and functions of the river. Processes are associated with physical, chemical, and biological processes in the river. The structure is linked with the composition of the river. The function is the use the river provides for human beings or society.

Over the past one or two hundred years, large-scale artificial “over-engineering” treatments, including embankment, dam construction, channelization, and bend straightening of rivers have been carried out [16–18]. Dam construction or hydropower stations hinder the connection of the upstream and downstream of the river, resulting in the obstruction of river habitats and unfavorable impacts on river biodiversity. The straightening of the river flow path reduced the surface area of the river and destroyed the natural form of the river, affecting the ecological flow. Increased demand for agricultural irrigation through agricultural water pumping stations also shorted the river flow. All of them brought out the loss of biological habitats and affected the growth of animals, plants, and microbes [19,20]. In addition, the urbanization and hardening of banks or channels reduced the area of riparian zone and floodplains, made rivers lose ecological resilience, and weakened their functions. The development of cascade power stations damaged the habitats of major fish, and consequently species resources declined [21–23]. The channelization of rivers destroyed the living environment of animals and plants and caused the ecological imbalance of the river

system. Eutrophication of river water, including degradation and disappearance of the river, was the malignant consequence of the above results, so that river health and the safety of water quality are undergoing serious threats.

With the demand for the balance of the river ecosystem, ecological restoration technologies (ERTs) in the river came into being. The exploration of 'River Restoration' originated in developed countries in the last century. 'Ecological Engineering' was used to restore the natural form, ecological function, and processes of the river [24,25]. Currently, the ERTs include ecological water transfer, fish passage construction, dam removal/retrofit, river geomorphological restoration, floodplain reconnection, revegetation, etc.

This study focused on investigating the characteristics of these technologies and in-depth understanding of the engineering effects of their applications, aiming to identify the pros and cons of these technologies, explore the applicability and limitations on river ecosystem, clarify the relationship between river ecological function and river restoration technology and provide technical support for the management of river ecological health.

2. Definition and Concept of Ecological Restoration Technologies in the River

Ecological restoration in the river is the process of recovering the degraded, damaged, and destroyed ecosystem of the river by restoring the ecological structure, function, and biotic integrity. Technologies were applied to recover water quality, habitat, biodiversity, and biotic integrity in the river, including engineering techniques or projects, methods, theories, management strategies, etc. [5–8]. Researches on ERTs are various and continues to deepen with the development and changes of rivers.

The earliest research on the ecological restoration of urban rivers started in Germany, Austria, and Switzerland. In 1938, the concept of "near-natural river management" proposed by Seifert, referring to a river ecological treatment plan that is close to nature, economical and practical, and maintains a beautiful appearance, marked the beginning of river ecological restoration [26,27]. In 1962, American ecologist Odum proposed the concept of ecological engineering that humans mainly used natural energy-based systems for environmental control. In 2003, the American Society of Civil Engineers [28] proposed that river restoration was an environmental protection measure for a nearly natural state of the river ecosystem restoration. The river ecosystem has sustainable characteristics, consequently promoting the value of the ecosystem and biodiversity.

Since the 1990s, China has gradually focused on developing ERTs. In 1999, the theoretical framework of "big water conservancy" emphasized that the development of the restoration in the river should take more consideration of the comprehensive watershed management on the integrated functions of water resources, environment, and ecology. The embryonic stage of the concept of ecological restoration in the river was from 2000 to 2005. However, the concept of "ecological hydraulics" demonstrated the shortcomings of water conservancy projects from the perspective needs of the ecosystem, and put forward engineering perspectives on a series of theories and methods [29]. The five-in-one theory of urban water ecosystem was composed of multiple processes, including water safety, water environment, water landscape, water culture, and water economy. Since 2005, ecological restoration projects in the river in China have rapidly been developing. Thus, the concept of ERTs in the river exhibits the typical characteristics of inter-discipline. In addition, if a natural river combines with a basin, it is necessary to consider the natural geographical characteristics of the watershed in the applications of ERTs in the river.

3. Factors Affecting River Biodiversity and Ecosystem

As one of the elements of geography, the natural properties of rivers are typically affected by environmental factors. Rainfall and evaporation significantly impact water flow into the river, affecting its hydrological conditions and hydraulic characteristics [30]. With the climate changes of global warming, the influence of natural factors cannot be ignored. Rainfall-induced runoff causes non-point source pollution and threatens the water quality of the river. Generally, non-point source pollution is linked with land use and human

activities in the catchment. The deterioration of water quality easily causes the growth of algal blooms. Algae consume a lot of dissolved oxygen, cause hypoxia in the water, and lead to fish death [31]. Preferable water quality is the basis for maintaining the diversity and integrity of river ecosystems and its ecological functions. The types of fish are linked with human fishing due to the high consumption of certain fish by humans. In terms of external interference, environmental factors and human factors affect river biodiversity and the ecosystem through direct and indirect effects.

In terms of the river system itself, a healthy river with rich biodiversity depends on the coordinated operation of multiple river processes and the stability of the structure, and then provides various functions for nature and humans. Intersection and integration effects among different processes caused the complexity of hydrological, chemical, ecological, and biological processes, thereby interacting with each other and affecting many factors. River geomorphology is associated with the shape of the river channel, riparian zone, bank, etc. These structures help create different micro-habitats and provide corresponding habitats for organisms and microorganisms [32]. Aquatic organisms, as the most important component of a river system, were linked with the health and diversity of the river ecosystem and affected water quality by multiple factors. However, the activity of aquatic organisms and microorganisms can react to water quality through processes such as the absorption, transformation, assimilation, and degradation of pollutants. Aquatic plants can increase the roughness of beaches through the blocking effect of stems and leaves, reduce flood discharge capacity, and affect sediment deposition, transportation, and evolution of river beds.

Various factors affect the complex processes of rivers, directly or indirectly impacting river biodiversity and ecosystem. The interaction between factors and processes has potential effects on river biodiversity and the ecosystem. ERTs based on hydrological, geomorphological, and biological processes are developed in large numbers. These artificial measures interfere with the processes and structure of the river. The near-natural restoration of the river affects the growth of river creatures, and consequently, the ecological succession of river creatures will improve biodiversity and the ecosystem. Finally, the interaction of artificial engineering and ecological succession determines the ecological development of near-natural restoration in a river system.

4. Classification of River Restoration Technologies

The practical exploration of river restoration has been widely carried out worldwide. ERTs are generally related to 'Ecological Engineering', aimed at achieving the natural form, ecological processes, and multiple functions of the river. The earliest practice of river ecological restoration was carried out in Germany in 1965 when Ernst Bittmann protected riverbank slopes with ecological reeds and willows along the Rhine [32]. Successively, there were the projects on 'multi-natural river ecological restoration', 'river renaturalization, 'giving space to rivers' performed in Netherlands, France, and Switzerland. In Asia, Japan took the lead on the River Restoration plan with their 'Multi-Natural Rivers Program'. A large number of ecological river restoration studies have been reported [33]. For example, Becker et al. [34] believed that the design of river restoration focused on establishing a meandering shape with a turning structure to strengthen the ecological environment in a river. Ecological restoration in the river should pay attention to imitating nature and maintaining nutrition and water circulation to improve the habitat quality of organisms and the biodiversity of species.

ERTs include dam removal/retrofit, fish passage construction, ecological water transfer, floodplain reconnection, stormwater management, natural shoreline restoration, instream species management, bank stabilization, revegetation, corridor restoration, channel reconfiguration, habitat improvement, etc. [35,36]. These technologies applied in engineering are referred to as restoration projects. They are very comprehensive and systematic, are linked with many aspects of water quality and hydrological processes, land use in the catchment, topography, bio ecology, and even have entertainment, economics, and cultural

aspects [37–39]. According to the survey, some links between the structure of the river and river restoration technologies exist, which also illustrated that the processes’ interactions are typically key features in the river system. Herein, the classification of different restoration technologies is proposed (Figure 2). Thus, the ecological impacts of river restoration technologies on rivers are so various that critically identifying characteristics of river restoration technologies is the key to river restoration.

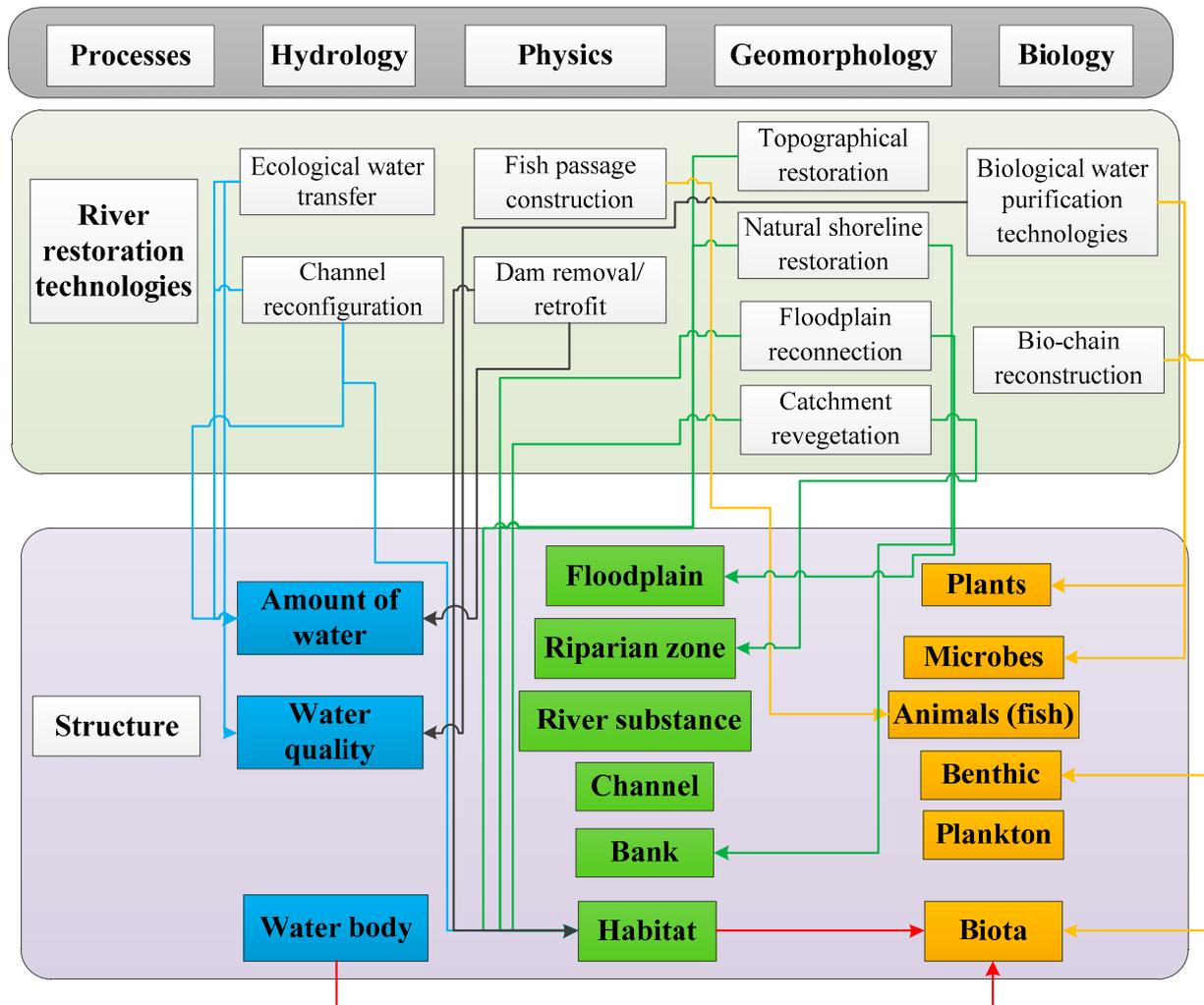


Figure 2. The classification of different restoration technologies.

4.1. Hydrological Technologies

4.1.1. Ecological Water Transfer

Urbanization and pollution increase seriously threaten the health of the river. Safe water quality is required for the growth of plants and animals. A water transfer project is one important measure of flow in the river, beneficial to improving water quality and environment carrying capacity. For example, the Yangtze River-Taihu Lake Water Transfer Project in Taihu Lake Basin was conducive to improving water quality [40]. However, long-term environmental flow modification disturbed the sediments and brought too much mud-sand into the lake, resulting in the release of phosphorus. So, the improvement of the water environment by ecological water transfer is time-effective.

Table 1 illustrates several rivers in different countries using eco-hydrological techniques. Weng et al. [41] presented that the water transfer project contributed to controlling salinity and improving the migration of fish and their eggs in the Yongjiang River Basin. The survey about ecological water transfer in the Yellow River Basin showed that eco-

hydrological technology was helpful for the growth and reproduction of fish, and the reproduction and population structure of fish [42]. The Three Gorges Project is by far the largest hydropower station. After its completion, it had a great impact on the water ecology in the catchment, especially the hydrological conditions of its upstream and downstream. From 2012 to 2014, the Three Gorges Reservoir implemented four experimental environmental flow modifications. The monitoring results of fish resources, hydrology, and water environment processes showed that flow modification played a certain role in promoting the natural reproduction of the four major home fishes [43,44]. Environmental flow modification may reduce the impact of the hazards of the Three Gorges Reservoir. However, Kuriqi et al. [45] found a rain-flood state with high environmental flow modification in winter is detrimental to fish habitats and the different life stages of fish in the Ocreza River in Portugal. Nonetheless, reasonable human intervention may reduce the impact of its natural hazards on the Ocreza River. The effects of ecological water transfer on the river fish are two-sided.

Zhang et al. [46] illustrated that the water transfer project in the Hei River Basin promoted the riparian restoration and rehabilitated the degraded habitat downstream, while the groundwater level dropped by about 5.8 m, and the river vegetation was degraded in the middle reaches. The different effects of ecological water transfer on the upstream and downstream illustrated that environmental flow modification had great limitations on the long-term sustainable development of the river.

Sun et al. [47] established a dynamic model for the ecological water replenishment and groundwater of the Yongding River in Beijing. Ecological water replenishment was conducive to the increase of groundwater levels. The rise of groundwater levels can impact the growth of ground plants. The ecological water Diversion Project also has a potential effect on the water quality of groundwater because of the exchange of different water sources [48].

Table 1. Application of hydrological technologies in different areas.

	Pros	Cons	Name of Rivers	Locations	References
Ecological water transfer	Promoting the exchange of energy and material, improving hydrological conditions	Great human disturbance resulted in uneven distribution of upstream and downstream and other pollutants input.	Heihe River	China	[46]
			Ocreza River	Portuguese	[45]
			Yongjiang River	China	[41]
			Three Gorges	China	[43]
Channel reconfiguration	Ensuring river connectivity, provide fish migration channels to protect biodiversity	Limited space cannot meet the needs of all fish.	Ahr River	Italian	[49]
			Trebbia River	Italy	[32]
			Lahn River	Germany	[50]

With climate change, many rivers have dried up. The ecological water transfer in the river has a great impact on the biodiversity of species. Ecological water transfer can effectively ensure the river's ecological flow and contribute to fish diversity. Ecological dispatch is a double-edged sword, which was helpful for the exchange of material between different water sources and the improvement of the water environment. However, this application of engineering will also bring negatively potential environmental impacts in the long-term run. Environmental hazards include water erosion, sediment transport, pesticides, harmful substances, and heavy metals.

4.1.2. Channel Reconfiguration

Channel reconfiguration is one important river ecological engineering measure. Channels in the river provide the available function for shipping. However, the sediment deposition and narrowed river caused the degradation of habitat, the decline of functions, and the loss of diversity, which threatened the health of the river ecosystem. The reconstruction and reconfiguration of the river channel is one vital way to restore the river's health.

In Campana's [49] study, since the 1960s, the Ahr River has experienced a narrowing of the river course, disconnection of the floodplain, river degradation, etc. Elevation reconstruction and shape restoration were carried out to realize the widening of the river course. River width adjustment, changes in sediment matrix, and floodplain reconnection in the Trebbia River helped restore river geomorphology [32]. Groll [50] confirmed that the section of the Lahn River with ecological restoration had better biodiversity and diversified habitats than the section without ecological restoration. Previous studies have shown that even in undisturbed rivers, various degrees of change always happens in habitat and biological succession over time and climate. Thus, using natural law to restore river functions is a difficult problem for river ecological restoration.

4.2. Physical Infrastructure Projects

4.2.1. Fish Passage Construction

The dam construction on the river hindered the connectivity of the river, blocked the links of the water environment between upstream and downstream, cut off the migration path of aquatic animals such as fish, and not only affected the hydrological environment but even influenced the local water temperature of the water column (Table 2). Frequent human activities aggravated the changes in aquatic habitats, caused great effects on the living environment of fish, severely restricted the growth and reproduction of fish and their populations, and resulted in the decline of biodiversity and ecosystem functions. The migratory characteristic of fish is their typically natural habit. However, the establishment of dams made many kinds of fish lose their migration channels and affected their growth habits [51]. The drastic changes in aquatic habitat caused some fish to die out, which seriously affected the ecosystem and biodiversity of the river. Fish passage construction provides migration channels for fish and promotes the protection of biodiversity, which also contributes to the connectivity of rivers [52].

Table 2. Advantages and Limitations of different physical infrastructure projects.

	Advantages	Limitations	Name of Rivers	Locations	References
Fish passage construction	Ensure river connectivity, provide fish migration channels and protect biodiversity	Space is limited and cannot meet the needs of all fish	Yanglong River	China	[51]
Dam Removal/Retrofit	Contribute to the reduction of water temperature, can cope with climate change, the river expansion, restore the natural circulation of the river, increase water environment carrying capacity, and biodiversity	Bring disturbance to the sediment, and the recovery period is too long.	Wuling Basin	China Taiwan	[1]
			Elwha River,	USA	[53]
			Wisconsin's river US	USA	[54]

Concerning the technologies of fish passage construction aimed to help fish shape migration channels, the following several principles were proposed: understanding the requirements of the project, applying the existing design and specifications, increasing the knowledge of fish, and ensuring controllable space. However, due to the limitations of the artificial design of fish passages, its function cannot meet the unique habits of each fish and all requirements of various fish. To satisfy the increased material growth needs of human beings, more and more hydropower stations are constructed on the river, which greatly changes the hydrology and water environment. In such circumstances, the construction of fishways contributed to protecting the interests of some fishes, alleviating the negative impact of human activities, and promoting the biodiversity of the damaged river.

4.2.2. Dam Removal/Retrofit

The United States started to dismantle old weirs and dams to restore river ecology in the 1990s. A total of 168 dangerous dams on small tributaries were demolished from 1999 to

2003. After the dams were demolished, the ecological environment of most rivers got well restored and improved, especially fish migration channels and living environment. So far, about 500 dams (weirs) have been demolished. Battle et al. [1] confirmed that when dam removal, the flow path of the upstream and downstream rivers reconnected, enhancing the river expansion and water environment carrying capacity.

The decrease in water temperature in the Wuling Basin after the removal of the dams indicated that the river connection through dam removal/retrofit was conducive to coping with climate change, regulating water temperature, maintaining biodiversity, and even the growth of salmon [1]. However, after dam removal/retrofit, the habitat restoration takes a long time, and it may not be able to restore the original state [53,54]. The dam removal/retrofit also causes disturbances and releases nutrients at the interface between water and sediment, affecting the water quality and even the ecology of the river, which could explain the reason why the ecological restoration and biodiversity of the river through dam removal/retrofit takes longer to recover [55]. Generally, in practice, some other restoration technologies for recovering basic functions and accelerating the self-repair capacity of the river channel are almost simultaneously carried out along with the dam removal/retrofit.

4.3. Ecological Geomorphological Restoration

4.3.1. Topographical Restoration

The natural river ecosystem is linked with the interaction effects of ecology, hydrology, and geomorphology. River geomorphology associated with geography affected water flow and provided various habits for the organisms. When carrying out river ecological restoration, understanding the gap in knowledge of ecology, hydrology, geomorphology, and the relationship between them was notable [22,56]. Traditional river restoration projects focused on specific species recovery and habitat reconstruction. However, this often overlooked the processes of the formation of river geomorphology, so the restoration plans cannot be self-sustained. Some river geomorphological technologies are shown in Table 3. With the continuous development of geomorphology, more and more techniques are used for river restoration. For example, Langat et al. [57] found river geomorphology was closely related to river biodiversity and riparian vegetation in the Tana River Basin. The topography changes affected river flow, sediment migration and transformation, and boundary conditions of the river bed. Different landform environments of geomorphology create different suitable habitats for the growth of various organisms, such as aquatic plants, animals, benthic organisms, microorganisms, etc. The geomorphology of the river is also associated with the biogeochemical process of the materials, plays an important role in the circulation of energy and materials, and affects the ecology and diversity of the river. For example, the influence between surface water quality and groundwater quality in the section with large curvature is greater compared with that in the straight section of the river [58,59]. Thence, ecological restoration should consider the impact of river geomorphology.

4.3.2. Natural Shoreline Restoration

Natural shoreline restoration is one part of river geomorphological restoration. The hardened channel along the water shoreline made the river lose its natural attributes and deprived the creatures of their habitats in the coastal zone. Following the formation conditions of natural geomorphology is conducive to restoring natural shorelines. From the perspective of the urban landscape, riverside vegetation is necessary for maintaining the meandering river flow path, which is conducive to the stability of the riverbank and provides a habitat for aquatic animals [60]. Thus, diverse modern elements and the needs of ecological tourism were incorporated during the restoration of the river bank. Many walking passages, rest areas, and viewing areas were established to achieve socioeconomic value, promoting the balance between riverbank restoration and the ecological corridor of tourism development [61]. Natural shoreline also has a preferable buffer function, an

important part of the riparian buffer zone. The connectivity processes between land and water depend on restoring natural shorelines. The permeable revetment project was the key to constructing natural shorelines conducive to creating a favorable growth environment for the organisms. Plants are key elements of the natural shoreline. A three-dimensional natural plant shoreline on both sides of the river composed of trees, shrubs, and grasses was conducive to the continuity of the ecosystem between the water and land. It could also form unique hydrological, physical, chemical, and biological processes that contribute to the growth of different aquatic species [62]. Hence, using a multifunctional ecological embankment and planting large aquatic plants to shape the natural shoreline and construct buffer zones had much more advantages compared to other embankments with permeable material. These plants (reeds, cattails, wicker, etc.) formed a plant grid and ecological slope protection. Furthermore, these plants create a fantastic landscape effect and can regulate the local climate [63]. Chen & Hou [64] found that the shoreline restoration of the Yangtze River helped construct the riverside buffer. The vegetation, natural shoreline, and connected wetland systems are healthier than the bare bank. Thus, the shoreline restoration in a river basin should consider the condition of riverbank vegetation and stability of the bank slope.

4.3.3. Floodplain Reconnection

Riparian areas are generally associated with wetlands, floodplains, and vegetation. Floodplains characterized by carbon storage, purification, and regulation, are an important component of the river. Some infrastructures, such as artificial dikes, canals, gravel dredging, and flow regulation systems, easily cause the horizontal disconnection of river floodplains. The reduction of floodplain hinders the connectivity of the river and also reduces floodplain productivity, nutrient exchange, and the spread of biota between rivers and floodplain wetlands [65]. Pander [66] confirmed that the expansion of the original floodplain of the Danube River in Europe was conducive to the recovery of fish, especially endangered fish, and the self-healing of the floodplain. According to the simulation result on the Tisza River in Europe, Guida et al. [67] found the reconstruction and reconnection of floodplains promoted the restoration of estuaries and riparian wetlands, as well as the reduction of flood peaks, and enhanced the buffering capacity of the river regarding floods. Singh et al. [68] confirmed that floodplain reconnection contributed to the increase of benthic biodiversity. Addy & Wilkinson [69] also proved that floodplain reconstruction achieved the reconnection of river and wetlands, helped to enhance the geographic and hydrological functions of the river, and improved the water storage capacity of the river and its resistance to floods. Floodplains could become good seedbanks with the transportation of water, atmosphere, migratory birds, and fish, which help vegetation grow in non-flooded areas and favor different habitats on vertical gradients when flooded. Hence, the macroscopic ecological effect came into being with floodplain reconnection.

4.3.4. Revegetation

The restoration of river plants and riparian plants can reduce soil erosion, increase the water storage capacity of rivers, improve the connection between rivers and groundwater, improve the biochemical and non-biochemical functions of rivers, and ultimately enhance ecosystem services, such as biodiversity, habitat, and entertainment [70]. Hu et al. [71] found that ensuring continuous river flow is the key to restoring river vegetation during their study of the inland river network in northern China. In recent years, ecological restoration projects in the Yellow River basin were carried out to enhance the vegetation coverage, but plant absorption and transpiration caused a lot of water loss from the sediment, exacerbated the water shortage, and resulted in the unsustainability of revegetation. Hence, revegetation restoration requires adequate water resources.

Table 3. Advantages and Limitations of different ecological geomorphological restoration.

	Advantages	Limitations	Name of Rivers	Locations	References
Topographical restoration	Contributing to navigation, enhancing river morphology restoration, increasing diversity of habitat	Impacting benthic habitats, controversial morphological theory limited the engineering applications.	Tana River	Kenya	[57]
Natural shoreline restoration	Restoring the riparian buffer, natural geomorphology, reconnecting the terrestrial and water ecosystem	Limited buffering effect and poor purification function	Yangtze River	China	[64]
			Tarim River	China	[60]
Floodplain reconnection	Enhancing the resistance capacity against flood, reconstructing damaged wetlands and biodiversity	Great investment, taking effect slowly, occupying a large area, difficult to manage.	Danube River	Europe	[66]
			Tisza River	Europe	[67]
			Mad River	USA	[68]
			Dee River	UK	[69]
Vegetation restoration along the riverbank	Recovering river function, reducing soil erosion	Plant growth requires a large amount of water and a high groundwater level.	Tarim and Hei river	China	[72]
			Tarim River	China	[60]
			Rhône River	France	[70]

Yu [60] found that the vegetation coverage of the dominant species *P. euphratica* in the Tarim River increased, but natural reproduction of seedlings did not occur. *P. euphratica* seeds were not easy to germinate, and the seedlings had difficulty surviving. The restoration of vegetation was also closely linked with soil moisture, groundwater level, and water circulation in the basin. The above analysis proved that vegetation restoration required a good supply of water resources. Revegetation along the riverbank, similar to floodplain restoration, was also an important technology for mitigating river degradation and maintaining river functions [72].

4.4. Biological Restoration

4.4.1. Biological Water Purification Technologies

Water quality is one of the most important indicators of the ecological health of the river. Ecological purification technologies to improve water quality attracted much attention in river restoration. Some in-situ technologies have also been used for river rehabilitation to keep a fine water environment and habitat for the river. For example, combination technologies (compound tower biological filter treatment process, five-level load reduction treatment process, the combination of floating islands with emergent plants, and ecological landscape restoration technology) were applied in Xiazhuangbang, Luoxi River, and Fenggou River. In addition, in-situ aeration is helpful in removing suspended matter, clarifying the water quality, and degrading the pollutants. The multi-stage series of constructed wetlands were established by combining different types of constructed wetlands to meet inflow fluctuations with complex water quality and hydrology in the Huai river [73]. The demonstration area of a multi-natural purification river was obtained through near-natural ecological reduction technology. Constructed wetlands were characterized by the function of purification, water storage, recycling wastewater resources, and diverse habitats, which is advantageous to the watershed ecology. Ultimately, such ecological engineering will affect the health and biodiversity of the river through the exchange of matter and energy between the river and constructed wetlands adjacent to rivers.

4.4.2. Bio-Chain Reconstruction

The integrity of the biological chain is an important indicator of river health. River comprehensive evaluation according to the ecological survey and biological indicators were used to diagnose problems of river health and ecosystem in a basin, which meet the

needs of current development [7,74]. Fish is an excellent biological index and can provide complete information about the ecological status of water bodies on various scales (regional or watershed scale) and even with different disturbances (organic and nutrient pollution, hydrology, or land changes) [75,76]. However, when the river was damaged, the river ecology was often out of balance, and large animals and plants gradually declined and seriously affected the integrity of the food chain. Therefore, ecological restoration based on the integrity of the bio-chain play a vital role in the sustainable ecosystem of the river.

The prohibition of fishing is an important way to promote the recovery of fishery resources. Breeding release is also a feasible measure for restoring the water ecological environment and biological populations. In addition, ecological water transfer also helps regulate the river environment and create suitable water levels and water conservancy conditions for the natural reproduction of fish [77]. These technologies provide specific measures for bio-chain reconstruction. In fact, the integrity of the bio-chain includes plants, animals, and even microorganisms. The ecological restoration project in the Huaihe River basin ensured the biological integrity by coupling algae, benthic organisms, and fish, which was conducive to maintaining ecological health and preserving water resources [78,79]. Aquatic or terrestrial animals and plants for the continuous integrity of bio-chain and revegetation in the permeable bank slopes were applied in the No. 4 River and Spoon River Project in Chenjia Town, Chongming, Shanghai, China [29].

5. River Management

The concepts of ERTs and management are interrelated. Generally, the theory of management contributes to identifying strengths and weaknesses in ERTs and enhances the improvement of ERTs. The management of ERTs plays an important role in improving river health. Taking into account the macro theory of managing the restoration in a basin is conducive to restoring the biodiversity in the river watershed. For example, the management model of ‘three-level control, three-level circulation, and three-level standards’ was targeted and developed in the typical polluted area in the Huai River. This aimed to purify, recycle wastewater resources and recharge river water resources for the severely polluted rivers with a shortage of baseflow. Various comprehensive targeted technologies in this model were developed. Finally, a set of in-situ water ecological restoration technologies and management strategies in the Huaihe River Basin were formed [80–82]. The division of the functional protected area and profile of protected species of mainstream fish (30 species) were proposed to ensure the integrity of the biological chain in the Liaohe River Basin of China.

The combination of different technologies in river management was used against one single technology, which contributed to the overall restoration and macro-control of the whole river ecosystem [83]. Several technologies, such as restoration of fish spawning sites, combined control technologies with hydrodynamic-water quality- aquatic organisms. Hydraulic regulation between rivers and lakes was used to recover the structure and function of ecosystems in the Dongjiang River basin in China [84]. Since the projects, aquatic community degradation has been effectively controlled, and biodiversity increased by 15–40%. The habitat restoration technologies in the main and tributary open channels were conducive to slope protection, revegetation, and buffer function in the riparian zone.

Many long-time follow-up investigations before and after the restoration technology should be highlighted in river management. These investigations are important to clarify the recovery effect of the technology, which is the basis for establishing a river health assessment system. Improving the evaluation system contributes to accurately identifying problems and promoting the optimization of technologies.

Due to increased human demand, drinking water safety has become increasingly prominent. Ecological technologies for improving self-purification performance in a river and the enhancement of environmental carrying capacity in a basin were highlighted in the global river governance and management. The interaction of river ecosystems and natural environmental indicators presents a great challenge for river management. With global

warming and the increase in rainfall, it is necessary to strengthen water storage resilience to resist continuous rain and flood. Multiple functions (e.g., unobstructed watercourse, clear water, green shore, rich fish, beautiful scene, and harmonious humanities) of a healthy river depend on the coordination and harmonious development of multidimensional processes, structure, and function. Perfect habitat structure, ecological flow guarantee, restoration of aquatic vegetation, and construction of an aquatic ecosystem are essential for healthy rivers. The diversity of the river ecosystem relies on friendly habitat conditions, so improving the natural habitat of the river and ensuring the needs of species survival is a prerequisite for multiple functions of rivers. The sustainability of the water environment and the rich biodiversity of aquatic organisms are typical signs of health in the river. The integration and perfection of multidimensional processes, structure, and function is the ultimate manifestation of ecological value.

6. Problems and Prospects

Due to the physical geographical properties of rivers, studies on ecological restoration at the basin level should be strengthened, and relevant technical standards and norms should attract more attention. The current studies have the following potential problems:

- (1) The systematic ecological monitoring system is imperfect, and the monitoring methods are difficult to be unified. Monitoring data such as fish, algae, benthic animals, habitat topography, and flow fields mostly relies on short-term measurements of scientific research, which is far from the conventional monitoring system [85].
- (2) The unified river ecological health evaluation system was almost unreported, which limited the development of management and the implementation of river ecological restoration. Although the biological indicator method can reflect the health of the river ecosystem, it is not enough to reflect the comprehensive health of the river due to limitations of the bio-chain [76].
- (3) Driving factors, mechanisms, and processes of the changes in the health of the mature river are not clear yet. The lack of long-term basic data, technical limitations, and insufficient funding led to the lag of research on the mechanism and processes.
- (4) The suitability management mechanism is not yet perfect concerning river ecological restoration technology, especially in China. Many restoration projects are often abandoned due to poor management. Little attention to the overall planning was paid between the river basin ecological restoration and local ecological restoration.

We propose the following development suggestions:

- (1) Strengthen continuous long-term monitoring with robust indicators before and after the restoration of the river to identify the restorative effects of restoration techniques. Indicators include hydrological, physicochemical, plants, animals, algae, zooplankton, microorganisms, benthic organism parameters, etc.
- (2) Based on current information processing technology, processing first-hand river data and establishing a multi-dimensionally unified dynamic evaluation system that adapts to the changing need of the times. Theoretical research was carried out step by step according to the research sequence of 'phenomenal basic data processing-impact factor extraction-mechanism generation-construction of evaluation system'.
- (3) Establishing a feedback and correction mechanism or processes model. Continuously learning from experience and lessons and improving and perfecting river ecological restoration measures.
- (4) Integrating the actual conditions of the river, planning by sections with 'one district, one policy', reasonably dividing the proportions of each district to limit interference, strengthening river basin cooperation, intensively developing and maintaining nature.

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