Advances in Ecological and Environmental Effects of Mountain River Sediment

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Abstract. Sediment is one of the main factors affecting the ecological environment of rivers, and its eco-environmental effect plays an important role in maintaining the balance of water environment and aquatic biodiversity. Sediment in mountain rivers has obvious characteristics such as wide gradation, which has unique impacts on the ecological environment. In addition, the increasingly intense human activities in mountain rivers, such as the construction and operation of large-scale cascade reservoirs, lead to further complicated changes in the ecological and environmental effects of sediment. In this paper, the environmental effects of mountain river sediment in adsorption, desorption and transport and the ecological effects on aquatic microorganisms, animals, plants and the entire food web were systematically reviewed. The problems existing in relevant researches were discussed, and the research prospects were presented, in order to provide guidance for the protection of mountain rivers.

Keywords: Mountain river · Cascade reservoir · Wide-graded sediment · Eco-environmental effect

1 Introduction

Mountain rivers are the pivotal corridors connecting mountains and plains, and are also the main source of supply, transport and storage of sediment. The unique characteristics of mountain river sediment are wide grain size distribution and large non-uniformity, that is, the wide-graded non-uniform sediment. The river bed composition is basically gravel, cobblesand or sand-gravel. In mountain rivers, the formation of wide-graded sediment depends on the thickness of bed cover and the non-uniformity of bed sediment. The non-uniform bed sediment is sorted and transported by the water flow, and the river bed is in an alternating process of bed armoring/stability. At the same time, fractural hillslope and weathered rock masses on both sides of the river provide a part of fine sediment, hence the mountain river sediment presents a unique wide-gradation feature (Lu and Zhang Hua-qing 1992).

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The formation and movement of wide-graded sediment are diverse and intricate. In the process of interacting with water flow and riverbed, the impact of sediment on the water environment and aquatic biological community is complex (Lee and Ferguson 2002; Liu et al. 2014). For example, sediment in mountain rivers affects water environmental conditions through adsorbing and desorbing the nutrients and pollutants (Beauger et al. 2006). Wide-graded sediment plays a key role in controlling the density and diversity of benthic and fish populations by reshaping biological habitats through forming step-pool system, rib-like, cluster-like and other riverbed structures under the effect of water flow (Wang et al. 2009b). With the development and utilization of mountain rivers in China, the eco-environmental characteristics and influencing factors have become a new research hotspot. At present, studies on mountain rivers mainly focus on ecological flow estimation, ecological health assessment and ecological function restoration (Bockelmann et al. 2004; Meng et al. 2009), a systematic understanding of the ecological and environmental effects of sediment in mountain rivers are still required.

At present, mountain rivers are disturbed by more and more intense human activities, especially the cascade reservoir construction (Cheng et al. 2022; Yuan et al. 2021). Cascade reservoirs transform continuous, rapid-flowing natural river systems into intermittent, slow-flowing reservoir systems, resulting in dramatic changes in river landforms, flow patterns and biochemical cycles (BIRGITTA et al. 2010; Winemiller et al. 2016). The repeated cumulative effects of cascade reservoirs on river flow, sediment transport, and ecosystems significantly affect the overall river health status through processes such as dam blockage, intermittent discharge, and reservoir backwater (Yuan et al. 2021). Studies have shown that the cumulative impact of cascade reservoirs on the hydrodynamic process and flow regime of the lower reaches of the Jinsha River is significantly greater than that of a single reservoir. At present, studies on the impact of cascade on mountain rivers mostly focus on the destruction of river connectivity, the change of water and sediment transport process and the evolution of reservoir ecosystem (Huang et al. 2018; Yang et al. 2020), and lack of comprehensive analysis of the response process of water/sediment-environment-ecology of the mountain rivers under the influence of cascade reservoirs. This paper systematically reviewed and analyzed the ecological and environmental effects of sediment in mountain rivers, focusing on the impact caused by the cascade reservoirs, and put forward its research prospects, which can provide a guidance for the protection of mountain rivers.

2 Environmental Effects of Mountain River Sediment

With the increase in population and industrial development, water pollution has become a global problem (Yusuf et al. 2022). Mountain rivers are important reservoirs of water storages, and the enrichment and migration status of pollutants are related to water resources security. The transport of sediment is closely related to the migration of pollutants from source to convergence, such as adsorption, transport, deposition, and transformation of pollutants in water bodies, which play an important role in the distribution of pollutants in mountain rivers (Fig. 1). Studying on sediment environmental effects contributes to a scientific comprehending of the spatial and temporal pattern and variation of water pollution in mountain rivers (Sw et al. 2021; Zhao et al. 2021).

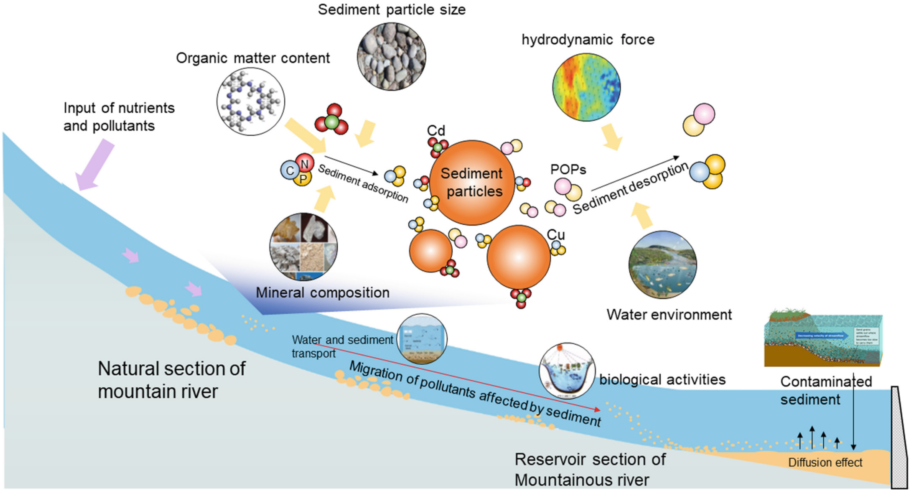

Fig. 1. Typical environmental effects related to sediment in mountain rivers

Under certain conditions, the transition of environmental substances from the dissolved state to adsorption state by sediment is called sediment adsorption. Sediment adsorption is a form of solid-liquid interface adsorption. The process of sediment adsorption is affected by its own characteristics and water environment. Factors affecting the adsorption of pollutants by sediment include sediment particle size, organic matter content, and mineral composition (Chen et al. 2021; Wang et al. 2009a). Finer particle size provides larger specific surface area and more adsorption sites, resulting in stronger adsorption capacity of sediment to heavy metals or organic pollutants. The coarse bedload in wide-graded mountain river sediment has limited adsorption capacity for pollutants. Therefore, when studying the sediment adsorption in mountain rivers, the impact of fine suspended load on pollutants should be considered.

Studies have shown that organic matter can promote the adsorption of pollutants by sediment (Xie et al. 2019). On the one hand, organic matter combines with minerals in the sediment to form complexes that absorb more pollutants through pore filling (Borggaard et al. 1990). On the other hand, organic matter promotes flocculation of fine particles and increases adsorption area (Gerbersdorf et al. 2008). For example, the adsorption capacity of fine-grained and high-organic-matter sediment in the urban section of the Yellow River is significantly higher than that of coarse-grained low-organic-matter sediment in the eroded loess section (Jiang et al. 2018). The surface of natural sediment in mountain rivers is wrapped by organic matter. Under the action of bridging, its specific surface area and pore size are significantly larger than those after artificial treatment, and the adsorption capacity is correspondingly enhanced (Wang et al. 2011). Moreover, the adsorption capacity of sediment is also related to the mineral composition of sediment. For example, the concentration of heavy metals such as Pb, Mn and Al in the deposited layer is positively correlated with the clay content, and the heavy metals exist in free form after separation from mineral oxides or as the surface coating of clay (Covelo et al. 2007; Miranda et al. 2022). The flow velocity of mountain rivers is fast, the clay content in the wide-graded sediment decreases, and the adsorption capacity for heavy metals decreases accordingly (Liao et al. 2017).

The kinetic model and isotherm adsorption model can quantitatively describe the process of sediment adsorption of pollutants, and are widely used in the studies of wide-graded sediment adsorption in mountain rivers (Liao et al. 2020). The kinetic model is used to describe the variation process of pollutants in the water-sediment phase with time, and the isothermal adsorption model is used to describe the distribution relationship of pollutants in the water-sediment phase under adsorption equilibrium state (Wu et al. 2021). The environment of mountain rivers is changeable, the temperature changes regularly with the altitude, the chemical conditions such as pH are affected by rainfall and human activities, and the properties of sediment are also distributed regionally due to different geological conditions, and the process of sediment adsorption is affected by the above factors. Combining the kinetic model with the isotherm adsorption model can explore the adsorption capacity of different particle sizes and different types of wide-graded sediments to various pollutants, and identify the key factors affecting the adsorption of wide-graded sediments.

The transition of pollutants from a sediment-based adsorption state to a dissolved state is called sediment desorption. The main influencing factors of sediment desorption include hydrodynamic force and water environment. In terms of hydrodynamic force, sediment desorption can be divided into two types according to the characteristics of water disturbance: 1) The water disturbance intensity is weak. The bed sediment does not move, and pollutants in the sediment gap migrate to the upper water through diffusion, which is affected by the pollutant diffusion flux, the pollutant content and the water depth; 2) When the water disturbance reaches a certain intensity, the bed sediment and suspended sediment exchange frequently, and the pollutants desorbed from them will affect the water quality. The seasonal distribution of water and sediment in mountain rivers is very uneven in the year. In dry seasons the general flow is relatively small and the bed surface is stable, so the desorption is mainly diffusion. While in flood seasons, the inflow and sediment increased sharply, the exchange between bed and suspended sediment strengthened, so the desorption was mainly caused by water disturbance. When discussing water environment, sediment desorption of pollutants is affected by pH, temperature and other factors. pH affects the desorption of sediment by changing the occurrence form of solutes. For example, strong alkali conditions promote phosphorus desorption, while strong acid conditions promote phosphorus adsorption. Under alkaline conditions, the phosphate ion in phosphate is replaced by OH^-, and desorption of phosphate by sediment is enhanced; under acidic conditions, phosphorus interacts with Fe and Al in sediment to generate insoluble phosphate; under neutral conditions, phosphorus mainly exists in the form of $H_2PO_4^-$ and $H_2PO_4^{2-}$(Zhou et al. 2005). Temperature changes the intensity of sediment desorption of pollutants by affecting microbial and algal activity. For example, as the temperature increases, the respiration of bacteria and algae in the sediment is enhanced, and the consumption of dissolved oxygen increases to form a low-redox environment, which induces the reduction of ferric iron to ferrous iron, and the release of phosphorus in iron and aluminum phosphate (Xia et al. 2008). There are obvious temperature gradients in different reaches of mountain rivers due to height differences. Compared with high-altitude rivers, low-altitude rivers have higher temperatures, which intensifies the desorption of pollutants and nutrients by sediment and may lead to regional eutrophication happened.

The migration and transformation of pollutants in water depends on water flow and sediment movement, while in mountain rivers, the migration of pollutants is affected by water and sediment transport (such as sediment re-suspension) and biological activities. Studies have confirmed that more than 60% of sediment re-suspension is caused by wind and current (Ding et al. 2018). The flow velocity is positively correlated with the pollutant concentration in the overlying water, and the pollutant release in the sediment increases with the flow velocity and decreases with the water depth. The natural situation is that the mountain rivers have small water depth and fast flow speed, so the pollutant migration will be relatively frequent when there is more erosion and fine suspended matter in the flood season. The migration of pollutants in sediment is mainly affected by biological effects, which is mainly transmitted with biological enrichment. The pollutants in the sediment are absorbed by benthic organisms through ingestion, or desorption into the overlying water, absorbed by organisms through body surface contact or respiration, and then transferred along the food chain and enriched in higher order organisms. Benthic activity caused the local fine sediment re-suspension, but had limited effect on coarse sediment, and the effect of biological activity on sediment re-suspension decreased in mountain rivers dominated by wide sediment gradation (Nasermoaddeli et al. 2017).

3 Ecological Effects of Mountain River Sediment

Sediment is one of the important habitat conditions for aquatic organisms, and the ecological effect of sediment is closely related to the stability of the ecosystem. Mountain rivers have abundant hydraulic resources and complex natural environment, which breeds diverse biological habitats and rich aquatic organisms, and the interaction between sediment and aquatic organisms is frequent. The gradation of sediment in mountain rivers is wide, and the ecological effect of sediment varies with particle size. Coarse sediment provides habitat for organisms, and fine sediment absorbs nutrients and plays an important role in biological growth and reproduction. At present, the research scope of the mountain river sediment's ecological effects includes microorganisms, aquatic plants and aquatic animals (Bylak and Kukuła 2022; Mikuś et al. 2021).

Microbes is essential in the biochemical cycles of river ecosystems (Liu et al. 2018). As the material transformation medium and growth carrier of microorganisms, sediment affects the structure, function and diversity of microbial communities (Liu et al. 2017). River sediment provides a large number of attachment sites for microorganisms and provides energy sources for microorganisms by adsorbing nutrients. Studies have proven that the microbial community structure of mountain rivers is significantly affected by nitrogen and phosphorus content in deposited sediments. High nitrogen and phosphorus content promotes chemoheterotrophy and improves microbial community diversity (Wang et al. 2021). Meanwhile, the oxygen concentration in the hyporheic zone of the wide-graded bed of mountain rivers varies significantly. The fine sediment deposition zone has a larger specific surface zone, but the dissolved oxygen content is limited due to the low water flow rate. The coarse sediment deposition zone can provide more dissolved nutrients and oxygen to the microbial community due to the high flow rate caused by intergranular gaps. These factors promote the formation of diverse microbial communities (Fang et al. 2017).

Aquatic plants are the main producers of aquatic ecosystems, which are at the first trophic level and the beginning of the food chain. Water transparency, nutrient concentration, hydrodynamic conditions and other factors all affect aquatic plants. The effects of wide-graded sediment in mountain rivers on the growth of aquatic plants are multiform. Riverbed sediment can provide attachment points for attached algae, emergent plants, and submerged plants, which is conducive to plant reproduction. Suspended sediment is easy to deposit in and behind the vegetation area, and the nutrients attached by sediment can promote the growth of vegetation (Liu and Nepf 2016). However, excessive suspended sediment will block the light, reduce the transparency, inhibit the photosynthesis of phytoplankton, submerged plants and other categories, which is not conducive to the growth of vegetation. Sediment adsorption/desorption of nutrients has an impact on phytoplankton growth and root uptake of other plant species. Some phytoplankton, such as cyanobacteria, can resist extreme conditions such as low temperature, freezing, and weak light by dormancy in deposited sediments, resulting in their spatial distribution changing with the movement of sediments (Ouyang et al. 2021). Gravel beaches in mountain rivers can effectively intercept fine sediment and organic debris, provide a good substrate for the germination and growth of terrestrial and hygrophytic plants (Mikuś et al. 2013), which is conducive to increasing plant community diversity in mountainous rivers and coastal areas. Compared with the downstream plain rivers, mountain rivers generally have smaller water depth, lower sediment concentration, higher transparency level, and the bed rock is not easy to move, which is more beneficial to the reproduction of algae attached to the substrate (Zhao et al. 2020).

Fig. 2. Examples of typical benthic invertebrates with different particle sizes

Sediment in mountain rivers affects aquatic animals mainly by controlling the habitat environment. Studies have shown that there is a close relationship between the benthic community structure and the grain size in the riverbed. For example, the bedrock riverbed is suitable for aquatic insects with strong grasping force and flatworms (such as planarians) to survive; Ephemeroptera, Trichopterans and other aquatic insects are predominant in pebbles and gravel. There are many organisms such as Oligochaeta in the silt. In sandy riverbed, shrimp, bivalves and gastropods can inhabit (Fig. 2). Mountain rivers are diverse in sediments with wide gradation, which is suitable for a variety of organisms to inhabit. The coarse grain gap provides a large living space for benthic organisms and is not easy to be destroyed by erosion, so it has high biodiversity and biomass (Zhang 2009). The wide-graded sediment in mountain rivers can form a certain riverbed structure due to its high heterogeneity, providing differentiated habitat conditions and shelters for aquatic organisms. For example, mountain stream bed is mostly composed of alternately connected gentle slopes and stacked falls, which is called step-pool system (Changzhili 2004). At the beginning of this century, scholars began to explore the ecological effects of step-deep pool system. For example, Changzhili (2004) pointed out that the step-deep pool system improved the biodiversity and riverbed stability of mountain rivers. The composition of the system fully highlights the characteristics of wide-graded sediment distribution in mountain rivers, providing conditions for the formation of diverse aquatic habitats: cobbles accumulated as steps, fine sediment deposits formed pools between each step, the step and bed consists of different particle size of sediment, water flows above the cobble and through its pores, forming diverse habitat spaces. At the same time, the step-pool system forms water flow structures such as water falling and hydraulic jump with abundant dissolved oxygen, which is conducive to the survival of benthic animals, small fishes and small amphibians (Fig. 3).

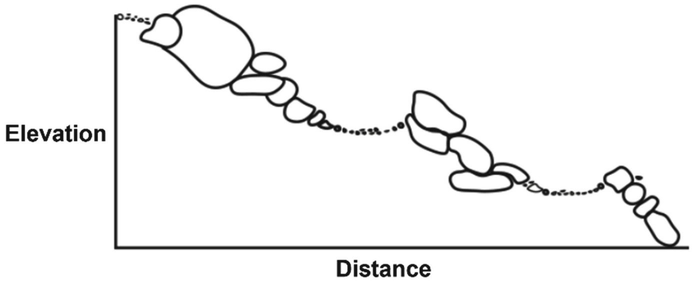

Fig. 3. Mountain River step-deep pool system typical longitudinal section

Overall, the wide-graded sediment in mountain rivers provides sufficient habitat conditions for microorganisms, aquatic animals and plants, and upstream water provides a continuous source of nutrients, thus forming a unique aquatic ecosystem (Zhang et al. 2021b). The structure and function of food web is one of the essential elements of ecosystem as a way of material and energy flux in between various organisms and habitat factors (Vesterinen et al. 2021). In mountain rivers, food web units mainly include various producers (phytoplankton, adherent algae, etc.) and consumers (benthic organisms, fish, etc.). The flux relationship of growth, death and predation of each unit is restricted by water flow, sediment, water quality and other indicators. As a nutrient carrier and a key habitat for organisms, the wide-graded sediment in mountain rivers undoubtedly has an important impact on the shaping of the structure and function of the food web. Understanding how the food web responds to the changes of water, sediment and water environment under the background of mountain rivers can provide new insights for the study of ecosystem stability.

4 Eco-Environmental Effects of Mountain River Sediment Under Influence of Reservoirs

The cascade development changes the continuous river system into a river-reservoir alternating discontinuous system, which changes the dynamic process of sediment in mountain rivers, and the sediment transformed from a single wide distribution to a spatial distribution of binary structure. The impact of cascade reservoirs on sediment is also different from the longitudinal changes of a single reservoir. The transport and siltation of sediment are affected by the overlapping effects of upstream dam discharge, downstream reservoir top support, and linkage regulation of upstream and downstream reservoirs, forming a step-by-step amplification cumulative effect (Yuan et al. 2021). The specific performance is that the sediment content of the water flow is greatly reduced, the particle size of the sand carried by the water flow is reduced, and the sediment transport capacity is decreased (Yan et al. 2021).

4.1 Changes in Environmental Effects of Sediment

The storage of cascade reservoirs results in the reduction of the total amount and grain size of sediment transported along mountain rivers. For example, after the construction of the cascade reservoirs along the lower reaches of the Jinsha River, the sediment load and sediment particle size discharged into the Three Gorges reach significantly decreased. the sediment amount from the Jinsha River into the Three Gorges Reach (in 2014) decreased by 147.6 million tons compared with that before (the average from 2003 to 2012). The proportion of sediment with particle size less than 0.062 mm (2014) increased by 19.6% compared with that before (1988–2012). Sediment retention by cascade reservoirs results in the retention of organic matter adsorbed by the sediment. From 1953 to 2016, the flux of particulate organic carbon transported from rivers to the ocean in China showed a downward trend, with an average annual decrease of 0.2 Tg C in total particulate organic carbon flux and the main reason for this phenomenon was sedimentation caused by reservoirs (Liu et al. 2020). The oxidative decomposition of particulate organic carbon in the silted sediment leads to the release of a large amount of carbon dioxide, which has an impact on the atmospheric environment. Due to the adsorption of sediment, the sedimentation of suspended sediment intercepted by the cascade reservoirs also leads to the retention of nutrients and reduces the supply of nutrients to the downstream. For example, due to the construction of the Three Gorges Reservoir, the transport of adsorbed phosphorus to the ocean in the upper reaches of the

Yangtze River decreased by about 22.5%. After a turbulent river is transformed into a reservoir, the environmental capacity is reduced, especially nutrients and pollutants are enriched in the reservoir area with sediment and gradually released to the water body, which will become a hidden danger to the river environmental safety in the long term. After the cascade development of the Lancang River Basin, the total phosphorus in each section of the main stream of the Lancang River generally exceeded the standard, and the water quality was Class V. Besides, the change of sediment particle size also affects the local nitrogen cycle in the reservoir area. Studies showed that the sediment with smaller particle size has larger specific surface area and higher organic carbon content, which leads to the growth of more denitrifying bacteria, resulting in a higher denitrification rate (Xia et al. 2017; Xia et al. 2018). Although a single reservoir also has the effect of decreasing particle size and transport capacity, the effect of cascade reservoir on sediment environment will be amplified step by step. For instance, cascade reservoir in Jinsha river reduced the concentration of suspended sediment in reservoir area and outlet, and significantly increased the concentration of particulate organic carbon in sediment. The concentration of particulate organic carbon in deposited sediment during the operation of cascade reservoir is 5 times that of single reservoir (Wu et al. 2020).

4.2 Changes in the Ecological Effect of Sediment

The effect of cascade reservoirs on sediment ecological effects is reflected in two aspects: regulating suspended sediment transport process and changing bed sediment conditions:

1. Control the suspended sediment transport process. In general, the sedimentation of suspended sediment in the reservoir area enhances the transparency of mountain rivers and, together with the reduced flow velocity, facilitates the growth of phytoplankton. However, the river habitat of cascade reservoirs in mountainous areas changes in a segmentalized manner due to multi-stage regulation. Taking the cascade reservoirs in the lower reaches of Jinsha River as an example, with the water storage of Xiluodu and Xiangjiaba reservoirs, the suspended sediment settled, and the phytoplankton and fish feeding on them increased. However, Wudongdong and Baihetan reservoirs still maintained normal flowing water habitat during the unfinished period, and the suspended sediment content was high, which was not conducive to the growth of phytoplankton, and the fish composition was dominated by the indigenous fluid-like water community. The temporal and spatial distribution of nutrients in mountain rivers changed with the change of suspended sediment transport process, which affected the community structure of algae and other aquatic plants. The sediment transported by rivers includes not only mineral particles, but also organic matter particles and bioclasts that can be eaten by organisms. The cascade reservoir, through the interception of multi-stage dams, flattens the downstream discharge, lowers the flow velocity of the reach, and weakens the sand-carrying capacity, which leads to the reduction of the nutrient and food contents carried by the water flow, thus significantly reducing the integrity of the river ecosystem(Duan et al. 2011). In addition, during the period of "Clear storage and muddy discharge" of some reservoirs, a large amount of sediment discharge also

has a negative impact on benthic organisms and fish, resulting in biomechanical damage, reduced food intake and individual death (Crosa et al. 2009).

2. Change the bed sediment characteristics. The decrease of the flow velocity in the reservoir area leads to the accumulation of sediment and nutrients in the riverbed and the acceleration of microbial growth and metabolism. Related metabolites (such as extracellular polymeric substances (EPS)) promote the formation of biofilm on the sediment surface, which affects the morphology, density and physical and chemical properties of sediment, leading to significant changes in sediment movement characteristics (Fang et al. 2017). The biofilm on the sediment surface can protect the sediment when it is eroded by water flow, and the network structure composed of EPS and other connected particle gaps enhances the anti-scour property of the sediment. Large cobbles in mountain river bed can provide shelter for benthic groups ranging from 2.5 mm to 10 mm, and small cobbles can also shelter scrapers, grazers and tearing of benthic animals, such as Rhithrogen, etc. With the sedimentation of reservoir sediment, cobble riverbed in reservoir area is covered by fine particles of sediment. The original benthic organisms lost a large number of shelters (Beauger et al. 2006), while the sediment was simplified and the riverbed structure in mountainous areas disappeared, resulting in a decrease in habitat conditions and the diversity of benthic organisms. For example, the species number and evenness index of benthic species in Xiluodu and Xiangjiaba reservoir areas of Jinsha River were lower than those in natural river channels, and the species with low oxygen tolerance and strong survival ability gradually became the dominant species in the reservoir areas. Therefore, some researchers believe that river cascade development will result in homogenized ecological environment and biome with obvious gradient (Petesse and Petrere 2012). In addition, fine-grained sediments in the mountainous river reservoir area will significantly reduce the porosity and dissolved oxygen content of the subsurface layer below the bed sediment, reduce the habitat depth of organisms, and threaten the subsurface microorganisms and benthic organisms. After scouring and armoring of the downstream riverbed of the reservoir, the gap fine sediment decreases, which may make the benthic species living in the original fine sediment, such as oligochaetes and chironomids, have no place to hide, and their biomass is greatly reduced. The process of riverbed evolution itself also has significant ecological effects, and the stronger riverbed evolution intensity will reduce the stability of the habitat and adversely affect the biological community. Erosion of river bed can wash out organic sediment and the benthic organisms in it, and rapid siltation can also reduce the quality of life of organisms, such as mayfly gills, affecting respiration and other functions (Duan et al. 2009). Furthermore, the destruction of benthic communities inevitably affects some mountain river fishes that feed on them. For example, fish that feed on benthic organisms, such as carp, are forced to consume food with low nutritional level due to the decrease of benthic organisms, leading to the decline of their nutritional level. The natural mountain rivers are in a relatively stable state of river evolution, but after the operation of the cascade reservoir, the changing backwater area, the perennial backwater area, and the downstream of the reservoir have the evolution process of alternating scouring and silting, continuous silting, continuous scouring, etc. Under these unstable states, the sediment activity will lead to the complex response of biological community.

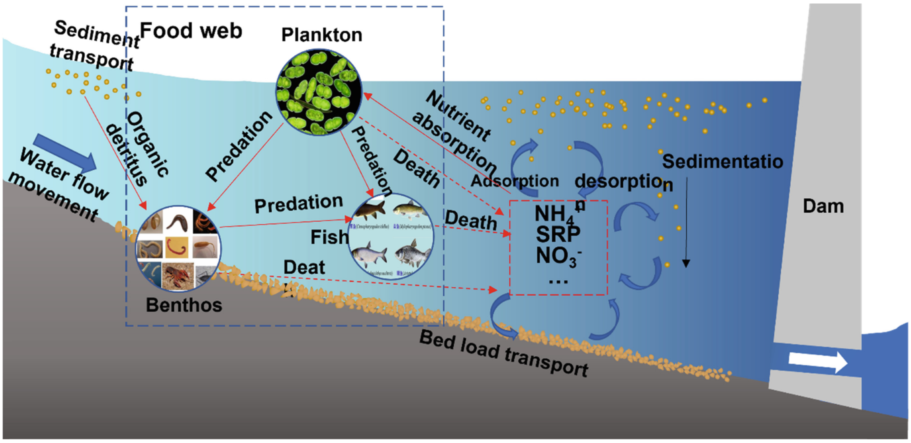

Fig. 4. Schematic diagram of the response mechanism of water/sediment-environment-ecology interaction (taking the reservoir area as an example)

4.3 Changes in Water/Sediment-Environment-Ecology Response Relationship

In summary, from the perspective of ecosystem as a whole, water and sediment regulation in cascade reservoirs of mountain rivers leads to the changes of various biological communities, and thus affects the interactions among species represented by food webs. The static water condition of the reservoir promotes the growth of algae, which leads to the transformation of the scavenged food web based on debris to the grazing food web based on algae (Mor et al. 2018). The operation of the reservoir results in the decrease of the habitats of original river organisms, which leads to the homogenization of biological communities in the reservoir and the decrease of food web diversity (Zhang et al. 2021a). At the same time, fine-grained sediment is deposited in the reservoir area, filling crevices of coarse-grained sediment in natural mountain rivers, resulting in the reduction of critical habitats and refuges, and the exposure of shallow benthic animals to water bodies, changing the predation relationship (Power et al. 2013). At present, studies on river food webs mainly focus on nutrient structure analysis and material/energy transfer process analysis [88, 89], while there are few studies on the relationship between food webs and hydrodynamic factors of water and sediment (Wootton et al. 1996). After the construction and operation of cascade reservoirs, a complete response process of water/sediment, water environment and water ecology (Fig. 4) are formed in the river. The material energy absorbed/desorbed by sediment can be absorbed by plankton, and then transmitted through the food web among benthic organisms, fish and other organisms. After the death of organisms, they are deposited and decomposed again, and become part of the sediment or migrate with water. Therefore, the changes of water flow and sediment transport brought by cascade reservoirs also transmit to the changes of biogenic substances, primary producers, consumers and other biological categories.

5 Conclusions and Future Perspectives

Mountain rivers play an important role in the conservation of water resources and biodiversity. With the implementation and promotion of sustainable development and ecological security strategy in China, ecological environmental effects of sediment in mountain rivers have gradually become an important research field. Sediment in mountain rivers significantly affects microbial, plankton, adherent algae and other species, especially the benthic community. The unique geomorphic characteristics and wide grain size distribution of mountain rivers contribute significantly to the formation of local microecosystem. The environmental effects of sediment adsorption and desorption are the key ways of pollutant migration and transformation. In recent decades, the construction and operation of cascade reservoirs in mountain rivers have caused great changes in the natural water and sediment processes, and the ecological and environmental effects of sediment have changed accordingly. On the one hand, the establishment of cascade reservoirs changes the characteristics and transport process of sediment, and greatly affects the pollutant migration and material circulation affected by sediment. On the other hand, the previous ecological process of mountain rivers is adjusted by the different response mechanisms of microorganisms, aquatic animals, plants and the whole food webs. At present, the research on the environmental effects of sediment adsorption and desorption in mountain rivers mainly focuses on laboratory simulation and mathematical models. Studies on sediment's ecological effects lack systematic analysis, which need massive data to form a complete knowledge framework. Recent studies can be further improved from the following aspects:

(1) The environmental characteristics of wide-graded sediment in mountain rivers. The sediment adsorption and desorption on pollutants are closely related to grain size and mineral composition of sediment. By improving the database of sediment environmental characteristics of major rivers and reservoirs, it can provide useful reference for understanding the law of pollutant migration and transformation, and provide corresponding basis for sediment pollution control in river basins.

(2) The combined approaches of ecology and environmental science with hydro-sediment dynamics to study the relationship between suspended/bed load transport rate and pollutant transport, especially the impact of wide-graded sediment on pollutants. Explore the whole series of pollutant migration and transformation processes including bedload transport and exchange with bed sediment, sediment adsorption/desorption, biological uptake, and enrichment.

(3) The response mechanism of water/sediment-environment-ecology interaction in cascade reservoirs of mountain rivers. The response process in river water/sediment, aquatic environment and aquatic ecology often involves the variation of multiple environmental factors and the succession of various biological communities. Especially under the impact of cascade reservoirs, the key environmental elements of the river and the structure and function of the food web may undergo major changes. It is necessary to conduct in-depth research on the complex comprehensive mechanism and carry out quantitative simulations.

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