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Conserving the unique aquatic ecosystem of the Jiuzhai National Heritage Site after the 2017 earthquake: Achievements and challenges

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Water resources are the key link within the unique landscape of the Jiuzhaigou World Natural Heritage Site. However, the earthquake on 8 August 2017 induced serious damage to the ecosystem of the Jiuzhaigou region. Water resource quantity was threatened by the direct destruction of the connectivity between the upstream and downstream river systems, whereas water quality and the original aquatic ecosystem were worsened indirectly by secondary disasters, such as landslides and debris flows triggered by earthquakes. It is urgent to protect water resources to maintain a healthy aquatic ecosystem for the Jiuzhaigou World Natural Heritage Site. Therefore, water resource protection strategies are developed by collaboratively considering water quantity, quality and aquatic ecology, including 1) studying the relationship between upstream and downstream in terms of water supply and connectivity, 2) developing emergency plans for extreme precipitation disasters and ecological water regulation schemes for extreme drought, 3) clarifying the impact of vegetation management measures on water conservation, nutrient cycling and water quality, 4) separating the contributions of earthquakes from related disasters, hydrodynamic changes, and lake bank vegetation succession to lake swamping, 5) identifying the potential water pollution risk caused by ecological restoration projects, analyzing the sources of pollutants such as nitrogen, phosphorus and atmospheric acid deposits and developing control measures, and 6) systematically evaluating aquatic ecological health and determining water ecological protection and restoration measures. This review may provide critical viewpoints for conserving aquatic ecosystems, not only in the Jiuzhai World Natural Heritage Site but also in other global conserved aquatic parks.

KEYWORDS

water resource conservation, earthquake, post-disaster management, ecological restoration projects, Jiuzhai National Park

1 Introduction

Water, the most essential natural resource upon which humans and other life on Earth depend, is more critical to aquatic ecosystems than to any other type of ecosystem because aquatic ecosystems are both in and around bodies of water. Aquatic ecosystems refer to freshwater, coastal and marine environments and play pivotal roles in stabilizing global biodiversity and the provision of numerous ecosystem services (Langhans et al., 2019; Vári et al., 2022). However, freshwater ecosystems are the most threatened systems in the world (Vörösmarty et al., 2010; Vári et al., 2022), especially aquatic ecosystems distributed in alpine regions that are highly sensitive to climate change (Khamis et al., 2014; Hua et al., 2021). Such irreversible damage caused directly by human activities and climate change threatens the sustainability of these freshwater ecosystems.

Jiuzhai Valley, or Jiuzhaigou in Chinese, located in northern Sichuan Province, eastern Tibetan Plateau, Southwest China, is best known for its unique blue and green lakes, spectacular waterfalls, and narrow conic karst land forms. The valley is included on both the UNESCO World Natural Heritage List (UNESCO, 1992) and the Biosphere Reserve List (UNESCO, 1997) due to its great naturalistic value and outstanding universal value. Since the advent of such designations, countermeasures have been issued to protect these unique areas, including their aquatic systems and water resources. For example, public toilets and drainage networks were built to collect sewage, and a trestle was built along most of the scenic areas by the Jiuzhaigou Administrative Bureau beginning in 2000 to lower the possible threats to water quality (Wang et al., 2018; Deng et al., 2020). However, increasing anthropogenic activities inevitably have a negative impact on aquatic ecosystems, as pointed out by Vörösmarty et al. (2010), Häder et al. (2020), Vári et al. (2022), and others. The Jiuzhai Valley is no exception (Deng et al., 2020), and ecosystem degradation, such as eutrophication (Ouyang et al., 2016; Pan et al., 2016; Wang et al., 2018) and travertine (or tufa) degradation (Qiao et al., 2016; Liu, 2017), has been reported.

On 8 August 2017, an earthquake with a surface-wave magnitude (Ms) of 7.0 and a moment magnitude (Mw) of 6.5 occurred in the Jiuzhai World Natural Heritage Site (Fan et al., 2018; Hu et al., 2019). The earthquake triggered 1883 coseismic landslides in an affected area of 8.1 km^2 and damaged road systems, tourism infrastructure, and aquatic systems in Jiuzhai Park to varying degrees (Wang et al., 2021). For example, landslides and debris flows can cause soil and vegetation to enter water bodies, worsen water quality and lead to lake siltation and swamping. With these new problems arising from the earthquake, the already fragile aquatic system in the Jiuzhai Valley may have further worsened. Considering that water is the spirit of Jiuzhai Valley and aquatic ecosystems provide both prominent naturalistic value and outstanding universal value, it is necessary to protect water resources to maintain healthy aquatic ecosystems. However, because the strong Ms 7.0 earthquake was the first recorded earthquake in a world natural heritage site in China and was also a unique event globally, prior knowledge and mature methods for conserving the area's distinct aquatic ecosystem are lacking.

Here, we review the effects of the 2017 earthquake on Jiuzhai Valley with the goal of identifying countermeasures for conserving the unique aquatic ecosystem.

2 Description of the Jiuzhai World Natural Heritage site

Jiuzhai Valley is China's premier national park and National Nature Reserve (NNR). The NNR covers approximately 650 km^2, and its three biosphere reserve zones, namely, the core, buffer, and experimental areas are 492, 92, and 66 km^2, respectively (Figure 1A,B). The highland temperate monsoon climate has a mean (2000–2019) annual air temperature and precipitation of 7.7°C and 740 mm, respectively. Most precipitation occurs during April–October (the rainy season). The elevation fluctuates greatly and gradually decreases from a maximum value of 4,890 m above sea level in the south to a minimum value of 1950 m above sea level in the north. The landscape is dominated by high mountains with dense forests and deep valleys as well as scattered mountain plains. The exposed strata are mainly neritic-littoral facies carbonate sediments (Hu et al., 2019). Because the NNR is part of the Songpan–Ganzi subblock in the Longmen Mountain thrust belt area in the transition zone from the Qinghai–Tibet Plateau to the Sichuan Basin, it is greatly affected by several faults both outside and inside the NNR, causing the area to be relatively vulnerable to landslides and debris flows triggered by earthquakes.

Jiuzhai Valley, composed of three gullies resulting in an inverted Y shape (Figure 1C), is in the experimental area. The upper rivers flow northward along the Rize and Zechawa Gullies, converge at NuoRiLang, pass through the Shuzheng Gully and finally flow into the Baishui River, a tributary of the Jialin River, at Sheep Cave. Detailed characteristics of the river system, such as the name and length of tributaries, are provided in Table 1. There are more than 20 individual lakes and 5 major waterfalls distributed along the rivers, combined with tufa landscapes forming a unique scenic area.

3 Effects of the 2017 earthquake on the aquatic system

The earthquake on 8 August 2017, with an epicenter located at 33.20° N, 103.82° E, approximately 5 km west of the core area

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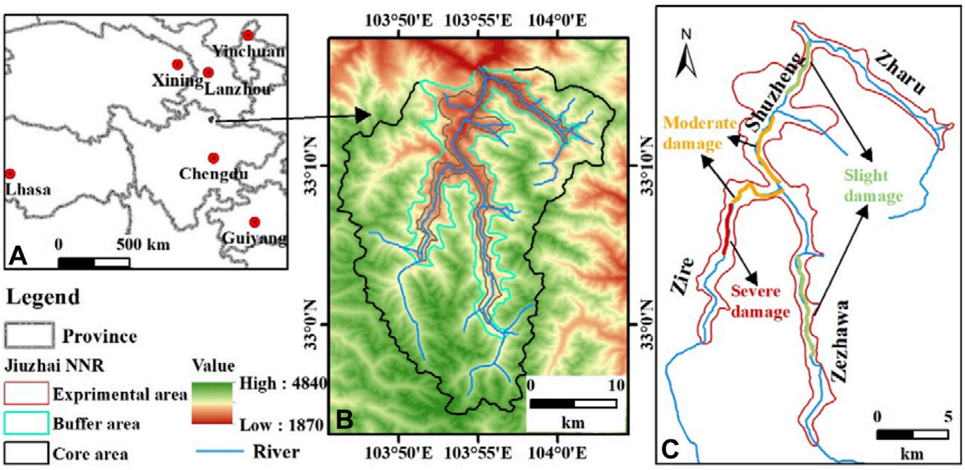

FIGURE 1
Information on the Jiuzhai World Natural Heritage (WNH) Site: **(A)** location of the Jiuzhai WNH Site in Sichuan Province, China; **(B)** the three biosphere reserve zones of the Jiuzhai National Nature Reserve (NNR) and corresponding elevations based on ASTER 30-m digital elevation models; and **(C)** damage conditions in Jiuzhai Valley, the experimental area of the Jiuzhai NNR.

TABLE 1 Characteristics of the main valleys and river systems in the Jiuzhai National Nature Reserve.

Main valley	Secondary valley			Tertiary valley		
	Name	River length before confluence (km)	Basin area (km^2)	Name	River length before confluence (km)	Basin area (km^2)
Jiuzhai	Shuzheng	13.48	187.55	Heye	4.32	24.52
				Zhuaru	18.36	108.20
				Heiguo	3.29	21.54
	Rize	29.14	245.68	Danzu	14.34	73.91
				Xuanque	4.69	19.26
				Zangmalong	14.19	68.51
				Primary forest	4.90	16.21
	Zechawa	31.51	220.08	Long Lake	11.95	75.47
				Left side of Long Lake	3.62	17.17
				Rongdong	2.30	13.70
				Kazhen	2.05	20.24

of the Jiuzhai NNR (Hu et al., 2019), was the third strongest earthquake in the Longmen Mountain area since the 2008 Wenchuan earthquake, which was categorized as Ms 8.0 (Fan et al., 2018). Jiuzhai Valley was destroyed. In particular, severe damage, defined as landslides in most areas and the destruction of all roads, occurred in the middle Rize Gully (Figure 1C). The lower Rize Gully and the upper Shuzheng Gully reported moderate damage, i.e., local landslides, falling rocks, and 2/3 trestle damage. Damages in the middle Zachawa Gully and the lower Shuzheng Gully were slight, with limited mountain collapse and falling rocks. The following sections will explain the direct and indirect effects of the earthquake on the aquatic system.

3.1 Direct effects

For the aquatic system, the most direct impact of the earthquake was the destruction of the connectivity between the upstream and downstream river systems, which may have

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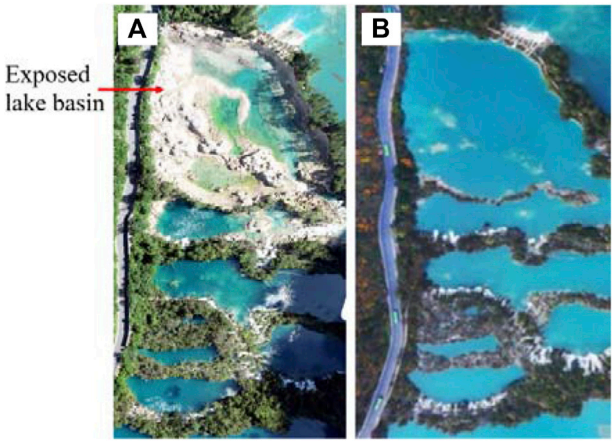

FIGURE 2
Sparkling Lake in the Jiuzhai World Natural Heritage Site after the 2017 earthquake **(A)** and restoration **(B)**. Note: photos were taken by unmanned aerial vehicles in 2020 and 2021.

FIGURE 3
Nuorilang Waterfall in the Jiuzhai World Natural Heritage Site before **(A)** and after the 2017 earthquake **(B)** and after restoration **(C)**. Note: the image in panel b taken from Zhang et al. (2021) shows that the waterfall dried up due to direct destruction of the connectivity between the upstream and downstream river systems; the photograph in panel c was taken in June 2020 by the authors.

caused underground funnels or cracks. A typical case was the collapse of the natural travertine dam break at Sparkling Lake (Huohua Hai in Chinese) (Figure 2), a major tourist attraction in the Jiuzhai NNR. In particular, the earthquake caused a 14 m depth breach, and the lake nearly dried up with obvious lake basin exposure due to the water level dropping by approximately 13 m (Wang et al., 2021). An additional example is the Norilang Waterfall, the widest travertine topped waterfall in the world. The earthquake damaged the dam and connectivity of the waterfall and upstream river, leading to waterfall disappearance (Figure 3) (Zhang et al., 2021). Due to the earthquake, several rivers and lakes were blocked, especially in the region from Arrow Bamboo Lake (Jianzhu Hai) to Mirror Lake (Jing Hai) in the Rize Gully, covering several famous attractions.

3.2 Indirect effects

Indirectly, secondary disasters triggered by earthquakes, such as rock collapse, landslides and debris flows, mainly occur along the riverine valleys not only cause damage to river and lake systems but also cause soil, sediment, and vegetation to enter water bodies, worsen water clarity and destroy the original aquatic ecosystem. According to investigation statistics from the Jiuzhaigou Administrative Bureau, there were 89 earthquake-induced secondary geohazards in the experimental area of the Jiuzhai NNR, including 55 collapses, nine landslides, 18 debris flows, and seven unstable slopes. For example, the area affected by the collapse and landslide near Panda Lake (Xiongmao Hai) was approximately 2 km^2 (Chen et al., 2018) (Figure 4). Furthermore, forests and other vegetation

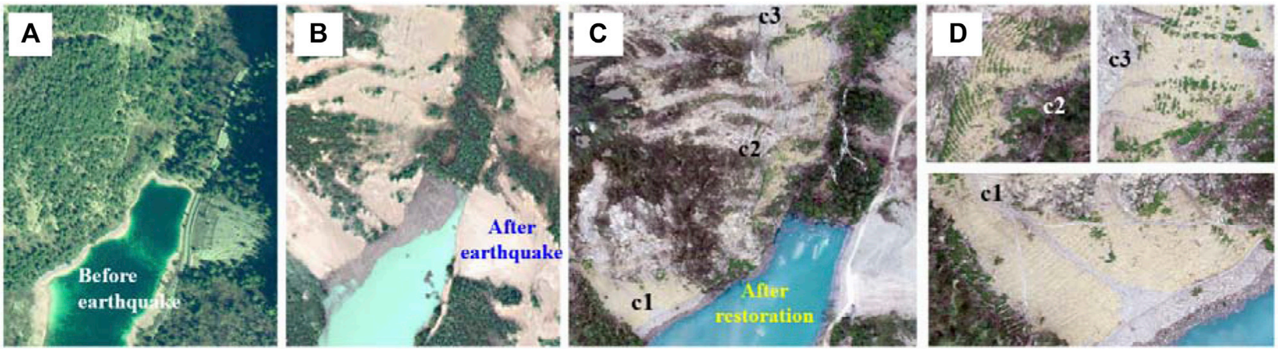

FIGURE 4
Panda Lake in the Jiuzhai World Natural Heritage Site before **(A)** the 2017 earthquake, just after the earthquake without any restoration **(B)**, and 3 years after the earthquake with restoration **(C,D)**. Note: all figures were taken by unmanned aerial vehicles; the image in panel b shows landslides triggered by earthquakes and their effects on water quality and the original aquatic ecosystem; the image in panel d shows enlarged areas of the vegetation restoration region shown in panel c, which was taken in June 2020.

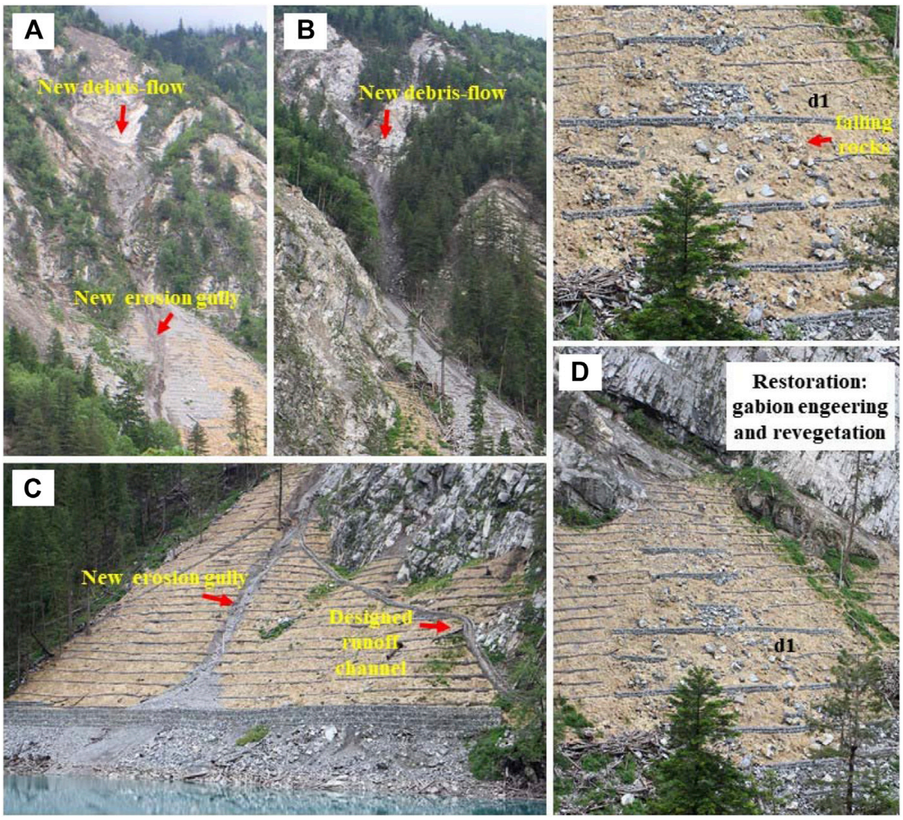

FIGURE 5
Unpredicted problems occurring after ecological restoration projects at Panda Lake. Note: the photographs in panels **(A-C)** show new debris-flow and new erosion gully; the photographs in panel **(D)** show falling rocks in the revegetated area; all photographs were taken in June 2020.

indirectly affect the hydrological cycle and both the quantity and quality of water resources. Vegetation coverage in the Jiuzhai NNR declined by approximately 28% due to earthquakes, landslides, and debris flows, which inevitably disrupted the balance of the previous ecohydrological system and resulted in negative effects on the aquatic environment.

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FIGURE 6
Visitors gathered at the Mirror Sea scenic spot despite the influence of COVID-19 (the photograph was taken in June 2020).

4 Conserving the unique aquatic ecosystem of the Jiuzhai NNR

Before the 2017 earthquake, substantial achievements were made in conserving the unique aquatic system of Jiuzhai Valley. To protect water quality, sewage systems were built in the valley (Wang et al., 2018; Deng et al., 2020). The number of tourists entering Jiuzhai Valley each day was restricted to 41000 and infrastructures, such as public toilets, was built to lower the possible threats to water quality. Therefore, the water quality in Jiuzhai Valley belongs to class I according to environmental quality standards for surface water (GB3838-2002), the highest quality in China. Moreover, personal cars were forbidden in the valley, and clean buses were arranged for tourism to reduce air pollution. Revegetation, including through the Grain for Green program, was performed to reduce soil erosion and conserve water resources in the ecosystem. Nonetheless, ecosystem degradation is inevitable in terms of eutrophication (Ouyang et al., 2016; Pan et al., 2016, 2017; Wang et al., 2018) and travertine (or tufa) degradation (Qiao et al., 2016; Liu, 2017). Overlying new problems arising from the 2017 earthquake, water and vegetation as well as related eco-environments should be treated together, and aquatic ecosystem conservation may be achieved by integrating catchment management (Langhans et al., 2019; Hewett et al., 2020; Noe et al., 2020). From this point of view, we propose the following guidelines for conserving the unique aquatic ecosystem of Jiuzhai Valley.

4.1 Countermeasures for maintaining adequate water quantity

A certain amount of water is key to maintaining the unique value of the Jiuzhai NNR. The quantity of water resources normally depends on the hydrological cycle (Oki and Kanae, 2006). In addition, the effects of vegetation on water yield and the hydrological cycle vary (Ellison et al., 2012; Goeking and Tarboton, 2020). Therefore, the following two activities deserve priority.

4.1.1 Clarifying the hydrological process between the upstream and downstream regions

Because the Jiuzhai NNR is located in a karst area and there are many underground rivers, the regional hydrological process remains unclear and requires in-depth study. For example, the complex hydrogeological conditions and topography as well as a lack of observations limits a systematic study of discharge and supply characteristics between the upper reaches of the Zechawa Gully and the lower Rize Gully, leading to inconsistent results for water exchange (Gan, 2007). In particular, Long Lake (Chang Hai) in the Zechawa Gully is significant in stabilizing downstream river systems, aquatic ecosystems, and landscapes. The lake should be protected and maintained in a healthy state to ensure a sufficient discharge for the lower basin. Moreover, the 2017 earthquake may have caused fracture leakage and complicated the already unclear hydrological process, which further increased the difficulty of exploring the water cycle.

In addition, water resources in the Jiuzhai NNR depend on precipitation and alpine snowmelt. Global climate change intensified the frequency of extreme hydrometeorological events, and heavy rainfall in the Jiuzhai NNR exhibited an increasing trend (Du et al., 2017). Furthermore, the Jiuzhai NNR is located on the Himalaya Qinghai-Tibet Plateau, which is extremely vulnerable to subtle changes in temperature and precipitation, but the advance and retreat of glaciers in this region are still controversial (Lugli et al., 2017), leading to high uncertainty in water resource quantity. Therefore, fine-scale weather (or climate) simulations should be carried out, and emergency plans for extreme wet and dry events could be developed accordingly to adapt to climate change and to support water resource management.

4.1.2 Optimizing forest management

Vegetation, including forest, is a prominent component of the unique landscape in the Jiuzhai NNR (Zhang et al., 2017). It was reported that vegetation restoration after the earthquake has increased vegetation coverage, which may have had a positive impact on the watershed hydrological process and promoted the restoration of aquatic areas (Chen et al., 2021). Nonetheless, relationship between forest cover and water yield are complex with unclear dynamics (Ellison et al., 2012). Vegetation change and its growth will alter the ratio of interception, infiltration and evapotranspiration to rainfall as well as land surface albedo and the water–carbon–energy nexus, complicating the hydrometeorological process. Subsequential alterations can change the local abiotic and biotic environments. A study revealed that in the Jiuzhai NNR, revegetation on nonforestland led to unintended side effects, i.e., a decrease in the diversity of the changed habitats, by changing the distribution of the nonforestland as well as plant communities along altitudes and slopes (Schmidt et al., 2017). These results indicate that caution should be taken when performing vegetation restoration.

We suggest nature-based solutions. Specifically, reducing pressures from human disturbance is enough to protect most areas of the Jiuzhai NNR because the plant species are coevolving with the surrounding environment and have adapted to natural disturbances. For areas close to scenic spots where revegetation and management are necessary, local species are preferred. Artificial forests with a single dominant species should be prioritized in terms of forest management because they are vulnerable to insect pests. In the Jiuzhai NNR, more than half of the *Pinus tabulaeformis* forests were endangered by *Sonsaucoccus sinensis* Chen (Liu et al., 2010). In addition, the subalpine environment in the Jiuzhai NNR is more suitable for broad leaf species than coniferous species under rising temperature and climate change (Bossard et al., 2015). However, deciduous broad leaf forests significantly increase the concentrations of dissolved organic carbon, hydrolyzable nitrogen and available phosphorus in the soil, increasing the risk of such elements entering water bodies and causing lake eutrophication (Xu et al., 2016). Therefore, it is necessary to systematically study the impact of forest management on water resource conservation, nutrient cycling and water quality.

4.2 Countermeasures for preventing water quality degradation

4.2.1 Post-earthquake reconstruction project management

After the earthquake, the Chinese government launched post-disaster reconstruction with an investment of 3.655 billion Chinese yuan, and these efforts mainly included engineering countermeasures, such as projects covering housing and public infrastructure rebuilding, secondary geohazard control, and ecological restoration. While these projects are necessary to reconstruct the Jiuzhai NNR and can effectively reduce the negative effects of collapses, landslides, debris flows, and other earthquake-induced secondary geohazards, relatively high-intensity reconstruction projects and improper activities may cause soil loss, which eventually occurs in water bodies and lakes (Liang et al., 2014), leading to swamping, as well as nonpoint source pollution, which can eventually be harmful to aquatic systems.

In addition to nonpoint source pollution, some materials used in construction contain toxics such as heavy metals, which will increase the risk of water pollution and water quality deterioration. A field investigation found that post-earthquake reconstruction projects increased the concentrations of zinc and other heavy metals in the soil around the project in Jiuzhai Valley (Sheng et al., 2020). To avoid such negative effects, construction management should be strengthened throughout the entire project. Materials containing less toxic or nontoxic components are encouraged, and the remaining materials should be cleaned and recycled immediately after finishing the construction. For areas with a potentially high risk of toxic pollutants, appropriate measures should be applied, such as using soil amendments to reduce the concentration of toxics. The results indicate that restoration methods and techniques are worthy of in-depth study.

Finally, unpredicted problems have occurred after ecological restoration projects. For example, ditches were built alongside the slope where landslides and debris flows occurred, aiming to prevent soil loss. However, due to the complex geological conditions in the Jiuzhai NNR, heavy rainfall triggered new debris flows, runoff did not necessarily follow the artificial ditches, and new erosion gullies appeared. As such, the intended purpose of soil and water conservation could not be achieved, threatening the littoral river systems and lakes. An example at Panda Lake (Xiongmao Hai) is shown in Figure 5. Considering that these reconstruction projects have been implemented, it is better to perform regular monitoring, analyze the existing problem, and implement corresponding remedies.

4.2.2 Pollutant management

Eutrophication is the greatest challenge except for swamping in the Jiuzhai NNR. Eutrophication occurs due to excessive nutrient loads, particularly phosphorus and nitrogen. There are two sources of phosphorus and nitrogen pollutants, endogenous and exogenous. The main potential source of endogenous pollutants is litter decomposition within the watershed (Xu et al., 2016; Zhang et al., 2021). The results from an investigation performed by the Jiuzhaigou Administrative Bureau showed that the closer the water body of a lake is to the land, the higher the concentrations of hydrolyzable nitrogen and available phosphorus are. Moreover, the litter decomposition rate in water bodies was higher than that on land. It is suggested that regular monitoring, cleaning, and collection of litter are necessary. A buffer zone can be established at the edge of the plant community to prevent litter from entering lakes if possible.

Regrading exogenous pollutants, atmospheric deposition is the major source in the Jiuzhai NNR. On the one hand, the increase in nitrogen deposition enhanced by human emissions combined with a warming temperature is conducive to the growth of algae in water bodies and increases the risk of eutrophication. On the other hand, atmospheric acid deposition, e.g., nitrogen and sulfur, will accelerate the acidification of water and destroy the unique travertine landscape. Studies have found that wet deposition is the main contributor to the accumulation of sulfate and inorganic nitrogen in the Jiuzhai NNR, with annual deposition amounts of 8 and 2.7 kg ha^{-1}, respectively, and that the pollutants mainly come from fossil fuels, agricultural activities, and scenic tourist buses

(Qiao et al., 2015; Qiao et al., 2016; Qiao et al., 2018). It is crucial to monitor and predict atmospheric acid deposition and to strictly control the source of pollutants within the Jiuzhai NNR, such as changing coal to other clean fuel in residents' daily lives and replacing gasoline tourist buses with electronic ones. Cooperation with adjacent cities around the Jiuzhai NNR to control the emission of air pollutants and agricultural nonpoint source pollution is also necessary to alleviate the impact of atmospheric deposition.

To reduce exogenous pollutants produced by tourists, it is necessary to restrict the number of tourists entering scenic spots. The more tourists there are, the more pollution there is and the worse the environmental quality is (Cao et al., 2016; Yuan et al., 2021). For example, the carbon dioxide concentration near a scenic spot in the valley was approximately 700 μL/L on average, increasing travertine loss (Qiu et al., 2022). A positive correlation was also found between the lake eutrophication diatom community and the number of tourists (Ouyang et al., 2016). Although the restricted number of tourists remains within the ecological footprint capacity of Jiuzhai Valley, instantaneous pressure for certain scenic areas may be an overburden and tourist density may exceed the local capacity. Taking Figure 6 as an example, a large number of tourists gathered at the Mirror Sea scenic spot even with the influence of COVID-19. Therefore, in addition to restricting the total number of tourists, new eco-friendly tourism policies, including the application of an instantaneous carrying capacity for tourists, should be further studied. Finally, as education is good for water-conservation behavior (Xiong et al., 2016), awareness education campaigns on civilized tourist behaviors should also be launched to conserve aquatic ecosystems.

5 Conclusion

A strong Ms 7.0 earthquake occurred at the Jiuzhai World Natural Heritage (WNH) Site in 2017, further increasing the risk of ecosystem degradation. Because the earthquake was the first to occur at one of China's world natural heritage sites and was a unique event globally, prior knowledge and mature methods for conserving the unique aquatic ecosystem were lacking. On the basis of reviewing recent achievements in postearthquake restoration at the Jiuzhai WNH site, this paper identified major challenges for further study, including 1) determining whether the 2017 earthquake caused fracture leakage and changed the hydrological process between the upstream and downstream regions of the Jiuzhai NNR, which is critical to maintain sufficient water for the Jiuzhai WNH Site; 2) clarifying the impacts of vegetation restoration and forest management on water yield, nutrient cycling and water quality; 3) studying restoration methods and techniques, given the occurrence of unpredicted problems after ecological restoration projects; 4) further exploring new eco-friendly tourism policies, especially in relation to the instantaneous carrying capacity of tourists, to directly lower the human-introduced pressure on the Jiuzhai WNH Site; and 5) seeking both scientific research and governmental collaboration to reduce endogenous and exogenous phosphorus and nitrogen pollutants in order to prevent eutrophication. The achievements and challenges summarized in this review may help enhance our understanding of the negative impacts of the earthquake on the Jiuzhai WNH Site and may provide critical highlights and scientific guidelines for conserving aquatic ecosystems, assisting not only managers of the Jiuzhai WNH Site but also managers, aquatic engineers and policymakers worldwide in the conservation of other aquatic ecosystems.

Author contributions

YX was responsible for the writing—original draft preparation, data processing and presentation, and visualization. JD was responsible for the writing—review and editing. GQ contributed to the methodology, supervision, project administration, funding acquisition review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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