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Sediment Source Fingerprinting and Its Control Strategies of the Lakes in Jiuzhaigou World Natural Heritage Site

Xiaoxue Shen [1], Ruili Li [1], Jie Du [2], Xianchenghao Jiang [1] and Guoyu Qiu [1,*]

[1] Guangdong Province Mangrove Engineering Technology Research Center, Peking University Shenzhen Graduate School, Shenzhen 518055, China
[2] Jiuzhaigou Administration Bureau, Jiuzhaigou 623402, China
* Correspondence: qiugy@pkusz.edu.cn; Tel.: +86-755-26033309

Abstract: Reliable quantitative information regarding sediment sources is essential for target mitigation, particularly in settings with a large number of loose provenances caused by earth disasters. The lakes in the Jiuzhaigou World Natural Heritage Site (WNHS) are facing serious environmental problems of silting and swamping, which threaten the sustainability of the area, especially after the earthquake on 8 August 2017 (the "8.8 earthquake"). Therefore, a field investigation was conducted after the "8.8 earthquake" (June 2020), and the Arrow Bamboo and Rhino Lakes, which were affected by the earthquakes to different degrees, were selected as the research objects. Based on the data of 27 environmental indicators from 31 surface sediment and soil samples in and around the lakes, the spatial distribution characteristics of the lake sediment sources were quantified using composite fingerprint recognition technology. Furthermore, a high protection standard of a WHNS and a process treatment scheme for reducing the siltation of the Jiuzhaigou lakes were proposed. The results showed that the contribution ratio of loose matter sources entering the lake on the road-side of the Arrow Bamboo and Rhino Lakes (16.5% and 21.8%, respectively) was lower than that on the forest-side (83.5% and 78.2%, respectively), indicating that physical barriers such as roads can effectively reduce the sediment input, while the lake forest side contributes a large number of loose matter sources, which has not attracted attention in the past and requires protection. High protection standards for the Jiuzhaigou WHNS are suggested. Accordingly, the entire control scheme of Jiuzhaigou lake sediment reduction including "monitoring–control–interception–buffer–cleaning" is provided. Source erosion monitoring is the first step in blocking the sediment source. Vegetation restoration and surface coverage should be conducted in areas where water and soil losses have occurred. Necessary engineering measures should be implemented to intercept loose material sources at points where geological disasters occur frequently. A buffer zone should be established between the lake and the mountain to intercept the sediment. Sediment caused by geological disasters with low interference must also be cleaned from the lake. The level of nutrients in the lake must be controlled by the regular cleaning of plant debris from the lake and lakeside.

Keywords: lake; sediment provenance; composite fingerprinting; prevention and control measures; World Natural Heritage Site; Jiuzhaigou

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1. Introduction

World Heritage Sites are internationally recognized as having the highest global conservation significance [1], which is of great practical significance for a high-standard of protection. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) adopted the Convention Concerning the Protection of the World Cultural and Natural Heritage on 16 November 1972, aiming to protect global common heritage of outstanding universal value. Thus, Jiuzhaigou in China has been established as a national nature reserve and a World Nature Heritage Site (WNHS) with high ecological, conservation, scientific, research, aesthetic, and tourism value. However, in recent years, due to the rapid development of tourism and its special geographical location, the local lake ecosystem has been facing a series of ecological environmental problems including water pollution [2], lake siltation and swamping [3], travertine degradation [4], and biodiversity threats [5,6], seriously endangering the sustainable beauty of the Jiuzhaigou WNHS.

One of the most serious and direct threats is the siltation of Jiuzhaigou lakes caused by earth disasters. Jiuzhaigou is frequently affected by earthquakes, landslides, collapses, and debris flows due to its unique geological environment. Jiuzhaigou belongs to the northwestern Sichuan fault block east of the Bayan–Kala block. Since 1876, fifteen earthquakes with Ms (surface wave magnitude) ≥6.0 have been recorded in the middle segment of the north–south seismic tectonic belt [7]. In particular, on 8 August 2017, a 7.0-magnitude earthquake (the "8.8 earthquake") with a focal depth of 20 km occurred 5 km from the core scenic area of Jiuzhaigou, causing 5563 co-seismic disasters in a 10.83 km^2 area including 5431 landslides and 132 debris flows. In addition, it was estimated that the source of the seismic damage in the 500 m buffer area of Panda Lake, Arrow Bamboo Lake, and Wuhua Lake in Jiuzhaigou covered as much as 41,140 m^3, 15,270 m^3, and 4878 m^3, respectively, accounting for approximately 2.29%, 1.64%, and 0.81% of the lake volume [8]. These loose provenances (especially the "8.8 earthquake") are bound to have a strong and far-reaching impact on the lakes of the Jiuzhaigou World Natural Heritage Site and increase the risk of lake siltation. Although the loose provenance in Jiuzhaigou has been identified, the manner and extent of its long-term impact on the lake are still unclear. The loose provenance around the lake flows into the lake from different directions, and quantitative analysis of its different spatial provenances is significant.

Sediment fingerprinting has been developed in recent years to directly evaluate sediment sources in basins but originated in the 1970s [9–11]. This technique is based on the following principles; (1) The screened fingerprint factors are significantly different among the potential sources in the basin; (2) the factors are stable during sediment erosion and transport, and their concentrations are relatively unchanged; and (3) the quantitative model based on the physical process of erosion and sediment yield in the watershed can estimate the contribution of potential sources [12]. Early studies have used a single sediment characteristic as a fingerprint, but it was later found that the use of composite fingerprints involving combinations of several characteristics could better distinguish several potential sources, reduce spurious matches, and more reliably estimate the relative contribution of potential sources [13,14]. Many soil and sediment properties have been used to fingerprint potential sources including mineralogy [15], geochemical and mineral magnetic measurements [16], sediment color [17], stable isotopes [18], soil enzymes [19], fallout radionuclides, and carbon and nitrogen parameters [20,21]. The composite fingerprint method has been widely used in the study of sediment source fingerprints, and fingerprint technology based on geochemical elements has become more common. Kroese et al. [22] used a multivariate Bayesian decomposition model to determine the main sediment source in an African smallholder watershed. Ahmady-Birgani et al. [23] quantified the relative contribution of each upstream geomorphic unit and determined the origin of the Lake Urmia dune, the second largest permanent salty lake in the world. Voli et al. [24] estimated the source of suspended sediments collected from tributaries entering Falls Lake. Fatahi et al. [25] estimated the subbasin spatial sediment source contributions in the arid Mehran River Basin in southern Iran based on the framework of generalized likelihood estimation (GLUE) and fingerprint analysis of the geochemical indicators. However, there has been no quantitative analysis of the spatial contribution of lake sediment sources in Jiuzhaigou, especially for the current situation where a large number of sources from seismic damage have entered the lake after an earthquake, increasing the risk of lake siltation, and the relevant research gaps must be filled.

However, past lake silting reduction measures in Jiuzhaigou have achieved certain results, and the loose source of matter produced by geological disasters has been reduced through engineering measures such as debris flow prevention and control [26]. The nutrient load input has been reduced through the restriction and coordination of tourist activities and local production and life [27,28], but the problem of lake siltation remains serious. Therefore, lakes with similar morphologies but different deposition degrees in the Jiuzhaigou core scenic area were selected for this study: Arrow Bamboo Lake and Rhino Lake (Figure 1). The areas around the lakes were divided into original forest land less disturbed by human activities and forest land along the highway with strong disturbance by human activities as the potential sediment source areas. Measuring the 27 environmental indicators, the potential source and contribution ratio of sediment in the Jiuzhaigou lakes were quantitatively analyzed based on the composite fingerprint method. Furthermore, considering the high standard protection principles of the ecological resources located in World Natural Heritage Sites, a set of feasible comprehensive management schemes with little landscape disturbance was proposed to provide decision-making guidance for the protection of these sites and the management of lake siltation.

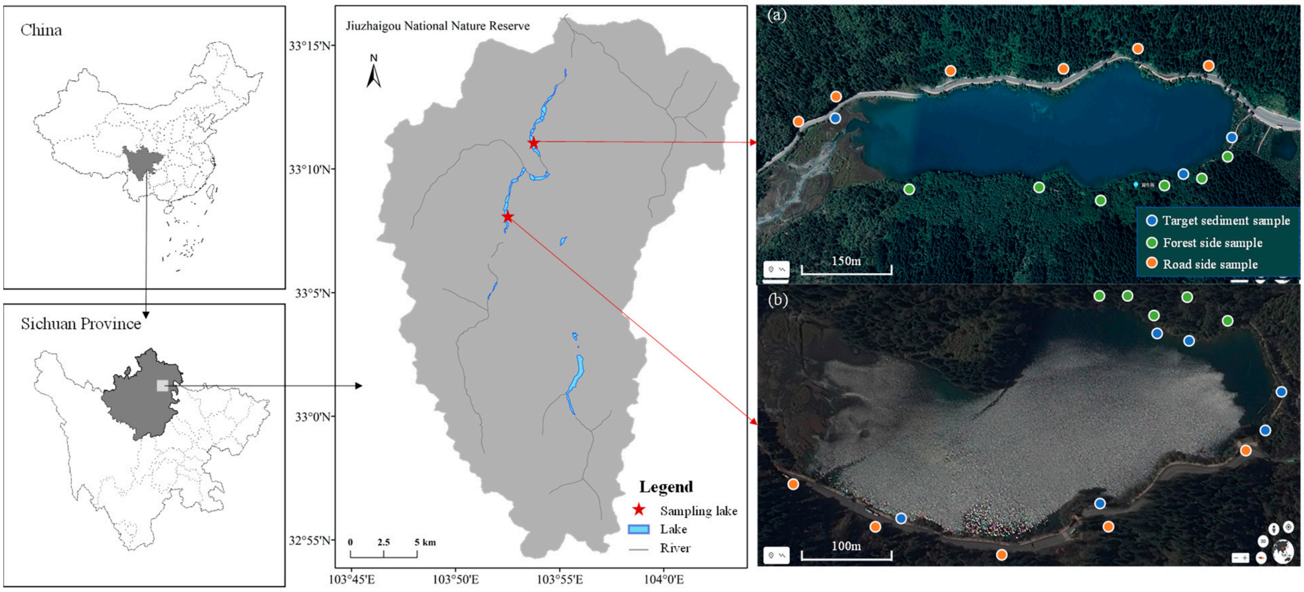

Figure 1. Study area (left and middle) and sampling sites (right). (**a**) Sampling sites at Rhino Lake; (**b**) Sampling sites at Arrow Bamboo Lake. The blue points in (**a**,**b**) are the target sediment samples, the green points are the forest side samples, and yellow points are the roadside samples.

2. Materials and Methods

2.1. Study Area

Jiuzhaigou was established as a national nature reserve in 1978 and a World Natural Heritage Site in 1992 with high ecological protection, scientific research, and aesthetic tourism value [29]. The Jiuzhaigou Nature Reserve (103°46′–104°05′ E, 32°53′–33°20′ N) is located in the south-central part of Jiuzhaigou County, Aba Tibetan Autonomous Prefecture, Sichuan Province [27] (Figure 1). The total protected area is 720 km^2, the peripheral protected area is 600 km^2, and the watershed area is 651 km^2 [27].

Jiuzhaigou belongs to the Baishuijiang River Basin in the peripheral mountainous area of the Sichuan Basin. The Shuzheng, Rize, and Zechazhuao gullies constitute the "Y" terrain [30]. The terrain is high in the south and low in the north, with towering peaks and deep valleys. Due to intense river cutting and erosion, the terrain is mainly an alpine valley area, with large fluctuations. The area is crisscrossed by valleys, and a dendritic water system has developed. The river network density is greater than 0.8 $km \cdot km^{-2}$ [31] with a width of less than 200 m and a maximum depth to width ratio of 37:1 [32]. Lakes are the main geomorphic type in the Jiuzhaigou valley floor, which is based on the structure, flowing water, and karst landforms of the original valley floor [33]; it was formed by travertine deposition and weir channel obstruction jointly promoted by climate, hydrodynamic conditions, hydrochemical characteristics, and biology [34,35].

Jiuzhaigou is located in the transition zone between the northern Sub-tropical Qinling–Daba humid region, the Qinghai–Tibet Plateau Bomi humid region, and the western Sichuan humid region [36]. The meteorological data at the center of Jiuzhaigou Nuorilang (103°52.24′E, 33°9.84′N; altitude: 2365 m) show that the average annual temperature in this area is 7.3 °C, the average temperature of the coldest month (January) is −8.7 °C, the average temperature of the hottest month (July) is 16.8 °C, the extreme minimum temperature is −17 °C, and the extreme maximum temperature is 32.6 °C, [32]. The annual duration of sunshine in Jiuzhaigou is approximately 1800 h, and the cumulative average daily temperature above 10 °C is 3000–3500 °C. The average annual rainfall in Jiuzhaigou is 760 mm [37], typically 700–800 mm. Precipitation is concentrated from April to October, accounting for approximately 70% of annual precipitation [38], and the annual precipitation change rate is approximately 10–15%. The annual relative humidity of Jiuzhaigou is 60–70%. The seasonal variation in humidity is consistent with that in rainfall. On a typical sunny day in the growing season, humidity shows great diurnal variation; it can vary from near saturation (~100%) in the early morning hours to extreme dryness (<10%) in the afternoon. The average annual wind speed in Jiuzhaigou from 2000 to 2013 was 0.5–1.2 $m \cdot s^{-1}$, and the wind direction was mainly northwest (NW) and south-southeast (SSE) [30].

The vegetation coverage rate in Jiuzhaigou exceeds 80%, and the forest coverage rate is approximately 65% [39]. It consists mainly of temperate and cold temperate plant communities, with a few subtropical plants.

2.2. Sampling and Laboratory Analysis

2.2.1. Sampling

In this study, field confirmation was conducted in June 2020, and based on the drainage distribution of Jiuzhaigou, Rhino Lake (the second-largest lake in the protected area) and Arrow Bamboo Lake were selected as they had similar lake morphologies but different earthquake influences. Basic morphological parameters are presented in Table S1. The environmental characteristics of the lakes are as follows. (1) Lake morphology: Both lakes are long and narrow, with water flowing from south to north and forest and road on both sides. However, the areas of the two lakes are different. The length of Arrow Bamboo Lake is 1184 m, and the length of Rhino Lake is 2000 m (Figure 1 and Table S1). (2) Degree of earthquake impact: From the damage degree of the lakeside and pedestrian plank roads, the degree of damage of Arrow Bamboo Lake was significantly higher than that of Rhino Lake. The Arrow Bamboo Lake road was almost "paralyzed" as the mountain earthquake damage source was large, and the Rhino Lake road side mountain had different degrees of landslides, but the road damage degree was better than that of Arrow Bamboo Lake. In addition, the forest-side boardwalk in Arrow Bamboo Lake was damaged, and there was an obvious mountain debris flow with a length of approximately 50–100 m, while the forest-side boardwalk in Rhino Lake was only slightly affected and could be visited normally by pedestrians (Figure 2). (3) Spatial distribution characteristics of lake siltation and swamping: Both lakes showed a higher degree of swamping development at the inlet and outlet; however, the comprehensive index value of Rhino Lake was slightly higher than that of Arrow Bamboo Lake [40].

The multipoint mixing method was adopted to collect the surface soil and sediment around the lake. First, dead branches and leaves were removed using shovels. Five 0–2 cm surface soil samples were collected at each sample point and mixed evenly, 1 kg of which was placed in the sample bag and marked accordingly. All sampling points were located using GPS (Figure 1). A total of 15 samples were collected from three lake surface sediment samples (blue markers) and 12 lake surface soil samples (yellow markers; six samples from roadside topsoil; green markers; and six samples from forest-side topsoil) at Rhino Lake. A total of 16 samples were collected from six lake surface sediment samples (blue markers) and ten surface soil samples (green markers; five samples from forest-side topsoil; yellow markers; five samples from roadside topsoil) at Arrow Bamboo Lake.

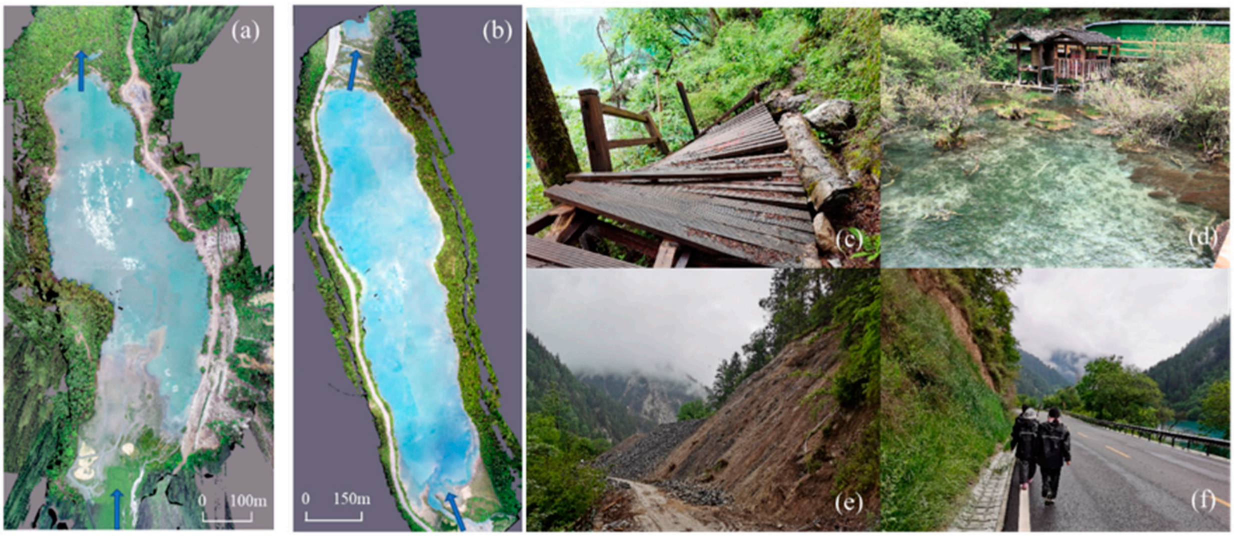

Figure 2. Digital orthophoto maps of (**a**) Arrow Bamboo Lake and (**b**) Rhino Lake (2020). (**c**,**e**) Field photos of the forest-side and road-side of Arrow Bamboo Lake, respectively; and (**d**,**f**) field photos of the forest-side and road-side of Rhino Lake, respectively.

2.2.2. Laboratory Analysis

Samples were collected on-site, bagged, numbered, and immediately transported to the laboratory. The samples were freeze-dried immediately for subsequent analyses.

Determination of the basic physicochemical properties. The soil moisture content was measured using the freeze-drying method. Soil pH and salinity were measured using calibrated pH (PB-10, Sartorius Inc., Göttingen, Germany) and conductivity meters (Laboratory Benchtop Meters, Shenzhen, China), respectively, with a sediment-to-water ratio of 1:5 (w/v). Particle size was measured using a laser particle sizer (Mastersize 3000, Malvern Panalytical Inc., Westborough, MA, USA). Sediment particle size was classified as clay (<4 μm), silt (4–63 μm), and sand (>63 μm) [3].

Total carbon (TC), total nitrogen (TN), and total phosphorus (TP) contents. TC and TN in the soil samples were determined using an elemental analyzer (V ario EL III Elementar, Hanau Germany Inc., Hanau, Germany). TP was determined by referring to standard HJ 632-2011 "Determination of total phosphorus in soil-alkali fusion-molybdenum-antimony resistance spectrophotometric method"; a sieve of 100 mesh dry soil sample was fused with sodium hydroxide and reacted with the molybdenum-antimony anti-color reagent under acidic conditions to produce molybdenum-blue, and the absorbance was measured at a wavelength of 700 nm. Based on different concentrations of the phosphorus standard solution, a standard curve was drawn, and the concentration of P in the sample was reversely derived.

Determination of metal element concentration. For the total metal analysis, sediment samples (0.1 g) were digested with 9 mL HNO_3, 3 mL HF, and 3 mL HCl in a microwave digestion system (MARS Xpress; CEM, Matthews, NC, USA). The concentrations of 18 metal elements: K, Mg, Mn, Cd, Co, Cr, Cu, Ni, Pb, Zn, Sb, Sn, Sr, Ca, Na, Fe, Al, and Ti were measured using inductively coupled plasma-mass spectrometry (ICP-MS) (iCAP Q ICP-MS, Thermo Fisher Inc., Waltham, MA, USA). Laboratory quality control consisted of the analysis of soil and sediment reference materials (GBW-07310; National Institute of Metrology, Beijing, China) and triplicate samples. The recoveries all fell within the range of 96.24–102.89%.

2.2.3. Acquisition and Processing of Unmanned Aerial Vehicle (UAV) Images

The Jiuzhaigou UAV visible light image data were acquired using a low-cost DJI Phantom 4 Pro quadcopter (SZ DJI Technology Co., Shenzhen, China). To increase the accuracy and reliability of the photogrammetric modeling, DJI GS Pro software was used to set the automatic cruise shooting of the UAV. The flying height was set to 20–120 m above the ground, with 85% forward overlap and 75% side overlap. During the flight, the visible-light camera on the UAV automatically captured pictures at an interval of two seconds. During the flight, every time a photo was taken, the location information of the UAV (longitude, latitude, altitude, etc.) was recorded in the photo for later modeling. The total number of 3D modeling photos for Rhino Lake and Arrow Bamboo Lake was 1054 and 1033, respectively. Based on Context Capture software (Bentley, V10.15.0.21), the image matching of UAV visible images, automatic aerial triangulation, and finally, the digital orthophoto images in the TIFF format were extracted (Figure 2).

2.3. Sediment Fingerprinting Analysis

2.3.1. Selection of the Optimum Composite Fingerprints

Collins et al. [41] were the first to formally propose the use of a non-parametric Kruskal–Wallis H test for multiple independent samples to identify discriminant fingerprint factors in numerous soil attributes and the use of multiple discriminant analysis (DFA) to achieve optimal combination screening of the fingerprint factors. This statistical method has been widely used in sediment source studies [42,43].

This study used IBM SPSS Statistics software (Version 26) and multivariate discriminant analysis to determine the optimal combination of fingerprint factors [44]. Specifically, the factors with significant differences ($p < 0.05$) obtained by the Kruskal–Wallis H test were used to perform multiple stepwise discriminant analysis and screen a group of fingerprint factor combinations with the most statistical significance. The most commonly used method in this analysis is the Wilks' Lambda algorithm, that is, the fingerprint factor combination obtained when the Wilks' Lambda value is the minimum of the best selected fingerprint factor combination [45]. Moreover, the correct discrimination rate of multiple discriminant analyses is required to reach 70% for a better discrimination effect [12].

2.3.2. Multivariate Mixed Model of Compound Fingerprint Recognition Technology

Due to the small area of the study and the focus on the peripheral area of the lake, the multivariate mixing model was adopted to analyze the sediment source [12] (i.e., based on the principle of the least squares method) to obtain the minimum value of the polynomial, mixing, and model, and the result was intended to be the optimal solution of the mixing model (i.e., the contribution of each sediment source). The multivariate mixed model is as follows:

$$R_{\text{es}} = \sum_{i=1}^{n} \left\{ \left[C_i - \left(\sum_{s=1}^{m} P_s S_{\text{si}} \right) \right] / C_i \right\}^2 \quad (1)$$

$$\sum_{s=1}^{n} P_s - 1 \quad (2)$$

$$0 \leq P_s \leq 1 \quad (3)$$

where R_{es} is the sum of residuals squared; C_{i} is the concentration of tracer property i in the suspended sediment sample; S_{si} is the mean concentration of tracer property i in the source groups; P_{s} is the relative proportion from the source groups; n is the number of fingerprint properties comprising the optimum composite fingerprint; and m is the number of sediment source categories. In addition, two preconditions must be satisfied when applying the function formula: (1) the contribution percentage of the sediment source area is 1; and (2) the model is constrained by the requirements that proportional source contributions lie between 0 and 1.

In this study, the selected composite fingerprint identification factor data and experimentally measured sediment data were used as the basic data, and the loading macro programming in Excel was used to solve and calculate the multivariate mixed model and quantitatively calculate the contribution of each sediment source to the sediment [46].

2.3.3. Reliability Test of Sediment Source Discrimination

In this study, the statistical measure, goodness-of-fit (GOF), was applied to assess the discriminant results [47], that is, to test the relative difference between the measured sediment fingerprint factor attribute value and that determined by the model. The calculation formula is as follows:

$$\mathrm{GOF} = \left\{ 1 - \frac{1}{n} \sum_{i=1}^{n} \left| C_i - \left(\sum_{s=1}^{m} P_s C_{si} \right) \right| / C_i \right\} \times 100\% \quad (4)$$

It is generally believed that when GOF >0.8, the multivariate mixing model calculation results are acceptable [41].

3. Results and Discussion

3.1. Identification and Screening of Fingerprint Factors of Lake Sediment Sources

Soil grain size [48], TC, TN, and TP [15], and the major and trace elements (including rare earth elements) [15,49] are widely used in fingerprint identification analysis. In this study, the grain size distribution in different source areas of Arrow Bamboo and Rhino Lakes were mainly composed of silt and gravel, and clay accounted for the smallest proportion (2.5–9.8%) (Figure S1). The proportion of each grain size in the sediments of the two lakes was between the soil on the forest-side and that on the highway (except for the proportion of clay particles in Arrow Bamboo Lake, Figure S1). The contents of TC, TN, and TP in the sediment and surrounding soil of Rhino Lake were higher than those of Arrow Bamboo Lake, especially in the soil on the forest-side (except for the contents of TC and TN on the highway side, Figure S2), and there were differences between the spatial distributions of nutrient elements in the sediments of the two lakes and the soil from different sources. The concentrations of metal elements in the sediments and surrounding soil of Rhino Lake were also higher than those of Arrow Bamboo Lake (except that the contents of Ca, Mg, Al, Fe, and Mn in the sediments and surrounding soil and Cd in the lake sediments of Arrow Bamboo Lake were higher than those of Rhino Lake), but the contents of the same heavy metals in different sources of the two lakes were different (Figure S3). This indicates that the soils in the different source areas of the two lakes are different.

The Kruskal–Wallis (KW) H-test (Kruskal–Wallis non-parametric test) was used to verify the data, whose core idea is to calculate the rank of each variable value after ascending and sorting multiple groups of sample data and then introducing variance analysis [46]. Preliminary screening was conducted for 27 alternative fingerprint factors in various sources and soils of Arrow Bamboo and Rhino Lakes to exclude factors with insignificant differences in potential sources. The analysis results showed that the p values of seven indices including Cd, Sn, Sb, Na, K, Al, and F, were less than 0.05, whereas the p values of 11 indices including C%, Silt %, Cu, Zn, Sr, Na, K, Mg, Ca, Al and Fe were less than 0.05. Through the test, as the fingerprint factor was preliminarily screened, these indices can be used for multivariate stepwise discriminant analysis (Table 1). The p values of the other indices were greater than 0.05, indicating that there was no significant difference in the content of these elements in all source types, which did not meet the screening conditions of the fingerprint factor. Therefore, these 16 factors were removed and not included in the next stage of discriminant analysis.

Table 1. Results of the Kruskal–Wallis H-test at Arrow Bamboo and Rhino Lakes.

	Arrow Bamboo Lake		**Rhino Lake**	
Latent Fingerprint Factor	***H*-Value**	***p*-Value**	***H*-Value**	***p*-Value**
TP	1.159	0.560	4.593	0.101
Water Content	1.734	0.420	4.543	0.103
pH	0.189	0.910	6.055	0.048 *

Table 1. *Cont.*

	Arrow Bamboo Lake		Rhino Lake	
Latent Fingerprint Factor	***H*-Value**	***p*-Value**	***H*-Value**	***p*-Value**
Salt Content	0.052	0.974	2.072	0.355
C%	1.922	0.382	6.802	0.033 *
N%	0.228	0.892	4.692	0.096
Clay%	0.193	0.908	4.308	0.116
Silt%	1.699	0.428	6.352	0.042 *
Sand%	1.42	0.491	4.945	0.084
Ti	0.735	0.692	4.308	0.116
Cr	4.412	0.110	4.857	0.088
Co	0.934	0.627	4.692	0.096
Ni	2.369	0.306	5.736	0.057
Cu	0.171	0.918	6.407	0.041 *
Zn	2.946	0.229	6.879	0.032 *
Sr	2.929	0.231	6.879	0.032 *
Cd	10.816	0.004 *	4.209	0.122
Sn	8.722	0.013 *	4.308	0.116
Sb	7.729	0.021 *	2.945	0.229
Pb	0.735	0.692	5.231	0.073
Na	8.782	0.012 *	9.692	0.008 *
K	11.016	0.004 *	9.692	0.008 *
Mg	3.400	0.183	9.308	0.010 *
Ca	2.059	0.357	9.308	0.010 *
Al	8.647	0.013 *	9.692	0.008 *
Mn	2.147	0.342	5.967	0.051
Fe	8.647	0.013 *	9.308	0.010 *

Note: * means significant at the level of 0.05.

3.2. The Best Combination of Fingerprint Factors for Lake Sediment Sources

Multivariate discriminant analysis introduced new fingerprint factor variables one by one through the "some in, some out" method and gradually removed the independent variables with no statistical significance after the introduction of new variables [50]. The correct discriminant rate of multivariate discriminant analysis should reach 70%, and the discriminant effect should be good [12]. In this study, multiple discriminant analysis was performed on the fingerprint factors of Arrow Bamboo Lake (seven types) and Rhino Lake (11 types). The results showed that Cd and K were the best fingerprint factors for the Arrow Bamboo Lake, forming the best fingerprint factor combination. Wilk's Lambda value changed from 0.603 to 0.176, and the discriminant ability reached 88.9%, showing a good discriminant effect (Table 2). K, Al, Fe, and Na were established as the best fingerprint factors and formed the best combination of fingerprint factors. Wilk's Lambda value changed from 0.011 to 0.002, and the discriminant ability reached 100% with better discriminant effect (Table 2). The overall correct and discriminant rates of the best combination of factors in the sediment sources of Arrow Bamboo Lake and Rhino Lake exceeded 80% (Table 3).

Table 2. Optimum composite fingerprint and classification accuracy at Arrow Bamboo and Rhino Lakes.

Lake	Step	Fingerprints	Single Factor Discrimination Accuracy	Wilk's Lambda	Cumulative Discrimination Accuracy
Arrow Bamboo Lake	1	Cd	62.5%	0.603	62.5%
	2	K	81.3%	0.176	88.9%
Rhino Lake	1	K	64.6%	0.011	64.6%
	2	Al	71.3%	0.016	75.9%
	3	Fe	59.4%	0.012	92.3%
	4	Na	67.2%	0.002	100%

Table 3. Discriminant results of the composite fingerprints at Arrow Bamboo and Rhino Lakes.

Lake	Index	Sediment source	Predicted Group Membership		Total
			Forest	Road	
Arrow Bamboo Lake	Count	Forest	4	0	4
		Road	1	4	5
	Discrimination accuracy (%)	Forest	100%	0	100%
		Road	20%	80%	100%
Rhino Lake	Count	Forest	6	0	6
		Road	0	6	6
	Discrimination accuracy (%)	Forest	100%	0	100%
		Road	0	100%	100%

Note: 88.9% and 100% of the samples from Arrow Bamboo and Rhino Lakes in the initial grouping cases were correctly classified.

3.3. Sediment Contribution and Reliability of Lake Sediment Sources

The results showed that the sediment contribution ratios of Arrow Bamboo and Rhino Lakes were 83.5% and 78.2% on the forest-side and 16.5% and 21.8% on the roadside, respectively (Figure 3). The average GOF values were 0.818 and 0.887, respectively (GOF > 0.8). The test results were reasonable. The proportion of sediment contribution from the forest side was much higher than that from the highway side in the surface sediments of the two lakes. Based on the analysis of the field investigation, the main reason is that both Arrow Bamboo Lake and Rhino Lake were affected by the entry of the seismic sources into the lake, while it was relatively difficult for the seismic sources on the road-side to enter the lake because of the physical barrier of the highway. In addition, because of the timely implementation of road dredging (clearing, compaction, etc.) after the earthquake, the source of the seismic damage from the mountain on the road-side could not continuously gather in the lake; thus, the contribution ratio was relatively low (Figure 2).

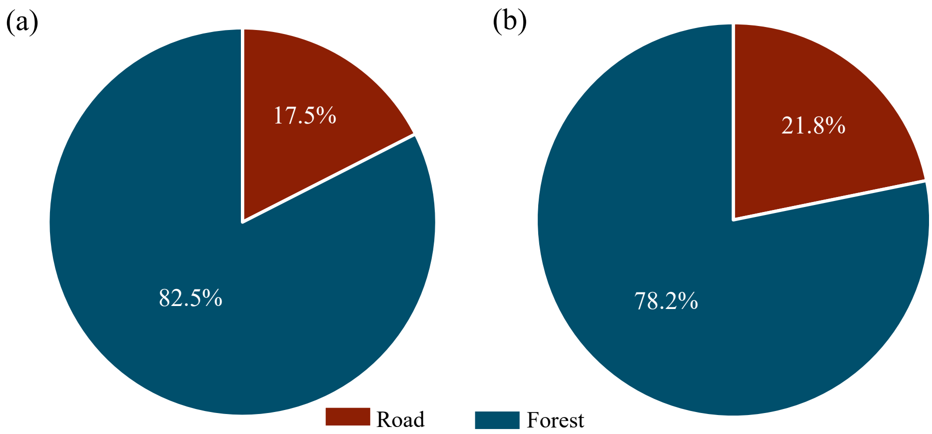

Figure 3. Contribution ratio of different sediment sources at (**a**) Arrow Bamboo Lake and (**b**) Rhino Lake.

In addition, the difference value of the sediment contribution ratio between the forest-side and road-side of Arrow Bamboo Lake was significantly larger than that of Rhino Lake because (1) there was an obvious landslide on the forest-side of Arrow Bamboo Lake, and a large source of seismic damage flowed directly into the lake (Figure 2a), while the seismic damage on the forest side of Rhino Lake was relatively light (Figure 2b). Moreover, during the field investigation, the Arrow Bamboo Lake forest-side walkway was found to be seriously damaged and impassable (Figure 2c), while the earthquake had little impact on the Rhino Lake forest-side walkway (Figure 2d). As the walkway itself could play a role in buffering the source of seismic damage, the proportion of sediment contribution on the forest-side of Rhino Lake was slightly lower than that of Arrow Bamboo Lake. (2) From the point of view of the roadside, although the road in Arrow Bamboo Lake was nearly paralyzed (Figure 2e), the road condition of Rhino Lake was better (Figure 2f), but both played obvious physical barrier roles, especially at Arrow Bamboo Lake.

3.4. Measures and Countermeasures for Alleviating Sedimentation in Jiuzhaigou Lakes

The results of this study showed that the provenance input around the Jiuzhaigou lakes after the earthquake cannot be ignored, and that physical obstructions such as roads can effectively reduce the sediment input around the lake. However, the lake–forest side contributed a significant amount of loose provenance, which has not been studied previously. In addition, our early results showed that the lake sediment and marsh development patterns in Jiuzhaigou were characterized by "shore invasiveness", and there was an increasing trend of aquatic plants in the lake [40]. At present, for the lake sediment problem in Jiuzhaigou, the administrative departments of the area have introduced a series of ecological and environmental protection policies, which have effectively reduced soil erosion caused by human activities (agricultural activities, deforestation, etc.). However, due to the special geographical location and topography of this area, frequent geological disasters have produced a large number of loose provenances, which has aggravated the risk of lake siltation. In particular, the "8.8 earthquake" changed the mountain surface structure, damaged stability, caused the reduction in the mudslide triggered threshold, and would also continue to threaten the lakes, in spite of the debris flow prevention and control measures, but several studies have suggested that the prevention and control works after the earthquake (completed in May 2019) failed to effectively protect the debris flow caused by the rainstorm with a 2-year rainfall return period. In addition, there has been a lack of attention to lake biofouling in Jiuzhaigou and a lack of necessary prevention and control measures; the control of lake nutrient levels must be implemented with stricter standards. Therefore, to maintain the sustainable beauty of the Jiuzhaigou WNHS, it is urgent to formulate high standards for the protection and management of natural heritage sites as well as a systematic governance plan that focuses on both external and internal control.

Therefore, this study first proposed the following four high standards. (1) Increased evaluation standards from that of an ordinary water landscape. Water quality assessment standards for ordinary water bodies can only identify and assess water body pollution. The assessment standards for water bodies such as the Jiuzhaigou lakes should be upgraded to more stringent pollution ratings and focus on the stability of longer time scales. (2) Protection standards based on aesthetic value. Jiuzhaigou attracts tourists both at home and abroad because of its unique natural landscape. If we take large-scale artificial structural measures to pursue the effect too quickly, the beauty of landscape resources will be greatly affected. Therefore, ecological prevention measures coordinated with the landscape resources are urgently needed. (3) Protection standards based on scientific values. Jiuzhaigou has joined the World Network of Biosphere Reserves, with a forest coverage rate of more than 80% and rich biodiversity. Therefore, it is necessary to strengthen the scientific research and adopt conservation strategies based on natural restoration, supplemented by artificial restoration to maximize the protection of local natural resources. (4) Criteria for sustainable development. Instead of looking at the current governance from a limited perspective, landscape resources should be protected over a longer time dimension. This standard requires that our protection methods be as simple and feasible as possible, reducing artificial traces. These measures can continue to work even with personnel change in the protection subject (management, specific executors, supervisors, etc.).

Based on the above criteria, this study proposes an integrated control scheme for the workflow closed loop as follows.

Monitoring. Jiuzhaigou is located in an area of frequent geological disasters. Earthquakes have not only triggered a large number of landslides, collapses, debris flows, and other secondary geological disasters, but also destroyed the original mountain structure, surface soil, and vegetation, reduced the threshold of debris-flow-triggered rainfall, and increased the risk of hidden dangers in the years and even tens of years after an earthquake. Large-scale debris flows caused by heavy rainfall pose a serious threat to lake siltation.

Therefore, early monitoring and accurate locating of geological disaster points are essential for eliminating the source of loose materials. Traditional remote sensing interpretation of satellite monitoring has a certain lag and limited accuracy. Thus, UAVs should be introduced to provide high-precision remote sensing image data, and UAV images used to generate high-resolution orthographic maps of landslides and digital terrain models of interferometric synthetic aperture radar (InSAR). Other technologies have been used to monitor surface deformation, obtain landslide boundaries, quickly draw landslide maps, and analyze spatial distribution and quantitative characteristics [51].

Control. Based on the results of geological hazard monitoring, for areas with serious soil erosion such as exposed sheet-like landslide zones, ecological restoration should be prioritized while considering local conditions to further control the expansion of soil erosion areas. Tree species that are suitable for living in the surrounding habitat and that increase the coverage of surface vegetation should be planted to optimize the soil structure and reduce soil erosion. Considering that the enhancement of soil compaction runoff in the early stages of vegetation restoration is not conducive to soil and water conservation, mulch can be appropriately added to the soil surface to improve the infiltration and interception ability of rainfall. For the selection of mulch, based on the scientific value of protection criteria, plant debris from nearby branches and leaves can be used as they play a role in coordinating the natural landscape. In addition, based on different terrain characteristics, appropriate engineering measures can be adopted to control soil erosion in a large area such as the construction of silt dams and trench construction. However, unlike the engineering measures taken in general areas, the Jiuzhaigou scenic area has no agricultural production and no regular or cash crops in demand. Therefore, it is necessary to consider the plants that grow well under natural conditions, coordinate with the surrounding landscape, and conform to local characteristics.

Interception. For the frequent points of earth disasters and areas with large potential earth disaster risk detected by monitoring, necessary engineering measures should be made such as installing retaining walls, check dams, and filter dams to intercept the earth disaster source. Although we have emphasized that the protection of the Jiuzhaigou WNHS should follow high standards and avoid artificial measures, because the scenic area itself in the high incidence area of geological disasters, even excluding the factor of human activity, there are still many earthquake hazard points, based on the consideration of sustainable ecological resource development, that need special protection in key areas. Check dams are suitable for the flow zone of debris flow gullies, where the steep slope changes to a gentle slope. Grille dams are used to store large solid materials to separate water and soil, and gap and comb dams are mainly used to block driftwood and prevent blockage. Based on the development of debris flows and the surrounding geological characteristics, appropriate engineering measures have been selected for effective source interception [52].

Buffer. Based on the results that loose provenances near the mountain side have a greater contribution to lake siltation, a mountain and lake buffer zone can be set up to protect the lake. At present, the lake side of the mountain has a plank road for tourists on foot, and solid matter or runoff from the mountain can still enter into the lake below the plank road, suggesting the installation of a drainage channel near the plank road to intercept runoff from rain or gravity into the lake sediment, based on the actual situation of regular intercept sediment cleaning and maintenance.

Clean up. The accumulated sediment must be cleaned. Affected by earthquakes such as the accumulation of earthquake-damaged material around certain lakes in Wuhua Lake, several large-scale mountains and falling rocks have accumulated near the lakes [40]. For rock falls and sediments that have entered the lake and are clearly damaging the lake landscape, a clean-up plan should be developed to remove these deposits with minimal impact on the lake, restore the natural form of the lake, and protect its landscape value. However, biofouling requires cleaning. It is suggested that the plant remains in the lake, and the lakeside should be regularly salvaged and cleaned to reduce nutrient re-release into the lake. Combined with the third measure, the debris can also be used as a natural mulch to cover the topsoil of severely eroded plots and enhance soil and water conservation.

4. Conclusions

The contribution of this study was based on 31 environmental samples and 27 environmental indicators obtained during the earthquake recovery period (June 2020) of the 8 August 2017 earthquake at the Jiuzhaigou WNHS. The contribution ratio of provenance input to the surrounding source areas of the Jiuzhaigou lakes was quantitatively analyzed for the first time using composite fingerprint analysis. This is of great practical importance for the control of lake siltation in Jiuzhaigou and for the maintenance of the sustainable beauty of the Jiuzhaigou WNHS. Our results show that the contribution of loose sources from the road-side to the lake of Arrow Bamboo Lake and Rhino Lake (16.5% and 21.8%, respectively) was much lower than that from the forest side (83.5% and 78.2%, respectively), indicating that physical barriers such as roads could effectively reduce the sediment input around the lake, while the lake and forest sides contributed a large amount of loose sources, which have not been examined in the past. Therefore, this study further suggests high protection standards based on the positioning of the Jiuzhaigou WNHS. Accordingly, we developed a set applicable to the lakes in Jiuzhaigou "external defense", "internal control", and the whole sedimentation reduction scheme involving "monitoring–control–intercept–buffer–clean up", which is expected to provide scientific guidance for lake sedimentation reduction at the Jiuzhaigou WNHS. Finally, the entire process and driving mechanism of the loose matter source entering the lake from the mountain through rainfall or gravity after an earth disaster remain unclear. In the future, the mechanism of loose matter sources entering the lake may be further analyzed in combination with runoff plot experiments to provide more accurate decision-making guidance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14233954/s1, Figure S1: Particle size distribution of different origins in Arrow Bamboo and Rhino lakes; Figure S2: Distribution of TC, TN, and TP content in different land types near Arrow Bamboo and Rhino lakes; Figure S3: Distribution of heavy metal content in different land types from Arrow Bamboo and Rhino lakes; Table S1: Basic parameters of the lakes in Jiuzhaigou Valley World Natural Heritage Site. [15,48,49,53].

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