The impact of stress factors from three land-use patterns on riparian zones degradation located within mega-reservoirs and around dams in China

Muhammad Arif[1], Zheng Jie[1], Muhammad Tahir[2], Hu Xin[1], and Changxiao Li[1]

[1]Southwest University
[2]Sasol Germany GmbH Brunsbuttel

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Abstract

There is currently a lack of evidence surrounding changes in the health of riparian zones under different land-use patterns within mega-reservoirs and around dams. Scientific evidence for the quantitative effects of stress indicators is vague and varies significantly among reservoirs and dams worldwide. In this study, we used a field-based approach to evaluate riparian health changes—influenced by pressure indicators—across 274 transects from three land-use areas (rural, rural–urban transitional, and urban) in the Three Gorges Dam Reservoir (TGDR) in China during 2019. Multivariate statistical techniques were applied to test for riparian zone changes under these variant land-use patterns. Our results showed that 13 pressure indicators significantly influenced 27 health indicators (including parameters for habitat, plant cover, regeneration, erosion, and exotics) of the riparian zones from the three land-use areas differently. Our results also showed that parameters for plant cover, erosion, and exotics were major contributors within the selected riparian health indicators, whereas land-use designs, farming systems, and pollutant activity variables were the pressure indicators with the strongest impact. Pearson correlation (with r ranging from -0.731 to 0.989) showed that urban transects exhibited the strongest comparative interaction, whereas rural–urban transitional transects formed the weakest association. Furthermore, the agglomerative hierarchical cluster analysis revealed similarities between rural and rural–urban transitional sites while confirming substantial dissimilarity in urban locations. These comprehensive and relevant results provide essential information for reservoir administrators to implement functional changes suited to TGDR land-use scenarios.

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Muhammad Arif [1, 2], Zheng Jie[1], Muhammad Tahir [3], Hu Xin[1], and Li Changxiao [1, 2, *]

1. Key Laboratory of Eco-Environments in the Three Gorges Reservoir Region (Ministry of Education), College of Life Sciences, Southwest University, Chongqing-400715, China; muhammadarif@swu.edu.cn (M.A.), jiezheng@email.swu.edu.cn (Z.J.), sthuxin@email.swu.edu.cn (H.X.), lichangx@swu.edu.cn (L.C.)
2. Biological Science Research Center, Academy for Advanced Interdisciplinary Studies, Southwest University, Chongqing-400715, China
3. HOT Microfluidics GmbH, Goslar-38640, Germany; mtahir@hoteng.com (M.T.)

Correspondence: Li Changxiao, Key Laboratory of Eco-Environments in the Three Gorges Reservoir Region (Ministry of Education), College of Life Sciences, Southwest University, Chongqing-400715, China; Email: lichangx@swu.edu.cn; Tel.: +86-23-68252365

Running heading: **Changes in reservoir riparian health conditions**

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Keywords: land-use patterns, rapid appraisal, stress indicators, quantitative assessment, riparian health condition, Three Gorges Dam Reservoir

1. Introduction

Human activities have caused substantial disorder in reservoir riparian zones across several countries (Arif et al., 2021; He et al., 2020), such as deterioration caused by urbanization and other industrial development (Belete et al., 2020; Bombino et al., 2019). Riparian zones ensure preliminary reservoir safety and, ultimately, naturally improve water quality on a large scale (Mello et al., 2018; Shahariar et al. 2021). Reservoirs and lakes are essential water sources that promote human welfare, production, and life-cycle conservation, and they provide 90% of the biosphere's freshwater (Dai et al., 2017). Reservoir riparian zones are biodiversity hotspots that form some of the world's most important natural ecological landscapes (Tape et al., 2016; Yu et al., 2016). However, these buffer zones are also among the most sensitive and non-recoverable natural ecosystems. Despite the increasing positive global effect of reservoirs, their riparian zones are changing and deteriorating owing to variations in land-use patterns (Dempsey et al., 2017; Weldegebriel et al. 2021). The impacts of land-use patterns on riparian health are complex (Castillo et al., 2012), and there is an urgent need to understand the relationship between land-use variation and the condition of riparian zones in reservoirs (Mello et al., 2018; Yu et al., 2016). Research on this topic is a prerequisite for managing large dams; it would produce vital information to help determine the potential impacts of land-use changes on the riparian zones of large reservoirs such as the Three Gorges Dam Reservoir (TGDR).

Due to the demand for urban and industrial land use, natural land surfaces are repeatedly converted to artificial land surfaces, consequently weakening marginal areas and causing increased heavy-metal loads and low water quality (Woźniak et al., 2022; Yu et al., 2016). These changes directly modify the land's physical features and alter riparian ecosystems along with their associated biodiversity, instream habitats, and water characteristics (Bombino et al., 2019; Puntenney-Desmond et al., 2020; Tape et al., 2016). Land use with a higher level of human activity, including industrial, commercial, residential, and transport activities, tends to permanently impact the riparian zone (Bombino et al., 2008; Catford et al., 2013; Galia et al., 2016). In earlier quantitative studies, negative correlations were found between artificial land use and riparian ecosystems (Rivaes et al., 2015; Shieh et al., 2007). However, the relationships between riparian health conditions and pressure activities, such as agricultural cropping and the implementation of farming systems, are more complicated. Previous studies have indicated that land-use changes and extensive environmentally unfriendly events might influence the vegetation in buffer zones, thereby significantly affecting riparian health and rapidly altering the area's physical features (Castillo et al., 2012; Sowińska-Świerkosz et al., 2014; Tao et al., 2020). Multipurpose studies have been conducted on riparian zones in various parts of China, as well as worldwide, and their impacts were assessed under different land-use scenarios (Yu et al., 2016; Zheng et al., 2021a). However, the literature is limited in terms of studies investigating the riparian zone response against pressure indicators from variant land-use patterns in extra-large reservoirs and around mega-dams such as the TGDR. Therefore, there is an urgent need to examine how riparian zones react under different land uses to ensure the conservation and sustainable management of these ecological landscapes.

However, land-use effects may vary in buffer zones depending on their particular use (Ferreira et al., 2005). Agricultural activities significantly affect rural sections, while concrete structures impact urban areas (Zheng et al., 2021b; Petts & Gurnell, 2005). Results from quantitative studies that compared correlations between near- and far-field developments showed a higher correlation in the near-field events, confirming that pressure impact was progressive within these regions, owing to their limited width (Johansen et al., 2007). Therefore, there is a need to understand the relationship between land use and riparian health variables on different scales. Such an understanding would be critical to the logical establishment of the whole riparian catchment zone and support the monitoring process.

Similarly, watershed protection strategies are mainly subject to the land-use patterns and management practices of individual regions (Nilsson & Svedmark, 2002). The demand for effective policies in China is at present higher than in the 1950s. The increasing population incentivizes planners to introduce substantial developments in the agricultural sector to meet the public's needs, which is the principal factor that resulted in the status change of water bodies. The area reduction ratio is particularly high for these water bodies, increasing from 135 to 8,700 km^2 from the 1970s to 2016 (Dai et al., 2017). The Chinese government is continuously implementing strategies to conserve water resources at the national level and is building new dams to ensure the optimal use of water sources. Due to the long history of human settlement in the area, the rivers in southwest China are among the most threatened ecosystems (Yuan et al., 2021), and their riparian zones are susceptible to prolonged submergence (Sarneel et al., 2019). Since big reservoirs can hold water for an extended period, riparian ecosystems and biodiversity can quickly deteriorate in reservoir regions (Zheng et al., 2021a; Wang et al., 2016; Yang et al., 2014). Compared with other rivers, the Yangtze River—the primary source of the TGDR—is extremely fragile. A previous report highlighted major pressures the river faced and described it as the world's most polluted waterway (Arif et al., 2021). These environmental and physical variations are the consequences of human disturbance that have altered the Yangtze River's land-use pattern.

This study focuses on various water sources flowing into the TGDR, the largest deep-water reservoir in China and the primary freshwater source of southwest China (Chen et al., 2021; He et al., 2021). The riparian zones of the TGDR are very vulnerable owing to their geomorphology and specific geographic locations, which are particularly important with regards to their ecological and environmental role (Sang et al., 2019). Once the river ecosystem is damaged, it is challenging to restore it to its original condition (Ding et al., 2021). Riparian health conditions in the TGDR are declining, and the problem has intensified because of recent land-use variations. However, the pressure effects cannot be fundamentally determined in the reservoir basin merely via the point source (Dempsey et al., 2017). Statistical models and theoretical studies are needed, as these generate technical information to combat the pressure effects of different land uses in various riparian zones of mega-dams. This study's primary objective was to investigate changes within the riparian zones of reservoirs and dams under the influence of stress indicators from different land uses (i.e., rural, rural–urban transitional, and urban). More precisely, we examined the variation between riparian health and pressure situations observed in rural, rural–urban transitional, and urban areas and identified the key indicators responsible for the total variation in these three regions' riparian zones. Furthermore, we explored the correlations between sets of pressure indicators and riparian health indicators (RHIs) and measured the ability of variables to interact with one another. Finally, we classified the statistical similarities between land-use sites along the TGDR. This research will help establish strategies to manage riparian zones under variant land uses on a large scale.

2. Materials and Methods

2.1. Study Area

The TGDR region was characterized into three zones, subject to their land-use: rural areas, rural–urban transitional areas, and urban areas. The sample transects were chosen from the reaches of rural, rural–urban transitional, and urban belts within the riparian zone of the TGDR territory (Figure 1). The investigated sites spanned a gross area of 45,100 km^2 involving 15 counties across two provinces (Chongqing and Hubei) of China and stretched from Jiangjin county to Zigui county (31°2'34.0"N, 109deg33'41.0"E). These counties form part of the humid subtropical climate zone, with monsoon weather. The mean annual air temperature of the sample locations was 17.5 +- 1.2 (mean +- standard deviation), and annual rainfall was 1,160.9 +- 118.7 mm (Figure 2). Morphologically, the maximum and minimum altitudes of these areas were 1,926.7 +- 683.8 m above sea level (a.s.l.) and 115.2 +- 45.0 m a.s.l., respectively. The length of the sampled streams was 68.1 +- 29.3 km. It is worth mentioning that the water level varies throughout the year, with a typical yearly flow of 10498.33 +- 851.87 (m^3/s) (Figure 3). This area was under broad-leaved and mixed forests, with croplands and gardens also present in several sites. Soil maturity and stability were lower owing to rock weathering in the newly formed riparian areas, and soil made of calcareous purple sand shale was found in the area (Li et al., 2021; Zheng et al., 2021a). Consequently, erosion activities were more intense at rural sites, whereas more concrete structures were found in urban and rural–urban transitional locations.

[Figures 1–3 to be inserted about here]

The pattern of RHIs was irregular in the transects of rural, rural–urban transitional, and urban belts, as well as their subsets. Similarly, pressure indicator sequences were inconsistent, depending on the geographical sites. A unique vertical division was observed among RHIs and pressure indicators across the TGDR geographical locations. Generally, the lower banks were quite exposed, and thin grass strips were present in small patches. These areas were relatively sandy and steep, and fluctuating waves exacerbated the erosion process from the navigational events across the whole reservoir. Erosion was evident in the rural and rural–urban transitional areas, although grasses entrenched in the middle bank areas helped naturally stabilize the banks. Organic litter was not detected owing to the absence of understory vegetation on the ground of the middle banks. Scattered understory and canopy cover on the upper banks kept these areas relatively stable. During field visits, the research team noted various sites used for sustaining the ecological integrity of terrestrial and aquatic ecosystems under different ecological restoration projects throughout the TGDR riparian zones. Humans have played a significant role in changing the environment and land use of the TGDR through deindustrialization, suburbanization, cultivation, fishing, and other ecologically unfriendly activities. Therefore, different pressure indicators were recognized in most of the sites within the study areas. All these factors were collectively responsible for deteriorating the riparian health conditions of the TGDR.

2.2. Identification of Survey Sites and Transects

This study was extensive and highly structured. A field-based approach was used to collect data in 274 transects, and field visits were carried out in the riparian zones of rural, rural–urban transitional, and urban areas of the TGDR during 2019. Researchers collaborated with the local field staff who worked within the TGDR territory and were familiar with the entire region. All sample sites and transects were identified with the assistance of the field staff representative. The qualitative visual assessment method was chosen for rapid assessment of the TGDR riparian zones. A total of 40 indicators were used in this study (27 RHIs, and 13 pressure indicators; Figure 4). Considering the nature of all these indicators, RHIs were divided into five groups: habitat (H), plant cover (PC), regeneration (R), erosion (Er), and exotics (Ex). All pressure indicators were treated collectively in one index. A standard transect (100 m long and 20 m wide) was used parallel to the river to measure the extent of each RHI and pressure indicator as followed by other researchers (see Arif et al., 2021; Johansen et al., 2007). Because of the irregular width of the TGDR riparian zone, three points were used in all transects to obtain accurate measurements.

[Figure 4 to be inserted about here]

2.3. Statistical Methods

According to situations and objectives, multivariate statistical techniques are used extensively in ecological and conservation studies to explain the environmental and land-use changes in riparian zones, for example, the algorithms found in Bombino et al. (2019), McIntosh (2015), and Zema et al. (2018). In this study, we used techniques including the Kruskal-Wallis non-parametric alternative to the analysis of variance (ANOVA), principal component analysis (PCA), Pearson correlation, and cluster analysis (CA). The Kruskal-Wallis test is a standard procedure used in scientific and non-scientific disciplines to analyze differences between means (McIntosh, 2015). The level of significance was established at both $p < 0.01$ and $p < 0.05$. All the transects were considered spatially independent in terms of group and indicator indexing for the rural, rural–urban transitional, and urban areas. PCA (factor analysis) is used in ecological and conservation studies to extract key elements, factors, and indicators from multidimensional data. This process is effective in clustering the indicators by creating diverse groups. Pearson correlation is a statistical metric used to determine linear relationships and measures the strength and direction between two random variables or indicators (Zhou et al., 2016). This method is used in data classification and analysis for various indices in scientific and non-scientific research (Pavanello et al., 2015; Zhou et al., 2016). CA is used to group similar or dissimilar characteristics among diverse random variables to establish parallel functionality (Bombino et al., 2019; Zema et al., 2018). In our study, the agglomerative hierarchical cluster (AHC) method was used to determine CA. Origin release 2021 (Northampton, MA, USA) was used for statistical analyses and graphing.

3. Results

3.1. Distribution of Riparian Health and Stress Factor Characteristics

The differences in riparian health conditions and pressure status are represented by their relative total score percentage (Figure 5). The condition mean score was relatively high in the rural–urban transitional areas (86.28%), whereas urban areas exhibited the lowest condition level, with a total score of 80.11%. The urban region also experienced the highest-pressure impact (38.41%), followed by rural–urban transitional (36.28%) and rural (35.02%) regions. Subsets of the condition index displayed irregular patterns. Considering all subsets collectively, rural–urban transitional areas exhibited a better riparian condition, with their subsets habitat, plant cover, regeneration, erosion, and exotics scoring 18.00, 23.43, 12.28, 16.31, and 16.49%, respectively. However, these same subsets showed an inferior status in the urban area, scoring 15.07, 22.22, 11.19, 16.85, and 14.81%, respectively.

[Figure 5 to be inserted about here]

Research data obtained from both indexing and subsets were tested for statistical significance of differences. The Kruskal-Wallis test results displayed notable diversity among the geographical locations and within riparian health and pressure indices, including subsets (Table 1). The indexing of RHIs (with their subsets) and pressure indicators consistently revealed significant differences ($p < 0.01$) across rural areas. The p -value remained at 0.000** for every indicator index. The pattern of the Kruskal-Wallis test results was different for the other two geographical locations. The indicator indices of rural–urban transitional areas were statistically significant at $p < 0.01$ for habitat, plant cover, erosion, exotics, condition, and pressure, and $p < 0.05$ for regeneration. The differences in urban areas were statistically significant at $p < 0.01$ for erosion and pressure and$p < 0.05$ for plant cover, regeneration, exotics, and condition. However, no significant difference was detected for habitat in these areas.

[Table 1 to be inserted about here]

3.2 Principal Factors of Stress and Riparian Health Condition

PCA is widely used for data matrix transformation and allows the researcher to understand the relationship between indicators by condensing the dimensionality of the data using factor analysis. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were used to check data legitimacy and consequently determine PCA suitability. Both tests verified that our data were statistically valid for PCA. The KMO tests resulted in scores of 0.858 and 0.731 for RHIs and stress indicators, respectively, which were higher than a score of 0.6, whereas Bartlett's tests appeared as 0.000, which was lower than 0.05. PCA results for RHIs and stress indicators are presented in Figures 6, respectively. Based on the initial eigenvalues, three components (holding 14 out of 27 indicators and accounting for 65.24% of the total variation) were extracted from the riparian zone health indicators, as shown in Figure 6A. These were confirmed as sufficient and authentic for parallel analysis using two additional steps—screen plot and Monte Carlo PCA. The first component (F1) was mostly condensed for PC1, H1, PC6, PC3b, R1, Er1 and Er3a, while four RHIs (Ex4, Ex1b, Ex3, and Ex2) and three RHIs (Er3b, Er3c, and Er3a) were shown in the second component (F2) and third component (F3). Following the same selection criteria, three components (holding 7 out of 13 indicators and accounting for 70.90 % of the total variation within the TGDR) were extracted from the stress indicators, as shown in Figure 6B. The rotated component matrix for stress indexing indicated that P8b, P9, P8a, and P3a, were strongly linked, based on similarly high values, in the first component (F1), and two stress indicators (P7 and P10) were shown in the second component (F2), with one indicator (P8c) in third component F3.

[Figure 6 to be inserted about here]

3.3 The Response of Stress and Riparian Health Indexing and Sub-Indexing

Pearson correlation revealed the inter-indicator relationships between stress indicators and RHIs, allowing us to understand riparian zone changes within the TGDR under land-use variations. Although PCA provided information on the key indicators responsible for the total variation in riparian zones with significant factor groups, Pearson correlation was performed for all RHIs and stress indicators, and valuable information was obtained independently for the key stress indicators (7) and RHIs (14). Pearson correlation relationships are described below.

With regards to the stress indicators, associations were continuously significant at $p < 0.01$ ($|r|$ [?] 0.933), and both positive (r [?] 0.933) and negative (r [?] 0.584) correlations were found between pressure indicators (Table 2). The highest correlations were generally observed in urban transects, whereas lower correlations were detected in rural transects (Supplementary A, Tables A.1–A.5).

The associations between RHIs within different geographical locations were widely significant at $p < 0.01$ or $p< 0.05$ ($|r|$ [?] 0.989), except for regeneration. Positive correlations were found in most of the situations for H (r [?] 0.624), PC (r [?] 0.989), R (r [?] 0.455), Er (r [?] 0.963), and Ex (r [?] 0.935) (Table 2). The transects from urban areas showed the highest correlation, whereas those from rural–urban transitional areas showed a lower correlation. Stronger relationships were formed from PC, Ex, and Er indicators, whereas a relatively lower correlation was observed from those of H and R (Supplementary A, Tables A.1–A.5).

During the last phase of the Pearson correlation, the correlations between pressure and condition indicators for the different geographical locations were determined. These correlations were significant both at $p < 0.01$ and $p < 0.05$ (r = -0.731 – 0.529) between the indicators of pressure and the indicators of H, PC, R, Er, and Ex (Table 2). The highest comparative correlation strength was generally observed in urban transects, whereas the lowest strength was primarily found in rural–urban transitional transects. The results showed that pressure indicators correlated with habitat (r = 0.207 – 0.624), plant cover (r = -0.658 – 0.436), regeneration (r = -0.693 – 0.377), erosion (r = -0.731 – 0.583), and exotics (r = 0.168 – 0.529) (Supplementary A, Tables A.1–A.5).

[Table 2 to be inserted about here]

Heat maps were developed separately for stress and riparian health indices as well as sub-indices to indicate their correlation strength via their colors (Figure 7). Results showed that indices and sub-indices exposed unique features for different land-uses. The correlations were relatively positive in rural areas, where conditions correlated with plant cover (0.852**), habitat (0.646**), erosion (0.597**), and regeneration (0.574**). Comparably, correlation strengths were moderate (both positive and negative) in rural–urban transitional areas. Exotics correlated negatively with regeneration (-0.483**), plant cover (-0.469**), erosion (-0.332**), and condition (-0.273*). In contrast, condition showed a relatively positive correlation with plant cover (0.781**), erosion (0.587**), and habitat (0.468**). Urban zones displayed a markedly strong positive (in condition and plant cover) and negative (in exotic and pressure) correlation among other indices and sub-indices.

[Figure 7 to be inserted about here]

3.4 Cluster Analysis (CA)

AHC was performed on the data collected from 274 transects in three geographical locations (rural, rural–urban transitional, and urban) within the TGDR. This test grouped the sites based on their RHI and pressure indicator characteristics. The results categorized the sites into three major cluster groups, with rural (A), rural–urban transitional (B), and urban (C). The findings revealed that indices and sub-indices revealed distinct traits for various land uses. The outcomes are shown in Figure 8.

[Figure 8 to be inserted about here]

4. Discussion

This study highlighted the significant changes in the riparian zone, induced by pressure indicators, under different land uses within the TGDR in China. The results also revealed the extensive distribution pattern for wide-ranging RHIs and pressure indicators in different geographical locations (rural, rural–urban transitional, and urban areas). These significant deteriorations are highlighted by Arif et al. (2021) within the TGDR. However, the indicators all followed different patterns as the situations changed, similar to results obtained in other land-use change studies (Rodrigues et al., 2018; Wohl, 2017). Geographical locations and humans played a central role in riparian zone changes (Ferreira et al., 2005; Perry et al., 2012). Our results showed that rural–urban transitional areas offered relatively better riparian zone conditions than urban and rural areas (Figure 5). Similar results were obtained for all the health indicators, as shown by their relatively high score percentages. Rural–urban transitional areas are distinctive locations, as they exhibit the characteristics of both rural and urban regions, containing vegetation similar to rural sites but being managed as urban sites. Although the administrators of the TGDR paid more attention to urban areas than rural–urban transitional and rural regions, urban riparian zones were more disturbed due to development and concrete-based activities, which explains why the pressure impact was highest in urban regions. A particular area can hold a specific stress milieu that alters environmental circumstances depending on the prevailing land-use system (Zheng et al., 2021b; Johansen et al., 2007). Southwest China has a mountainous topography (Sang et al., 2019; Wang et al., 2016; Yang & Li, 2016), and riparian areas in this region are highly variable due to environmental changes caused by the contingent pressure indicators. As a result of the building of the TGDR, the whole riparian zone structure in the reservoir was modified (Zheng et al., 2021a). Geographical circumstances are responsible for the riparian vegetation at the time of the study being different from past natural cover (Wang et al., 2016; Yang et al., 2014). Similar results from other parts of the globe, such as Brazil (Mello et al., 2018), have led to recommendations to conserve riparian zones with unique characteristics, such as the TGDR.

The Kruskal-Wallis tests distinguished sharp contrasts between the different transects of geographical locations and RHIs. The test results confirmed the extent to which geographical locations significantly changed with respect to habitat, plant cover, regeneration, erosion, and exotic characteristics of the reservoir, as well as in the development of riparian vegetation, as demonstrated by Zema et al. (2018) using a different statistical approach. Dam construction can cause nearby land to change and, consequently, alter river features (Bombino et al., 2014). These morphological changes modify the river width and circumference, which change the river hydrology (Shieh et al., 2007). Multiple factors influence the dynamics of pressure indicators, and hydro-morphological changes are key reasons to boost their impact (Bombino et al., 2008; Galia et al., 2016; Hooke & Mant, 2000). As riparian health conditions respond to these variations when exposed to changing environments and land use, these fluctuations can influence the plant community in terms of structure and development (Steiger et al., 2005). However, the impact on riparian zones varies with transect location and magnitude of the fluctuation (Bombino et al., 2009). Although these transects were located in different geographical sites, their features were, to some extent, identical. The study sites were very similar in terms of vegetation indicators, structure, and the extent of riparian vegetation. The differences within a riparian structure can be attributed to the unique environmental characteristics of individual land uses. The interactions between geographical location and RHIs were always significant for rural and rural–urban transitional site indicators (H, PC, R, Er, Ex, and C). However, significant effects were detected on stress indicators among transect locations across the entire TGDR area. Zema et al. (2018) similarly found significant changes in riparian zone conditions, considering the environment and land-use variation, as expected within a dam territory, and multivariate statistical analysis confirmed similar results in buffer zones in Italy (Zema et al., 2015). These techniques have been widely employed and appear to be valid in ecological studies (Kazakis et al., 2018; Zema et al., 2015).

PCA was conducted for RHIs and pressure indicators, as these were correlated in an earlier study (Arif et al., 2021). The selected RHIs displayed more than 65.24% variance in the data set, while the pressure indicators accounted for 70.90% of the total variance (Figures 6). PCA indicated the extent to which the original or essential indicators modified variance during data configuration. The results of these loadings confirmed the close relationships between riparian health and stress groups by considering each group individually. Three critical components for each indexing, as shown by PCA, were defined for riparian health and pressure indicators. These factors expressed strong values, ranging from low to high (-0.624 – 0.963) from all indicators (positive and negative loads), as shown in Figures 6. The rotated component matrix values for riparian health and pressure showed that all factor groups fell within similar values. PCA displayed distinct similarity (positive values) and contrasts (negative values) from indexing and subsets (for habitats, plant cover, regeneration, erosion, and exotic parameters). Moreover, most of the pressure characteristics functioned as expected. This process demonstrates that PCA can aggregate key indicators without the need for a broader set of indicators (McIntosh, 2015; Zema et al., 2018).

By contrast, the loads on PCA were found to be insignificant (relative to evident loadings for characteristics of the riparian zone) among several individual indicators within different geographical locations in the TGDR. Regarding contribution and effectiveness, these indicators presumably played a role in transect locations regarding the geographic areas within the TGDR. The history of selective indicators can be traced from similar studies conducted on Australian riparian zones (Johansen et al., 2007; Johansen et al., 2008). Vegetation cover is a significant indicator of riparian health conditions (Oliveira et al., 2016; Wang et al., 2013) compared to other indicators. It is multilayered and may assist other indicators in performing their roles as a safety filter (Ding et al., 2021). However, the understory cover of riparian vegetation seemed more highly influenced than other vegetation characteristics and subsequently disappeared in areas of hydro-fluctuation. All RHIs, however, were affected by flow regulation. They displayed more drastic changes in the upper sections and a parallel decrease in the lower parts of the dam (Zema et al., 2018), indicating that the riparian health of different sites mostly depends on their geographical locations. As a result, this boosted the impact of erosion and increased the invasion of exotic species in the TGDR; similar observations have been recorded near other dams (Jian et al., 2018; Merritt & Cooper, 2000).

Pearson correlation equations applied to riparian pressure indicators are considered independent variables (x), while those applied to RHIs are considered dependent variables (y) in different geographical locations. These equation ranges are shown in Table 2 and Figure 7. The equations in Table 2 contained high descriptive levels (r = -0.731 – 0.529) and showed regression strength for the different transect areas (rural, rural–urban transitional, and urban). Following a more in-depth analysis of each of the regression strengths, the Pearson correlation values showed that RHIs influenced changes in the riparian zone condition, the impact of the pressure indicators modified riparian health, and riparian health characteristics varied according to the transect location in the TGDR (Supplementary A, Tables A.1–A.5). As expected, in our study the extent of riparian health response to the effects of postoperative pressure adjustment through environmental and land-use changes highlighted the hierarchical relationships among different transects (Mantyka-Pringle et al., 2014). We discovered that even under similar conditions, pressure indicators in these riparian areas might react in reverse. The pressure distribution pattern mainly depended on the geographical locations and their structural designs (Catford et al., 2013; Nilsson et al., 2013; Singer et al., 2013). In our study, this pressure increased the riparian condition fragmentation and altered the distribution pattern (latitude and longitude) in the TGDR area, resulting in different Pearson correlation strengths (Figure 7). Transects from urban areas displayed the highest correlation between RHIs, whereas these associations were relatively low in rural–urban transitional regions. Correlation strengths for pressure indicators were generally highest in urban transects and lowest in rural transects. Associations between pressure indicators and RHIs revealed that the highest correlation strengths were from urban areas, while the most moderate associations were from rural–urban transition areas. Our study can help assess the impact of pressure indicators that operate in complex patterns since pressure indicators are causing changes in riparian health, influenced by environmental and land-use changes in the TGDR. Our findings were consistent with those from several other studies (Petts & Gurnell, 2005; Rood, 2006; Tealdi, 2011), although not with those from certain specific riparian zones (Johansen et al., 2007; Johansen et al., 2008).

We found multiple scenarios (for parameters for habitat, plant cover, regeneration, erosion, and exotics) where the average pressure impacted on different land-uses. These results confirmed that riparian area conditions are not always affected by the same pressure indicators (Lamb et al., 2003), which is why urban areas showed significant structural changes and even displayed a strong reaction to pressure indicators, resulting in rapid changes in riparian conditions (Dempsey et al., 2017). Occasionally, pressure indicators did not significantly affect riparian conditions, resulting in steady and healthy conditions (Lamb et al., 2003). If a pressure indicator in a given area does not cause a significant long-term change in buffer areas, resulting in a stable state, the riparian conditions will not alter significantly. The present study showed that dependence on riparian area conditions strongly correlated with pressure on the indicators (Table 2). These indicators can cause the buffer zone to deform, causing structural changes and lowering the efficiency that maintains the riparian zone condition (Biswas & Mallik, 2010; Mallik et al., 2011).

The AHC method exposed dissimilarities between different land uses. According to published literature (Bombino et al., 2019), all geographical areas that retained parallel sites were clustered in the same set. It was evident that humans contributed to altering the environmental and land-use scenarios, which ultimately caused significant changes in riparian zones. Our findings agree with those from studies investigating other regions with characteristics comparable to the TGDR region (Rodrigues et al., 2018; Wohl, 2017).

Overall, our study attempted to eliminate traditional analytical methods based on field observations and instead assessed the deteriorated impact of the dam on habitats, vegetation, regeneration, erosion, and exotic indicators in different environmental and land-use conditions under the influence of pressure indicators. Pearson correlation provided a quantitative assessment of the riparian zone's ecological responses to the pressure indicators of big dams. These correlation strengths confirmed that certain steps are required to develop management strategies that will minimize the impacts of the dam on riparian conditions, under the influence of environmental and land uses, as highlighted by others (Aguiar et al., 2016; Henry & Amoros, 1996; Mantyka-Pringle et al., 2014). We examined the changes in riparian zones under the influence of land-use changes and observed the effect of pressure indicators on rural, rural–urban transitional, and urban areas within the TGDR. This vast reservoir is a combination of multiple main streams and linked tributaries. Stream bodies emerge from different parts of China and have dissimilar topographies, resulting in variation in the riparian zones of these water bodies. Future research should investigate indicators that influence diverse water bodies in the TGDR; since the uses of these water bodies are different, pressure impacts could vary as well. Ultimately, riparian zones may experience an unequal degree of pressure. Therefore, future work should focus on changes in the riparian conditions of large dams and water bodies such as the TGDR. The results will provide comprehensive information to the reservoir administrator, thereby helping them implement functional changes commensurate with the condition of their respective water body.

5. Conclusion

This evidence confirmed marked differences in riparian zone health conditions with respect to land-use patterns in the TGDR. Overall, the Kruskal-Wallis tests illustrated the significant contrast between the different transects of geographical locations and RHIs ($p< 0.05$). The results of factor analysis for riparian zone variables were more complex, and the source of trace indicators harder to isolate. A combination of multivariate statistical methods successfully identified the critical riparian health indicators (14 out of 27) that signify changes in the buffer zones caused by the pressure indicators (7 out of 13) under the influence of different land uses. Among the selected riparian health indicators, the data confirmed that plant cover, erosion, and exotic parameters possessed a high number of variables. The variables that caused the most disturbance, considered pressure indicators, were land-use designs, farming systems, and activities involving pollutants. From a methodological perspective, it was challenging to determine the effect of pressure indicators on larger areas in the same manner. The use of two approaches provided the right solution and proved to be a reliable tool for dealing with this situation. We found that even under similar conditions, pressure impact was different in these riparian areas. Generally, the Pearson correlation showed the highest comparative interaction strength from the urban transects, whereas the rural–urban transitional transects displayed the lowest association. The AHC exposed similarities between rural and rural–urban transitional sites, which confirmed the substantial dissimilarity of urban locations. These results demonstrate significant dissimilarities in the riparian zones of different geographical sites within the TGDR, indicating the requirement for distinct operational practices in these areas. Our findings are comprehensive and provide the necessary information for reservoir administrators to implement functional changes suited to particular riparian area situations.

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