Study on method for assessment of the physical structure integrity in Chagan lake in China based on remote sensing

Bo-lin Fu, Ying Li, Bai Zhang, Bai-shu Yin, Hong-lei Zhu and Ze-feng Xin

ABSTRACT

This paper, taking Chagan lake as the study area, uses and improves MWR V1.0 *(Rivers (Lake) Health Assessment Indicators, Standards and Methods V1.0)* relating to the theory and method of physical structure integrity assessment. A 500 m × 1000 m grid on the lakeshore zone is a basic evaluation unit, and then a lakeshore physical structural integrity evaluation system using remote sensing (RS) and geographic information system (GIS) technology is established, which contains a target layer, criterion layer and indicator layer. The criterion layer consists of lakeshore condition, shoreline development rate and lake atrophy rate, and the index layer is composed of slope, vegetation cover rate and water level change rate, and another eight indicators. The results showed that for the 23 monitoring points in Chagan lake and the 15 monitoring points in Xinmiao lake, the evaluation results based on RS were 0.60–0.74 and 0.35–0.52, respectively, and the field evaluation results were 0.64–0.77 and 0.35–0.55, respectively. The evaluation results of the two methods consistently indicated that the physical structure of the lakeshore of Chagan lake was healthy and the Xinmiao's lakeshore was sub-health. On this basis, a piecewise evaluation method of physical structure integrity based on the division of the nature reserve function was proposed in this paper.

Key words | indicator system, lakeshore zone, physical structural integrity, RS and GIS, basic evaluation unit

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INTRODUCTION

The lakeshore zone is an ecological transition zone of material, energy and information exchange between land and water ecosystems, and it has great significance to maintain a healthy lake life and protect the sound development of society and economy (Jørgensen 1995). With the intensification of global climate change and human activities, lake areas have drastically reduced, pollution has been aggravated, and environmental degradation and other problems have become increasingly prominent. The lake has become the most sensitive and profound geographic unit in regional natural environment change and the interaction between humans and nature (Xu *et al.* 2001; Leng *et al.* 2012). Lake health assessment has become a hot topic in the study of lake ecosystems. The lakeshore physical structure integrity is an important component of lake health assessment. In addition, lakeshore zone conditions were the basis to evaluate whether the lake ecosystem is healthy or not (Xu *et al.* 2001). Currently, the research about lake health has mainly concentrated on lake ecosystem health and lake morphology health (Xu 1996; Liu *et al.* 2004; Shuai *et al.* 2012). The connotation of lakeshore health has not yet been clarified and the study of physical structural integrity evaluation on the lakeshore zone has been limited; thus, a complete and proven comprehensive evaluation index system has not been developed.

Nowadays, physical structural integrity evaluation methods about the lakeshore zone are mainly based on field measurement by the Chinese Ministry of Water Resources *River (Lake) Health Assessment Indicators, Standards and Methods V1.0* (MWR V1.0) (Peng & Gippel 2010). The evaluation method is based on expertise, selecting monitoring sites and laying 10 m × 50 m monitoring quadrats. Evaluation results were obtained by artificial statistical methods. With the double impact of natural conditions and subjective factors, the field measurement cannot take into account representation, convenience and safety at the same time, and it is difficult to fully and accurately present the structural stability condition of the lakeshore zone. Meanwhile, most of the existing methods

doi: 10.2166/wst.2014.405

concentrate on field surveys of a few hundreds of metres, which is very laborious and uneconomic when trying to evaluate whole catchments or long river riparian zones.

Remote sensing (RS) techniques have the ability to obtain surface information rapidly and in real-time. A geographic information system (GIS) has a powerful computing, spatial analysis and visualization capability. RS and GIS technology have a large number of applications in the study of riparian zone conditions, the relationship between land use and water quality, lake morphological health assessment and other aspects (Johansen *et al.* 2007, 2010; Fernández *et al.* 2012). In this paper, we present an assessment method for physical structure integrity based on RS by reference to MWR V1.0 and the lake morphology health assessment relevant theories and methods. Therefore the next objective was to demonstrate the effectiveness and rationality of the evaluation approach based on RS by comparative analysis with the field evaluation results. Furthermore, a piecewise assessment approach of physical structure integrity based on the division of a nature reserve function is also proposed.

STUDY AREA AND DATA SOURCES

Study area

Chagan lake is located in the Chagan Lake Nature Conservation, which is in the center of the Songneng Plain, at the intersection of the Huolin river and Neng river (Figure 1(a)). The topography is low, flat and gently undulating. Elevation is 120 m–160 m. Chagan Lake Nature Conservation is divided into three parts: core, buffer and experimental area. The core is the key protection area. The experimental area is for development. The buffer is a transition zone between the core and experimental area (Figure 1(b)). At present, there is overgrazing, reclaimed wetland, oil field development, tourism development and other human activities in this area. This anthropogenic pressure has accelerated lakeshore zone erosion and progressively destroyed the structural stability of the lakeshore zone. Eventually, Huolin river, which is one of the main water sources to the lake, flows intermittently. The ecosystem health of Chagan lake has been greatly impacted. Therefore the physical structure integrity assessment of the lakeshore zone is imperative.

Data sources

RS data and processing

Considering the quality of the image and the time required to do a field survey, multi-spectral Landsat 5 TM (thematic mapper) images of the study area were captured on 14 June 2010. Path/row is 119/29. The spatial resolution of multispectral bands is 30 m. Other data sets included 1:100000 LUCC (land use and cover change) data in 2005 and 1:500000 geomorphic data compiled by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 1950s 1:100000 topographic map and SRTM (Shuttle Radar Topography Mission) 90 m digital elevation model (DEM).

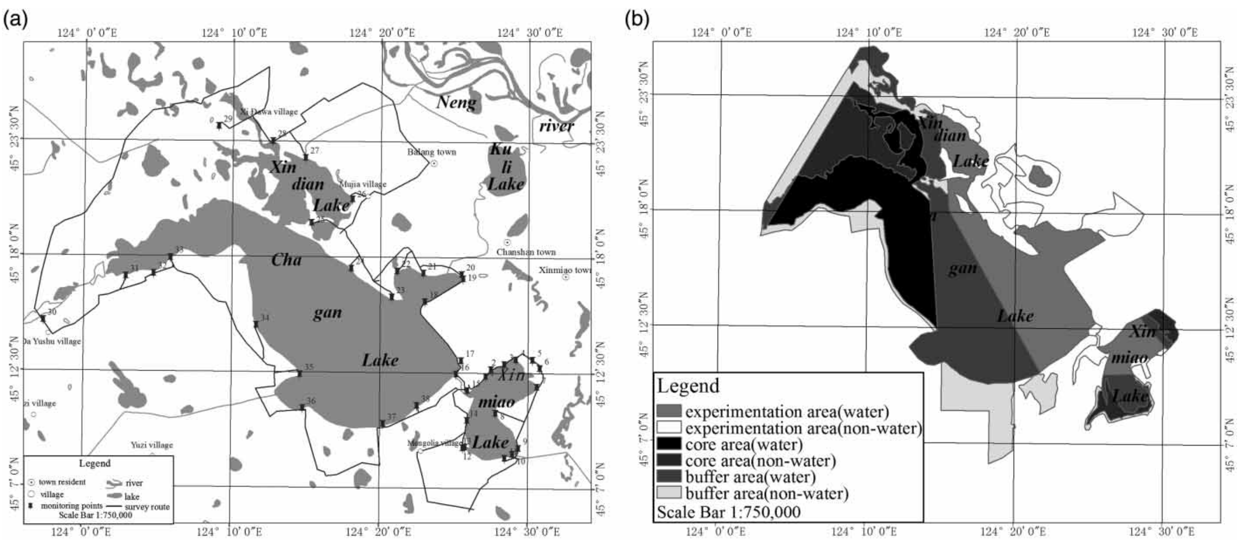

Figure 1 | Location of study area and field survey route.

The lakeshore zone LUCC data were acquired by pretreating Landsat TM images in 2010, setting up interpretation keys of field work, referring to LUCC data in 2005 and the inverted NDVI in 2010, and then interpreting the TM image. According to the field work, the interpretation precision was 86.37%. The LUCC data in 2010 were reclassified into paddy field, non-irrigated farmland, land for rural and urban residents, and industrial land as anthropogenic interference activities.

Field data collection

With the lake surrounding landform, landscape pattern, transportation accessibility and other aspects, the lakeshore zone in the study area was set up with 38 monitoring sites (Figure 1(a)). The positions of monitoring points were accessed by global positioning system (GPS), and each monitoring point was delimited by a 10 m × 50 m quadrat. The slope angle and slope length on the lakeshore zone was directly measured by a Leica DISTO D5 laser rangefinder and then slope height was calculated. The approach of taking the average of a multi-person visual estimation was used to gain vegetation coverage rate in survey samples. Vegetation coverage was measured for all 1 m × 1 m quadrats within the 10 m × 50 m evaluation area. Field photos were taken by Nikon D90 camera vertical shooting quadrats. These photos were subsequently processed to calculate vegetation coverage in every quadrat with the binary segmentation method using the image processing software ENVI 5.0, and then all vegetation coverage in the evaluation area was worked out. Human intervention activities and the lakeside matrix were recorded by taking photos with a Nikon D90 camera.

METHODS

Evaluation scope

Lakes are water bodies always in a state of change. The lakeshore zone has the most intense interaction for the land and water transition zone. The structural stability and morphological structure characteristics are all in constant change (Soucha *et al.* 1996). The field observation object was a lakeside zone of land with a width of less than 50 m. The study area is located in an alluvial lacustrine plain and an alluvial plain, and the lakeshore zone's width far exceeds 50 m. Field survey plots were difficult to evaluate completely, so the evaluation results clearly do not fully and accurately reflect the structural stability of the lakeshore zone.

In addition, numerous studies have demonstrated that a certain range of LUCC conditions around the lake were correlated to water quality (Allan 2004; King *et al.* 2005; Zampella *et al.* 2007). Land-use coverage on the riparian zone has been as an indicator of riparian quality (Amis *et al.* 2007; Fernández *et al.* 2014). And current studies have indicated that the optimum width of a riparian buffer to protect from impacts related to human land use depended greatly on what resource was being protected. The existing studies have shown that efficient buffer widths range from 10 feet (3.048 metres) for bank stabilization and stream shading, to over 300 feet (91.44 metres) for wildlife habitat (US Army Corps of Engineers 1991; Wenger 1999; Hawes & Smith 2005).

Combining the above three aspects, the shoreline of Chagan lake of 1 km width towards the land was set as the evaluation object.

Evaluating index system construction

Evaluating index system construction

The indicators of field measurement derived from MWR V1.0 methods, which have been practiced for physical structure integrity assessment (Xu *et al.* 2001; Jansen 2005; Dixon *et al.* 2006; del Tánago & de Jalón Lastra 2011). Combining the lake morphology health (Leng *et al.* 2012) and MWR V1.0, a complete system of physical structure assessment based on the RS was established. The indicators of the system could be directly accessed by the RS technique (such as water level change rate (WD), vegetation fraction and shoreline development rate (SDR)) and also have significance for the lakeshore zone structural stability. (Table 1).

Ecological significance of some indicators

In this paper, some indicators in the index system (such as vegetation coverage rate) are the same as MWR V1.0, and their ecological significance has been explained in detail. This paper focuses on interpretation of the following two indexes.

The WD is the 1950s and 2010 variations of lake water level in the 500 m × 1000 m grid, using 500 m as a splitting criterion to divide the shoreline, and then each 500 m shoreline was extended to a 1000 m buffer from the shoreline to the center of the lake by ArcGIS software. The formula (Equation (1)) was used to calculate the change in lake surface area

Table 1 | Physical structure of evaluation system

Criterion layer	Indicator layer	Measuring layer field measurement	RS measurement
Lakeshore condition (LC)	Lakeshore stability (BKS)	Lakeshore slope angle (SA) Lakeshore slope height (SH) Vegetation coverage rate (SC) Lakeshore matrix (SM) Lakeshore erosion (ST)	Lakeshore slope angle (SA) WD Vegetation coverage rate (SC) Lakeshore matrix (SM)
	Vegetation fraction (BVC)	Vegetation coverage	Vegetation coverage
	Human intervention intensity (RD)	Lakeside park, road, sand quarrying, farming, tourism and nine other kinds of human activities	Agriculture land, residents, industrial and mining, and six other kinds of LUCC types
Shoreline development rate (SDR)			Evaluation year (SDI_C) and historical years (SDI_R) shoreline development index
Lake atrophy rate (ASR)		Evaluation year (A_C) and historical years (A_R) lake area	Evaluation year (A_C) and historical years (A_R) lake area

between the 1950s and 2010 Peng & Gippel (2010).

$$WD = \frac{U_b - U_a}{U_a} \times 100\% \quad (1)$$

U_a and U_b are respectively the 1950s and 2010 lake water area. The index directly reflects the fluctuation of lake water, and the water level fluctuation is closely related to the slope condition of the lakeshore zone. In the grid, the greater the water level varies, the more gentle the slope is; conversely, the slope is steeper.

The shoreline development index (SDI) is calculated by the formula given in Equation (2), following Leng *et al.* (2012).

$$SDI = \frac{S}{2\sqrt{\pi A}} \quad (2)$$

S represents the lake perimeter and A is the lake area. The index mainly reflects the extent of irregularity of the lakeside. The larger the SDI value, the higher the shoreline complexity of the lake is, the more susceptible is the lakeshore habitat diversity. Meanwhile, The lakeshore zone area is larger, and it is more possible to support lake primary productivity (Leng *et al.* 2012).

Accessing indicators accessing and establishment of the basic assessment unit

Within the scope of the evaluation objects, a 1:100000 topographic map and SRTM DEM data were used to calculate lakeshore slope, and LUCC data for 2010 after classification was used to extract natural vegetation coverage rate and human disturbance. A 1:500000 geomorphic map was combined with the geomorphological partition table (Table 2) to obtain the surface lithology and the 1950s shoreline. Vegetation coverage was quantitatively inversed by Landsat TM images in 2010 (Gitelson *et al.* 2002) and the shoreline was extracted (Figure 2).

A 500 m length was used to equally divide the shoreline, and then from each shoreline division towards land a 1 km rectangular buffer was taken, creating a 500 m × 1000 m grid, by ArcGIS software as the basic assessment unit. The study area was covered by 312 basic assessment units.

Table 2 | Landform distribution[1]

Landform types	Lithology	Distribution location
Alluvial lacustrine plain	Loess-like loam	The northern Qian country and Chagan lake
	Loess-like loam	The southern and western Chagan lake
	Loam, clay	Depression on alluvial lacustrine low plain
Alluvial plain	Cohesive soil and sand	The left bank of second Songhua river
	Cohesive soil and sand	On both sides of Huolin river valley
	Loam, clay	Chagan lake

[1]From 1:500000 geomorphic map.

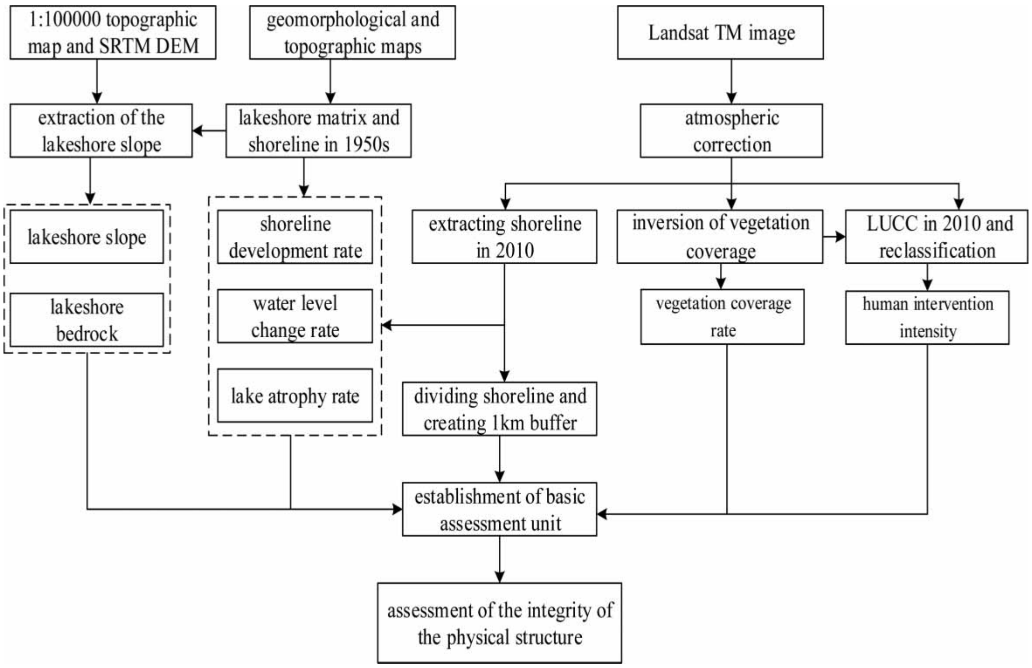

Figure 2 | Technical process of extracting indicators.

Evaluation methods and scoring criteria

Establishing a quantitative or qualitative index system was the cornerstone of physical structure integrity assessment. The indicators' calculation methods were based on MWR V1.0 except for BVC and ASR (Table 3). The quantifying score criteria of all indicators was based on MWR V1.0. The score criterion of SDR was the same as ASR.

The physical structure score (PFr) was calculated by Equation (3), and its variables and weighted values are in Table 4. The weight and the formula (Equation (3)) were both given by MWR V1.0. However, lake and river connectivity has not been an indicator, for Huolin river has been an intermittent stream. Lake and river connectivity has been displaced by SDR in the method of RS, and the weight of SDR was the same as lake and river connectivity.

$$PFr = LCr \times LCw + SDRr \times SDRw + ASRr \times ASRw \quad (3)$$

Table 3 | Indicators calculation method

Indicator	Calculation method
BVC	$BVC = (NDVI \times NDVI_{min})/(NDVI_{max} \times NDVI_{min})^1$
RD	$RD = 1 - \frac{\sum_{i=1}^{6} Area_i}{Area}$
SDR	$SDR = 1 - \frac{SDI_{C2}}{SDI_R}$

[1]The formula of BVC was given by Gitelson et al. (2002).

Table 4 | The weight value of physical structure evaluation

Physical structure score	Weight markers	Weight of RS	Weight of field
LCr	LCw	1/2	2/3
SDRr	SDRw	1/4	
ASRr	ASRw	1/4	1/3

RESULTS AND DISCUSSION

According to the calculation method for shoreline development rate and lake atrophy rate, and then with reference to MWR V1.0 and score criteria (Table 3), the score of shoreline development rate and lake atrophy rate is shown in

Table 5 | Score of shoreline development rate and lake atrophy rate

Lake	SDI		SDR (%)	SDRr	ASR (%)	ASRr
Chagan	$A_R = 3.05$	$A_C = 2.80$	19	60	−27.45	100
Xinmiao	$A_R = 2.71$	$A_C = 2.27$	11	40	26.14	20

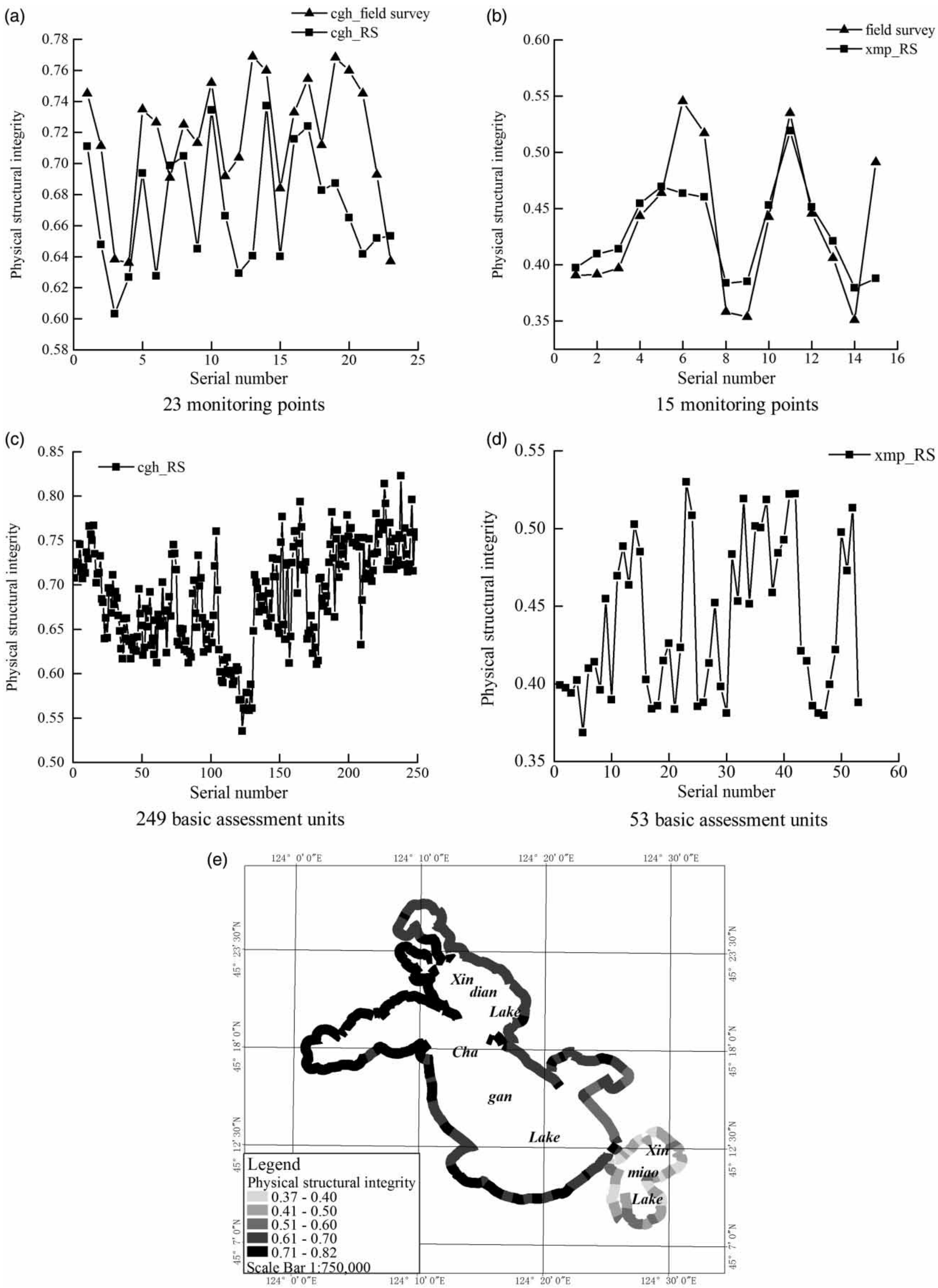

Figure 3 | Physical structure evaluation results: cgh - Chagan lake, xmp - Xinmiao lake.

Table 5. For 38 monitoring points, the physical structure evaluation results are shown in Figures 3(a) and 3(b). The physical structure evaluation results in the entire lakeshore are shown in Figures 3(c), 3(d) and 3(e). The physical structure evaluation and the lakeshore zone condition of values in Figure 3 were divided by 100.

By comparing evaluation results of the two methods, combined with the river (lake) health assessment scale (Table 6), the following conclusions could be drawn:

- In the monitoring point scale (Figures 3(a) and 3(b)). In the 38 monitoring points (Chagan lake 23, Xinmiao lake 15), the physical structure evaluation results based on RS and field measurement in Chagan lake were respectively 0.60–0.74 and 0.64–0.77, which indicated that the entire lakeshore was in the healthy condition. The Xinmiao lake's evaluation result was 0.38–0.52 and 0.35–0.55 respectively, which shows that one section of the lakeshore was in poor health, and the other section was sub-healthy. There was a little difference in the assessment results of the two methods, but these differences were within 0.2, hardly more than the threshold of deciding the grade of health type, and would not affect the final evaluation result of lakeshore health status (Figures 3(a) and 3(b)). One reason for this discrepancy of the evaluation results was that the RS method was different from the field survey for the human intervention intensity and vegetation coverage rate. The difference of their numerical results was about 0.27–0.32. And when calculating the lakeshore zone stability and lakeshore zone status, the differences would be transmitted. These reasons for the differences in vegetation coverage rate were that field measurement was based on the discrete 10 m × 50 m quadrat and the layout of the quadrat had a high subjective content. In addition, field survey obtained vegetation coverage rate by taking the average of a multi-person visual estimation, whereas the RS method obtained vegetation coverage rate by image classification and geo-information extraction, which was a continuous and integral acquisition, and was relatively objective. The other reasons for the differences were image spatial resolution, the images' interpretation precision and the different indicators in calculating the lakeshore stability and human intervention intensity in the measuring layer (Table 1).
- In the integral evaluation scale. The results of the physical structure assessment of the two methods in judging the health status about physical structure integrity was consistent (Table 7). Meanwhile, according to Table 6 (Peng & Gippel 2010), the results showed that Chagan lake's physical structure was healthy, and Xinmiao lake was sub-healthy.
- The consistency of the physical structure assessment results in two scales further demonstrated the reliability of the 1 km evaluation object and the rationality of SDI as the evaluation index for the assessment of physical structure integrity. In addition, the physical structure assessment method based on RS can obtain the health status of physical structure integrity for the entire lakeshore zone (Figures 3(c), 3(d) and 3(e)), which was better than that of the field survey method. Simultaneously, the results, which can be seen in Figure 3(e), were that the physical structure integrity of a part of the lakeshore zone due to human disturbance was not the healthy state, but the integral assessment method based on field measurement was not informed.

Table 6 | River (lake) health assessment rating

Grade	Status	Value range
1	Ideal situation	0.8–1
2	Health	0.6–0.8
3	Sub-health	0.4–0.6
4	Poor health	0.2–0.4
5	Morbidity	0–0.2

Table 7 | Physical structure value of lakeshore

Lakeshore	Average value of field	Average value of RS
Chagan	0.72	0.67
Xinmiao	0.44	0.43

PIECEWISE EVALUATION BASED ON THE DIVISION OF NATURE RESERVE FUNCTION

The consistency of evaluation results demonstrated the feasibility of the assessment method based on RS. However, the field evaluation method only provided a final evaluation value, which was too rough to guide the protection work for the lakeshore zone. The paper, therefore, proposed a piecewise evaluation method that used Chagan Lake Natural Conservation Functional Divisions (Figure 1(b)) as a benchmark to segment and evaluate the entire lakeshore, which could reflect the health status of its functional division, thus enabling more targeted protection measures. The final physical structure evaluation results are shown in Table 8.

Table 8 | Evaluation results based on division of nature reserve function

Lakeshore	Core area	Buffer area	Experimentation area
Chagan	0.74	0.70	0.65
Xinmiao	0.48	0.40	0.44

The above results show that the lakeshore zone of the core and buffer zone in Chagan lake was healthy. The experimental zone, all in all, was in a state of health, but part of the lakeshore was in a state of sub-health (Figure 3(e)). This showed that the intensity of human activities had seriously damaged the ecological system of the lakeshore zone, and protection needed to be strengthened. The core, buffer and experimental zone in the Xinmiao lake were in a state of sub-health. So restorative protection has been imperative.

CONCLUSION

This paper proposed a lakeshore zone physical structural integrity evaluation method based on RS and compared it with the traditional method. The evaluation results were consistent generally with the field measured results, which fully demonstrated the feasibility of the method and the rationality of the index system, and then a piecewise evaluation method based on the division of the nature reserve function was proposed, which made the evaluation result have more practical guiding significance. However, river (lake) health assessment is still in the exploratory phase; its index system and the evaluation criteria and the methods of evaluation remain to be further studied.

The physical structure integrity assessment covers many scientific and technological topics and different evaluation objects with different geomorphological conditions. The evaluation of the physical structure based on RS in this paper was based on the plain lake. For the study area, good applicability of the method has been demonstrated. However, its applicability to other types of lake need further research.

REFERENCES

Allan, J. D. 2004 Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* **35** (1), 257–284.

Amis, M. A., Rouget, M., Balmford, A., Thuiller, W., Kleynhans, C. J., Day, J. & Nel, J. 2007 Predicting freshwater habitat integrity using land-use surrogates. *Water SA* **33** (2), 215–221.

del Tánago, M. G. & de Jalón Lastra, D. G. 2011 Riparian Quality Index (RQI): A methodology for characterising and assessing the environmental conditions of riparian zones. *Limnetica* **30** (2), 235–254.

Dixon, I., Douglas, M., Dowe, J. & Burrows, D. 2006 *Tropical Rapid Appraisal of Riparian Condition*. Land & Water Australia, Canberra.

Fernández, D., Barquín, J., Álvarez-Cabria, M. & Peñas, F. J. 2012 Quantifying the performance of automated GIS-based geomorphological approaches for riparian zone delineation using digital elevation models. *Hydrology & Earth System Sciences* **16** (10), 3851–3862.

Fernández, D., Barquín, J., Álvarez-Cabria, M. & Peñas, F. J. 2014 Land-use coverage as an indicator of riparian quality. *Ecological Indicators* **41**, 165–174.

Gitelson, A. A., Kaufman, Y. J., Stark, R. & Rundquist, D. 2002 Novel algorithms for remote estimation of vegetation fraction. *Remote Sensing of Environment* **80** (1), 76–87.

Hawes, E. & Smith, M. 2005 *Riparian Buffer Zones: Functions and Recommended Widths*. Report to Eightmile River Wild and Scenic Study Committee, Australia.

Jansen, A. 2005 *Rapid Appraisal of Riparian Condition: Version Two*. Land & Water Australia, Canberra.

Johansen, K., Phinn, S., Dixon, I., Douglas, M. & Lowry, J. 2007 Comparison of image and rapid field assessments of riparian zone condition in Australian tropical savannas. *Forest Ecology and Management* **240** (1–3), 42–60.

Johansen, K., Phinn, S. & Witte, C. 2010 Mapping of riparian zone attributes using discrete return LiDAR, QuickBird and SPOT-5 imagery: Assessing accuracy and costs. *Remote Sensing of Environment* **114** (11), 2679–2691.

Jørgensen, S. E. 1995 The application of ecological indicators to assess the ecological condition of a lake. *Lakes & Reservoirs: Research & Management* **1** (3), 177–182.

King, R. S., Baker, M. E., Whigham, D. F., Weller, D. E., Jordan, T. E., Kazyak, P. F. & Hurd, M. K. 2005 Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecological Applications* **15** (1), 137–153.

Leng, H., Zhang, T.-f., Wang, C.-l. & Li, N. 2012 Implication of lake's healthy morphology and its assessment through set pair analysis: A case study of Dazong Lake. *Journal of Hohai University (Natural Sciences)* **40** (5), 514–519.

Liu, Y., Guo, C.-h., Dai, L.-y. & Lu, F.-y. 2004 An assessing approach for lake ecosystem health. *Acta Scientiae Circumstantiae* **24** (4), 723–729.

Peng, Q.-w. & Gippel, C. 2010 River (Lake) Health Indicators, Standards and Methods V1.0. The Ministry of Water Resources of the People's Republic of China, Beijing, China.

Shuai, H., Li, J-b., Xia, B.-c., Liu, C.-p. & Li, Y.-d. 2012 Health evaluation of Dongting Lake based on morphological characters. *Acta Ecologica Sinica* **32** (8), 2588–2595.

Soucha, C., Wolfe, C. P. & Grimmtind, C. S. B. 1996 Wetland evaporation and energy partitioning: Indiana dunes national lakeshore. *Journal of Hydrology* **184** (3), 189–208.

US Army Corps of Engineers, New England Division 1991 *Buffer Strips for Riparian Zone Management*. Report to the Vermont Department of Environmental Conservation, Vermont, USA.

Wenger, S. 1999 *A Review of the Scientific Literature on Riparian Buffer Width, Extent and Vegetation*. Institute of Ecology, University of Georgia, Athens, GA, USA.

Xu, F. 1996 Ecosystem health assessment of Lake Chao, a shallow eutrophic Chinese lake. *Lakes & Reservoirs: Research & Management* **2** (1–2), 101–109.

Xu, F.-L., Tao, S., Dawson, R. W., Li, P.-g. & Cao, J. 2001 Lake ecosystem health assessment: indicators and methods. *Water Research* **35** (13), 3157–3167.

Zampella, R. A., Procopio, N. A., Lathrop, R. G. & Dow, C. L. 2007 Relationship of land use/land cover patterns and surface-water quality in the Mullica river basin. *Journal of the American Water Resources Association* **43** (3), 594–604.

First received 10 June 2014; accepted in revised form 10 September 2014. Available online 24 September 2014