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An indicator system for assessing the impact of human activities on river structure

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ABSTRACT

The impact of human activities on river systems has reached a state in which they can no longer be considered to be controlled only by natural processes of the Earth but also by anthropogenic forces in many regions of world. However, most approaches for assessing the impact still consider human activities to be an external influence in the study of feedback mechanisms between human activities and river systems, and they are usually complicated and specialized. This paper aims to develop an indicator system that includes the artificial water surface ratio (*AWSR*), artificial water surface density ratio (*AWSDR*), disruption of longitudinal connectivity ratio (*DLCR*), artificial river ratio (*ARR*), sinuosity of artificial cutoff (*SAC*), channelization ratio (*CR*), artificial levee ratio (*ALR*), road along river ratio (*RARR*), artificial sediment transport ratio (*ASTR*) and the integrated river structure impact index (*IRSII*) to quantitatively assess the impact of human activities on river structure by comparing natural and anthropogenic forces in a river system. The Nanliu River basin under the dramatic impact of human activities was selected to validate the indicator system. The case results showed the Nanliu River has become an anthropogenic river according to its high *IRSII* value (greater than 0.49). The artificial water surface area and artificial sediment discharge were 2.96 (*AWSR* = 2.96) and 2.51 (*ASTR* = *2.51*) times of the outcome of natural process. The river was dramatically blocked by human-made buildings (*DLCR* = *68.63)* and artificial channel accounts for 54.23% of total length of natural river (*ARR* = *0.54*). Within the river basin, upper and lower sub-basins in areas with a higher economic level were more affected by human activities. Future management of the Nanliu River basin should focus on restoration of river connectivity, sand mining and irrigation issues. Unlike most previous assessment methods, the approach developed in this study is simple and readily comprehensible by the public and decision makers, cost-effective for long-term monitoring and not subject to the reference condition.

1. Introduction

Rivers are of immense importance geologically, hydrologically, biologically, historically, and culturally (Sponseller et al., 2013; Poff, 2014). Rivers have been used by humans in support of economic development activities for the past several decades. Approximately 45,000 large dams greater than 15 m in height have been built to retain approximately 15% of the world's total runoff (40 000 km^3y^{-1}) (Nilsson et al., 2005). Approximately 54% of geographically accessible global runoff is currently being used to supply human-related services (Postel et al., 1996). The estimated amount of sediment that has been deliberately shifted by humans (57,000 Mt) around the world is 2.59 times the amount naturally moved by river systems from the land to the oceans (Douglas and Lawson, 2000; Price et al., 2011). Only 23% of flow was uninterrupted to the ocean (Grill et al., 2019). Major river systems, such as the Ganges River, Yellow River, Indus River and Colorado River, are severely fragmented and have ceased to flow to the sea from time to time. Sear and Newson (2003) found that over 60% of the river channel structure around the world have been changed or altered because of urbanization. The impact of human activities on river

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Table 1
Indicators for assessing human impact on river structure.

Indicator	Acronym	Scale of measurement	Description
Artificial water surface ratio	*AWSR*	Catchment	the area ratio of human-made water surface to natural water surface
Artificial water surface density ratio	*AWSDR*	Catchment	the area ratio of constructing water surface area density to global mean water ratio
Disruption of longitudinal connectivity ratio	*DLCR*	Reach	the degree of river channel blockage by human-made buildings compared to an ideal condition
Artificial river ratio	*ARR*	Reach	the length ratio of human-made river to natural river
Sinuosity of artificial cutoff	*SAC*	Reach	the degree of shortening of a sinuosity reach
Channelization ratio	*CR*	Reach	the length ratio of human-modified and controlled channel to natural river
Artificial levee ratio	*ALR*	Reach	the ratio of river length confined by human-made levees to natural river
Road along river ratio	*RARR*	Reach	the parallel ratio between roads and natural rivers
Artificial sediment transport ratio	*ASTR*	Reach	the ratio of sediment transport by anthropogenic forces to by natural forces

systems has now reached a state in which the river systems can no longer be considered to be controlled solely by Earth system processes and also influenced by increasing anthropogenic forces (Turner et al., 1990; Messerli et al., 2000; Meybeck, 2003) due to the combined effects of increasing human population, efficient technology and the ability to pay for its deployment (Haff, 2002). Thus, an assessment of the impact of human activities on river systems is needed to understand the evolution of rivers driven by these two forces in order to maintain their function and support sustainable management practices.

Indicators are recognized as valuable tools that provide signals of change and a valuable means of communication (Dale and Beyeler 2001; Del et al., 2016). Many indicators based on chemical, biotic, hydrological, morphological, habitat (e.g., the River Habitat Survey, Rapid Assessment Protocols and Index of Stream Condition) and landscape aspects have been developed to quantify human impact on river systems (Singh et al., 2009). Chemical indices require laborious field monitoring and experimentation, and water quality always changes due to seasonal variation. Biotic indicators such as the Index of Biotic Integrity (Karr, 1981) and the River Invertebrate Prediction and Classification System (RIV-PACS) rely on a reference condition as a benchmark, i.e., a non-impacted or less impacted river system, but we all know that it is a considerable challenge to find this reference condition, especially in the Anthropocene. Morphological indicators, such as the Morphological Quality Index (MQI), also need reference conditions against which the deviation of present geomorphic reach conditions is measured (Rinaldi et al., 2013). Hydrological indicators, such as the Index of Hydrologic Alteration (Richter et al., 1996), and hydraulic flow methods do not directly link to habitat. In addition, these historic and long-term flow data are not always readily available. Landscape indicators such as average buffer width (Weller et al., 1998) mostly focus on the terrestrial system and miss the river channel. In general, these traditional approaches cannot directly quantify human impact from a simple and visual angle.

Compared to these chemical, biotic, hydrological, morphological, habitat and landscape indicators (Gergel et al., 2002), river structure may be a good visual angle from which to evaluate human impact on river systems because: (1) river structure controls its functions according to the law of structure and function of systematicism (Wei and Zeng, 1995); (2) river structure is directly changed by human activities, ranging from engineering related to rivers (e.g., dams, weirs, floodgates, pipelines, canals, ponds, dredging, sand mining, roads, buildings, revetment, gabion, riprap protection, refuse dump, and pump station) to engineering-induced disasters such as landslides, invasion by exotic species, destruction or degradation of habitat (Döll et al., 2009) and is usually dominated by these activities over a long term (Ji et al., 2014); (3) many parameters of river structure on a broad scale (reach and basin) can be acquired through remote sensing (RS) and geographic information system (GIS), which are easy to measure and visual. Several single river structure indicators have been developed, for example, drainage density, water surface ratio, complexity of river, stability of river, and storage capacity (Ji et al., 2014), however, these indicators are not sufficiently comprehensive to assess the impact of human activities from a system perspective.

The Nanliu River basin, located in the northern part of Beibu Gulf, is the largest river in the southwest China. With the rise of Beibu Gulf Economic Zone for China's national strategy, the Nanliu River basin is experiencing rapid changes. The river system has increasingly been impacted by human activities and caused environmental issues. Growing literatures have researched the Nanliu River in many fields (Li et al., 2017; Zhao et al., 2017; Tong et al., 2018; Yang et al., 2018; Liang et al., 2019; Lin et al., 2019), but no similar study related to assessment the impact of human activities on river system has been carried out.

Given this background, our paper aims to develop an indicator system to assess the impact of human activities on river structures by comparing the natural and anthropogenic forces that act on the river systems using GIS and RS techniques, in which the Nanliu River basin is used as an example.

2. Methods and data

2.1. Development of a river structure assessment indicator system

Based on the principles that indicators should be simple, practical and visual, this paper proposed the following 9 indicators to assess human impact on river structures by comparing outcomes of two forces (anthropogenic vs. natural forces) within a river system (Table 1). Finally, these indicators were normalized and integrated into an index for easy practice operation.

(1) Artificial water surface ratio

Water surface area is a very visual parameter in quantifying human alterations and plays an important role in explaining a change in ecological conditions. Compared to natural water surface, artificial water bodies are widely distributed in the world. For example, at least 2.6 million small, artificial water bodies (e.g., ponds) dot the landscape of the United States and account for approximately 20% of its standing water area (Smith et al., 2002). These artificial water bodies have impacted on hydrology, sedimentology, geochemistry and ecology in their area (Smith et al., 2002; Fairchild and Velinsky, 2006). Similar to the widely used index of water surface ratio (Ji et al., 2014), we proposed an artificial water surface ratio that was calculated as below:

$$AWSR = \frac{AWS_{area}}{NWS_{area}} \ (NWS_{area} \neq 0) \quad (1)$$

where *AWSR* is the area ratio of artificial water surface to natural water surface on a basin scale that indicates how many man-made water bodies are inserted into fnatural river systems; AWS_{area} is the area of artificial water bodies created by all kinds of water conservancy facilities, such as reservoirs and artificial ponds; NWS_{area} is the area of natural water surface from natural rivers and lakes. In general, the range of *AWSR* is $[0, +\infty)$. A higher value of *AWSR* indicates a higher anthropogenic force on the river system. $AWSR = 1$ indicate that these

two forces are at equilibrium from the perspective of water surface area. The water surface area is mainly controlled by anthropogenic force when *AWSR* is greater than 1.

(2) Artificial water surface density ratio

Artificial water bodies have increased the ratio of water surface area to total basin area in a river basin. This variation could result in habitat alteration, degradation of water quality, change of groundwater recharge and connectivity of the river basin especially in agriculture regions (Tarolli and Sofia, 2016). Artificial water surface density is the ratio of AWS_{area} to the whole basin area ($Basin_{area}$) that represents the degree to which land surface has been modified to water surface by human activities. We assume that global mean land water ratio (2.73%) is a natural background value (Cao et al., 2014). Artificial water surface density ratio (*AWSDR*) was designed to compare with this natural background as below:

$$AWSDR = \frac{100 \times AWS_{area}}{2.73 \times Basin_{area}} \tag{2}$$

In general, the value range of *AWSDR* is $[0, +\infty)$. A higher *AWSDR* value indicates that more artificial water area was built and more land surface was covered by artificial water bodies in a basin. The river system was controlled by anthropogenic force from the viewpoint of water surface density when *AWSDR* is greater than 1.

(3) Disruption of longitudinal connectivity ratio

Longitudinal connectivity from a hydrologic viewpoint is considered as a water-mediated transfer of matter, energy or organisms within or between elements of the hydrological cycle. It is important in river ecology due to its relation to the community structure and biodiversity patterns in river channels and its role as a transport pathway for species migration and organic/inorganic matter into the downstream (Wohl et al., 2019). However, river longitudinal connectivity is presently disrupted. The River Fragmentation Index (Grill et al., 2015), the River Connectivity Index (Grill et al., 2014) and Degree of fragmentation (Grill et al., 2019) are three indicators that evaluate the effect of river fragmentation by reservoirs or dams on structural connectivity per basin or sub-basin. These indicators represent the ratio of the controlled river volume in a basin. In an attempt to directly capture the obstruction of the river structure in a river channel, Liermann et al. (2012) used the longest undammed river length to derive the percentage of unobstructed watercourse to reflect the connectivity, which is direct, simple and useful. We were inspired to develop the longitudinal connectivity (*DLC*) index that is defined as below:

$$DLC = \frac{N}{L} \tag{3}$$

$$DLCR = \frac{DLC}{0.6} \tag{4}$$

where *DLC* is the disruption of longitudinal connectivity of a river that indicates the frequency, intensity and level of blockage to water flow, sediment transport and fish migration by man-made buildings. The *DLC* is usually represented as the number of buildings per 100 km channel length. *N* is the number of the buildings such as dams, gates and weirs. *L* is the river length and its unit is 100 km. Natural barriers (e.g., waterfalls) or some artificial barriers with something like fish passages are assumed not to have any negative impact on river connectivity (O'Hanley, 2011).

An ideal *DLC* value of a natural river is small, 0.6 buildings / 100 km (Water Resources and Hydropower Planning and Design General Institute, 2010). *DLCR* was designed to compare with this ideal *DLC* condition and indicate the degree of river channel blockage by human-made buildings. *DLCR* is dimensionless and its range is $[0, +\infty)$. A high *DLCR* value means the river system is more blocked.

(4) Artificial river ratio

Natural river length is always a basic parameter in the assessment of river structure. In the Anthropocene, the artificial river, such as irrigation canals, ditches and aqueducts, becomes part of the river network. An artificial river plays different roles in landscape, ecology, and water quality. Thus, the artificial river ratio was proposed to compare the channels made by natural and anthropogenic forces, in length and was calculated as below:

$$ARR = \frac{AL}{L} \tag{5}$$

where *ARR* is the artificial river ratio and equals the length ratio of an artificial channel (*AL*) and natural river (*L*). Artificial channels indicate the force of human activity cast on the river structure. In general, the value range of *ARR* is $[0, +\infty)$. High *ARR* values reflect a low degree of naturalness of the whole river system. The river channel is mainly created by anthropogenic force when *ARR* is greater than 1, whereas by natural force.

(5) Sinuosity of artificial cutoff

Cutoff is a physical evolution process of a meandering channel (Li and Gao, 2019). However, artificial cutoff is a man-made process of straightening a sinuous channel for the purpose of flood control, infrastructure protection or navigation, which is a major measure of channel realignment (Smith and Winkley, 1996). The morphological complexity, hydrodynamic process and length of meandering river were reduced after artificial cutoffs (Li and Gao, 2019). Artificial cutoff projects are widely distributed around the world. For example, 16 artificial cutoffs had been constructed and shortened the channel by 243 km in Lower Mississippi River as early as from 1929 to 1945 (Smith and Winkley, 1996). The most obvious change of each cutoff is its sinuosity. River sinuosity reflects the capacity of a river for horizontal movement (Zhao and Ding, 2016). Thus, the sinuosity of artificial cutoff (*SAC*) was proposed as an indicator to compare channel lengths between sinuous channels derived by the hydrologic process and straight channel derived by anthropogenic force. It can be calculated as below:

$$SAC = \frac{SL}{LL} \tag{6}$$

where *SL* is the length of the sinuosity reach of a cut and *LL* is the length of a new man-made line reach. In general, the range of *CR* is $[1, +\infty)$. High *SAC* values reflect a highly shortened degree of river system.

(6) Channelization ratio

Channelization is a group of engineering practices to ensure river navigation, flood protection and increasing the sediment transport capacity (Scorpio et al., 2018). Channelization basically fixes the evolutionary trajectory of channel and limited horizontal movement of rivers. In Europe, channelization has been planned since the 18th century, and now they seem to be everywhere around world. Channelization in most cases has resulted in channel narrowing, bed-level lowering, simplification of channel morphology and ecological degradation (Oscoz et al., 2005; Zawiejska and Wyżga, 2010; Scorpio et al., 2018). To evaluate the impact of these modified channels, the channelization ratio (*CR*) was designed and calculated as below:

$$CR = \frac{C}{L} \tag{7}$$

where *C* is the length of the channelization channel and *L* is the length of the natural river. The range of *CR* is $[0, +\infty)$. River channels are mainly created by natural force ($CR \in [0,1)$) or anthropogenic force (*CR*

$\in (1, +\infty)$).

(7) Artificial levee ratio

In natural conditions, valley floor width indicates the maximum lateral extent of river movement and the degree to which the river is confined within its valley (Polvi et al., 2011; Zhao and Ding, 2016; Zhao et al., 2019). The lateral dimension of a river expresses the link between riverine systems and wetlands and floodplains. Nowadays, most river channels could not freely laterally move within the valley floor because they are directly limited by an artificial levee, i.e., artificial levees provide a smaller space than the valley floor for river lateral movement. Therefore, interactions between rivers and their levees will be more violent during a flood. Thus, the artificial levee ratio was designed to compare artificial confined channel with natural confined channel. It can be calculated as below:

$$ALR = \frac{LEL}{L} \tag{8}$$

where *ALR* is the artificial levee ratio, *LEL* is the length of the artificial levee and *L* is the length of the natural river. In general, the range of *ALR* is $[0, +\infty)$. Lateral movement extent of river system is mainly defined by natural force ($ALR \in [0,1)$) or anthropogenic force ($ALR \in (1, +\infty)$).

(8) Road along river ratio

Many road networks are parallelly distributed along river systems. Compared to natural river system (exclusive of irrigation canals, ditches and aqueducts), these roads are so close to a river in a giver buffer area, which seems to be a part of the river system. These two networks have many types of interaction (Jones et al., 2000). Roads can affect the manner in which incoming precipitation is routed through a basin to produce a flood (Jones & Grant, 1996). Water carried by roads will be delivered to streams to coincide with the flood peak. They also indirectly change river structure, disrupt the lateral connectivity from floodplains and longitudinal connectivity at intersections with streams in particular culverts (Grill et al., 2019). Road construction would induce landslides and increase the crushed zone that could persistently modify the river structure. Road drainage systems (a portion of the road network) have the potential to act as extensions of the river drainage network (Wemple et al., 1996). Roads also provide opportunities for humans to reach and impact the river structure. In addition, road transport is a main source of water pollution. The road density was used as a dominant pressure indicator to assess river connectivity status (Grill et al., 2019). Here, we assumed that road and natural river networks are products of anthropogenic and natural forces in a given buffer area along river systems, receptively. These two products were compared and calculated as follows:

$$RARR = \frac{R}{L} \tag{9}$$

where *RARR* is the ratio of roads along a river system; *R* is a length of road along a river system and less than a given distance (e.g., 50 m) to near channels; and *L* is total length of natural river system. In general, the range of *RARR* is $[0, +\infty)$. *RARR* approximately indicates the percentage of the length of natural river was attached by roads.

(9) Artificial sediment transport ratio

Sediment transport is a basic function of a natural river system. Sediment is a gift for the ocean and the fundamental material that forms a delta. In addition, it is a very important building material; therefore, legal and illegal sand mining is very popular. Thus sediment discharge change resulted from human impact are often considered as an index (Fan et al., 2006; Syvitski and Kettner, 2011; Wang et al., 2016; Allison et al., 2017), but they miss the part of sediment change from sand mining. Sand mining has induced problems such as the breaking of river banks and riverbeds, an increase of geological disasters, and invasion of farmland. Therefore, the artificial sediment transport ratio (*ASTR*) was developed to compare river sediment discharge with sediment discharge by sand mining in a river system. It represents the ability of sediment transport through human activities compared to the hydrological process. It was calculated by the equation below:

$$ASTR = \frac{M}{ST} \tag{10}$$

where *M* is a quantity of sand mining and transport and *ST* is a quantity of sediment transport of suspended load and bed load through river flow. In general, the range of *ASTR* is $[0, +\infty)$. The sediment transport of river system could be mainly driven by water flow ($ASTR \in [0,1)$) or sand mining ($ASTR \in (1, +\infty)$).

(10) Integrated river structure impact index

To improve the practicability of these indicators during practice operation, the nine aforementioned indicators were normalized ($y = \text{atan}(x) \times \frac{2}{\pi}$) and integrated into one index, the integrated river structure impact index (*IRSII*), was calculated by the equation below:

$$IRSII = \frac{\frac{2}{\pi} \times \sum_{i=1}^{n} w_i \times atan(R)}{\sum_{i=1}^{n} w_i} \tag{11}$$

where *R* is one of aforementioned indicator and w_i denote the weighting coefficient of the *i*-th indicator; *n* is the number of *R*. The range of *IRSII is* [0,1) since the normalized function was computed.

According to the comparison of outcomes of anthropogenic vs. natural forces, each *R* could be classified into four categories (nature strong control: 0–0.5; nature control: 0.5–1; artificial control: 1–2; artificial strong control: greater than 2). Correspondingly, the range values of *IRSII* were computed into four categories (nature strong control: 0–0.29; nature control: 0.29–0.48; artificial control: 0.48–0.61; artificial strong control: 0.61–1).

2.2. Study area

The Nanliu River basin is located in the southeast of China's Guangxi Zhuang Autonomous Region (Guangxi) with an approximate main stream length of 285 km and a drainage area of 9232 km^2 (Fig. 1). The basin elevation ranges from sea level to 1244 m with an average of 620 m. The mean annual rainfall in this basin is between 1400 and 1760 mm (Tong et al., 2018). According to 2016 statistics, the total population of the Nanliu River basin is 4.06 million and the corresponding population density is 435 persons per square kilometer, which is 3.04 times the national average in China (143 persons per square kilometer in 2013). For the GDP, in the Nanliu River basin it is 93.33 billion yuan, accounting for 5.09% of the Guangxi GDP, compared to 3.90% of the total basin land area. Therefore, the Nanliu River basin has been drastically changed by various human activities.

Fig. 2 shows the population and economic development in each sub-basin. The 20 sub-basins were categorized into two groups according to the GDP values per area and population density. Dingchuan, Qingwan, Rendong, Shasheng, Shatian, Beiliu-Fumian and Fumian-Bobai sub-basins are in a group with large populations and high economic pressure, while the rest of sub-basins belong to the other group.

2.3. Data sources and processing

Remote sensing images of the Nanliu River basin were acquired from the MAP WORLD of Guangxi (http://www.mapgx.com/ime-gx), with spatial resolutions of 0.8 ~ 2 m, to visually interpret and map river structure and human activities as vector polygons (e.g., natural river

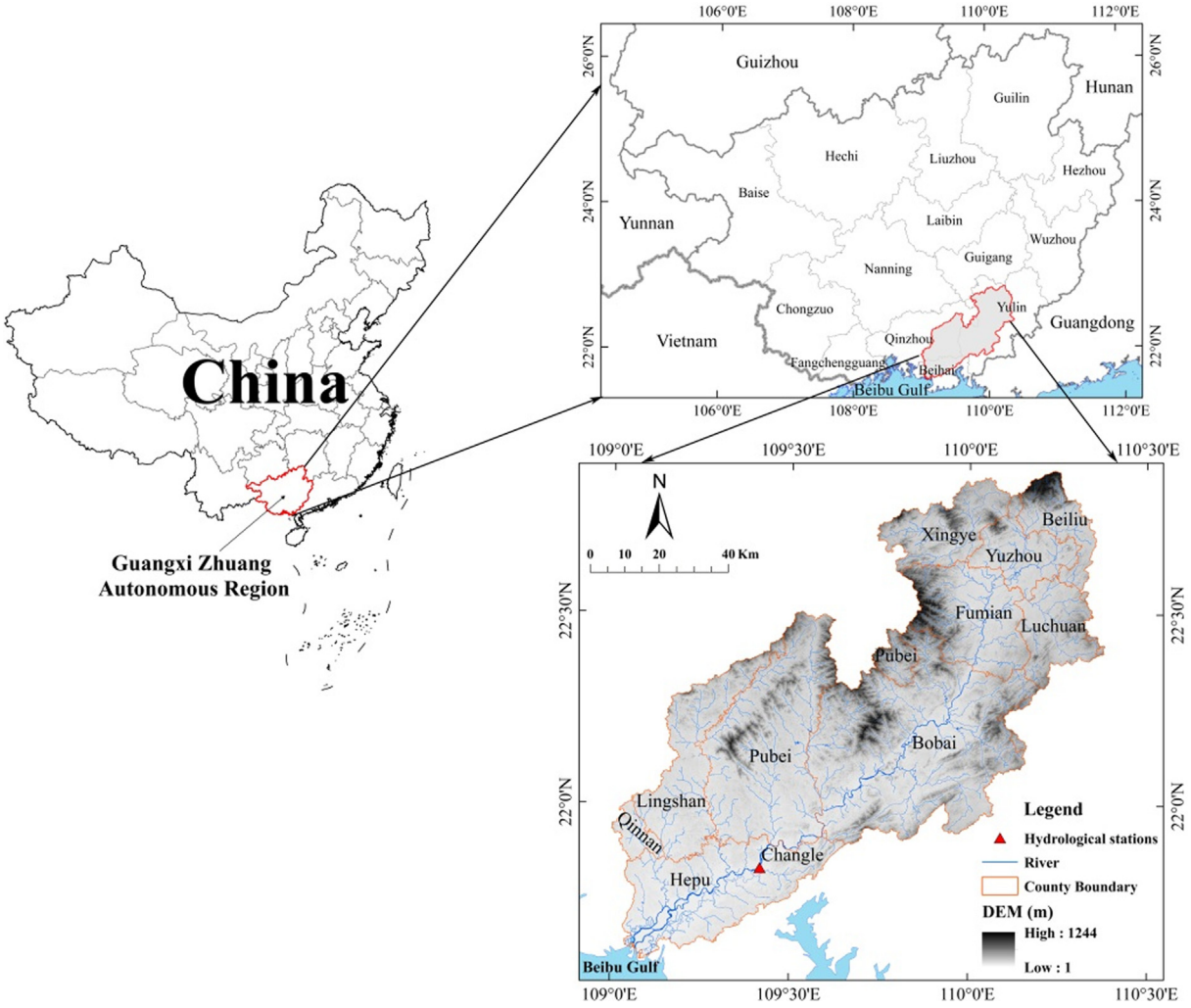


Fig. 1. Location and topography of the Nanliu River basin. The Changle hydrologic station controls a 6645 km^2 drainage area accounting for 71.98% of the basin that is the station near the Beibu Gulf (approximate 72 km) and has provided long-term measurements since it was built in 1952 (Zhao et al., 2017).

networks, lakes, ponds, reservoirs, mining sand areas and reservoir), vector polylines (e.g., ditches/aqueducts, channelization, levee, artificial cutoffs and road networks) and vector points (e.g., gate dams and pump stations), in ArcGIS 10.1. Correspondingly, their attributes such as locations, areas or lengths were derived and assigned to these vector objects. The Kappa coefficient was then used to evaluate the accuracy of extracted information. A Kappa greater than 0.75 was considered good enough for further analysis. A field trip was conducted to validate the interpreted sand mining areas and investigate the sand mining condition in 2018. DEMs with 30-m spatial resolutions were downloaded from Geospatial Data Cloud (http://www.gscloud.cn/). Natural river network was initially delineated base on above DEMs and represented by vector polylines, then delineated the 20 sub-basins using ArcGIS 10.1. The 1:50,000 Digital Line Graphic (DLG) dataset was collected from the Guangxi Bureau of Surveying, Mapping and Geoinformation to correct the interpreted (vector polygons) and delineated (vector

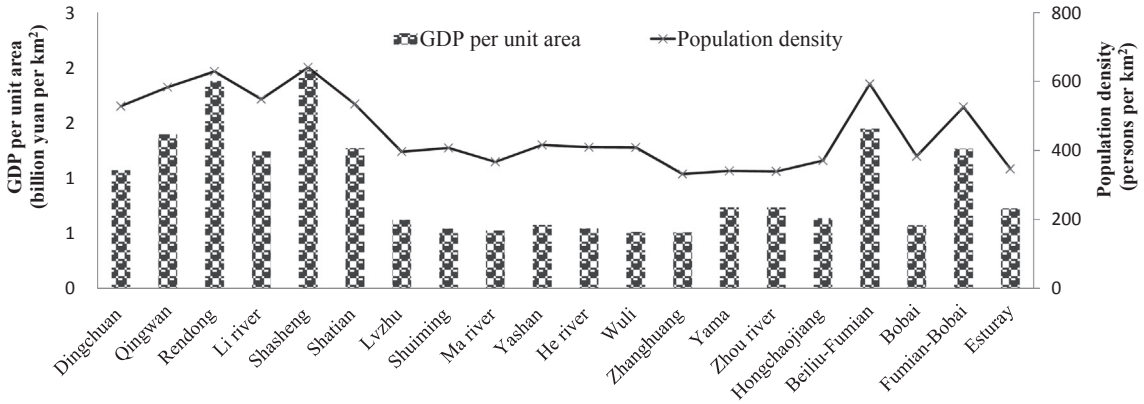


Fig. 2. Accumulated gross domestic product (GDP) per km^2 (1996 ~ 2016) and population density for 20 sub-basins of Nanliu River basin in 2016.

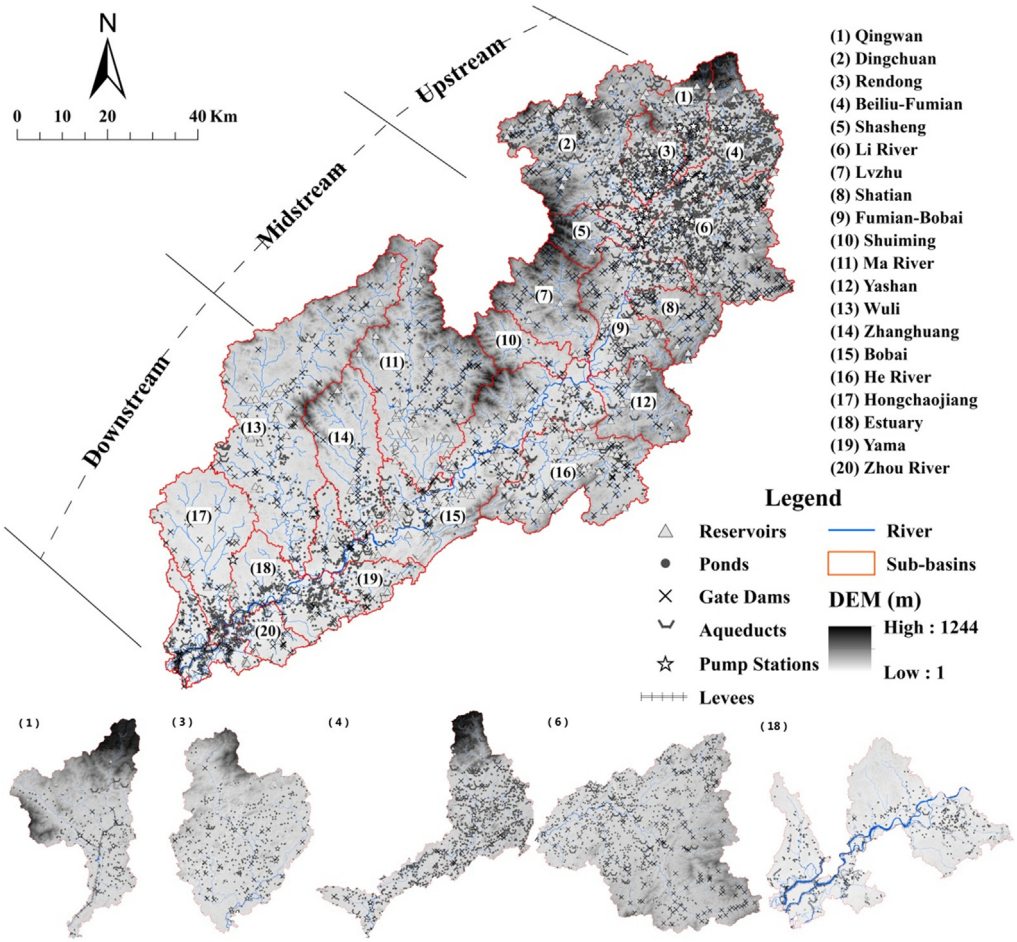


Fig. 3. Distribution of water projects in the Nanliu River basin. Five sub-basins were specially highlighted to show the density of these projects.

polylines) river network. As a result, the total length and area of natural river network in the Nanliu river basin is 3210.26 km and 83.55 km^2, respectively. Annual sediment discharge data at Changle station were collected from the Guangxi Coastal Hydrology and Water Resources Bureau to calculate the quantity of sediment transport.

3. Results

3.1. Mapping and quantification of human activities

All kinds of projects were found using the RS interpretation and then mapped (Fig. 3). There were 345 reservoirs and 4,728 ponds, and their areas are 192.24 km^2 and 54.74 km^2, respectively. There were 977 gate dams and 40 pump stations and 219 aqueducts with the length of 1740.85 km. These aqueducts (ditches) are too narrow to consider polygon objects. Most levees were distributed along main stream with a total length of 183.49 km. Channelization was largely made in city areas and total length is 181.83 km (Table 2). On average, there were approximately 0.68 projects per square kilometer and 0.04 reservoirs per square kilometer. Fig. 3 presents five representative sub-basins to show that the projects were very crowded in this basin and that the projects in the upper and lower basins were denser. Furthermore, water projects in the upper basin are densely dispersed over the region while water projects in lower basin are gathered along the river.

The road network (1288.84 km) was built within 50-m buffer area of natural river system. The road types ranked by their lengths along the river system are township road > county road > provincial road > national road > accommodation highway (Fig. 4). The length of the township road was the longest.

Sand mining was widely found in the Nanliu River basin. The area (429.95×10^4 m^2) of sand mining was mapped, and the volume (3139.60×10^4 m^3) was estimated (Table 3). Sand mining was found to spread from downstream to middle stream and from main streams to tributaries. Sand mining sites were mostly located in the main stream of

Table 2
Water projects in study area.

Types	Numbers /(area or length)	Main functions
Reservoirs	345 / 192.45 km^2	Hydroelectricity, irrigation, water supply, flood control
Ponds	4728 / 54.74 km^2	Irrigation, providing aquatic products, sewage treatment
Aqueducts	219 / 1740.85 km	Irrigation
Levees	183.49 km	Flood control
Channelization	181.83 km	Flood control, bank protection, navigation
Gate dams	977	Irrigation, flood control
Pump stations	40	Irrigation, water supply
Artificial cutoffs	19 / 12.48 km	Flood control, navigation

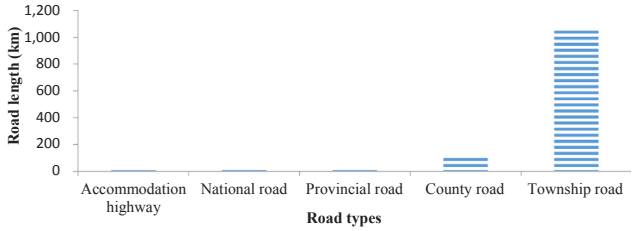


Fig. 4. Distribution of the lengths of different road types along the river system.

Table 3
Distribution of sand mining sites in the Nanliu River basin.

Site	Sand mining		Main distribution area
	Area ($\times 10^4$ m^2)	Volume ($\times 10^4$ m^3)	
Bobai County	49.83	389.20	Lingjiao, Shahe and Lvzhu town
Hepo County	308.70	2179.66	Shiwan, Changle and Shikang town
Pubei County	71.27	569.41.	Quanshui town
Yuzhou District	0.15	1.33	Shatian town
Total	429.95	3139.60	

the Nanliu River, Wuli River and Zhanghuang River sub-basins, especially in the conjunctions of these rivers.

3.2. Impact of human activities on the river structure through comparison between the natural and anthropogenic forces

3.2.1. Nanliu river basin as a whole

The artificial water surface area in the whole basin was 2.96 times the natural water surface area (*AWSR* = 2.96) and up to 2.66% of the total basin area (*AWSDR* = 0.97). The artificial water surface area was mainly formed by 345 reservoirs, and then by 4,728 ponds. These indicated that the area of water surface in Nanliu River basin is mainly controlled by anthropogenic force (e.g., excavation) rather than natural force. On average, there were 41.18 human-made buildings in the flow stream per 100 km river length (*DLCR* = 68.63). These buildings mainly include reservoirs, gate dams and some ponds in the flow stream.

The river length formed by artificial force is greater than half of the natural river length (*ARR* = 0.54). Although channelized river channel is relatively small in whole Nanliu River basin (*CR* = 0.06), but it is highly concentrated in city areas. Artificial levee length accounts for 5.72% of the total natural river length (*ALR* = 0.06). In addition, we clearly found that road network in whole basin is closely connected with river network with a high *RARR* value (0.38), primarily due to the contribution of township roads. This suggested that approximate 38.28% of natural river length was closely attached by roads.

A total of 19 artificial cutoff projects were found in the upper basin (Yulin City and Beiliu City) and middle basin (Bobai County) in Fig. 5. Eighteen man-made cutoff projects were built in high sinuosity reaches, and these river channel lengths were sharply shortened after project construction (Fig. 5). The *SAC* values of these projects range from 1.33 to 9.99, and the average is 2.67, which means that 18.31 km of 30.79 km of the total length of natural sinuous reaches were eliminated by these projects. It was also found that most artificial cutoff projects were located in the main stream and in the upper basin in Yulin City, including Yuzhou and Fumian districts, a relatively well-developed city with a large population.

The period (2000 ~ 2016) is said as golden years for sand mining in Nanliu River basin (Li et al., 2017). Sand mining was conservatively estimated to 4395.40 Mt based on its volume (3139.60×10^4 m^3) and density (1.4 ton m^{-3}). Cumulative sediment discharge at Changle station during 2000–2016 was approximately 1250.66 Mt that adds 10% of suspended load discharge (Fig. 6) as bed load discharge (Wang, 1986). The sediment from human mining was estimated as 2.51 times that of river transport (*ASTR* = 2.51), which implied that anthropogenic force became the dominant force in sand transport.

Fig. 7 shows the results of the impact of human activity in the whole Nanliu River basin. Clearly, there is a large gap in the nine index values. The values of *AWSR, DLCR, SAC and ASTR* are high while the remaining indices belong to the other group with low values. According to equation (11) with an equal weight, the value of *IRSII is 0.49 that* belongs to artificial control degree, which suggests that anthropogenic force instead of natural force became a controlling power of change of river structure in the Nanliu River system.

3.2.2. Sub-basin situations

Table 4 and Fig. 8 show the influence of different human activities on river structure in the sub-basins. It is clear that *AWSR, AWSDR, DLCR* and *RARR* form a group with dense, high values in most sub-basins and that other indicators *(ARR, CR* and *ALR*) are a separate group with few high values. These findings imply that artificial water bodies, interaction between roads and rivers and disruption of longitudinal connectivity were big issues for entire basin, while other issues were only relevant for a few sub-basins.

In general, the largest influence on river structure resides in the upper basin (relatively developed area) and lower basin (estuary region). Specifically, Qingwan, Dingchuan, Rendong, Beiliu-Fumian and Li River sub-basins in the upper basin and Yama River and Zhou River sub-basins in the lower basin comprise a typical high cluster region for the 7 indicator values (Fig. 8).

From the viewpoint of *AWSR*, the Ma River and the Hongchaojiang sub-basins were at the maximum (22.63 and 21.95) and the minimum was the Estuary sub-basin (0.41). There are large gaps between these sub-basins, which is mainly due to the impact of some large reservoirs. For example, the two large reservoirs, Hongchaojiang reservoir (7.14×10^8 m^3) and Hepu reservoir (12.47×10^8 m^3), of the Nanliu River basin are located in the Ma River sub-basin and Hongchaojiang sub-basin. Therefore, the *AWSDR* values of these basins are highest. Other dams and ponds built in tributaries were relatively small. Although these projects created small water surface, they have greatly changed the river structure on a small scale.

All sub-basins had a very high *DLCR* values, including 70% of sub-basins, with more than 50 times of the ideal condition. In another word, all sub-basins in the Nanliu River basin were in very bad condition regarding longitudinal connectivity. This was probably the result of using irrigation in the service of agriculture, livestock breeding and the jeans industry, and in providing hydropower. For example, Li River basin was highlighted with an inconceivable value (*DLCR* = 159.10) that is mainly attributed to the pig industry (a traditional small family business).

Most artificial channels are located in upper basins, such as the Rendong basin (*ARR* = 2.30), Qingwan sub-basin (*ARR* = 1.99), Li River sub-basin (*ARR* = 1.55) and Fumian-Bobai sub-basin (*ARR* = 1.26). Artificial channel lengths in these basins are greater than their natural river lengths (Table 4). Flood banks and river channelization were usually built in urban areas with dense populations and affluence, such as the urban area in the Yuzhou district, Pubei County and Hepu County (Fig. 9). Most channelized channels were intensively built in Qingwan (*CR* = 0.36), Estuary (*CR* = 0.29) and Beiliu-Fumian (*CR* = 0.16) sub-basins while *CR* values of the rest of sub-basins are less than 0.06. All sub-basins have big differences in *ALR* values between the maximum (0.44) and minimum (0). The Zhou River and Estuary sub-basins both are located in the estuary area of the Nanliu River basin where there are multiple channels. Obviously, the *ALR* values of these two sub-basins were up to 0.44 and 0.38, respectively and much higher than other sub-basins because more flood bank

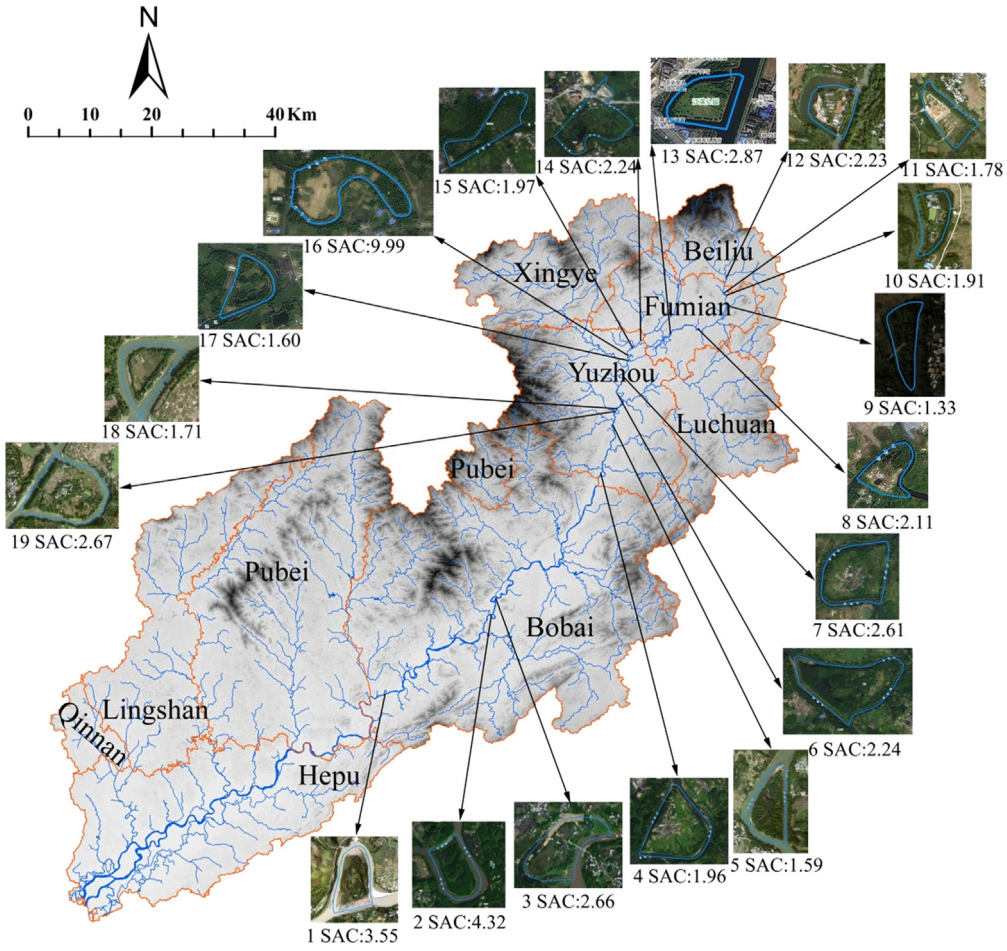


Fig. 5. Distribution of artificial cutoff projects with their sinuosity values in the Nanliu River basin.

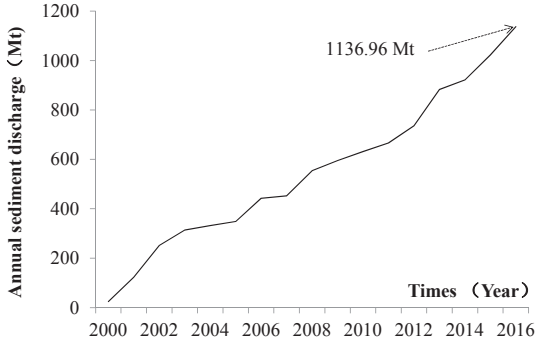


Fig. 6. Annual cumulative suspended load discharge at Changle station.

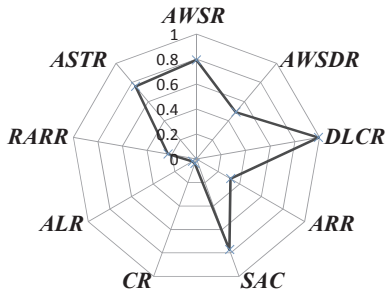


Fig. 7. Nine indicators analysis for the entire river basin.

Table 4
Comparison of indices used to quantify human impact on different sub-basins.

Sub-basin	*AWSR*	*AWSDR*	*DLCR*	*ARR*	*CR*	*ALR*	*RARR*
Qingwan	4.08	0.76	87.22	1.99	0.36	0.19	0.34
Dingchuan	3.51	0.60	85.03	0.80	0.04	0.02	0.38
Rendong	10.45	1.53	98.48	2.30	0.06	0.01	0.26
Beiliu-Fumian	4.20	1.15	67.32	1.92	0.16	0.07	0.35
Shasheng	2.94	0.50	53.15	0.88	0.02	0.02	0.53
Li River	5.30	0.89	159.10	1.55	0.01	0.01	0.44
Lvzhu	3.26	0.46	53.35	0.04	0.00	0.00	0.74
Shatian	1.11	0.21	139.6	0.69	0.02	0.00	0.56
Fumian-Bobai	1.19	0.55	112.97	1.26	0.04	0.00	0.37
Shuiming	0.5	0.05	25.1	0.04	0	0.00	0.64
Ma River	22.63	2.33	47.62	0.04	0.03	0.01	0.43
Yashan	1.22	0.32	59.02	0.34	0.01	0.00	0.45
Wuli	0.93	0.16	43.8	0.08	0.01	0.00	0.44
Zhanghuang	1.72	0.16	35.75	0.08	0.04	0.02	0.52
Bobai	0.89	0.70	66.05	0.30	0.02	0.02	0.30
He River	2.24	0.44	103.73	0.43	0.01	0.00	0.37
Hongchaojiang	21.95	4.77	33.37	0.00	0.00	0.06	0.18
Estuary	0.41	0.53	31.4	0.00	0.29	0.44	0.19
Yama	10.97	1.48	66.45	0.00	0.00	0.02	0.26
Zhou River	12.77	2.29	57.25	0.00	0.00	0.38	0.15
Entire basin	2.96	0.97	68.63	0.54	0.06	0.06	0.38

construction are very necessary for these areas.

The situation of the road network along the river system is very common in all sub-basins of the study area. The *RARR* range is from 0.74 to 0.15 with an average of 0.38. This finding is mostly observed because the Nanliu River basin is densely populated and most people live along the river system. In addition, reservoirs, dams and farmland

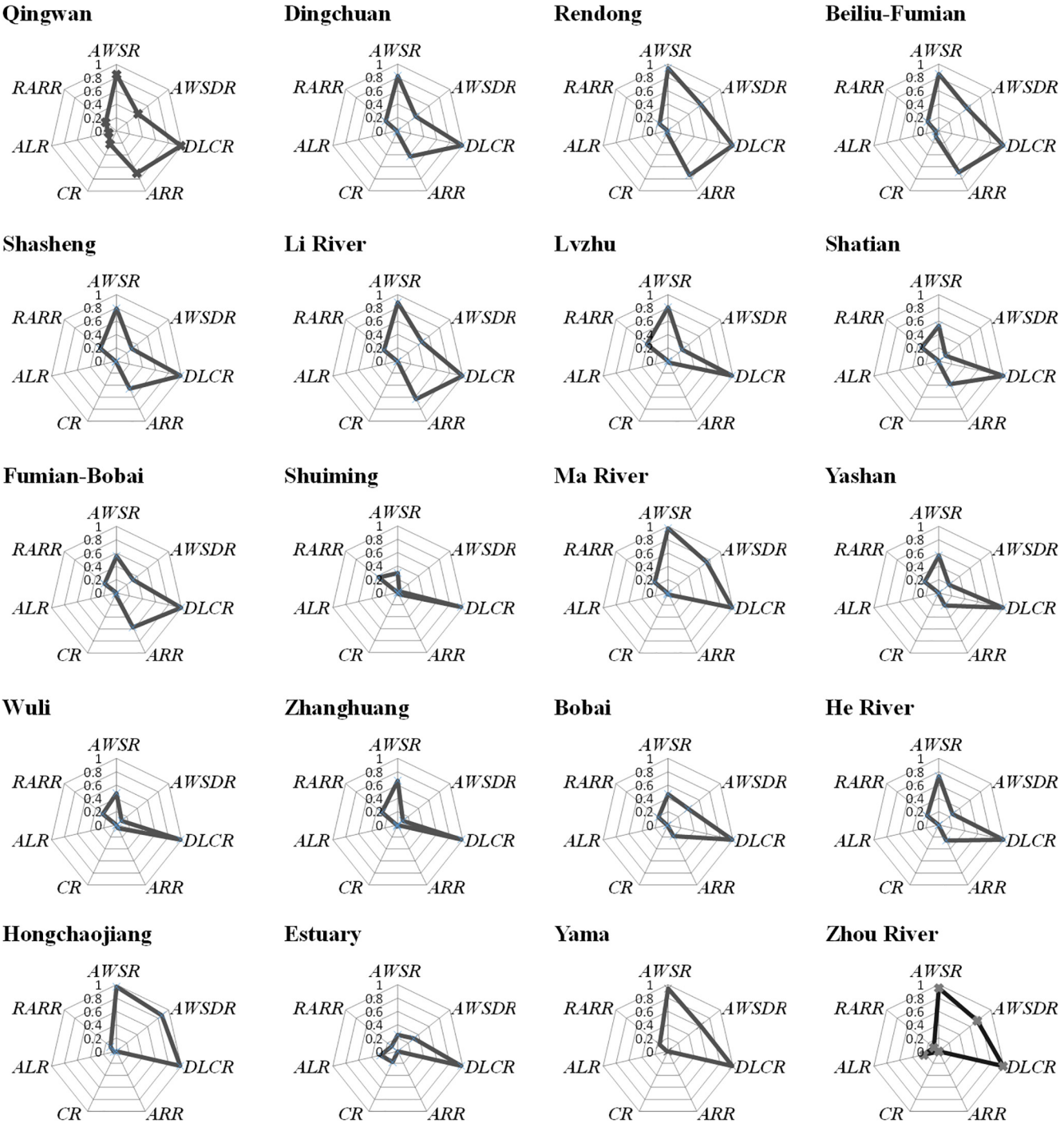


Fig. 8. Seven-index analysis for 20 sub-basins from upstream to downstream, quantities reported as values of normalization ($f(x) = \text{atan}(x) \times \frac{2}{\pi}$).



Fig. 9. Examples of flood banks in (a) the Yuzhou district, (b) Pubei County and (c) Hepu County.

need roads for access.

4. Discussion

To our knowledge, this is the first study to develop an indicator system to assess human impacts on river structure from the viewpoint of a comparison between anthropogenic and natural forces. The proposed indicator system, similar to landscape indicators such as forest cover (Detenbeck et al., 1993), could provide a direct measure of human alteration in a basin. Evaluating the change in river structure offers new insights into the influence of human activity on river systems. Compared to traditional indicator systems, such as chemical, biotic, hydrological and habitat, the river structure viewpoint is more direct, simpler and more visible. Simple metrics proposed in this study may be most useful (Gergel et al., 2002; Rinaldi et al., 2013) due to its easiness to connect public interests and management (Weber and Ringold, 2019). For example, no. 16 project in Fig. 5 (*SAC* = 9.9) showed that the sinuous channel was replaced by only 10% straight channel (0.28 km) of the original length (2.78 km). Thus, a flood could quickly pour through Yulin City, which is easy to calculate, understand and explain to the public and management, even without background knowledge.

Furthermore, the proposed indicator system in this study has been designed to compare the accumulative outcomes of natural and anthropogenic forces until a given time. Thus, this method does not need to set a reference condition to compare, which enhances its practicality because the reference conditions, historical or natural, always limits many methods (e.g., RIV-PACS, MQI). With the same assessment conducted in different time periods, this method can be used to detect the change of river structure, and change of its natural and anthropogenic forces. In other words, this method could track the impact of human activities on river structure.

This assessment indicator system spans a broad spatial extent with adequate resolution and accuracy that are fundamentally scientific. These indices focus on the surface characteristics of river structures that are more easily and more economically acquired by RS and GIS techniques than other methods (e.g., IBI, RIV-PACS, and IHA) on a large scale. Some free platforms for data sources, such as Google Earth, MAP WORLD of Guangxi, the United States Geological Survey, the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) provide free access to data this method needed. This is very helpful for wide applications of the method. We believe that the proposed indicators and methods can be applied in multiple ways because they could be simple, straightforward, effectively and easily understood by different people, including scientists, planners, managers and the general public.

Our findings in Nanliu River basin have implied that river functions have been degraded because of high modification of river structure. For example, the decrease of transporting function of sediment entering the sea is due to human activities such as hydraulic engineering and forest conservation (Li et al., 2017). The basin management strategy should focus on river restoration in the future. According to the highlighted high values of *DLCR, RARR, AWSR, ARR and ASTR* for the whole basin, prioritizing stream restoration actions in the Nanliu River basin probably is (1) to remove migration barriers (corresponding to the *DLCR*); (2) to restore watershed processes such as instream flows, sediment reduction and riparian areas (corresponding to the *DLCR, ASTR, AWSR* and *RARR*); and (3) to enhance instream habitats (corresponding to the *DLCR* and *ARR*). These are consistent with the recommended strategies and citations from Beechie et al. (2008). Accordingly, the priority areas for restoration are the seven sub-basins (Qingwan, Rendong, Dingchuan, Beiliu-Fumian, Li River, Yama River and Zhou River), which have high values of the abovementioned indices (Fig. 8). The Qingwan, Rendong, Dingchuan, Beiliu-Fumian and Li River basins are relatively developed areas (Fig. 2) and are under high pressure from population density and economic development.

Prioritization for the removal of artificial in-stream structures to enhance river connectivity to activate river vigor in a cost-effective way (O'Hanley, 2011) is probably a viable solution for the Nanliu River basin. For example, the removal of these dams is a growing movement in the United States to restore rivers (Roy et al., 2018). This is because these dams aging or problem infrastructures (Roy et al., 2018) which have lost their original functions, have negative ecological or indigenous impacts, or are expensive to maintain (Roy et al., 2018).

According to the *ASTR* value (2.51) for the whole basin, we realized that sand mining in the study area far exceeded the natural process. Illegal sand mining in downstream of the Nanliu River has been reported many times and has attracted the attention of government officials and the public because it caused a series of direct problems, such as intrusion of farmland and banks, induction of social contradictions, destruction of riverbeds, as well as some indirect problems (Li et al., 2017). For example, the riverbed width of a reach of the main stream in Shiwan town, Hepo County, was expanded from the original 100 m to 500 m due to illegal sand mining. *ASTR* value can assist water managers in realizing the seriousness of the problem and help them make the decision to stop sand mining instead of only against illegal sand mining.

The high values of *AWSR, AWSDR, ARR* and *DLCR* in Fig. 8 indicate that the demand of irrigation water usage is large. It can also be seen in Table 2 that 'irrigation' is the main purposes of water projects. Agriculture is the basis for human survival in this basin, consuming up to 65.5% (Guangxi water resources bulletin in 2016) of total water use to feed approximately 4.06 million people. However, the efficiency coefficient of irrigation water usage in the Nanliu River basin (approximately 0.47) is much smaller than the national level (0.54), and smaller than the level in Guangxi (0.48). Thus, the efficiency of irrigation water use should be improved through agronomic techniques, irrigation systems engineering, and demand-based irrigation scheduling.

In general, the proposed indicator system in this study performed well in the Nanliu River basin because it has captured its major issues of ecological environment and provided suitable management strategy and key regions for the Nanliu River basin.

This assessment indicator system could identify the changes of river structure and functions and help river restoration, thus it could be attempted to integrate with the river restoration method based on fluvial geomorphology (river structure), such as the River Style framework (Brierley and Fryirs, 2000; Brierley et al., 2011; Brierley and Fryirs, 2016), to develop a flexible, simplified and cost-effective management programme for Chinese river restoration. For instance, the REFORM (REstoring rivers FOR effective catchment Management) that provided an open-ended hydromorphology framework to support cost-effective implementation of restoration measures in restoring river ecosystems in Europe was built heavily on the River Style framework (Gurnell et al., 2016).

Three limitations of this study should be noted. First, the accuracy of the data may be not very high. For example, some instream structures might be missed because of the lower resolution of remote sensing images. Second, we did not take into account the effect of multicollinearity among these indicators. Third, more cases should be conducted to validate the applicability of this indicator system.

5. Conclusions

We developed an indicator system that included 9 indicators (*AWSR*, *AWSDR*, *DLCR*, *ARR*, *SAC*, *CR*, *ALR*, *RARR* and *ASTR)* and an integrated river structure impact index *(IRSII*) to assess the influence of human activities on river system structure. The natural and anthropogenic forces within a river system were compared through measuring changes in the structures with GIS and RS techniques.

The case study of the Nanliu River basin showed that the river has become an artificial river according to *IRSII* (0.49), which suggest that anthropogenic forces are large than natural forces in general. Specifically, the artificial water surface area and length are both larger

than the natural ones; the artificial sediment discharge is 2.51 times that of the natural process ($ASTR$ = 2.51). Furthermore, an average of 41.18 human-made buildings was installed in a 100-km river channel. The road and river networks interact considerably, and 38.28% of total natural river network is side by side with the road network. We noticed that sub-basins with high values are the Qingwan, Dingchuan, Beiliu-Fumian, Rendong, Li River, Yama River and Zhou River sub-basins. In future, the restoration strategy of the Nanliu River basin should focus on river connectivity, sand mining and irrigation issues.

Author contributions

All authors contributed significantly to this work. Yinjun Zhao designed the framework and wrote the manuscript. Lan Zeng, Junming Liu, Jianming Deng, Kai Tong and Jiaxu Li collected and analyzed the data and prepared the figures. Yongping Wei revised the paper and provided comments. Qucheng Deng corrected the English grammar and provided comments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allison, M.A., Nittrouer, C.A., Ogston, A.S., Mullarney, J.C., Nguyen, T.T., 2017. Sedimentation and survival of the Mekong Delta: A case study of decreased sediment supply and accelerating rates of relative sea level rise. Oceanography 30, 98–109.
Beechie, T., Pess, G., Roni, P., Giannico, G., 2008. Setting river restoration priorities: a review of approaches and a general protocol for identifying and prioritizing actions. North Am. J. Fish. Manag. 28, 891–905.
Brierley, G.J., Fryirs, K., 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environ. Manage. 25, 661–679.
Brierley, G.J., Fryirs, K.A., 2016. The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. River Res. Appl. 32, 823–835.
Brierley, G., Fryirs, K., Cook, N., Outhet, D., Raine, A., Parsons, L., Healey, M., 2011. Geomorphology in action: Linking policy with on-the-ground actions through applications of the River Styles framework. Appl. Geogr. 31, 1132–1143.
Cao, X., Chen, J., Chen, L., Liao, A., Sun, F., Li, Y., Li, L., Lin, Z., Pang, Z., Chen, J., He, C., Peng, S., 2014. Preliminary analysis of spatiotemporal pattern of global land surface water. Science China Earth Sciences 57, 2330–2339.
Dale, V.H., Beyeler, S.C., 2001. Challenges in the development and use of ecological indicators. Ecol. Ind. 1, 3–10.
Del Tánago, M.G., Gurnell, A.M., Belletti, B., De Jalón, D.G., 2016. Indicators of river system hydromorphological character and dynamics: understanding current conditions and guiding sustainable river management. Aquat. Sci. 78, 35–55.
Detenbeck, N.E., Johnston, C.A., Niemi, G.J., 1993. Wetland effects on lake water quality in the Minneapolis/St. Paul metropolitan area. Landscape Ecology 8, 39–61.
Douglas, I., Nigel, L., 2000. The Human Dimensions of Geomorphological Work in Britain. J. Ind. Ecol. 4, 9–33.
Döll, P., Fiedler, K., Zhang, J., 2009. Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. Hydrol. Earth Syst. Sci. 13, 2413–2432.
Fairchild, G.W., Velinsky, D.J., 2006. Effects of small ponds on stream water chemistry. Lake Reservoir Manage. 22, 321–330.
Fan, H., Huang, H.J., Zeng, T., 2006. Impacts of anthropogenic activity on the recent evolution of the Huanghe (Yellow) River Delta. J. Coastal Res. 22, 919–929.
Gergel, S.E., Turner, M.G., Miller, J.R., Melack, J.M., Stanley, E.H., 2002. Landscape indicators of human impacts to riverine systems. Aquat. Sci. 64, 118–128.
Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M.E., Meng, J., Mulligan, M., Nillson, C., Olden, J.D., Opperman, J.J., Petry, P., Rediy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P.H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-flowing rivers. Nature 569, 215–221.
Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C., Liermann, C.R., 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environ. Res. Lett. 10, 015001.
Grill, G., Dallaire, C.O., Chouinard, E.F., Sindorf, N., Lehner, B., 2014. Development of new indicators to evaluate river fragmentation and flow regulation at large scales: A case study for the Mekong River Basin. Ecol. Ind. 45, 148–159.
Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat. Sci. 78, 1–16.
Haff, P.K., 2002. Neogeomorphology. Eos, Transactions American Geophysical Union 83, 310–317.
Jones, J.A., Swanson, F.J., Wemple, B.C., Snyder, K.U., 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conserv. Biol. 14, 76–85.
Ji, X.M., Xu, Y.P., Han, L.F., Yang, L., 2014. Impacts of urbanization on river system structure: a case study on Qinhuai River Basin, Yangtze River Delta. Water Sci. Technol. 70, 671–677.
Jones, J.A., Grant, G.E., 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resour. Res. 32, 959–974.
Karr, J.R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6, 21–27.
Li, S.S., Dai, Z.J., Mei, X.F., Huang, H., Wei, W., Gao, J.J., 2017. Dramatic variations in water discharge and sediment load from Nanliu River (China) to the Beibu gulf during 1960s–2013. Quat. Int. 440, 12–23.
Li, Z.W., Gao, P., 2019. Channel adjustment after artificial neck cutoffs in a meandering river of the Zoige basin within the Qinghai-Tibet Plateau, China. Catena 172, 255–265.
Liang, Z., Chen, S., Hu, J., Huang, C., Zhang, A., Xiao, L., Zhang, Z., Tong, X., 2019. Hydrologic Evaluation of Integrated Multi-Satellite Retrievals for GPM over Nanliu River Basin in Tropical Humid Southern China. Water 11, 932.
Liermann, C.R., Nilsson, C., Robertson, J., Ng, R.Y., 2012. Implications of Dam Obstruction for Global Freshwater Fish Diversity. BioScience 62, 539–548.
Lin, Z.K., Wang, A.J., Ye, X., 2019. The erosion–deposition process and associated control mechanisms of the Nanliu River subaqueous delta, Southern China coast. Anthropocene Coasts 2, 171–192.
Messerli, B., Grosjean, M., Hofer, T., Nunez, L., Pfister, C., 2000. From nature-dominated to human-dominated environmental changes. Quat. Sci. Rev. 19, 459–479.
Meybeck, M., 2003. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. Philosophical Transactions of the Royal Society of London B: Biological Sciences 358, 1935–1955.
Smith, L.M., Winkley, B.R., 1996. The response of the Lower Mississippi River to river engineering. Eng. Geol. 45, 433–455.
Smith, S.V., Renwick, W.H., Bartley, J.D., Buddemeier, R.W., 2002. Distribution and significance of small, artificial water bodies across the United States landscape. Sci. Total Environ. 299, 21–36.
Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.
O'Hanley, J.R., 2011. Open rivers: barrier removal planning and the restoration of free-flowing rivers. J. Environ. Manage. 92, 3112–3120.
Oscoz, J., Leunda, P.M., Miranda, R., García-Fresca, C., Campos, F., Escala, M.C., 2005. River channelization effects on fish population structure in the Larraun river (Northern Spain). Hydrobiologia 543, 191–198.
Poff, N. L., 2014. Rivers of the Anthropocene?. Frontiers in Ecology and the Environment 12, 427-427.
Postel, S.L., Daily, G.C., Ehrlich, P.R., Daily, C., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.
Polvi, L.E., Wohl, E.E., Merritt, D.M., 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology 125, 504–516.
Price, S.J., Ford, J.R., Cooper, A.H., Neal, C., 2011. Humans as major geological and geomorphological agents in the Anthropocene: the significance of artificial ground in Great Britain. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369, 1056–1084.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). Geomorphology 180, 96–108.
Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10, 1163–1174.
Roy, S.G., Uchida, E., de Souza, S.P., Blachly, B., Fox, E., Gardner, K., Gold, A.J., Jansujwicz, J., Klein, S., McGreavy, B., Mo, W., Smith, S.M.C., Vogler, E., Wilson, K., Zydlewski, J., Hart, D., 2018. A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost. Proc. Natl. Acad. Sci. 115, 12069–12074.
Scorpio, V., Zen, S., Bertoldi, W., Surian, N., Mastronunzio, M., Dai Prá, E., Zolezzi, G., Comiti, F., 2018. Channelization of a large Alpine river: what is left of its original morphodynamics? Earth Surf. Proc. Land. 43, 1044–1062.
Sear, D.A., Newson, M.D., 2003. Environmental change in river channels: a neglected element. Towards geomorphological typologies, standards and monitoring. Sci. Total Environ. 310, 17–23.
Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Ind. 9, 189–212.
Sponseller, R.A., Heffernan, J.B., Fisher, S.G., 2013. On the multiple ecological roles of

water in river networks. Ecosphere 4, 1–14.
Syvitski, J.P., Kettner, A., 2011. Sediment flux and the Anthropocene. Philos. Trans. R. Soc. Lond. A: Math. Phys. Eng. Sci. 369, 957–975.
Tong, K., Zhao, Y.J., Wei, Y.P., Hu, B., Lu, Y., 2018. Evaluation and Hydrological Validation of GPM Precipitation Products over the Nanliu River Basin. Beibu Gulf. Water 10, 1777.
Tarolli, P., Sofia, G., 2016. Human topographic signatures and derived geomorphic processes across landscapes. Geomorphology 255, 140–161.
Turner, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B., 1990. The Earth as transformed by human action. Cambridge University Press, London.
Wang, S., Fu, B.J., Piao, S.L., Lü, Y.H., Ciais, P., Feng, X.M., Wang, Y.F., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9 (38), 38–41.
Wang, W.J., 1986. The effect of sediment loads discharged by the rivers in south China on the coast and shelf. Journal of Sediment Research 27–36 (in Chinese).
Water Resources and Hydropower Planning and Design General Institute of China, 2010. A key ecological indicator system for water project planning and design, and its guiding. (in Chinese).
Wemple, B.C., Jones, J.A., Grant, G.E., 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon1. JAWRA Journal of the American Water Resources Association 32, 1195–1207.
Wei, H.S., Zeng, G.P., 1995. Systematicism: Philosophy of System Science 12, 201–275 (in Chinese).
Weller, D.E., Jordan, T.E., Correll, D.L., 1998. Heuristic models for material discharge from landscapes with riparian buffers. Ecol. Appl. 8, 1156–1169.
Weber, M.A., Ringold, P.L., 2019. River metrics by the public, for the public. PLoS ONE 14, e0214986. https://doi.org/10.1371/journal.pone.0214986.
Wohl, E., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K.A., Grant, G., Hilton, R.G., Lane, S.N., Magilligan, F.J., Meitzen, K.M., Passalacqua, P., Poeppl, R.E., Rathburn, S.L., Sklar, L.S., 2019. Connectivity as an emergent property of geomorphic systems. Earth Surf. Proc. Land. 44, 4–26.
Yang, M., Xiao, W., Zhao, Y., Li, X., Huang, Y., Lu, F., Hou, B., Li, B., 2018. Assessment of potential climate change effects on the rice yield and water footprint in the Nanliujiang Catchment. China. Sustainability 10, 242.
Zawiejska, J., Wyżga, B., 2010. Twentieth-century channel change on the Dunajec River, southern Poland: patterns, causes and controls. Geomorphology 117, 234–246.
Zhao, Y.J., Ding, A.Z., 2016. A decision classifier to classify rivers for river management based on their structure in China: an example from the Yongding River. Water Sci. Technol. 74, 1539–1552.
Zhao, Y.J., Xie, Q.Y., Lu, Y., Hu, B.Q., 2017. Hydrologic evaluation of TRMM multi-satellite precipitation analysis for Nanliu River Basin in Humid Southwestern China. Sci. Rep. 7, 2470.
Zhao, Y.J., Wu, P.F., Li, J.X., Lin, Q., Lu, Y., 2019. A new algorithm for the automatic extraction of valley floor width. Geomorphology 35, 37–47.