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# Development of a bacteria-based index of biotic integrity (Ba-IBI) for assessing ecological health of the Three Gorges Reservoir in different operation periods

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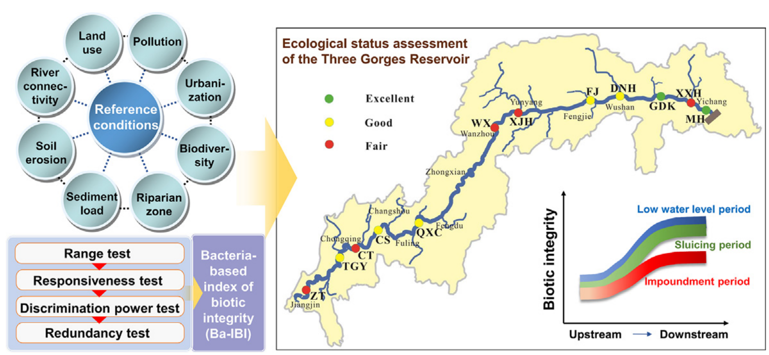
## HIGHLIGHTS

- A bacteria-based index of biotic integrity was developed in Three Gorges Reservoir.
- Samples were collected in the low water level, impoundment and sluicing periods.
- Hydromorphology and anthropogenic disturbances were used to define reference sites.
- Five core metrics discriminate between reference and impaired conditions.
- The novel index assessed the spatial and temporal variation of the ecological status.

## GRAPHICAL ABSTRACT

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## ABSTRACT

It is urgently needed to quantitatively assess ecological health of the Three Gorges Reservoir (TGR) when considering its special environmental conditions and temporal variations caused by reservoir operation. This study developed a bacteria-based index of biotic integrity (Ba-IBI) based on sediment samples collected along the TGR in low water level period, impoundment period and sluicing period, respectively. Reference conditions were defined using 8 ecological variables describing the hydromorphology and anthropogenic disturbances around the sites. Five core metrics, including % Acidobacteria, % Gemmatimonadetes, % *Geobacter*, Methanotroph and Phototroph, were selected after the screening processes. The developed index could clearly discriminate reference and impaired conditions and exhibited significant relationship with environmental parameters according to the redundancy ($p < 0.01$) and multivariable linear regression analysis ($R^2 = 0.76$). By implementing Ba-IBI in the TGR, the ecological health of the sampling sites was defined as "Excellent" (25%), "Good" (50%) and "Fair" (25%) separately. The spatial variation of biotic integrity was closely associated with environmental and ecological changes, especially the increase of nutrient concentrations. This study revealed a significant tendency that the ecological health in the low water level and sluicing periods was better than that in the impoundment period, which could be attributed to the hydrodynamic changes due to water level fluctuation. This study provides a comprehensive understanding of ecological health of the TGR in different operation periods and the index offers a guideline for the reservoir regulation in the similar areas.



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## 1. Introduction

With the development of national economy and society, the aquatic environments and their biota were constantly affected by anthropogenic activities such as water abstraction, sewage discharge, over exploitation of land and water project construction (Marzin et al., 2012). Rivers have attracted flocks of scholars and researchers due to their functions of maintaining natural ecological balance and serving society development. The Yangtze River, the longest river in Asia and the third-longest river in the world, flows a total length of 6300 km and a drainage area of 1,800,000 km$^2$ (Chen et al., 2001). Built in the middle reaches of the Yangtze River, the Three Gorges Dam (TGD) is currently the world's largest dam and results in the formation of a deep water reservoir, the Three Gorges Reservoir (TGR). The TGR has fully operated since 2010 with water release in flood season (May to September) and water storage in drought season (November to March of the following year), giving rise to the fluctuation of water level from 145 m to 175 m (Han et al., 2017). The annual operation of the reservoir has resulted in several ecological problems such as algal bloom in the tributaries, sedimentation, debris flow and a series of environment changes in the water level fluctuation zone (Wang et al., 2013). Wilcox et al. (2002) proposed that variation from water level fluctuation could be much greater than variation from anthropogenic stress, causing unpredictable responses. Consequently, obvious spatial and temporal variations of the aquatic ecosystem are presented within the TGR.

As the key channel connecting the southwest and the east, the TGR and its annual operation not only provides drinking water for the Chongqing southwestern economic center and the Hubei province of China, but also impacts the water security of cities in the lower regions of the Yangtze River (Gao et al., 2017). Therefore, studies on the water quality monitoring and aquatic ecosystem assessment of the TGR have been increasing over the years (Li et al., 2013). Several studies reported water quality data from the Yangtze River mostly focusing on organic or inorganic parameters, the mechanism of pollutants, the pollution load and source (L. Huang et al., 2015; Ma et al., 2011). Numerous studies monitored water quality in the TGR using multiple analysis approaches such as multi-objective environmental reservoir operation methodology (Hu et al., 2016), risky grade index (RGI) and coverage area index (Zhou et al., 2017). Temporal variations of the nutrients, biochemical indexes and heavy metals during the stable operation of the TGR were also assessed (Gao et al., 2016). Although some indices based on physicochemical parameters have been chosen to evaluate the environmental condition of the TGR, there is still need to modify the more narrowly defined chemical criteria and to develop biological criteria based on ecological principles.

Changes in environmental parameters, hydromorphology and ecosystem health have already been linked to the variation of the biotic indices based on the taxonomic and/or functional characteristics of biological aggregates (Villeneuve et al., 2018). Such environmental assessments were often undertaken by using the index of biotic integrity (IBI), which was first introduced by Karr (1981) and widely used to assess ecological health (Karr et al., 1986). Organisms such as macroinvertebrates (Klemm et al., 2003), fish (Mercado-Silva et al., 2002), algae (Zalack et al., 2010) and plankton (Wu et al., 2012) were commonly used as indicators to evaluate the health of aquatic environments. However, the construction of the TGD could alter the hydrologic regimes and connectivities, resulting in transformation of the Yangtze River from a riverine system into a lacustrine system. Due to the migration restrictions, spawning grounds destructions, habitats and food web changes, the behavior and functions of most macro-organisms were affected (Franssen, 2012). Thus, the traditional index of biotic integrity could not be used to assess ecological health of the TGR effectively and a new indicator is needed to be proposed.

In aquatic systems, sediment bacteria are the foundation of biogeochemical cycles, participating in a great number of biochemical processes such as phosphorous cycling and nitrogen transformation. As the most numerous and active organisms in the basal trophic level of stream food web, bacteria have short life cycles and are sensitive to environmental changes (Lau et al., 2015). Bacterial communities have been proved to be better indicator of ecological health compared with macro-organisms due to their sensitivity to the external influence. In our previous research, bacterial communities have been included in the process of biotic integrity assessment and the sensitivity and reliability of the index were validated (J. Li et al., 2017). Bacterial communities also exhibited temporal variations with seasonal or temporal environmental changes (Z. Li et al., 2017) and were believed to be sensitive to water level fluctuation caused by reservoir operation (Weise et al., 2016). Previous research about bacterial communities in the TGR mainly focused on their spatial distribution (Yan et al., 2015), yet failed to illustrate bacterial response to the operation of the TGR. Additionally, bacteria used in water quality monitoring of the TGR only involved a few forms such as fecal indicator bacteria (Wang et al., 2015). Thus, a quantitative assessment based on the bacterial communities was expected to illustrate ecological health of the TGR.

Considering the above factors, the main objective of our study was to assess ecological health of the Three Gorges Reservoir in different operation periods by developing a bacteria-based index of biotic integrity (Ba-IBI). Water and sediment samples were collected from 12 sampling sites across the TGR during three sampling campaigns. Redundancy and multivariable linear regression analysis were carried out for clarifying the correlation between the Ba-IBI and environmental parameters. Temporal variation of biotic integrity associated with water level fluctuation caused by reservoir operation was also investigated. This study provides a better understanding on ecological health of the TGR and illustrates the potential effects of reservoir operation on bacteria-based biotic integrity.

## 2. Materials and methods

### 2.1. Study area and data collection

The Three Gorges Reservoir (TGR), downstream from Yichang of Hubei Province up to Jiangjin of Chongqing municipality (105°50′-111°40′ E, 28°31′-31°44′ N), is currently the largest artificial reservoir of the world. The TGR area covers approximately 55,000 km$^2$ and includes 20 country-level administrative districts. Belonging to the subtropical climate, the average temperature of the area is 17.8 °C and the average annual rainfall is 1100 mm. The northern and eastern parts of the TGR are dominated by high mountains and the western parts are low plains (Teng et al., 2017). In this study, 12 sampling sites were selected from upstream to downstream of the TGR as shown in Fig. 1.

The monthly average of hydrology data such as water level, flow velocity and precipitation, were obtained from the Hydrology bureau of Changjiang Water Resources Commission, as well as the websites of "The Yangtze River Hydrology" (http://www.cjh.com.cn) and "The National Hydrological and Rainfall Regime" (http://xxfb.hydroinfo.gov.cn). The meteorological factors within the study area, such as air temperature, wind speed, relative humidity, were collected from the National Meteorological Information Centre of China (NMIC) (http://data.cma.cn). Soil type data as well as the Land Use and Land Cover (LULC) data were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The administrative divisions and population information were obtained from the website of "Information Management Center for the Ecological and Environment Monitoring of the Three Gorges Project" (http://www.tgenviron.org).

### 2.2. Sampling and sample analysis

We carried out 3 sampling campaigns in the low water level period (September 2016), impounding period (December 2016) and sluicing period (April 2017), respectively. During each sampling campaign, samples