Ecological Indicators 100 (2019) 20–29

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Spatiotemporal variations of aquatic ecosystem health status in Tolo Harbor, Hong Kong from 1986 to 2014

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ARTICLE INFO

Keywords:
Ecosystem health assessment
Physical-Chemical-Biological index Triangle Area Method (PCBTAM)
Spatio-temporal variation
Tolo Harbor

ABSTRACT

Tolo Harbor is a nearly land-locked body of water located northeast of Hong Kong with only one narrow exit opening to the sea at Mirs Bay. Rapid urbanization accompanied by various anthropogenic stresses caused the frequent occurrences of red tides and associated fish kills, as well as coral deaths, in Tolo Harbor in the late 1980s. To stop "Hong Kong's First Marine Disaster", the Tolo Harbor Action Plan (THAP) has been employed by the Hong Kong Government since 1988. The present study evaluated the spatiotemporal variations of aquatic ecosystem health (AEH) in Tolo Harbor, using monthly monitoring data from 1986 to 2014. The Physical-Chemical-Biological index Triangle Area Method (PCBTAM) was developed to integrate physical, chemical and biological indicators and to identify the dominating factors. The results showed that the AEH of Tolo Harbor would be divided into six periods with two deteriorations and two convalescences. The first deterioration was caused by violent anthropogenic impacts, mainly from urban areas. With the implementation of THAP, the AEH was significantly improved. Later, the harbor underwent a physical index-dominated deterioration. With the rapid decrease of the physical index in 2009, Tolo Harbor came into a stable healthy stage. A spatial gradient of AEH in Tolo Harbor, from bad to good, was: Harbor Subzone > Buffer Subzone > Channel Subzone. In addition, seasonal component extraction illustrated that the AEH had a bad tendency in most months and the biological index dominated the AEH tendency pattern.

1. Introduction

The application of the notion of "health" in medical science to ecosystems in the middle 1980s resulted in a new concept, ecosystem health (Rapport, 1995). Since that time, the field of ecosystem health has achieved much progress with increasing attention from environmentalists and ecologists in academic and government publications, as well as in the popular media (Xu and Tao, 2000). During the last three decades, many environmental programs on the health state of various ecosystems (e.g., lake, river, wetland, farmland, forest, etc.) were established in the USA (Shear, 1996; Noble and Dirzo, 1997; Rapport et al., 1998b; WRI, 2002), Canada (Shear, 1996; Smit, 1998; IDRC, 2002a,b; NWRI, 2002), and China (Xu et al., 1999, 2001a,b, 2004a,b). The multi-definitions of ecosystem health from ecologists, economists, philosophers and managers (Karr et al., 1986; Schaeffer et al., 1988; Rapport, 1989; Kay, 1991; Norton, 1992; Haskell et al., 1992; Ulanowicz, 1992) have been replaced by a comprehensive definition from Costanza (1992) and an interdisciplinary definition from the International Society for Ecosystem Health (ISEH) (Rapport et al., 1998a,b). The assessment indicators of ecosystem health have been developed from the single and composite species indicators (Karr et al., 1986; Karr, 1992) to the comprehensive indicators covering the structural, functional and system-level aspects of ecosystems (Rapport et al., 1985; Karr et al., 1986; Schindler, 1990; Ulanowicz, 1992; Costanza, 1992; Jørgensen, 1995a,b; Xu et al., 1999, 2001a).

Currently, many procedures and methods for ecosystem health assessment (EHA) have been developed, including the exergy-based EHA (Jørgensen, 1995b), direct measurement followed by ecological modeling (Xu et al., 2001a,b), ecosystem health index methodology (EHIM) (Xu et al., 2005), entropy weight comprehensive health index method (Xu and Xu, 2008), and analytic hierarchy process (AHP) method (Ma et al., 2011). For marine ecosystem health assessment, the stress-response method (Xu et al., 2004b), grey system method (GSM) and pollution index number method (PINM) (Li et al., 2010), as well as the pressure-state-response (PSR) method (Pu et al., 2012) were established. For forest ecosystem health assessment, the primary proposed methods include the multilevel fuzzy competitive evaluation (MFCE) (Li and Wang, 2004), back propagation (BP) neutral networks method

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https://doi.org/10.1016/j.ecolind.2018.04.056
Received 10 July 2017; Received in revised form 12 April 2018; Accepted 23 April 2018
Available online 26 April 2018

(Gan et al., 2007), principal component analysis method (Zhao et al., 2008), and grey relation projection method (Zhang et al., 2010). For the evaluation of urban ecosystem health, the catastrophe progression method (CPM) (Wei et al., 2008), exergy synthesis and set pair analysis method (EM-SPA) (Su et al., 2012), entropy-weight method (Liu et al., 2014; Gao et al., 2015), and maximum information entropy method (MIEM) (Zhao and Chai, 2015) were proposed. The development and application of these methods have significantly contributed to the progress of ecosystem health assessment. However, environmental managers and the public have always anticipated a more intuitive method for ecosystem health assessment and an easier approach for integrating multiple indicators.

Tolo Harbor is a nearly land-locked water body with only one narrow channel connecting it to the open sea at Mirs Bay and is located in the northeast of the New Territories of Hong Kong, China (Chau et al., 1996). The adverse topography and annually prevailing northeasterly winds led to weak water circulation and interfered with the rapid exportation of pollutants in Tolo Harbor (Xu et al., 2004a; Tang et al., 2015). Since 1986, when the Environmental Protection Department (EPD, 2015b) was created, a comprehensive marine water quality monitoring program has been initiated in order to protect the marine environment of Hong Kong (EPD, 2015a). In Tolo Harbor, seven monitoring stations were established to obtain the data of more than 20 indicators at least once a month. Among the seven monitoring stations, TM2, TM3 and TM4 were in the Harbor Subzone, TM5 and TM6 were in the Buffer Subzone, and TM7 and TM8 were in the Channel Subzone (Fig. 1). In our pervious study (Xu et al., 2004b), the aquatic ecological health status of three subzones in the 1970s, 1980s and 1990s was assessed semi-quantitatively, based on the direct comparison of monitoring values of some indicators. In the present study, we propose a new method, the Physical-Chemical-Biological index Triangle Area Method (PCBTAM), to evaluate quantitatively the spatiotemporal long-term variations of aquatic ecosystem health (AEH) status during the last three decades in Tolo Harbor, with the expectation of enhancing the intuitive evaluation results.

2. Methodology

2.1. PCBTAM design

Generally, the measured indicators belong to three categories: physical, chemical, and biological. If we calculated an integrated index of each indicator category with a range from 0 to 1, these indexes can

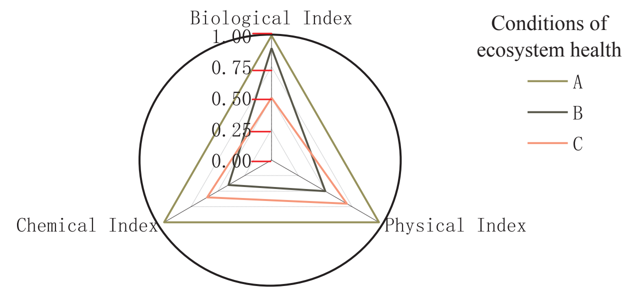

Fig. 2. Schematic diagram of the Physical, Chemical, Biological index Triangle Area Method (PCBTAM). A, B, C: conditions of ecosystem health with different physical, chemical and biological indexes. Comparison of the triangle area enables the variation of ecosystem health to be assessed intuitively. Triangle area: 1.30 for A, 0.44 for B, and 0.46 for C. A large triangle area indicates worse ecosystem health. Condition A: heavily polluted; and conditions B and C: moderately polluted.

be mapped to three radii of a trisected unit circle, and each index's value is mapped to a point on the corresponding radii of the trisected unit circle. Connecting the point on each radius forms a triangle whose area is expected to synthetically reflect the ecosystem health status (Fig. 1). The area of the triangle is calculated by Eq. (1):

$$S = \frac{\sqrt{3}}{4} \times (P \times C + C \times B + B \times P) \tag{1}$$

where P, C and B refer to the physical index, chemical index and biological index, respectively; and S indicates the triangle area, or Ecosystem Health Index (*EHI*), and the triangle is called the Physical, Chemical, Biological index Triangle (P-C-B Triangle) since its area is calculated by physical, chemical and biological indexes.

The method stipulates that a large area of the P-C-B Triangle indicates poor ecosystem health. The schematic diagram of the P-C-B Triangle is shown in Fig. 2. In Fig. 2, A, B and C refer to three different conditions of ecosystem health. Depending on the calculated triangle area of each condition (1.30 for A, 0.44 for B, and 0.46 for C), the ecosystem health status was ordered as B < C < A. Conditions B and C are moderately polluted, and condition A is heavily polluted.

2.2. AEH assessment for Tolo Harbor based on PCBTAM

The flow chart of AEH assessment for Tolo Harbor is shown in Fig. 3. The process includes four major steps: indicator selection, index

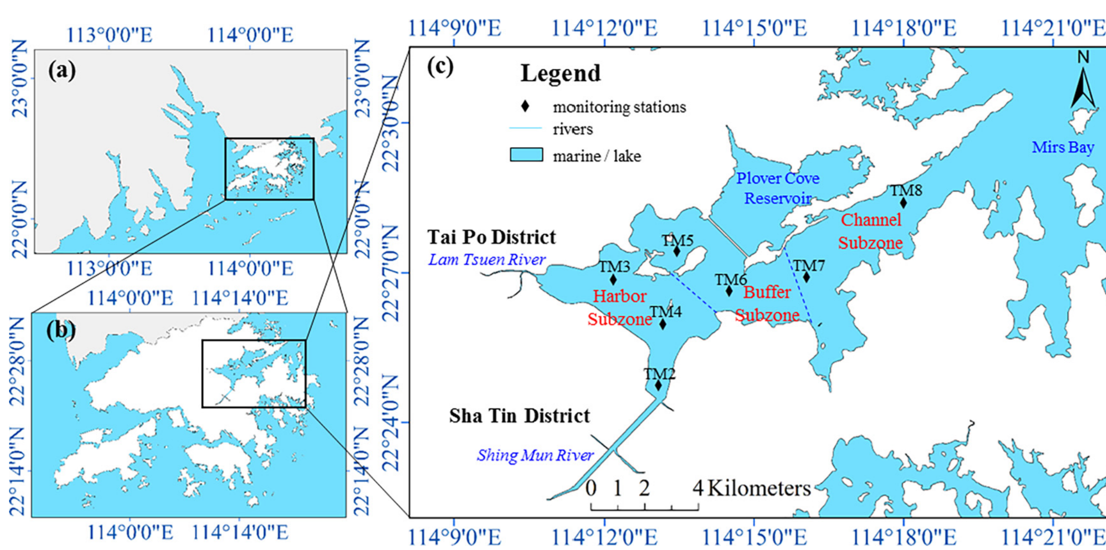

Fig. 1. Locations of (a) Hong Kong, (b) Tolo Harbor and (c) the marine water monitoring stations of the Environmental Pollution Department in Tolo Harbor. TM2 to TM8: monitoring station names.

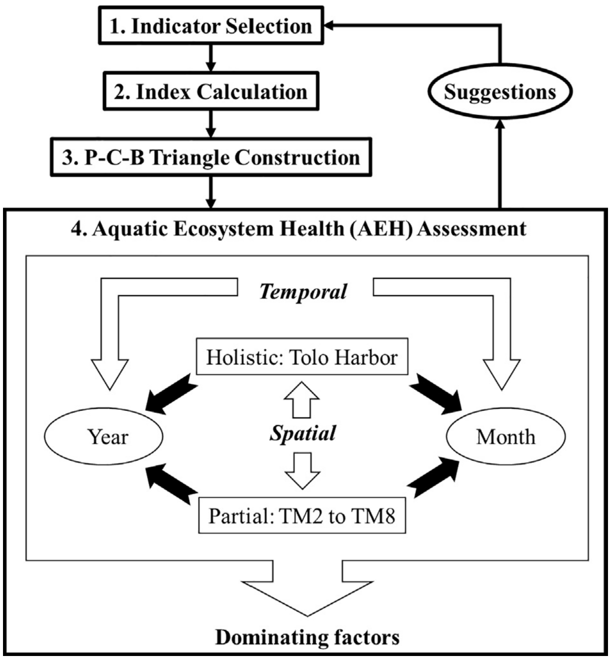

Fig. 3. The flow chart of aquatic ecosystem health (AEH) assessment for Tolo Harbor using PCBTAM. The process includes four major steps. In AEH assessment, spatial resolution: entire harbor (Tolo Harbor) and monitoring stations (TM2 to TM8); and temporal resolution: year and month. The aim of our assessment is to determine the dominating factors that influence the ecosystem health of Tolo Harbor on different spatiotemporal scales. Some constructive suggestions may be proposed after finishing the assessment, and some new indicators may also be monitored in the future.

calculation, P-C-B Triangle construction and AEH assessment.

2.2.1. Indicator selection

In order to evaluate quantitatively the spatiotemporal long-term variations of aquatic ecosystem health (AEH) status during the last three decades in Tolo Harbor, the indicators were selected from the monitoring indicators in the Marine Water Quality Monitoring Program set by HKEPD in 1986. Indicator selection follow the principles below: 1) Measurability: the required data of each indicator in the indicator system can be obtained conveniently and accurately by monitoring approaches, statistical methods, or the calculation of related data. 2) Responsiveness: the indicators must have timely and sensitive responses to the stress factors that affect ecosystem health status. 3) Comparability: the indicators should be comparable for an object or different objects on different spatial or temporal scales for facilitating related research and management. 4) Concentration-effect relationship: the indicators should have a significant relationship with their effects on ecosystem health in selected concentration ranges. 5) Representativeness: the indicators must represent the ecosystem health status to a large extent. This is because, on the one hand, the number of dominant ecosystem health stress factors is usually limited, and on the other hand, it is almost impossible to conduct all encompassing monitoring of ecosystem health due to the limits of cost and technology.

According to the principles of indicator selection, TN, TP, and BOD_5 were selected as chemical indicators, while turbidity and Chl-*a* were selected as physical indicator and biological indicator, respectively. The suitability and data source for the five selected indicators for ecosystem health assessment in Tolo Harbor are presented in Table 1.

2.2.2. Scaling of physical, chemical and biological indicators

The second step for employing the PCBTAM is scaling the selected indicators, ranging from 0 to 1, for mapping data to a figure.

Measured indicators are divided into two classes. Class 1: a higher indicator value indicates worse ecosystem health, such as 5-day biological oxygen demand (BOD_5), total nitrogen (TN), total phosphorus (TP), chlorophyll-a (Chl-a) and turbidity. Class 2: a lower indicator value indicates worse ecosystem health, such as Dissolved Oxygen (DO).

For Class 1 indicators, they were scaled by Eq. (2):

$$X_j^{scaled} = \frac{X_j}{\max\limits_{0<j\leqslant n}\{X_j\}} \tag{2}$$

where X refers to the indicator; X_j indicates the jth value of the indicator data array; n denotes the data number of the indicator data array; $\max\limits_{0<j\leqslant n}\{X_j\}$ means the maximum of the indicator data array; and X_j^{scaled} expresses the scaled jth value of the indicator data array.

For Class 2 indicators, they were scaled by Eq. (3):

$$X_j^{scaled} = \frac{\min\limits_{0<j\leqslant n}\{X_j\}}{X_j} \tag{3}$$

where X refers to the indicator; X_j indicates the jth value of the indicator data array; n denotes the data number of the indicator data array; $\min\limits_{0<j\leqslant n}\{X_j\}$ means the minimum of the indicator data array; and X_j^{scaled} expresses the scaled jth value of the indicator data array.

2.2.3. Calculation of the physical, chemical and biological indexes

The physical index, chemical index and biological index were calculated by integrating scaled indicator values using Eq. (4):

$$Y_j = \frac{1}{m}\sum_{X\in Y} X_j^{scaled} \tag{4}$$

where Y refers to P, C and B in Eq. (1); Y_j indicates the jth Y-category index of the calculated data array; m denotes the number of indicators belonging to the Y-category; and $X \in Y$ means that indicator X belongs to the Y-category.

The following four datasets were used for the assessment: Dataset 1: monthly dataset of TM2 to TM8; Dataset 2: annual dataset of TM2 to TM8; Dataset 3: monthly dataset of the entire harbor; and Dataset 4: annual dataset of the entire harbor. The dataset structure and detailed data procedures are provided in Appendix A.

2.2.4. Construction of the P-C-B Triangle and the calculation of the associated triangle area

The P-C-B Triangle was constructed by mapping the calculated P_j, C_j and B_j values to the corresponding radii. The triangle area, or EHI, was calculated by inserting P_j, C_j and B_j values into Eq. (1). The diagram radar in Excel 2016 (Microsoft Corp., USA) was applied to construct the P-C-B Triangle using the calculation results of P_j, C_j and B_j by Eqs. (2)–(4). *EHI* was obtained by inserting P_j, C_j and B_j into Eq. (1). Dataset 1 and Dataset 2 were used to obtain the monthly and annual EHI of TM2 to TM8, respectively. Dataset 3 and Dataset 4 were used to obtain the monthly and annual EHI of Tolo Harbor, respectively.

3. Results

3.1. Annual variations of AEH in Tolo Harbor

The annual EHIs of TM2 to TM8 are shown in Fig. 4. According to time series clustering analysis, the AEH of Tolo Harbor during 1986–2014 was divided into six stages: Hong Kong's First Marine Disaster (1986–1988), Rapid Saltation (1989–1990), Effective Period of Tolo Harbor Action Plan (1991–1994), Secondary Deterioration (1995–2001), Convalescence (2002–2008) and Stable Health (since 2009), where the middle four periods (1989–2008) are classified as the Transition Stage between the stages of Hong Kong's First Marine Disaster and Stable Health. The P-C-B Triangles of different stages are

Table 1
Measurability, responsiveness, comparability, concentration-effect relationship and representativeness of selected indicators for ecosystem health assessment in Tolo Harbor.

Selected indicators	Principles				
	Measurability*	Responsiveness	Comparability	Concentration-effect relationship	Representativeness
Turbidity	Monthly data of all monitoring stations during 1986 to 2014 (EPD data), the integrality of processed data is 100%	Reflects the degree of clarity and light transmittance of marine water, indicates the concentration of suspended matters and their sizes, shapes, refraction coefficients, etc. (Chau and Muttil, 2007)	On the time scale of year and month Between each monitoring station	Higher value indicates worse AEH**	Physical indicator
TN	Monthly data of all monitoring stations during 1986–2014 (EPD data), the integrality of processed data is 100%	Reflects the degree of eutrophication caused by sewage discharge, livestock waste, industrial waste, urban and rural runoff (Chau and Muttil, 2007)	On the time scale of year and month Between each monitoring station	Higher value indicates worse AEH	Chemical indicator
TP	Monthly data of all monitoring stations during 1986 to 2014 (EPD data), the integrality of processed data is 100%	Reflects the degree of eutrophication caused by sewage discharge, livestock waste, industrial waste, urban and rural runoff (Chau and Muttil, 2007)	On the time scale of year and month Between each monitoring station	Higher value indicates worse AEH	Chemical indicator
BOD_5	Monthly data of all monitoring stations during 1986–2014 (EPD data), the integrality of processed data is 100%	Reflects the organically polluted status of marine water (Yung et al., 1997; Chau and Muttil, 2007)	On the time scale of year and month Between each monitoring station	Higher value indicates worse AEH	Chemical indicator
Chl-*a*	Monthly data of all monitoring stations during 1986–2014 (EPD data), the integrality of processed data is 99.83%	Reflects the degree of eutrophication caused by sewage discharge, livestock waste, industrial waste, urban and rural runoff, and the biomass of algae and phytoplankton (Yung et al., 1997; Chau and Muttil, 2007)	On the time scale of year and month Between each monitoring station	Higher value indicates worse AEH	Biological indicator

Notes:
* See Appendix A for details.
** AEH: aquatic ecosystem health.

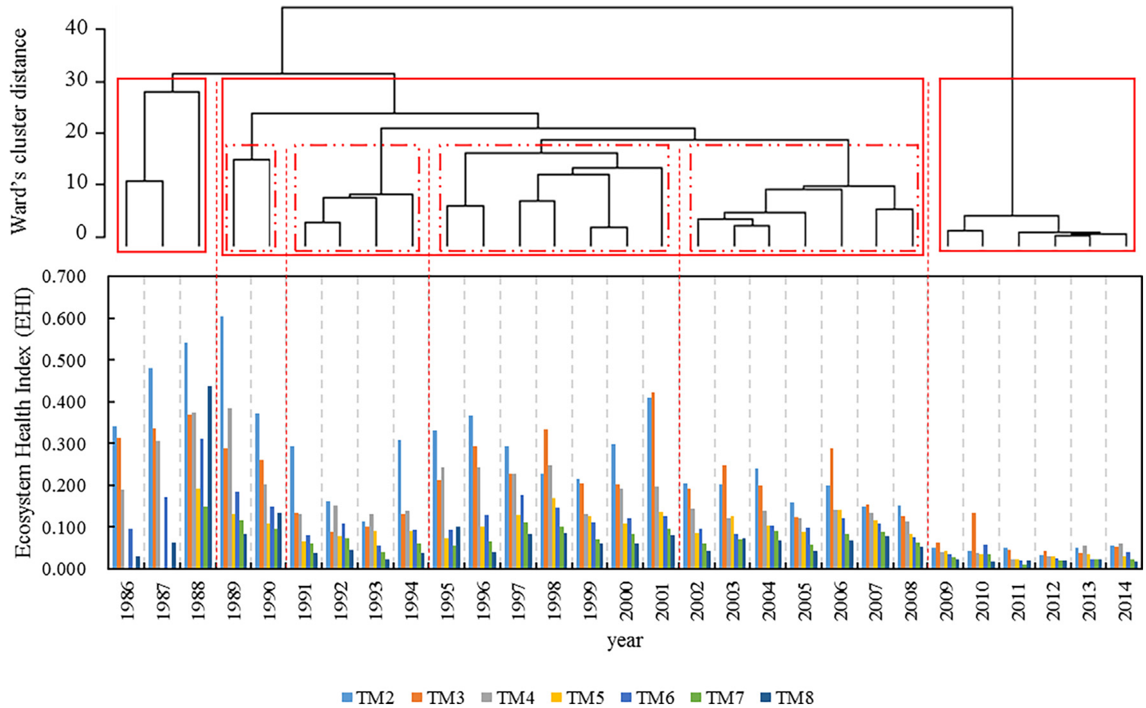

Fig. 4. The annual variations of the Ecosystem Health Indexes (EHIs) of Tolo Harbor and TM2 to TM8 using the PCBTAM. Cluster data source: annual EHI of TM2 to TM8; and method: Euclidean. Red boxes: clustered periods (solid) and stages (dash dot dot). Red vertical lines: lines to divide different stages. The AEH of Tolo Harbor during 1986 to 2014 was divided into six stages. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shown in Fig. 5.

The AEH of Tolo Harbor saw its worst period in the late-1980s (Muttil and Chau, 2007; Sivapragasam et al., 2010). The P-C-B Triangles were continuously growing bigger, and the physical, chemical and biological indexes were all increasing (Fig. 5a). In 1988, the EHI achieved the highest value (0.758). According to the shape of the P-C-B Triangles, the three indexes were all the dominating factors that influence the AEH. This continuous deterioration period was called "Hong Kong' s First Marine Disaster" (Xu et al., 2004a).

Under serious ecological disaster, the Hong Kong government issued a series of Tolo Harbor Action Plan (THAP) since 1988 to improve the deteriorating ecological environment (Xu et al., 2006; Lee et al., 2012). After the implementation of THAP, the chemical index and biological index decreased successively, causing a rapid decrease of EHI in the stage of Rapid Saltation (Fig. 5b).

During the Effective Period of Tolo Harbor Action Plan, the EHI decreased to a lower level (ranging from 0.162 to 0.259). The AEH had significantly improved (Sivapragasam et al., 2010). The P-C-B Triangles posed a sharp angle at the axis of the chemical index (Fig. 5c). It reflected that anthropogenic impacts such as sewage discharge, livestock waste, industrial waste, urban and rural runoff were the dominating pollution factors.

Unfortunately, the AEH of Tolo Harbor has been in a continuous deterioration since the mid-1990s, and the EHI ranged from 0.288 to 0.448. Compared with the triangles of the prior stage, the increase of the biological index caused the P-C-B Triangles to become larger at the beginning of the Secondary Deterioration. During the late part of this stage, the shape of the P-C-B Triangles changed significantly. The angle at the axis of the chemical index became obtuse, and the angle at the axis of the physical index became sharp (Fig. 5d). This illustrated that urban organic pollution was controlled during the late part of this stage, and suspended matter may caused the AEH deterioration.

During Convalescence, the average EHI was approximately 0.11 lower than that of the Secondary Deterioration. The biological index reduced significantly, and the P-C-B Triangles were obviously sharp at the axis of the physical index.

In the stage of Stable Health, the EHI of Tolo Harbor was at its lowest level (0.084 on average). The size of the P-C-B Triangles was the smallest among the six stages, and the shape of the P-C-B Triangles approximated to equilateral triangles. The significant decrease of the physical index led to the improvement of AEH.

3.2. Spatial pattern of AEH in different stages

Fig. 6 showed the spatial AEH distribution of six stages. The AEH of Tolo Harbor underwent two deteriorations and two convalescences.

During Hong Kong's First Marine Disaster, the EHI in the Harbor Subzone (TM2 to TM4) were distinctly higher than those in the Buffer Subzone (TM5 and TM6) and Channel Subzone (TM7 and TM8), especially in TM2. The shape of the P-C-B Triangles illustrated that all of the physical, chemical and biological indexes were dominating factors in TM2 to TM8 (Fig. 6a). Since the monitoring stations TM2 and TM3 are located near the estuary of the Shing Mun River in the Sha Tin District and the estuary of the Lam Tsuen River in the Tai Po District (Fig. 2), the pollution source should be mainly from urban areas (Owen and Sandhu, 2000), especially from the Sha Tin District. Therefore, the disaster was probably caused by anthropogenic activities, particularly those from the Sha Tin District (Chen et al., 2015).

After the implementation of THAP, the P-C-B Triangles shrank from the Harbor Subzone to the Channel Subzone, indicating that the AEH in the Channel Subzone and Buffer Subzone was improved. However, the AEH in the Harbor Subzone was still poor, particularly in TM2 (Fig. 6b).

During the first convalescence, the EHI had small spatial differences. The P-C-B Triangles showed spatial homogeneity, posing a sharp angle at the axis of the chemical index (Fig. 6c).

In the second deterioration, the spatial pattern was the same as that of Hong Kong's First Marine Disaster (Fig. 6d). The increase of EHI in the Harbor Subzone indicated that the pollution probably still originated from urban area. Comparing the shape of the P-C-B Triangles with previous stage, the physical index together with the chemical

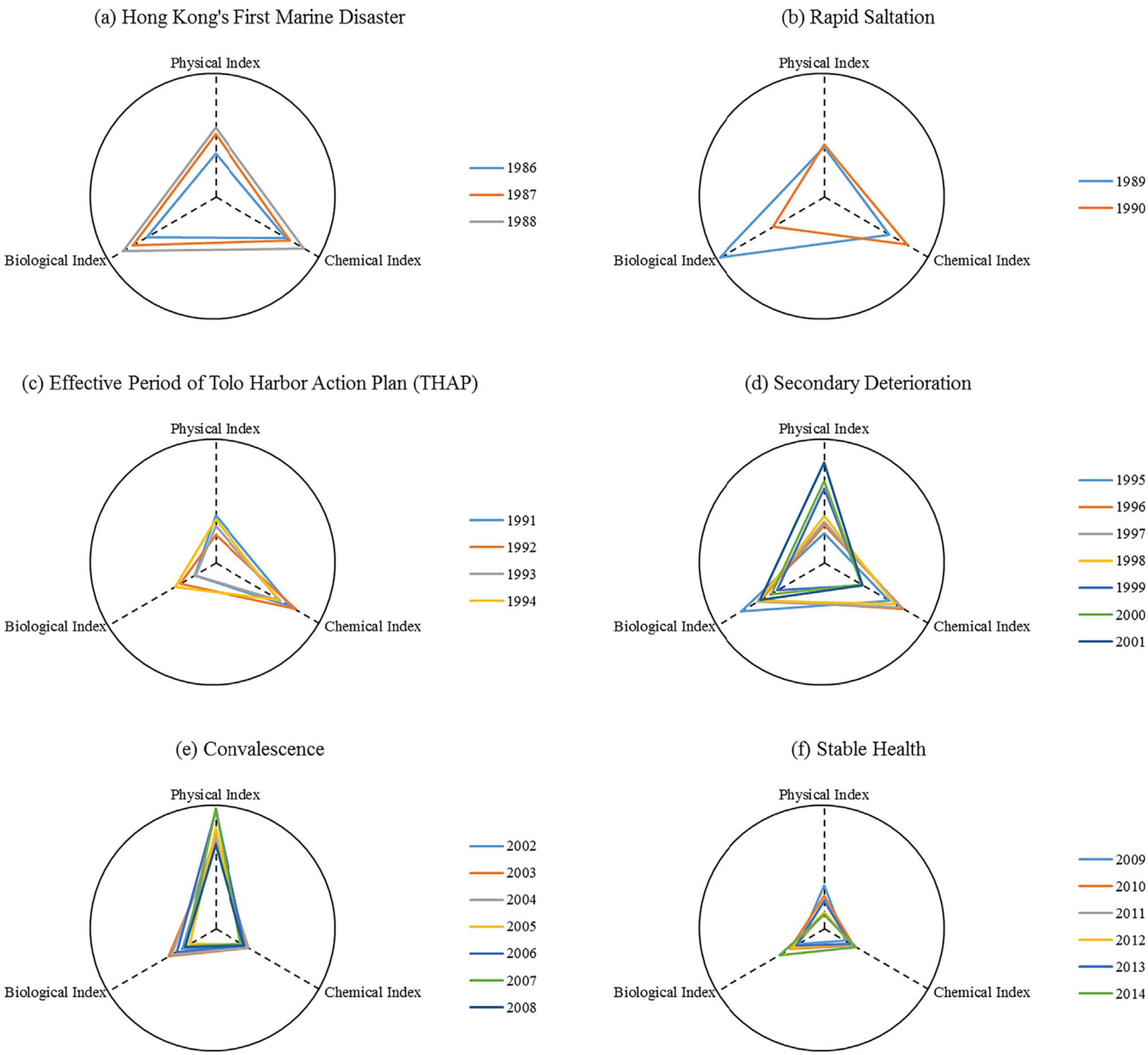

Fig. 5. The P-C-B Triangles in the stages of (a) Hong Kong's First Marine Disaster, (b) Rapid Saltation, (c) Effective Period of Tolo Harbor Action Plan, (d) Secondary Deterioration, (e) Convalescence, and (f) Stable Health. A larger triangle area means worse aquatic ecosystem health (AEH). Dominating factors of different stages could be recognized by comparing the size and shape of the P-C-B Triangles.

index were the dominating factors. The reason for deterioration was probably the resuspension of historically sedimentary contaminates since the P-C-B Triangles posed a sharp angle at the axis of the physical index (Fig. 6e).

In the second convalescence, the spatial pattern was the same as that of the first convalescence. The EHI had small spatial differences (Fig. 6e). The P-C-B Triangles posed a spatial homogeneity with a sharp angle at the axis of the physical index. Since 2009, the spatial differences of EHI disappeared. The P-C-B Triangles were all small in size and approximately equilateral in shape (Fig. 6f).

3.3. Seasonal pattern of AEH in Tolo Harbor

Monthly variation of the EHI of Tolo Harbor is shown in Fig. 7a. According to the variation states, EHI had significant seasonal fluctuations. Thus, the additive model of seasonal decomposition (SPSS 20, IBM Inc., USA) was applied to extract the seasonal component and long-term trend.

The results showed that the AEH tendency of Tolo Harbor was at its best in January and at its worst in April (Fig. 7c). The seasonal components from December to March in the next year were continuously at a significantly negative level (−0.018 to −0.012), reflecting a better ecosystem health tendency during the first quarter. An AEH mutation occurred between March and April, in that the seasonal component changed dramatically from a continuously negative value (−0.016) into a significantly positive value (0.051). In the second quarter, the seasonal components were all positive with a decreasing trend (decreasing from 0.051 to 0.004). Afterwards, it posed an increasing trend in the third quarter (increasing from −0.012 to 0.007). During the fourth quarter, all the seasonal components were negative.

Monthly time series of the physical, chemical and biological indexes were also decomposed to determine which index mainly influenced the seasonal AEH pattern (Fig. 7c). Spearman correlation illustrated that the biological index dominated this pattern in most months ($p < 0.01$).

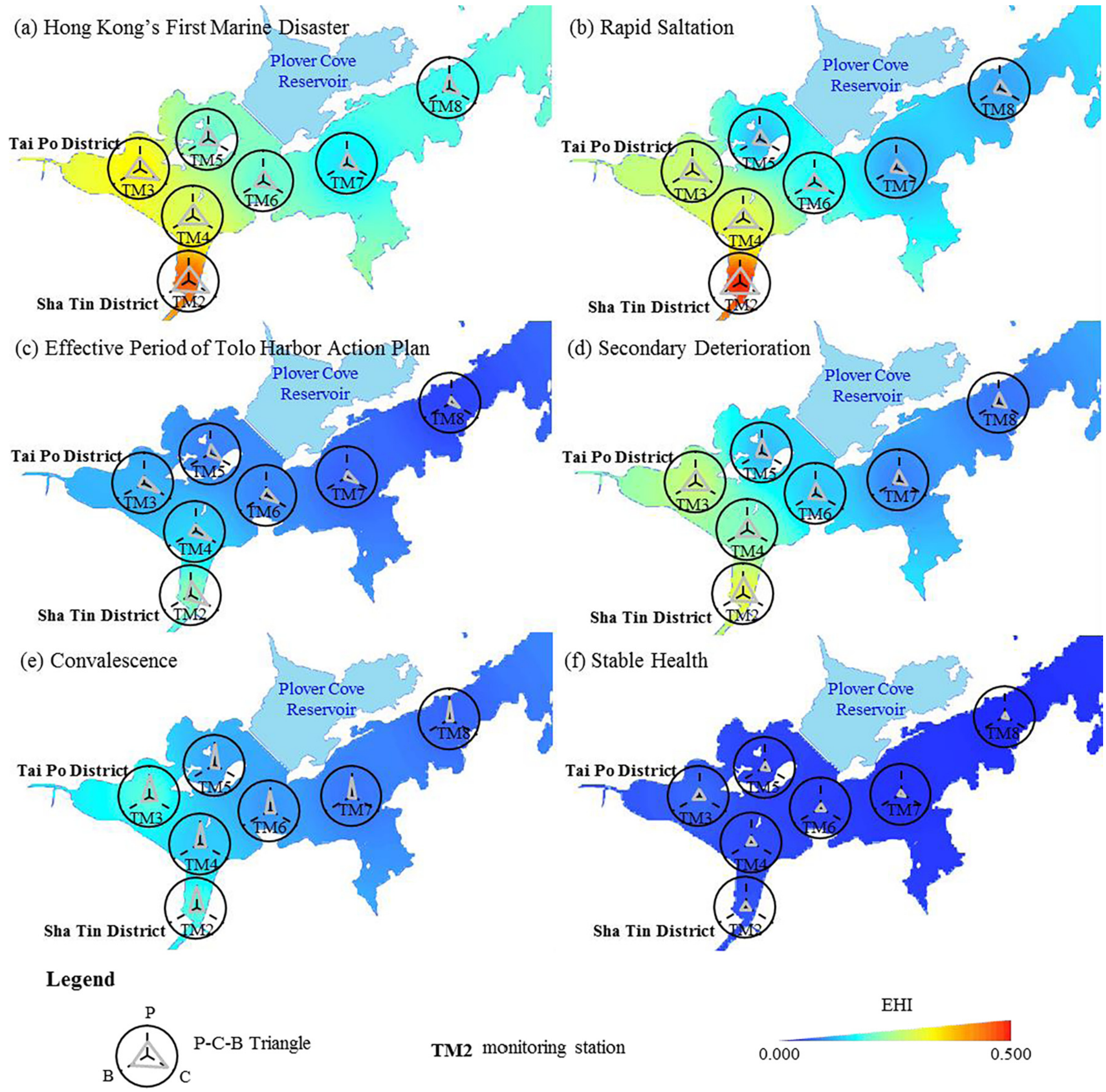

Fig. 6. Spatial pattern of the aquatic ecosystem health (AEH) of Tolo Harbor at different stages. Legend abbreviations: P-physical index; C-chemical index; B-biological index; and EHI-ecosystem health index. Spatial interpolation: data: averaged annual EHI of monitoring station in each stage; method: Inverse Distance Weighted (IDW); and mapping relation: color gradient, with decreasing pollution (decreasing EHI) from red-yellow-light blue-dark blue. The P-C-B Triangles were comprised the of averaged annual physical index, chemical index and biological index of each monitoring station at each stage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Possible mechanism for AEH variation in Tolo Harbor

4.1.1. Physical index-driven secondary deterioration

The AEH of Tolo Harbor underwent a physical index-driven secondary deterioration. The mechanism was probably related to the restoration of the aquatic organic structure. With the improvement of AEH, the aquatic organism structure was restored. The activities of organisms living in sediment could largely influence the environmental processes of sediment (Evans, 2001). Due to the occurrence of periodic hypoxia, some DO-sensitive benthic epifauna moved between Tolo Harbor and Mirs Bay (Fleddum et al., 2011), probably causing the resuspension of historically sedimentary contaminates.

4.1.2. Bad tendency in most months

Tolo Harbor was considered to be naturally eutrophic because of the adverse geographical environment (Lee et al., 2012). Starting from March, when the water temperature rose and solar radiation intensified, the biomass of algae began to increase, and chlorophyll-*a* can attain its annual maximum (Chau, 2004). With the accumulation of nutrients in bottom water and their transportation to surface water, it is easy to create an eutrophic condition (Xu et al., 2010; Lee et al., 2012) and lead to algae blooms, resulting in the occurrence of an ecosystem health mutation between March and April. The pollution discharge and accumulation throughout the year provided sufficient nutrients for continuously high algae levels and prepared sufficient nutrients for next year's algae blooms. Therefore, the AEH had a bad tendency in most months that was driven by the biological index.

4.2. About assessment method

An ideal assessment method should be capable of providing an easy but scientific pathway to simplify and quantify the complex ecological phenomenon, making predictable responses to anthropogenic destructions, and linking to adequate scales and managing targets. It would be better for environmental managers and the public if the method was an intuitive visualization.

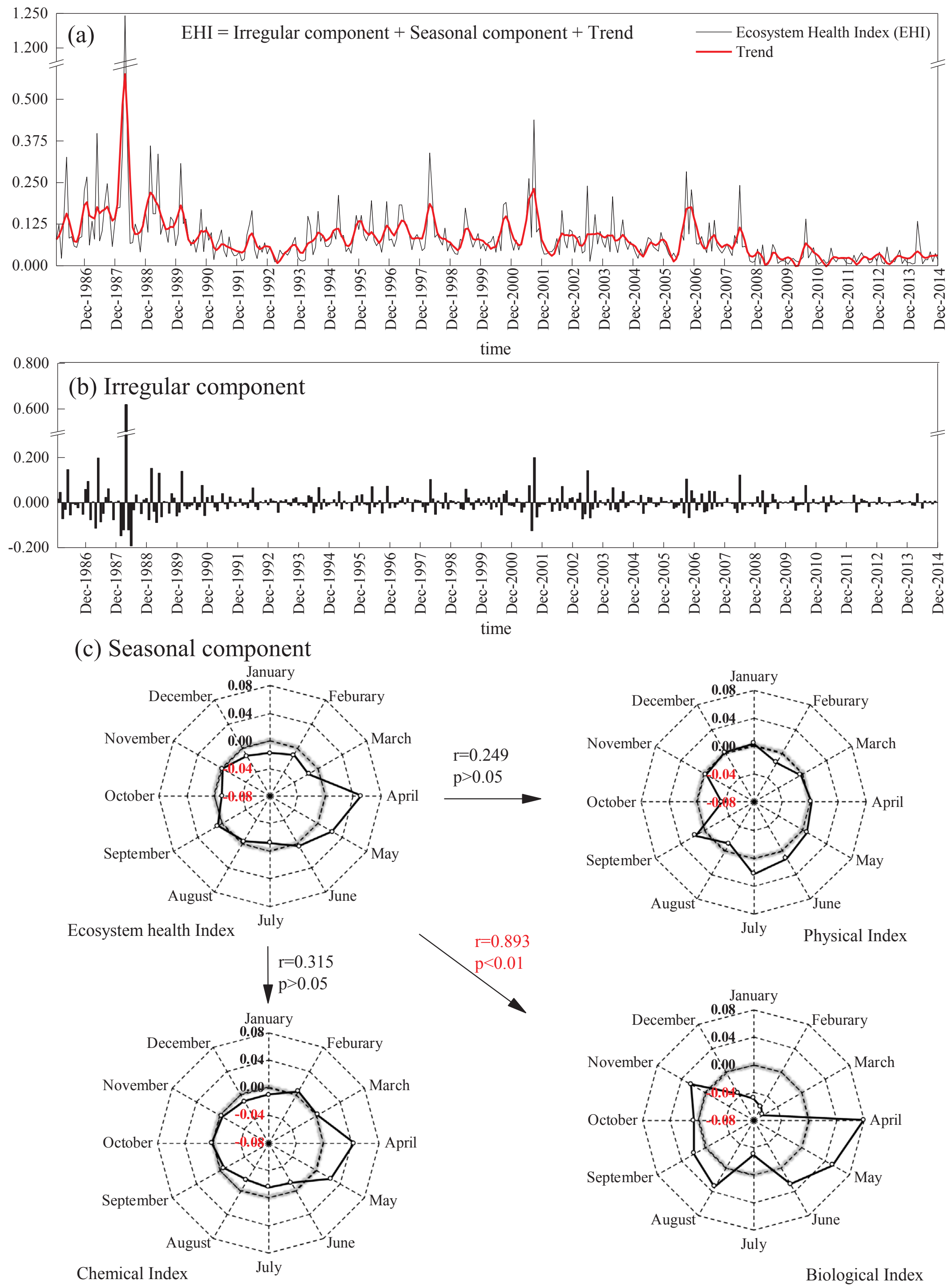

Fig. 7. Seasonal decomposition of monthly time series to identify the aquatic ecosystem health (AEH) tendency in different months and the dominating factor on a monthly time scale. (a) Monthly variation of the Ecosystem Health Index (EHI) in Tolo Harbor and the long-term trend. Model: addictive model (SPSS 20, IBM Inc., USA); and EHI consisted of three parts: irregular component, seasonal component and long-term trend. (b) Irregular component of the monthly time series. Irregular component: noise, or random fluctuation. (c) Decomposed seasonal components of the EHI and Physical, Chemical, Biological Indexes. Positive value (in black): bad tendency; and negative value (in red): good tendency. The AEH in Tolo Harbor had a bad tendency in most months, and the biological index dominated the AEH tendency pattern (Spearman correlation, $p < 0.01$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this paper, PCBTAM was mainly proposed to enhance the intuitiveness of the assessment results. The EHI and indicator category indexes were mapped into the P-C-B Triangles, making the assessment a greatly intuitive visualization. The dominating factors were easily recognized from the shape of the triangle. For example, in Fig. 6e, the P-C-B Triangles were sharp at the axis of the physical index, and it was easily known that the dominating factor at this stage was physical index-driven. When overlaying all the P-C-B Triangles of each stage, the temporal AEH variations were obviously realized from the size of triangles and the changing of the three indexes was prominently observed from the shape of the triangles (Fig. 5).

In the novel PCBTAM, multiple indicators were integrated into one index to make the assessment result easier. Five principles of indicator selection were defined to make the method scientifically reflect the ecological phenomenon and to make predictable responses to anthropogenic destructions.

PCBTAM was also a flexible method for environmental managers. The selected indicators were alternative according to the specific management demands. The environmental standard values could be inserted into Eqs. (2)–(4) to construct the reference P-C-B Triangles. It was easy to judge whether the ecosystem health was up to standards and which indexes were especially high by comparing the monitoring triangles to reference triangles. In this way, targeted therapies may be implemented without too much delay.

The PCBTAM belongs to the indicator system methods. For indicator system methods, only by synthetically utilizing multi-aspect indicators can we obtain the needful characteristics as much as possible to give more comprehensive information for ecosystem health assessment. With the characteristics of openness, complexity and uncertainty of the ecosystem, its health category is extremely wide. The health category includes not only physical indicators, chemical indicators and biological indicators but also social indicators, economic indicators and anthropic indicators. For example, Shear (1996) proposed a comprehensive indicator system including the indicators of biology, ecology, society, economy and human health on the collective program of Canada and the United States to evaluate the ecosystem health of the Great Lakes. Jørgensen (1997) also proposed a comprehensive indicator system containing the aspects of population, resources, environment, society, economy and disasters, hoping to use multiple descriptions to show all the characteristics of ecosystem health. Therefore, as a flexible method, the PCBTAM can be further modified to cover more indicators. The dimension of this method needs to expand, and a stereoscopic geometry was expected to replace the planar figure.

When any other components such as habitat, flow, socioeconomics than physical, chemical, biological indicators are introduced, the graphical shapes and corresponded area calculation formulas will be changed completely. This means that the shape will not be a triangle but depending on the number of sides (components). It may be a quadrilateral, pentagonal, hexagonal figure, or a non-planar geometry, and the equation for the area or volume inside the figure that represents the health status of an ecosystem will completely change. This will be a completely different method or model with PCBTAM. A polygonal graph or a non-planar geometry would be constructed according to the number of selected indicators, and the equation for the area or volume inside the figure needs to be developed.

5. Conclusion

A novel method for ecosystem health assessment was designed, and turbidity, TN, TP, BOD_5 and Chl-*a* were selected as reference indicators for evaluating the AEH in Tolo Harbor. The AEH of Tolo Harbor during 1986–2014 was divided into six stages and underwent two deteriorations and two convalescences. Seasonal component extraction indicated that Tolo Harbor had a bad AEH tendency in most months. The dominating factors on different spatiotemporal scales were recognized, and the possible mechanisms for AEH variations were also discussed. The method, PCBTAM, is a simple but scientific assessment method with enhancing the intuitiveness of the assessment results.

Acknowledgments

The funding for this study was provided by the National Science Foundation of China (NSFC) (41030529, 41271462). This work is also supported by a grant from the 111 Project (B14001) and from the Undergraduate Student Research Training Program of the Ministry of Education.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2018.04.056.

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