

Developing nutrient criteria for the Jiulong River Estuary, Southeast China

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Abstract

One of the key concerns in estuarine and coastal environments is eutrophication, which is known to be closely connected to nutrient enrichment. To control and improve surface water quality, nutrient criteria are recommended in order to provide reference conditions for the environment. However, the current datasets of nutrient criteria in China are either designed for surface water or sea water, and as such these are not suitable for assessing estuarine water quality, especially given the unique ecosystem and dynamic properties of estuaries. To address this issue in current estuarine water management, nutrient criteria have been developed for a local estuary in the southeast of China. Segmentation of the Jiulong River Estuary, China was firstly analysed through field investigations carried out during 2013–2014, which resulted in the delineation of three segments characterized by their distinct properties in relation to salinity, hydrology, ecosystems, etc. Historical records from 1997 to 2014 were then analysed using statistical modelling to develop candidate nutrient criteria for the estuary. This stage of the analysis was undertaken in combination with the study of nutrient status records from the 1980s, which were used to establish a baseline reference condition. The recommended criteria values of dissolved inorganic nitrogen (DIN) in Segments I, II and III of the Jiulong River Estuary are 64, 21 and 14 $\mu\text{mol/L}$, respectively, and the corresponding values for soluble reactive phosphorus (SRP) are 0.89, 0.76 and 0.89 $\mu\text{mol/L}$, respectively. It should be emphasised that these values are site-dependent, and that different results may be achieved at other locations depending on the physical and biogeochemical characteristics of an estuary, or even a single site within a catchment. It is hoped that by demonstrating a possible methodological approach and methods of nutrient criteria derivation in the Jiulong River Estuary, the current study will offer researchers some fundamental basis from which to begin to develop more complete nutrient criteria indices for the study of nutrient conditions in other estuaries throughout China.

Key words: estuarine segmentation, nutrient criteria, ecosystems based approach

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1 Introduction

The problem of nitrogen and phosphorus pollution is not new (e.g., Carpenter et al., 1998). Excess loading of nitrogen and phosphorus to surface water bodies is one of the leading causes of water quality impairments world-wide (Smith, 2003); and this extends to both fresh and marine waters (Li et al., 2011; Cao et al., 2005). Estuaries and coastal waters are especially vulnerable to nitrogen and phosphorus pollution because they are the ultimate receiving waters for most major watersheds transporting nitrogen and phosphorus loads from multiple upstream sources (Zaldívar et al., 2008). Nutrient enrichment is the most common cause of eutrophication and the subsequent development of harmful algal blooms, and unfortunately this is the case for the Jiulong River and Jiulong River Estuary, in the southeast of China (Chen et al., 2013b). Since the establishment of the Xiamen Special Economic Zone in 1986, the adjacent Jiulong River Estuary has experienced vast anthropogenic perturbations due to the

rapid economic development in this region. It is observed that concentrations of $\text{NO}_3\text{-N}$ and SRP in the Jiulong River Estuary have increased by 2–3 times, and red tide events have occurred more frequently during the last three decades (Hong et al., 1999; Yan et al., 2012).

To protect estuarine water bodies from the harmful, adverse effects of nutrient pollution, standard environmental values are needed to provide baseline reference criteria for management. In China, to monitor and assess estuarine water quality, the Sea Water Quality Standard (GB 3097-1997) is utilized as an environment reference point. However, an estuary, as a transitional zone between inland freshwater and coastal marine environments, retains some of the characteristics of both environments, and estuaries also have unique properties of their own (Whitfield and Elliott, 2011). Therefore, water quality standard sets for inland surface freshwater (Environment Quality Standards for Surface Water, GB 3838-2002) and sea water (Sea Water Quality Standard,

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GB 3097-1997), respectively, are not necessarily suitable standards to apply to estuarine environmental management strategies in China. The need for water quality standards for estuary's in China is elevated on the agenda due to the aforementioned pollution issues and a lack of defined criteria from which to assess the impacts of pollutants in the estuarine zone.

However, despite the clear need for baseline studies, research aimed at deriving estuarine nutrient criteria is rarely reported in the literature in China. By contrast, a pilot study, has been conducted in the United States, where estuarine nutrient criteria were established for 19 estuaries in the State of Florida (US EPA, 2012). This work presented two important components for development of estuarine and coastal nutrient criteria that inform the current study: the need for the establishment of distinct divisions or segments (zones) within estuarine and coastal systems; and the development of approaches to determine nutrient criteria in estuarine and coastal areas. Neither of these components has been developed to date in China, or indeed other developing countries, despite the fact that profound environmental pollution is shown to increase with the intensification of economic activities (Wang and Aubrey, 1987; Liu et al., 2011).

On the basis of estuarine segmentation, some analytical approaches have been attempted in the USA with the aim of establishing estuarine and coastal nutrient criteria (US EPA, 2001). The most popular approaches include using reference condition, statistical- and mechanistic models. The reference condition approach is more applicable when a least-disturbed, healthy water body environment can be referred back to (Herlihy et al., 2008), and statistical models can be developed where enough monitoring data are available (i.e., stressor-response relationships). In a situation where a reference site is unavailable, and monitoring data are insufficient, which are common issues, especially in developing countries without a history of long-term water quality

monitoring, mechanistic models can provide an alternative approach for predicting the protective values of nutrient concentrations. In some cases, all of the above approaches could be applied in conjunction, in an effort to achieve a fully integrated dataset for determining optimal nutrient balances for water quality assessment purposes.

The aim of the current paper is to establish, test and verify nutrient criteria in the Jiulong River Estuary, Southeast China, as a case study for monitoring and management purposes. Segmentation in this area has been explored, and subsequently reference conditions and statistical model analysis were applied and compared in order to determine the appropriate methodology for the local environment. By presenting this pilot study, we hope that estuarine nutrient criteria can be further understood, studied and developed in China and internationally, and that this study forms a preliminary contribution to the development of a comprehensive set of guidelines for water quality management in China and further afield.

2 Methods

2.1 Study area

The Jiulong River Estuary is a subtropical drowned river valley estuary in south-eastern China, on the west coast of the Taiwan Strait (Fig. 1). The estuary is approximately 21 km in length, 6.5 km in width (on average ~4.5–9 km), and between 3 m and 16 m in depth (Cai et al., 1999). The Jiulong River and its tributaries, including the North, West and South Brooks, are the primary sources of freshwater to the Jiulong River Estuary. Due to the influence of the East Asian monsoon, the mean annual precipitation and temperature in the region are in the range of 1 400–1 800 mm and 19–21°C, respectively. The combined mean annual runoff of the North and West Brooks into the estuary is

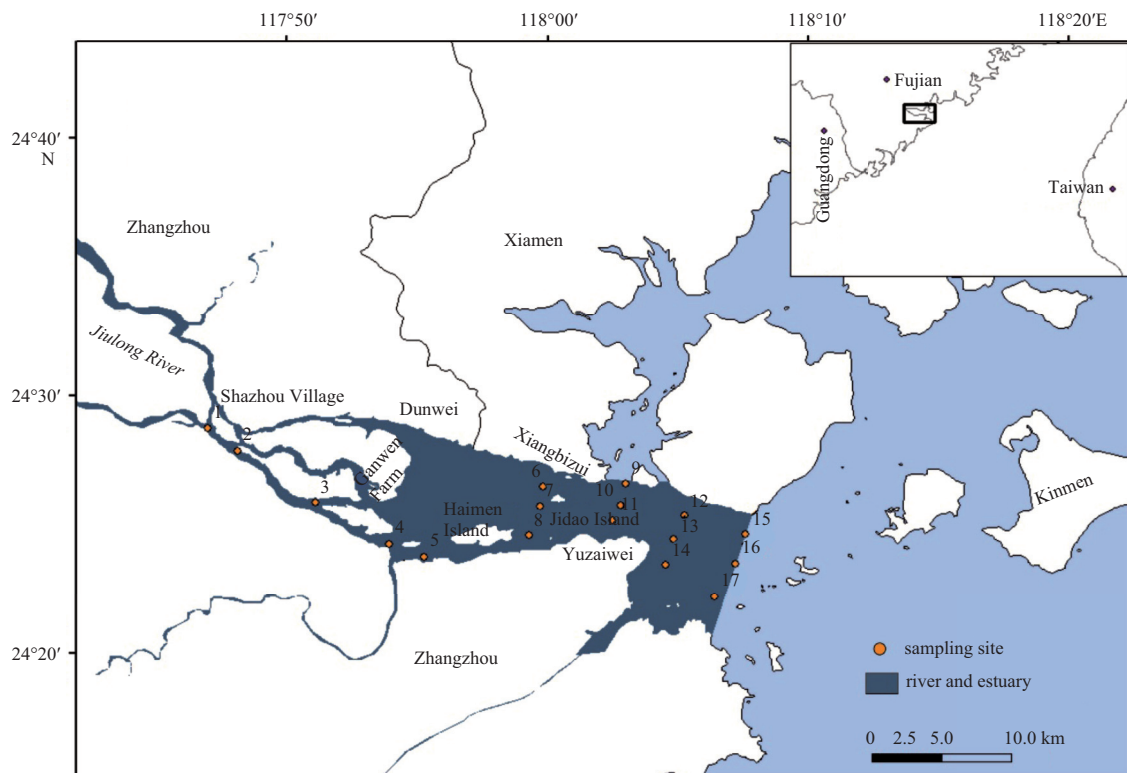


Fig. 1. Map of the study area showing sampling sites.

$11 \times 10^9 \text{ m}^3$, and high discharge (~75%) occurs mostly during the wet season from April to September (Chen et al., 2013a). The tides in the estuary are semidiurnal with a mean tidal range of 2.7–4 m from the upper to the lower estuary (Luo et al., 2012). The salinity mixing behaviour of the estuary exhibits a well-stratified regime during low and ebb tides, but is vertically homogeneous during high and flood tides (Wang et al., 1986).

2.2 Data sources

There are several data sources utilized in this study. The most recent data were collected during 2014–2015, when comprehensive physical, chemical, biological and sedimentological investigations were carried out in the estuary. Detailed sampling information is presented in Section 2.3. Historical data for the local environment was collected from literature sources (Chen, 1993; Cai, 1988; Chen et al., 1985; Lin et al., 2013), monitoring station records and government statistics reports (Xiamen's Environment Quality Bulletin, <http://www.xmhyj.gov.cn/Ocean/Index>). Among which, nutrient (N and P) concentration records from field investigations conducted in the 1980s were used to establish baseline reference conditions; seawater quality monitoring data obtained during the period of 1997–2014 were used in combination with the data from the current study for statistical model analysis; and algal bloom events records from 1987 to 2014 were collected from the statistical reports of the local environment office. Data normalizations were conducted for the compiled nutrient concentration and then statistically analysed in the SPSS22.0 software package. The most complete and detailed nutrient records from the historical dataset are values for DIN and SRP, which suggests that these are the only nutrient indicators that can be appropriately used in the development of the proposed baseline nutrient criteria at this stage of the study.

2.3 Sampling methods

As one of the data resources, recent field cruises (2014–2015) were conducted during the spring (25 April 2014, air temperature between 20–25°C), summer (1 September 2014, air temperature between 23–29°C), autumn (10 November 2014, air temperature between 18–25°C) and winter (6 January 2015, air temperature between 13–20°C) in the Jiulong River Estuary. The locations of the sampling sites are illustrated in Fig. 1. Sampling at each site was conducted twice during each cruise across a complete tidal cycle; whilst samples were taken from near surface, middle water column and channel bottom at each site.

Attributes that were investigated include the salinity (Sa), water temperature (Wt), water clarity, pH values, suspended sediment (SS); tested nutrients include the total nitrogen (TN), total phosphorous (TP), soluble reactive phosphorous (SRP), dissolved inorganic nitrogen (DIN) and dissolved silica (DSi). The sampling methods are based on China Marine Monitoring Standards (GB 17378.4-2007), of which the Sa and Wt were tested using CTD instrument (AAQ1183), water clarity was visually measured with Secchi disk, pH was tested in portable Multi-parameter water quality meter (420D-01A), and SS was measured by weighting the leftovers after filtering the water samples. ArcGIS was used to conduct geo-information analysis based on the average value of each attribute measured at every single site. For the analysis of DIN and SRP, water samples, taken by 5 L Niskin bottles (model QCCC-5, National Ocean Technology Center, China), were filtered with 0.45 μm cellulose acetate membranes on site, and then treated with 1‰–2‰ chloroform and preserved at 4°C in 350 mL polyethylene bottles. Value of DIN is the sum of NO_3^- , NO_2^- and NO_4^+ , and value of PO_4^{3-} was taken as the

SRP. All nutrient values were tested using an AA3 Auto-Analyzer (Bran+Luebbe Co., Germany) which has detection limits of 0.1, 0.04, 0.5 and 0.08 $\mu\text{mol/L}$ for NO_3^- , NO_2^- , NO_4^+ and PO_4^{3-} , respectively (Wu et al., 2017).

2.4 Segmentation

Morphology and salinity are natural factors that strongly influence the processes controlling the effects of human pressures on the overall nutrient status of water bodies. Morphological characteristics affect hydrodynamics and mixing, and salinity is a controlling parameter for biogeochemical processes. As a result, these factors were considered as primary dividers for the delimitation of segments/zones (Liu et al., 2011).

A spatial framework based on salinity segmentation was applied to provide additional natural segmentation criteria for water bodies within the estuary, thus complementing the morphological division. Three salinity classes were defined based on the NOAA National Estuarine Inventory (NOAA, 1985, 1999): tidal fresh (0–0.5), mixing (0.5–25) and seawater (>25) zones, which broadly correspond to the Venice classification (Venice System, 1958). Any apparent differences between segments were analysed in SPSS (One-way ANOVA) on indicators including pH, SS, water clarity and water temperature in order to assess their significance.

Salinity for each sampling site was determined from the average values of the *in situ* records and represents average values through the water column. The spatial patterns in salinity were obtained using an inverse distance interpolator in the GIS, based on the averaged salinity values for each sampling site: tubular estuaries will normally be split into three zones and estuaries with a more complex topography and circulation may additionally be divided laterally. Although not all systems have all three zones, this allows for a consistent approach enabling comparisons between highly diverse systems.

2.5 Analytical approaches

Reference conditions and statistical analysis models were applied in this study. Although the water quality in the Jiulong River Estuary is not currently in a positive state, it was considered to be close to the natural baseline condition as determined from the 1980s literature, at a time when the local economy was in the early stages of development.

To analysis the protective value of DIN, statistical modelling was applied to the dataset. Normalization of nutrient concentrations was adapted before applying the statistical analysis in order to remove the concentrating/diluting effect of salinity changes (Dore et al., 2003). Furthermore, in order to enable comparison with the current standards for estuarine water quality assessment in China, which are the Sea Water Quality Standards, normalization of the nutrient concentrations in the estuary is also necessary. The nutrient concentrations measured in this study were all normalized to a constant salinity of 30. Equations for normalization are listed below. Given the strong dynamic mixing processes in estuaries, proportions of mixed freshwater and seawater under certain salinity conditions can be deduced from the following equations without the need to consider the density differences between freshwater and seawater.

$$R = \frac{V_r}{V} = \frac{S_m - S_r}{S_m - S_f}, \quad (1)$$

$$M = \frac{V_m}{V} = \frac{S - S_r}{S_m - S_f}, \quad (2)$$

where R and M represent proportions of freshwater and seawater under certain salinity levels in a unit volume of brackish water sample, respectively; V_r , V_m and V represent volume of freshwater, seawater and brackish water, respectively; S_r , S_m and S represent salinity of freshwater, seawater and brackish water, respectively.

In the Jiulong River Estuary and adjacent water areas, it is considered that the value of S_r is nearly zero and S_m is 34 (Yan et al., 2012; Liu et al., 2008; Wang et al., 2000), on this basis the concentrations of nutrients in the mixed water under certain salinity conditions can be calculated using Eq. (3) when the mixing process is dominant.

$$C = R \times C_r + M \times C_m, \quad (3)$$

where C represents nutrient concentration in mixing water; C_r and C_m represent nutrient concentrations of riverine freshwater and seawater, respectively. Specifically, DIN concentration becomes approximately $1.0 \mu\text{mol/L}$ where seawater salinity approaching 34 which indicates no influences from freshwater in the study area (Yan et al., 2012). Therefore, this equation can be further developed into Eq. (4):

$$C = R \times \left(\frac{C_t - M_t \times C_m}{R_t} \right) + M \times C_m, \quad (4)$$

where C_t represents the lowest value of normalized nutrient concentration, M_t and R_t represent the normalized proportions of sea water and freshwater, and C_m represents the nutrient concentration in coastal water. In the southeast coast of China, the C_m

value for DIN is $1 \mu\text{mol/L}$ (Chen, 2008).

3 Results

3.1 Salinity patterns

By applying the interpolation method, the spatial patterns in salinity across the four seasons (four cruises) are presented, and clear divisions can be observed (Fig. 2). From the aspect of morphology, the distance between Xiangbizui and Yuzaiwei (Fig. 1) represents the narrowest part of the estuary. From this point riverwards, the hydrology is strongly affected by tides, and the salinity is less than 25 on average (Fig. 2). In this area, the water clarity is the lowest (0.7-1.2 m) but the maximum flow rate during the ebb was observed at 1.82 m/s and the maximum rate of flood tide is 0.8 m/s (Luo et al., 2012; Wang and Jiang, 2013). A separation line starts at Dunwei and continues through Ganwen Farm and onto sampling Site 4 (sampling Sites 3 and 4, Fig. 1). This indicates the interface where the strongest mixing processes occur between freshwater and sea water. As might be anticipated, the tidal speed decreases with distance to the freshwater outlet. The values for the majority of the attributes studied in this area (salinity, pH, SS, etc.) exhibit a wide range of variability (see Appendix). From this point upwards in the catchment, the waterbody's are mainly dominated by freshwater flows and are only occasionally affected by tidal currents.

3.2 Reference segments and conditions

The total segmented area is defined as follows. The seaward edge of the segmented area is at longitude $118^{\circ}08'E$, where the salinity is about 30 (Fig. 2). The upper edge of the segmented area was determined to start at Shazhou Village where the channel

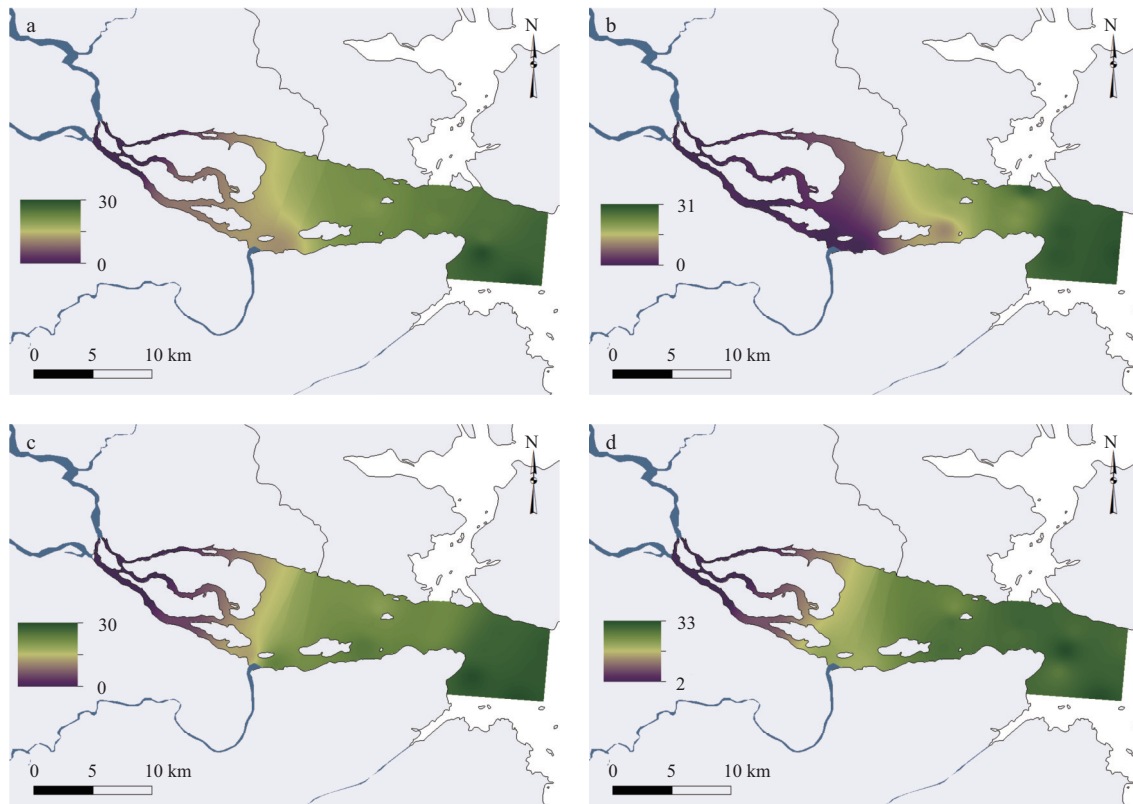


Fig. 2. Salinity gradient in the Jiulong River Estuary at various times: a. spring (April 2014), b. summer (September 2014), c. autumn (November 2014), and d. winter (January 2015).

pattern of the Jiulong River changes from single to multiple-branches (Fig. 1). Based on the morphological characteristics of the estuary, the segmented area is defined between latitude 24°19'–24°29'N and longitudinal 117°46'–118°08'E.

Combining the estuarine geography as well as modern administrative zones, the spatial patterns in salinity in the estuary (Fig. 2) reveal the possible segmentation solutions that can be implemented (Fig. 3). Segment I contains the upper estuary where the water characteristics are dominated by freshwater, and salinity values are less than 15 at over 90 of the sampling locations; Segment II is the middle estuary which is a zone of maximum mixing between saltwater and freshwater in different proportions. Salinity values in this zone are less than 28 at over 90 of the sampling sites; finally, Segment III as the lower estuary is a marine dominated zone where salinity values are less than 30 at in excess of 90 of the sampling sites. Statistical analysis of variance (one-way ANOVA) between the segments was undertaken on the physical attributes (salinity, pH, SS, water temperature) (Table A1). As can be seen, most of the differences between segments are statistically significant ($P < 0.05$). Moreover, one-way ANOVA tests of nutrient concentration variances were conducted for the surface waters of the estuarine, based on data collected during

2014–2015, and significant differences were found ($P < 0.05$) (see Appendix). The reference conditions in each segment were then identified based on the nutrient records from the 1980s, which have shown that the average normalized values of DIN in Segments I, II and III were 50.13, 24.33 and 16.50 $\mu\text{mol/L}$, respectively, and the average concentration of SRP was 0.52 $\mu\text{mol/L}$ (Chen, 1993; Chen et al., 1985; Yang et al., 1996).

3.3 Nutrient-salinity sensitivity

Correlations between nutrients and salinity were explored using data from 1997 to 2014 in combination with the data from 2014–2015 (Fig. 4). The results show that the concentrations of DIN and SRP behave differently in association with the salinity gradient in the estuary (Fig. 4). DIN decreases with increasing salinity; whereas SRP, although exhibiting a similar trend in association with salinity, is not as significant as DIN in terms of the interaction between changes in salinity. Similar correlations have also been observed in other research in this region (Yang et al., 1996; Yan et al., 2012).

3.4 Nutrient-algal bloom sensitivity

Algal blooms, especially in the case of red tide events, have

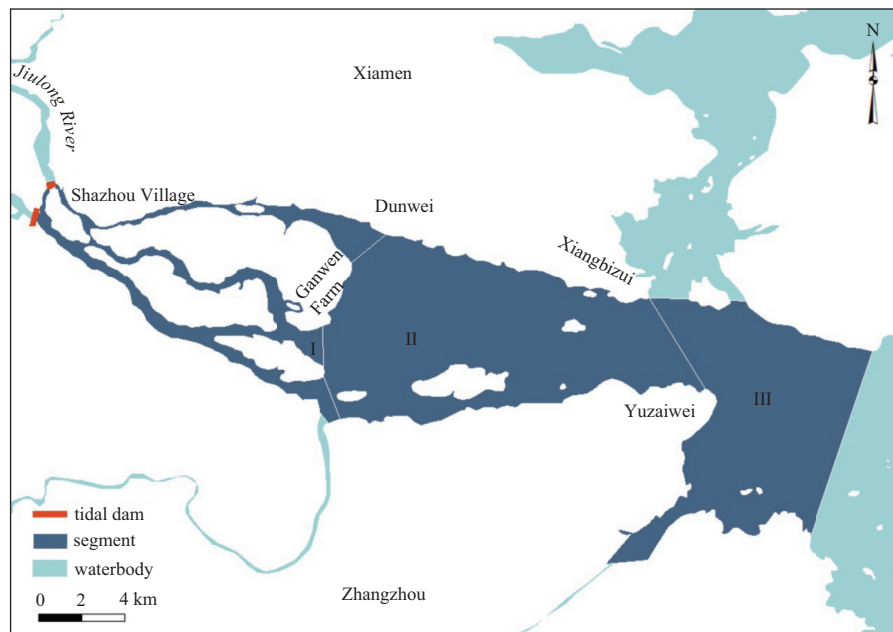


Fig. 3. Segmentation results of the Jiulong estuarine water body.

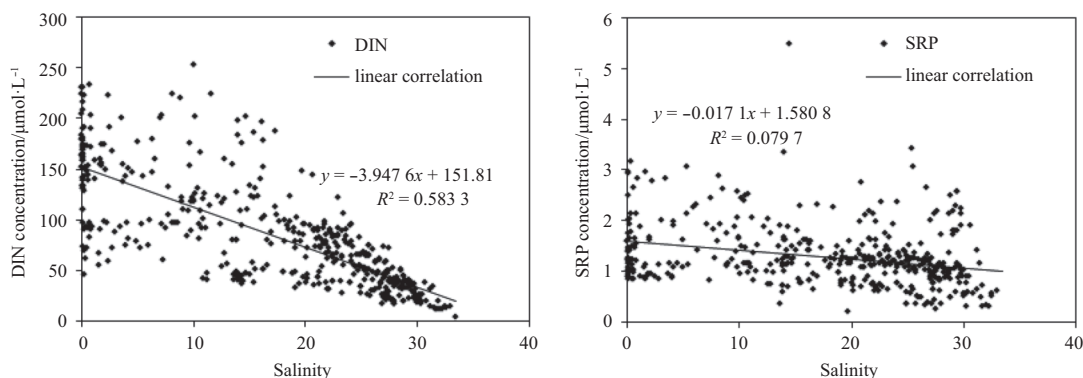


Fig. 4. Relationship between nutrient concentrations and salinity in Jiulong River Estuary (data from 1997–2014).

been occurring frequently in the Jiulong River Estuary and adjacent bay and coast areas since 2000 (Yan et al., 2016). Because the occurrence of algal blooms is connected to a tipping point, when the ecosystem turns into an extreme nutrient enriched situation, the lowest values of nutrient concentration observed during these events should provide the important threshold values with respect to eutrophic condition. The correlation between nutrient concentrations and the occurrence of red tides was, therefore, analysed in order to identify the lowest values of nutrient concentrations stimulating these events, which would then suggest the maximum values of candidate nutrient levels. Based on historical data from the China Oceanic Information Network and reports on marine environment quality in Xiamen, 61 red

tide events were documented from 1987 to 2014 in the water area around the Xiamen Island, however, only two of these events occurred in the Jiulong River Estuary (OFBX, 2015). Moreover, 29 of all red tide events were not able to be utilized in this analysis due to the lack of corresponding nutrient records. As a result, the nutrient concentrations (DIN and SRP) monitored in the remainder of the thirty-two events were graphed (Fig. 5). Normalized DIN concentration was also explored and compared, but SRP concentration was not normalized as this parameter is insensitive to changes in salinity, as can be seen in Fig. 4. It should be noted that the red tide events observed in the Jiulong River Estuary occurred in April of 2003 and July of 2007, and that these correspond to the 10th and 19th events marked in Fig. 5.

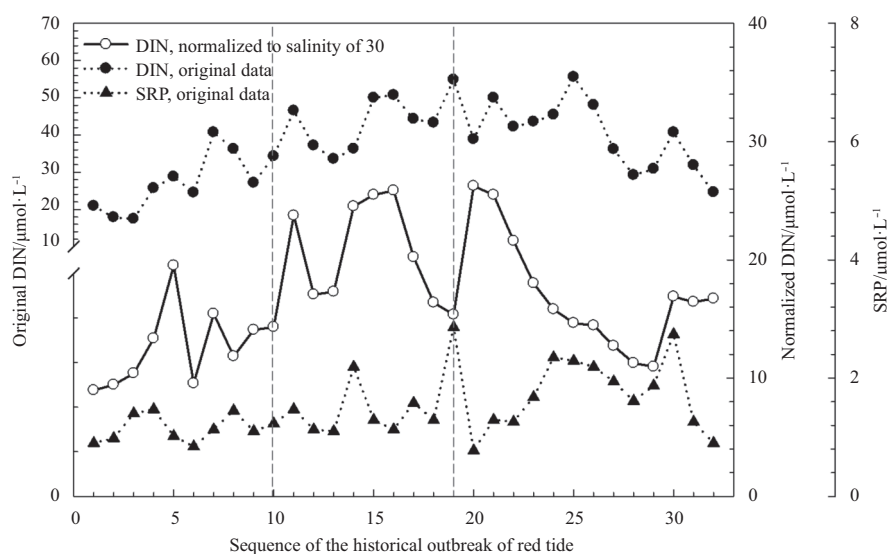


Fig. 5. Concentrations of original/normalized DIN and original SRP monitored during red tide events in the Jiulong River Estuary and adjacent bay and coastal area (original DIN were normalized to salinity of 30).

When comparing the two red tide events that occurred in the Jiulong River Estuary, the lowest original and normalized values of DIN concentration (34.28 and 14.31 $\mu\text{mol/L}$, respectively) were both observed in the event in 2003. In addition, the lowest value of SRP concentration in the estuary is 1.23 $\mu\text{mol/L}$ was observed in the same event. Considering the relationship of phosphate to nitrate uptake for photosynthesis, the candidate values of DIN and SRP in water are expected to be 16:1 based on the theory of Redfield ratio (Redfield, 1958; Hodgkiss and Ho, 1997). Therefore, the lowest value of SRP was revised to 0.89 $\mu\text{mol/L}$, where the lowest corrected value of DIN is 14.31 $\mu\text{mol/L}$ (salinity of 30).

3.5 Candidate DIN criterion by statistical model analysis

To identify the candidate nutrient criteria for all segments, statistical analysis was also applied to the concentrations of DIN because of its significant association with salinity. Based on Eq. (4), the correlation between DIN and salinity was explored (Fig. 6). As the ranges of salinity in every segment have been identified, as shown in the results of Section 3.2, the ranges of DIN concentration in each segment were then calculated (shown in Table 1). Quality standards of Class I sea water were also listed for comparison with the candidate nutrient criteria.

3.6 Frequency distributions of DIN and SRP

To obtain insights into how often different concentration levels were observed in the Jiulong River Estuary, cumulative fre-

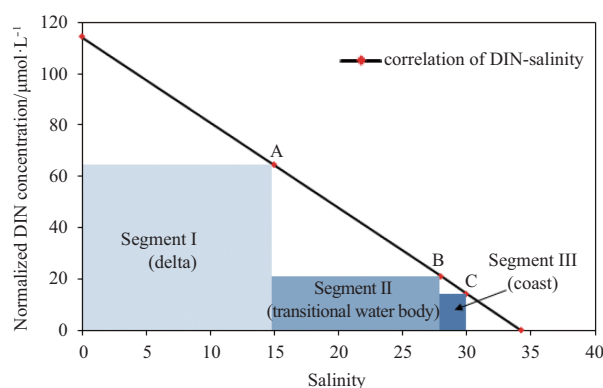


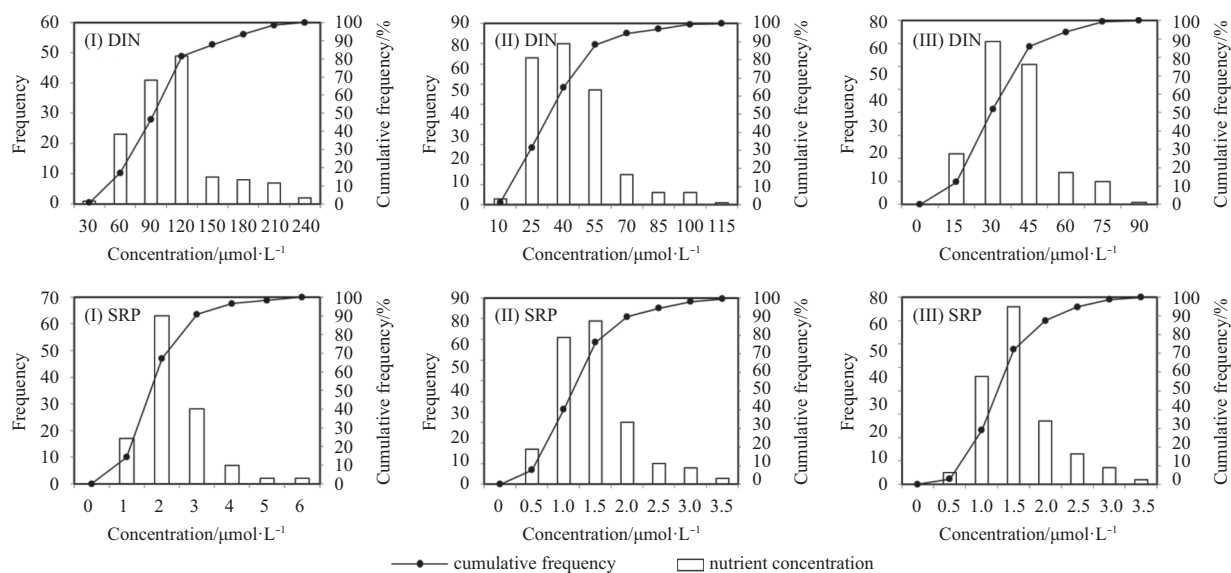
Fig. 6. Correlation between DIN concentrations to salinity (values at Points A, B and C were used to suggest the candidate criteria for DIN in Segments I, II and III, respectively).

quency distributions were applied based on the historical data from 1997 to 2014 (Fig. 7). Given the large variation in salinity occurring, due to the dynamic processes in the estuary, the maximum salinity value for each segment was determined by the 90 percentile range of sample values, as described in Section 3.2. On the basis of this original DIN concentrations from Segment I to III are normalized to constant salinity values of 15, 28 and 30, respectively. To achieve better environment conditions in where minor

Table 1. Candidate nutrient values in each segment derived from various methods in comparison with the current standard criteria

Criterion/ $\mu\text{mol}\cdot\text{L}^{-1}$	Reference condition ¹⁾			Statistical model ²⁾			Cumulative frequency ³⁾						Proposed criteria			Standard for sea water of Class I (GB 3097-1997)
	I	II	III	I	II	III	I		II		III		I	II	III	
							10%	25%	10%	25%	10%	25%				
DIN	50.13	24.33	16.5	64.22	20.97	14.31	46.99	68.84	13.60	21.19	11.93	19.43	64	21	14	14.29
SRP	0.52	0.52	0.52	0.89	0.89	0.89	0.68	1.19	0.54	0.76	0.63	0.91	0.89	0.76	0.89	0.48

Note: Values of DIN in Segments I, II and III were normalized to a salinity of 15, 28 and 30, correspondingly. ¹⁾ Values were collected from literature as explained in Section 3.2; ²⁾ method adapted in Section 3.5; ³⁾ method adapted in Section 3.6.

**Fig. 7.** Frequency distributions of DIN and SPR in each segment of the Jiulong River Estuary.

nutrient enrichment is present, lower nutrient concentration values are desirable which correspond to the cumulative frequency of 10% and 25% (Fig. 7) (US EPA, 2001). A central assumption of this approach is that at least at some times in the population of historical data, the water quality was as better as that in less disturbed conditions, which will be reflected in the values of the individual variables (US EPA, 2000). As the result, the corresponding values were identified as the candidate nutrient criteria as listed in Table 1.

3.7 Determination of candidate nutrient criteria

By utilizing the reference condition and statistical methods described above, candidate nutrient criteria were derived from each method (listed in Table 1), and compared to the current nutrient criteria in use in China. Because no estuarine segmentations have been applied in China to date, the current nutrient criteria provide assessment values for the whole estuarine water area. Recommended nutrient criteria values are decided by comparing all candidate values, but it was noted that the candidate values that were derived from the statistical model are connected to the threshold values of eutrophication. Therefore, nutrient values higher than the statistically modelled values present the potential for eutrophication, and the lower the nutrient values the stricter the criteria are. As a result, recommended nutrient criteria in this study are proposed and listed in Table 1.

4 Discussion

4.1 Segmentation

The segmentation of the Jiulong River Estuary is contiguous and consistent with a “standard” estuary structure (Perillo et al.,

1999; Perillo, 1995). In Segment II, the mixing process between fresh and salt water is so strong that the highest difference between the maximum rate of ebb and flood tide (1 cm/s) was observed in this segment, as well as the widest range of variation in salinity, SS, etc. (Fig. 2). Furthermore, developing local aquaculture industries have been concentrated in this part of the region, which is why key environmental issues in terms of hydrology and nutrient pollution, etc. need to be assessed and managed within the estuary. In Segment I, the water body is mainly dominated by fresh flows; whilst in Segment III, the water body is mainly dominated by coastal currents. The dynamics, as well as geographic characteristics, of the three segments are distinct from each other, which suggests that a reasonable segmentation has been achieved. In addition, the one-way ANOVA test results shown in Section 3.2 suggest that the three segments all differ in their salinity and morphological characteristics, which have close connections with the biological, chemical and physical processes in the estuarine environment (Cook, 1982; Telesh and Khebovich, 2010).

However, to make the case for this approach to segmentation to be more widely accepted and developed in the management of other similar estuaries, the systematic estuary segmentation method needs further development in China. The Jiulong River Estuary is relatively small and simple, so using the Venice salinity ranges to zone the estuary into three segments is a practical, realistic and achievable approach. However, for a larger estuary, it is critical to divide the estuary into different segments that are shown to behave differently with respect to nutrient inputs as well as other key parameters. For instance, the water quality and biological communities of an estuary are affected by multiple factors related to the shape and size of the estuary, its connec-

tions to the ocean, geology, climate, and watershed characteristics (e.g., watershed area and land use). Because each of these factors can vary from one system to another, causing the water quality and aquatic populations of flora and fauna in each estuary to be distinct, the segmentation of estuaries would help to integrate and coordinate efforts within a watershed in order to most effectively and efficiently assess dominant conditions and implement pollution controls (US EPA, 2008; Elliott and McLusky, 2002).

4.2 Nutrient criteria development

The nutrient criteria derived in this study include two water quality attributes: DIN and SRP. This contrasts with the attributes used in some preliminary case studies, where TN, TP, chlorophyll *a*, etc. were used in assessing estuarine and coastal water nutrient criteria, e.g., in Florida (US EPA, 2012), but the use of two water quality attributes in the current study is determined by the practical situation in China. In the Sea Water Quality Standards (GB 3097-1997) that are applied in China, only DIN and SRP are required for water quality monitoring and assessment. Additionally, chlorophyll *a* is another parameter that is not included in the standards, and these results in its absence in the criteria derived from the current study. The chlorophyll *a* criteria should be introduced because chlorophyll *a* can be a sensitive biological parameter that would serve as a signal to the environmental manager that nutrient pollution is creating an imbalance in the natural populations of aquatic flora and fauna in the estuarine waters being studied.

To realize environmental management targets, water quality records from the 1980s have been utilized as the reference condition in this study. Extensive economic activities have been on-going in China since the 1980s, and these have resulted in severe environmental pollution. Therefore, water quality in the early 1980s is regarded as a close approximation to an undisturbed condition, which contrasts to the situation outside of China, where significant pollution has occurred to many developed areas since this time. This is especially the case in those countries which experienced the aftermath of the industrial revolution (Albert, 1988; Tinsley, 1998; Jones, 2006). Another interesting phenomenon is the Redfield ratio indicated in the Jiulong River Estuary during this period. When comparing the concentration values of DIN to SRP (N/P) in each segment, based on the values of reference conditions listed in Table 1, values of 96, 47 and 32 were obtained at the river-estuary boundary (Segment I), estuary (Segment II) and estuary-sea boundary (Segment III) locations. These values are much higher than the commonly recommended value of 16 (Redfield, 1958).

The application of statistical methodology provides other candidate nutrient criteria for comparison with the reference condition. Observation of the time series data from 1997 to 2015 shows that the DIN concentrations in the Jiulong River Estuary exhibit conservative mixing behaviour with salinity, which is possibly connected to the short hydraulic retention time in the study area. However, the SRP concentrations show low variability in the area where salinities are less than 25, due to absorption-desorption processes (Yan et al., 2012; Zhang et al., 1999; Yang et al., 1998; Chen et al., 1997), and in the areas where salinity is more than 25 SRP concentrations mainly show physical mixing and dilution, which are consistent with the observations of Yang et al. (1996) and Yan et al. (2012).

Furthermore, in a region which is in the process of fast economic and societal development, it takes significant time and effort to recover water quality to anything approximating an undis-

turbed condition. Because of this, responses from biological endpoints are practical indicators for use in highlighting the tipping point at which water quality could be balanced to maintain adequate local estuarine productivity. Red tides are the most common pollution hazards in the Jiulong River Estuary, and are, therefore, analysed in combination with the nutrient conditions during the periods when these events occur. However, it is difficult to collect data for red tide events; especially in relation to the nutrient levels before the occurrence of a red tide. This data is obviously very important in determining the nutrient levels that triggering the event, but as they occur at a moment that is difficult to catch and detect (Smayda, 2008). Moreover, it is still unclear what the precise relationship is between nutrient levels and algal blooms (Heisler et al., 2008). Therefore, we attempted to explore the baseline for determining the candidate nutrient criteria derived from statistical approaches by studying the correspondence between nutrient concentrations and red tide events, in an attempt to demonstrate a possible way of deriving nutrient criteria, although it should be reiterated that there were, in fact, only two red tide events recorded in the estuary. This is why three methodological approaches, including the reference conditions, statistical modelling and cumulative frequency analysis were all applied and compared to implement the derivation processes.

The proposed nutrient criteria (Table 1) are the result of the comparison of all candidate nutrient criteria, and the combination of responses from the biological endpoints. Values of the proposed nutrient criteria are higher than the reference condition, but slightly lower than the statistically derived criteria, as corrected by the responding values from red tide events. Furthermore, the Redfield ratio was again considered in the determination of SRP values for each segment in order to achieve a sustainable and productive water environment (Chen et al., 2013b). In particular, the proposed criteria are higher than the corresponding values required in the current sea water quality standards for Class I sea water, as shown in Table 1, as the coastal area to the south of Xiamen Island is currently a conservation area for China White Dolphins. This difference suggests that the different characteristics of biochemical process between estuarine and coastal water environments, and regulation via the setting of nutrient criteria for estuaries is necessitated.

However, it is important to address the fact that the values listed in Table 1 are only aimed at demonstrating nutrient criteria derivation in the estuarine environment, and they are not designed for direct use in environmental management. In contrast to the lack of data in many other estuaries in China, previous studies of the environment in the Jiulong River Estuary are relative complete, a factor which enables the exploration undertaken in this study (Liu et al., 2011). More importantly, because of the complexity and dynamic nature of estuarine water bodies, differences in salinity within each estuary dominated in different ecological zones. Therefore, an important observation from the USEPA study was that 89 discrete segments within all of the estuarine systems studied in Florida were proposed, and numeric TN, TP, and chlorophyll criteria in each segment were then derived on the basis of this (US EPA, 2012). To achieve such targets in China, and to make the results applicable for management, long-term and complete research agendas must be undertaken.

5 Conclusions

In this study, the Jiulong River Estuary is divided into three segments based on isohaline GIS analysis and geomorphological structure, and the baseline condition is assessed by monitoring data obtained between 2014 and 2015. According to the hydrolo-

gical and geographical characteristics, as well as for convenience in administrative management of the divisions, the Jiulong River Estuary was divided into three segments corresponding to the upper, middle and lower estuary, with increasing salinity from west to east.

The results show that there were significant differences between the studied characteristics among the segments. Therefore, the segmentation developed for the Jiulong River Estuary is rational. This segmentation should enhance efforts aimed at normalizing human exploitation activities, the conservation of marine resources and the improvement of regional ecological environments. However, because of the complexity of the environment in the Jiulong River Estuary and its adjacent waters, and the increasing levels of human activity in the area, the segmentation of the estuary should be improved further in correlation with ecological endpoints.

The proposed nutrient criteria for the Jiulong River Estuary include DIN and SRP, and the values are different in each segment as shown in Table 1. It is worth noting that nutrient criteria presented in this study is site-dependent due to the unique characteristics of the study site, and as such it is not necessarily applicable to any other estuaries. For each distinct estuary, the selection of approaches, and methodologies, has to be determined by the specific characteristics of the estuarine environment and the data that is available. By presenting a set of nutrient criteria derived from a typical estuary, it is hoped that the idea of setting up estuarine nutrient criteria can be further adapted at a national scale, as this would contribute to improvements in our understanding and development of eutrophication regulations in estuarine and coastal areas.

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Appendix:

Table A1. Variances in salinity, pH, SS and water temperature among segments (one-way ANOVA test) (data: 2014–2015)

Source	Season	Sum of squares	<i>df</i>	Mean square	<i>F</i>	<i>P</i>
Salinity	spring	620.54	2	310.27	18.909	0.000
	summer	2 108.768	2	1 054.384	25.683	0.000
	autumn	1 145.679	2	572.84	35.921	0.000
	winter	1 027.799	2	513.900	18.073	0.000
pH	spring	0.474	2	0.237	53.504	0.000
	summer	3.34	2	1.67	23.826	0.000
	autumn	0.832	2	0.416	25.372	0.000
	winter	0.328	2	0.164	16.781	0.000
SS	spring	2 301.921	2	1 150.961	6.932	0.011
	summer	14 429.09	2	7 214.546	7.368	0.007
	autumn	17 630.1	2	8 815.051	17.294	0.000
	winter	9 904.438	2	4 952.219	3.643	0.053*
Water clarity	spring	0.908	2	0.454	15.039	0.001
	summer	1.686	2	0.843	16.890	0.000
	autumn	0.36	2	0.18	12.407	0.001
	winter	0.316	2	0.158	8.022	0.005
Water temperature	spring	11.045	2	5.522	34.361	0.000
	summer	3.655	2	1.828	3.482	0.059*
	autumn	2.6	2	1.3	19.274	0.000
	winter	15.434	2	7.717	11.320	0.001

Note: Data with * highlights non-significant variance between segments.

Table A2. DO concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	5.54	5.02	6.06	25.231	0
	II	6.735	5.93	7.05		
	III	7.707 1	7.43	8.19		
Summer	I	61.375	60.4	63.4	15.607	0
	II	76.533 3	47.3	101.4		
	III	103.5	78.9	110.2		
Autumn	I	5.272 5	4.2	6.59	29.246	0
	II	7.373 3	6.62	7.7		
	III	7.844 3	7.45	8.25		
Winter	I	8.072 5	6.61	9.16	13.994	0
	II	9.453 3	8.99	9.72		
	III	9.747 1	9.69	9.81		

Table A3. COD concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	3.565	3.13	4	21.61	0
	II	1.551 7	1.14	2.89		
	III	1.081 4	0.9	1.24		
Summer	I	4.407 5	4.26	4.61	30.683	0
	II	2.37	1.34	3.95		
	III	1.467 1	1.22	1.93		
Autumn	I	4	2.47	5.52	10.133	0.002
	II	2.666 7	1.13	5.69		
	III	0.828 6	0.51	1.32		
Winter	I	3.18	1.67	4.21	25.436	0
	II	1.188 3	0.82	1.48		
	III	0.942 9	0.75	1.08		

Table A4. DIN concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	281.17	264.29	298.05	23.095	0
	II	145.186 7	107.34	236.99		
	III	76.684 3	40.37	129.68		
Summer	I	342.645	307.29	386.41	20.096	0
	II	171.64	72.83	336.59		
	III	55.777 1	32.17	118.87		
Autumn	I	245.387 5	173.92	294.33	36.017	0
	II	109.035	88.85	149.68		
	III	68.577 1	45.19	129.24		
Winter	I	313.608 6	165.49	439.82	19.583	0
	II	104.551 2	71.21	168.36		
	III	69.782 3	44.7	88.49		

Table A5. SRP concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	3.935	3.87	4	10.683	0.002
	II	3.041 7	2.21	4.18		
	III	1.842 9	1.16	2.99		
Summer	I	6.655	5.26	8.35	32.261	0
	II	2.223 3	1.07	4.97		
	III	0.841 4	0.41	2.4		
Autumn	I	3.735	3.35	4.12	8.605	0.004
	II	2.826 7	2.24	3.24		
	III	2.332 9	1.57	3.64		
Winter	I	3.412 5	1.7	4.86	5.817	0.014
	II	1.246 7	0.45	1.76		
	III	1.691 4	1	3.73		

Table A6. Si concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	182.14	172.35	191.93	11.958	0.001
	II	126.103 3	94.79	163.4		
	III	52.212 9	5.56	120.81		
Summer	I	13.977 5	8.51	20.03	2.368	0.13
	II	12.975	8.45	20.26		
	III	7.644 3	2.98	20.15		
Autumn	I	23.142 5	16.78	29.78	1.781	0.205
	II	17.036 7	10.31	24.59		
	III	15.214 3	7.49	31.4		
Winter	I	149.677 5	110.13	220.97	14.166	0
	II	68.751 7	29.68	109.78		
	III	49.287 1	26.37	70.92		

Table A7. TN concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	350.55	340.45	360.65	23.378	0
	II	189.411 7	129.88	302.55		
	III	122.374 3	103	145.56		
Summer	I	326.967 5	208.7	394.62	16.634	0
	II	147.31	50.71	291.01		
	III	58.787 1	20.94	168.65		
Autumn	I	206.769 3	162.23	252.97	9.126	0.003
	II	133.218 8	85.15	235.57		
	III	95.689 4	52.83	120.37		
Winter	I	271.457 5	190.08	349	1.429	0.272
	II	187.661 7	161.53	248.88		
	III	202.858 6	144.91	432.94		

Table A8. TP concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	26.005	23.14	28.87	1.889	0.193
	II	20.505	13.35	30.07		
	III	16.967 1	10.49	29.32		
Summer	I	13.905	10.18	18.18	24.575	0
	II	4.761 7	1.97	12.81		
	III	1.111 4	0.33	2.63		
Autumn	I	7.499 5	7.04	8.34	33.566	0
	II	4.417 7	3.48	6.83		
	III	3.020 9	2.3	3.59		
Winter	I	9.06	6.07	13.28	12.867	0.001
	II	4.76	3.76	6.18		
	III	4.398 6	3.5	5.56		

Table A9. Chl *a* concentrations and variances between segments (data: 2014–2015)

Season	Segment	Mean	Minimum	Maximum	<i>F</i>	<i>P</i>
Spring	I	2.162 5	0.51	3.82	2.22	0.151
	II	0.894 5	0.6	1.44		
	III	1.095	0.8	1.82		
Summer	I	18.875	16.3	24.6	16.807	0
	II	5.6	2.5	18		
	III	5	3.4	5.8		
Autumn	I	6.402 5	2.62	8.62	22.351	0
	II	1.706 7	1.43	2.05		
	III	1.382 9	0.95	2.69		
Winter	I	8.585	4.59	12.65	12.866	0.001
	II	2.71	1.54	3.77		
	III	2.602 9	1.19	4.1		