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Ecological responses to the coastal exploitation of urban agglomerations along the Pearl River Estuary

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Abstract

With the rapid development of urban agglomerations in the Pearl River Estuary (PRE), an increasing number of ecological problems have been exposed to the surrounding coastal zones. The timely and accurate understanding of the eco-environment in PRE has become of increasing concern. This study aimed to quantitatively evaluate multi-temporal eco-environment conditions and then detect the conflicting patterns of the eco-environment under the influence of coastal exploitation in PRE. The ecological index was derived from remote sensing images by means of principal component analysis, and the composite coastal development index was then constructed to characterize the coastal exploitation from the perspective of ecological influence, which was implemented by using the panel data analysis. This method was verified with a significant test accuracy of 0.9. Based on this, the coupling coordination patterns of the coastal economy–environment system were disclosed for all six prefectural units at both the pixel scale and the city scale. The results showed that the coupling coordination degree and inner coupling relationships in each city presented periodical characteristics, with the highest values in 2008 and the lowest values in 1988. The dominant conflict between coastal exploitation and the eco-environment in each period was capricious. This evaluation will provide a reference for decision-making in coastal zone planning and ecological red line policy to encourage the sustainable development of coastal zones.

1. Introduction

The discovery of eco-environmental variations is an increasingly popular topic. The coastal eco-environment has a high sensitivity to hydro-dynamic processes and complex human activities (Davoodi et al 2017). Ecological environments in coastal zones may be inclined to deteriorate due to economic development, particularly coastal exploitation. A series of research works have proven this phenomenon and reported that many wetlands were lost, coastal natural landscapes were destroyed and local eco-environments were greatly threatened by coastal exploitation such as reclamation activities (Wang 2010). These negative effects on the eco-environment have often correspondingly constrained coastal development via particular environmental choices, population migrations, competitions for funds, and policy interventions (Liu et al 2005).

Therefore, the application of scientific evaluation systems from different perspectives to measure relationships at different scales has been attractive to national researchers for a long time. For instance, Nitivattananon and Sirinonil (2019) analyzed the relationships between tourism, coastal areas, the environment, and climate change. They recommended strategies for enhancing the governance of Thailand’s coastal areas. Research by Tomaselli et al (2019) indicated that most respondents in a survey disagreed with the notion of ‘growth at all costs’ in Canada and found that it is necessary to speed up the improvement of the evaluation of
the environment–economy relationship and find a harmonious development pattern. In China, the discussion of an ecological response to coastal exploitation has been particularly popular. For instance, an eco-environment index system was set up to study the ecological status by Nie and Tao (2009) in the Bohai Bay. Related researches indicated that a discussion of the interactive coupling relationship between coastal exploitation and the surrounding eco-environment is bound to become a popular area in ecology study (Kates et al 2001, Clark 2007, Reid et al 2010, Fang et al 2016).

Coupling theory in physics was thus induced into the comprehensive economy–environment evaluation index system, and this has been widely used in the evaluation of the eco-environment (Qiu et al 2017). Comprehensive assessment indicators for regional economic development and environmental pollution subsystems were constructed to calculate the coupling coordination degree for a quantitative spatial assessment (Ma et al 2013). Bi et al (2017) established a coupled coordination degree model to evaluate ecological civilization construction and urbanization in China at the provincial scale. At small scales, Zhang (2014) established a coupling model to evaluate the coupling relationship of the economy–environment system, and it proved that the change in the coupling coordination degree can reveal the relationship between the local development and eco-environment. Both national and multi-scale cases show that there are strong correlations between costal exploitation and the surrounding eco-environment, and monitoring the effects of coastal exploitation on the eco-environment is of great significance and is also essential for sustainable development (Mohanta and Sharma 2017).

With the wide application of remote sensing technology, the data used to assess the eco-environment are more diverse and richer (Esty et al 2005, Revenga 2005). For instance, in Ranchi, India, Landsat data were used to derive the land use and land surface temperature to ascertain the effect of urbanization on the thermal environment; the results are very useful for decision making regarding an environmentally smart city (Mohanta and Sharma 2017). Related studies proved that the application of remote sensing images has made it possible to establish an increasingly mature evaluation system to analyze the relationship between coastal exploitation and the surrounding eco-environment. However, establishing quantitative indices to study multi-temporal ecological responses to coastal exploitation will still be a significant step, and it is necessary to discuss what indices will be selected and which index will make the main contribution to coastal eco-environment, as well as what spatio-temporal conflicting patterns have been present or will appear between coastal exploitation and the ecological environment.

As one of the earliest developed regions, the Pearl River Estuary (PRE) has been a hot spot of coastal exploitation since China’s reform and opening-up (Yang et al 2016). This has resulted in typical adverse effects on the ecological environment of the surrounding urban agglomerations. Eco-environmental issues have gradually become an important topic for coastal management to assess the eco-environmental quality of this region (Yu et al 2019). Recently, the strategy of the Guangdong–Hong Kong–Macao Greater Bay Area will further boost the rate of economic development in PRE (Li and Zhou 2017).

What are the ecological responses of coastal urban agglomerations under this growth? To answer this question, it is important to discover the historic trend of the eco-environment in this region and detect the conflicts between coastal exploitation and ecological preservation. Therefore, in this study, we aimed to discover multi-temporal ecological responses to coastal exploitation in PRE. Principle component analysis (PCA) and panel data analysis (PDA) were, respectively, used to build an ecological index (EI) and composite coastal development index (CCDI). This can quantitatively determine the contribution of each index to the coastal eco-environment. A multi-temporal coupling relationship between coastal exploitation and ecological environment was then evaluated. It is expected that this work can not only provide effective support for ecological preservation but also assist the government in regulating economic development.

2. Materials and method

2.1. Study area and data source

The PRE (figure 1) is situated in the north shelf of the South China Sea (SCS) (Ye et al 2014), which ranges from 112° 58′ E to 114° 03′ E longitude and 21° 52′ N to 22° 46′ N latitude. The PRE has a trumpet-shaped water area with eight river inlets on its bank that face south; the West River (Wong et al 2003), the North River, Dongjiang, the Taji River, creeks and other rivers are located in the Pearl Delta River (PRD) network area. The economy of PRD has continued growing rapidly, and the GDP increased from 8 billion to 799.99 billion USD from China’s Reform and Opening up until 2012 (Huang 2014). The water area of Pearl River covers approximately 7000 km² with a 30 m water depth. The tide in the estuary is a semidiurnal tide, and the average tidal range is 0.86–1.63 m. The flow of waters in the estuary area is affected by the run-off and tide. The flow and material transport change in time and space. The range affected by the tide occupies basically the whole delta in the dry season and represents the intersection of the coastal river network plain with the tidal current (Ai et al 2019).

Landsat thematic mapper (TM)/outgoing long-wave radiation (OLR) images were collected to extract the ecological information. A total of 30 images from 1988 to 2017 were freely downloaded from
https://earthexplorer.usgs.gov/, and Table 1 lists the basic information of the collected images. All of the images were compared with topographic maps for geometric corrections, and the error was never greater than 0.5 pixels. Additionally, these images were atmospherically corrected using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) tool embedded in ENVI, which made the extraction precision of the EI much higher.

2.2. Measuring the ecological conditions
Several indices have been successfully used to describe the ecological status. Among them, four indices, including the fractional vegetation ($F_v$), normalized difference built-up index (NDBI), wetness component of the tasseled cap transformation (Wet), and surface temperature (TS), have been generally adopted (Xu 2013). In this study, these four indices were derived from remote sensing images to represent the greenness, degree of exploitation and development, wetness, and heat conditions, respectively. Commonly, $F_v$ is indirectly calculated by establishing its relationship with the normalized differential vegetation index (NDVI). If using images collected from Landsat 5 TM, the indicators can be calculated using the following equations (Xu 2013):

$$\text{Wet} = 0.2626 + 0.2141 b_1 + 0.0926 b_2 + 0.0656 b_3 + 0.7629 b_4$$

$$F_v = (\text{NDVI} > 0.7) * 1 + (\text{NDVI} < 0.05) * 0 + (\text{NDVI} > 0.05 \text{ and NDVI} < 0.7) * \left(\frac{\text{NDVI} - 0.05}{0.7 - 0.05}\right)$$
\[
\text{NDBI} = \frac{(b_5 - b_7)}{(b_5 + b_7)} \tag{3}
\]
\[
\text{NDVI} = \frac{(b_4 - b_7)}{(b_4 + b_7)} \tag{4}
\]
\[
TS = k_i / \log 10(k_i / B(TS)) + 1 - 273.15 \tag{5}
\]
\[
B(TS) = (b_8 - L_u - \tau * (1 - \varepsilon) * L_d) / (L_u + \varepsilon) \tag{6}
\]
\[
\varepsilon = 0.004 * Fv + 0.986 \tag{7}
\]
where \(b_i (i = 1, 2 \ldots 5, 7)\) is the reflectance value of the corresponding band, \(\text{NDVI}\) is the normalized vegetation index, \(B(TS)\) is the blackbody radiance at the same temperature, \(b_8\) is the radiance of the thermal infrared band, and \(\varepsilon\) represents the surface emissivity. \(k_i = 1321.08\) and \(k_2 = 774.89\) in OLR images, while other values can be found in the header file of the images.

The indispensable atmospheric profile parameters \(\tau\) (the atmospheric transmittance in the infrared band), \(L_u\) (the atmospheric radiation upward), and \(L_d\) (the atmospheric radiation downward) were obtained from \text{http://atmcorr.gsfc.nasa.gov}. Because the atmospheric profile parameters cannot be acquired before 2000, TS was indirectly calculated referring to the study by Xue (2012). Based on the regulations of temperature changes, the correlation between \(Fv\) and TS was established using the results obtained in 2008 and 2017 to calculate TS in 1998 and 1988.

Next, an aggregative indicator EI was established using PCA to assess the ecological conditions as well as their spatiotemporal variations. PCA has proven to be an efficient method for extracting significant information from raw datasets, which will commonly make the data simple and orderly by reducing its dimensions to less than the number of original indicators, depending on the goals of the investigation, contribution of the components, and methods (Friston et al. 1993).

With the derived result of PCA, the EI can be calculated as

\[
EI = 1 - \{ PC_1 + PC_2 + \ldots + PC_n [f(\text{NDVI, Wet, St, NDBSI})]\}, \tag{8}
\]

where \(PC_n\) was defined as the \(n\)th principal component. A total of four principal components will be derived with the selected four ecological indicators.

### 2.3. The coupling relation between the coastal ecology and development level

With the acceleration of the coastal exploitation space, the ecological conditions of the regions along the coastline have changed over the time. The response of the ecological conditions to the development level was quantitatively measured by using the PDA method. PDA is a statistical model that combines cross-section and time series data, which can be regarded as panel data, to offer analysis and interpretation advantages over separate cross-section or time series data analyses (Mátýás and Sevestre 1992). The time fixed effects regression model that satisfied the panel data of coastal cities was chosen in this study and expressed as follows:

\[
EI_t = \beta_0 + \beta_1 X_{it} + \beta_2 X_{2it} + \cdots + \beta_k X_{kit} + \varepsilon_t, \tag{9}
\]

where the \(i (i = 1, 2, 3, \ldots, n)\) indices refer to cross-section realizations, and the \(t (t = 1, 2, 3, \ldots, T)\) indices refer to time series realizations. The individual effect \(\varepsilon_t\) was regarded to be constant in time \((t)\) and specific to the individual cross-sectional unit \((i)\), which was assumed to capture the unobservable and nonmeasurable characteristics that differentiate the individual units (Sherron and Allen 2000).

An initial CCDI, considering its influence on the ecological environment, was then compiled, which was expressed as

\[
\text{CCDI} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k \tag{10}
\]

where \(\beta_k, X_k\) are the same definitions as those in formula (9). To make the values comparative among different years, values of EI and CCDI for each city over all study years were standardized with the max-min method.

Next, a coordination model was induced to quantitatively measure the complex relationship between the development levels and ecological conditions. Coordination, which refers to the benign relationship among the elements within a system (Gao and Gao 2012), has been commonly used to measure the relationships among different factors. To measure whether this presents a benign relationship between the development level and ecological condition, the coupling degree \((C)\), coordination degree \((T)\), and inner coupling degree \((IC)\) were used. Additionally, the indicator of the coupling coordination degree \((ICD)\) was further built to measure the influence and association of coastal development and the ecological environment. These indicators were expressed as follows:

\[
C = (\text{EI}_\text{ND} * \text{CCDI}_\text{ND}) / (|\text{EI}_\text{ND} + \text{CCDI}_\text{ND}|) / 2 \tag{11}
\]
\[
T = \alpha \ast EI + \beta \ast \text{CCDI} \quad \alpha = 0.5, \quad \beta = 0.5 \tag{12}
\]
\[
\text{IC} = EI - \text{CCDI} \tag{13}
\]
Table 2. Partial results obtained from principal component analysis (PCA) for the four factors.

| Indicator | pc1  | pc2  | pc3  | pc4  |
|-----------|------|------|------|------|
| Fv        | 0.966| -0.074| -0.249| 1.15E-07 |
| NDBI      | 0.2807| -0.958| -0.058| 1.05E-17 |
| TS        | 0.9656| 0.07398| 0.2494| 1.152E-07 |
| Wet       | 0.7954| 0.15842| -0.585| 5.5044E-16 |
| eigenvalue| 2.5761| 0.95388| 0.47| 2.65E-14 |
| per_sum   | 64.404| 88.2507| 100| 100 |

Note: PC1, PC2, PC3 and PC4 represents first principal component, second principal component, third principal component and fourth principal component, respectively; per_sum represents the summation contribution of the principal components. Unabridged results derived from PCA were provided in supplementary materials and is available online at stacks.iop.org/ERL/14/124008/mmmedia.

Table 3. The panel data of the ecological index (EI), coastal development factors, and coupling degree (GZ: Guangzhou, DG: Dongguan, SZ: Shenzhen, ZS: Zhongshan, ZH: Zhuhai, AM: Macau peninsula).

| City | Year | EI | DJ | DV | DD | CCDI | EI_ND | CCDI_ND | C | T | IC | ICD |
|------|------|----|----|----|----|------|-------|---------|---|---|----|-----|
| ZH   | 1988 | 0.58| 0.10| 14.74| 0.10| 0.23| 0.52| 1.00| 0.81| 0.40| 0.35| 0.37 |
| GZ   | 1988 | 0.24| 0.00| 3.22| 0.02| 0.03| 0.0| 0.61| 0.47| 0.13| 0.21| 0.17 |
| DG   | 1988 | 0.65| 0.00| 0.41| 0.02| -0.02| 0.03| 0.63| 0.50| 0.65| 0.31| 0.68| 0.46 |
| ZS   | 1988 | 0.27| 0.01| 1.03| 0.04| -0.07| 0.04| 0.42| 0.44| 0.10| 0.34| 0.18 |
| SZ   | 1988 | 0.42| 0.01| 1.37| 0.03| -0.02| 0.28| 0.52| 0.56| 0.20| 0.44| 0.30 |
| AM   | 1988 | 0.33| 0.11| 0.13| 0.18| -0.26| 0.15| 0.04| 0.18| 0.04| 0.60| 0.15 |
| ZH   | 1988 | 0.47| 0.08| 11.17| 0.09| 0.15| 0.36| 0.84| 0.70| 0.31| 0.33| 0.32 |
| GZ   | 1988 | 0.47| 0.00| 1.91| 0.02| 0.01| 0.35| 0.57| 0.61| 0.24| 0.46| 0.33 |
| DG   | 1988 | 0.42| 0.00| 0.86| 0.03| -0.04| 0.28| 0.48| 0.55| 0.19| 0.46| 0.30 |
| ZS   | 1988 | 0.50| 0.00| 0.27| 0.02| -0.04| 0.39| 0.47| 0.58| 0.23| 0.54| 0.35 |
| SZ   | 1988 | 0.45| 0.02| 3.88| 0.04| 0.01| 0.3| 0.58| 0.60| 0.23| 0.44| 0.32 |
| AM   | 1988 | 0.31| 0.24| 0.27| 0.26| -0.29| 0.11| 0.00| 0.00| 0.01| 0.60| 0.09 |
| ZH   | 2008 | 0.89| 0.0| 6.08| 0.06| 0.09| 1| 0.74| 0.34| 0.50| 0.28| 0.49| 0.80| 0.63 |
| DG   | 2008 | 0.40| 0.0| 0.45| 0.01| -0.01| 0.25| 0.54| 0.56| 0.20| 0.41| 0.29 |
| ZS   | 2008 | 0.54| 0.0| 0.28| 0.02| -0.03| 0.47| 0.50| 0.61| 0.26| 0.57| 0.38 |
| SZ   | 2008 | 0.61| 0.0| 1.32| 0.05| -0.07| 0.56| 0.41| 0.59| 0.27| 0.68| 0.42 |
| AM   | 2008 | 0.74| 0.0| 2.33| 0.03| -0.01| 0.77| 0.54| 0.70| 0.36| 0.75| 0.52 |
| ZH   | 2017 | 0.34| 0.03| 4.03| 0.05| 0.00| 0.16| 0.57| 0.54| 0.17| 0.34| 0.24 |
| GZ   | 2017 | 0.49| 0.0| 0.17| 0.00| -0.01| 0.39| 0.54| 0.61| 0.24| 0.50| 0.35 |
| DG   | 2017 | 0.53| 0.0| 0.12| 0.01| -0.02| 0.45| 0.52| 0.62| 0.26| 0.55| 0.38 |
| ZS   | 2017 | 0.46| 0.0| 0.02| 0.01| -0.01| 0.33| 0.53| 0.59| 0.22| 0.47| 0.32 |
| SZ   | 2017 | 0.69| 0.0| 1.77| 0.03| -0.02| 0.69| 0.52| 0.68| 0.34| 0.70| 0.49 |
| AM   | 2017 | 0.34| 0.25| 0.28| 0.27| -0.28| 0.15| 0.00| 0.04| 0.03| 0.62| 0.13 |

3. Results

3.1. Ecological conditions of the coastal cities in the PRE

The four indicators mentioned above were calculated from remote sensing images for 1988, 1998, 2008, and 2017. PCA was further carried out, and table 2 lists the partial results.

Although the contribution percentage of PC1 was not large enough, the results calculated with formula (8) were very similar using PC1 and the sum of PC1 to PC3, respectively. This indicates that Fv was positively related to PC1 while NDBI was negatively related, which conformed to the objective principle of ecological assessment. Therefore, PC1 was chosen to calculate the EI values of each city. The results are shown in figure 2. The higher the value of EI was, the better the
status of the eco-environment was. Five grades were classified including the worst, worse, general, better, and the best.

Figure 2 shows that the overall ecological environment presented the worst situation in 1988, while it improved in 1998 and 2008, and the best situation was in 2017, indicating that the ecological situation in PRE improved generally over recent decades. The ecology in the northeast of Guangzhou was obviously improved in 1998. Especially, most regions—except the west and south of Guangzhou—presented a good ecological condition in 2017. Zhuhai’s eco-environment was the
worst in 2017 compared with other years. The ecological situation of Dongguan has gone through repeated changes, which presented periodical trends such as moving good to bad and then improving. Shenzhen’s ecological situation was better than other regions from 1998 to 2008.

3.2. Relationships between the ecological conditions and the development levels

Regarding urban agglomeration in PRE, the variation in the ecological condition was mainly influenced by coastal exploitation. The natural shoreline was profoundly transformed, and the percentage of natural shorelines had notably decreased (Ai et al 2019). It was proved that development level can be measured well with the three indicators of the development intensity (DI), development velocity (DV), and development density (DD) (Ye et al 2017). Additionally, the degree of coastal exploitation also proved to be greatly related with these indicators (Ai et al 2019). DI reflects the scale and proportion of development and construction in a coastal zone and is expressed by the ratio of the built-up area to the total area. DV reflects whether the coastal development is either fast or slow and is expressed as the ratio of the development area to the development time. DD, which is also known as the development compactness, reflects the plane layout concentration of the coastal development. These factors can be used to quantify the impact of human activities on the ecology (Ai et al 2019).

Therefore, DI, DV, and DD were used to build the CCDI to represent the development conditions of each coastal city in this study. With the derived values of EI in 1988, 1998, 2008, and 2017 at the pixel scale, the panel data (table 3) of the coastal cities were processed by using the time fixed effects regression model with Eviews software.

According to the PDA, the results conform to an accuracy level of 90%. The regression coefficients and test results indicated that DD showed a significant negative correlation with EI, while DI had a strong positive influence during the past 30 years, and DV exhibited a relatively weak impact on ecological conditions. Based on this, the CCDI can be correspondingly expressed as

\[
\text{CCDI} = 1.305617 \times \text{DI} + 0.021878 \times \text{DV} - 2.284813 \times \text{DD}. \tag{15}
\]

To describe the degree and compare the difference of coastal exploitation in different years, we mapped the CCDI_ND of urban agglomeration in PRE based on the derived values of CCDI. Figure 3 shows that this is largest in Zhuhai but smallest in the Macau peninsula and parallel in Guangzhou and Shenzhen except in 1988. The degree and the difference of coastal exploitation among the six cities was inclined to decrease over the past 30 years.

### Table 4. The coupling coordination grade of the urban agglomeration in PRE over 30 years.

| Year | Guangzhou | Shenzhen | Zhuhai | Dongguan | Zhongshan | Macau |
|------|-----------|----------|--------|----------|-----------|-------|
| 1988 | —         | +        | +      | ++       | —         | − −   |
| 1998 | + −       | ++       | +      | ++       | +         | −     |
| 2008 | + −       | ++       | +      | − −       | − −       | −     |
| 2017 | + −       | ++       | +      | ++       | − −       | −     |

Note. ++, harmony; +, transition; −, slight disharmony; − −, disharmony.
relationship had been turned from disharmonious to harmonious overall; however, the Macau Peninsula was still in disharmony. In 2008, the coupling coordination degree improved substantially, and a harmonious coupling relationship was observed in Zhuhai and Shenzhen. The latter was the actual response to the government’s policy adjustment and the effect of building a civilized and ecological Olympic environment.

3.3.2. Inner coupling relationship at the pixel level

The inner coupling coordination degrees were further calculated by formula (14), and the results are shown in figure 4. It can be seen that the inner coupling
coordination degree remained almost stable, except in 1988, but the specific coupling relationships inside the cities were more varied. Only a small part of the complicated coupling relationship between the coastal development and the eco-environment was detected. During the past 30 years, the specific coupling relationships in cities could be divided into three types: most regions presented the development type, the second most common was the ecotype, and the last was the harmony type. The harmony type was generally rare before 2008, but was observed in Dongguan (in 2008) and Guangzhou (in 2017). The latter showed that people gave up rapid development to benefit the environment; they were trying their best to find a balanced way to develop the economy and to achieve a balance between the economy and environmental protection. If the specific coupling relationships within cities could be digitized and the ecological type was assumed to be the largest, then the specific coupling relationships of the cities in terms of the four stages could be expressed as 2008 > 2017 > 1988 > 1998. At the city scale, the specific coupling relationship could be expressed as Zhuhai > Zhongshan > Shenzhen > Dongguan > the Macau Peninsula > Guangzhou. The inner coupling relationship exhibited a notable difference in Dongguan and Shenzhen. These two cities were further selected as the typical sample areas to discuss their coordination patterns and the reasons behind them.

3.4. A case study of Dongguan city and Shenzhen city

Dongguan City was in the development transition period based on the assessment of the coupling coordination degree for the past 30 years (figure 5), but the specific coupling form varied and exhibited periodical differences. The coupling relationship was almost harmonious in 1988, but turned disharmonious in most regions along the coastal line in 1998. The latter showed that the coastal exploitation was excessive and unreasonable, and the environment was getting worse compared to that in 1988; in other words, the coastal development did not

Figure 5. The coupling relationship of Dongguan City over 30 years.
contribute to the protection of the eco-environment, and the disharmonious development came at the expense of other factors. Realizing the severe influence, the local government started to take measures to protect the eco-environment, especially in dealing with pollution, and the coupling pattern was converted from a disharmonious to mitigating state in 2008, even though harmonious coupling was observed in the east of Dongguan. However, the coupling degree became worse in 2017 compared with 2008, which showed that the continuous progress of coastal exploitation in Dongguan resulted in a large impact on regional ecosystem services (Xu 2013).

With regards to Shenzhen, the best coupling relationship was observed in 2008 (figure 6(b)). The coupling coordination degree was changed from transition to harmony. Except for the influence of the economic development, the proposal of the ecological red line policy had a notable achievement in 2005 (Yang et al 2014). A comparison of the relationship results from 1998 to 2008 provided the best verification. Most regions of Shenzhen City exhibited changes in the ecological harmony for the better, but parts of the southwestern coastal area were always located in the region of the development type, which explained why the function of the regime was limited by the coastal construction and development. A green economy strategy was needed to achieve sustainable transformation, which aimed more at an ecological modernization of the global economy than at a transformation into a sustainable economic system (Bruckmeier 2016).

4. Discussion

Using satellite images to develop environmental indicators can provide an important link between science and policy; the results can provide efficient references for decision makers to solve potential environmental problems (De Sherbinin et al 2014). In fact, this has been proven in a series of evaluation methods used in many inland areas. For example, He et al (2018) evaluated the ecological environment and provided an important reference for the relevant department based on GF-1 satellite imagery. The evaluation system established in this study was also proved to be feasible in reflecting the specific impact of human activities on the eco-environment and can promote application in other coastal areas. The analysis of the coupling relationship between the ecological condition and development level can efficiently detect the areas of conflict between development and the eco-environment, which can provide a data basis for delineating ecological red lines. Moreover, the case analysis of Shenzhen indicated that the ecological red line policy played a significant role in promoting the ecological conditions to be gradually improved. There is also some discussion of the effect of the environment and economy for the evolution of a future flexible working model (Yu et al 2019). If the ecological indicators are further refined referring to the method of this study, the research may be improved, and ecological policies will be more favorable. This study can possibly bring potential benefits to balance urban development and the economy.

However, all indicators designed in this study were obtained from approximately a total of 30 remote sensing images. Although collection dates were as close as possible and ranged from October to January of the next year under the cloudless weather condition, atmospheric conditions were variable and the land cover, especially the vegetation cover, may present temporal variation; thus, the images acquired from different days or hours may result in a certain deviation in terms of
ecological indicators, which correspondingly influences the results of the coupling degree. Therefore, removing these influences in image processing is a problem that deserves careful consideration. On the other hand, multifactorial factors can be used to measure the level of coastal development, which is greatly related to the distribution of land use/land cover (Ge et al. 2011, Huang 2014). The relationship between the ecology and coastal exploitation was actually affected by various factors according to ecological theories. A comprehensive coupling relationship assessment should include the ecological assessment of estuarine water quality and be supplemented with a series of indicators to measure the economic benefits considering the particularity of the study area. Inducing these indicators may cause variations in analysis results, especially the coupling degree, which should be further discussed and improved in subsequent research work.

Balancing the coastal exploitation and ecological protection will still be attractive and remains a question worthy of discussion. The green economy strategy was once raised and aimed more at an ecological modernization of the global economy than at a transformation into a sustainable economic system (Bruckmeier 2016). Accurate assessments of the coupled coordination development relationship between ecological civil construction and urbanization could provide practical guidance for China to promote new levels of urbanization and sustainable development (Bi et al. 2017). The coupling analysis is required to be refined at a smaller scale, such as the district scale or even the community scale. In this way, a more detailed analysis of historical ecological responses will be achieved, and the future trend of the ecological response to coastal development can also be predicted, which could be of higher guiding significance for sustainable development.

5. Conclusion

The ecological responses to coastal exploitation in urban agglomerations primarily exhibited a complicated pattern. This study detected the ecological conditions under the coastal exploitation of the urban agglomerations along PRE by constructing the EI, which was calculated by means of PCA based on four indicators: the fractional vegetation (Fv), NDBI, wetness (Wet), and surface temperature (TS). The EI results showed that the ecological situation was worst in 1988, but improved in 1998 and 2008, while the ecological situation in 2017 was the best.

The variations in the ecological conditions were mainly influenced by coastal development. The CCDI was further developed by means of PDA to reflect the development level of each coastal area. A total of three indicators—the development intensity (DI), development velocity (DV), and development density (DD)—were used. The responses of the ecological conditions to the development levels were discussed using the coupling coordination degree between EI and CCDI. The results showed that the coupling coordination degree presented an obvious periodical difference, and the dominant relationship between the coastal development and the eco-environment was capricious. The coordination degree was best in 2008 but was worst in 1988 because of the rapid economic development since 1978. A harmonious region was observed in Zhuhai, and due to the demarcation of the ecological red line policy in Shenzhen, its coordination degree became harmonious; other cities were in the transitional development phase except Guangzhou and the Macao Peninsula.

This study indicated that the relationship between coastal development and the eco-environment can reflect the disparity of the development patterns well among different cities in PRE. The results can provide basic data and referable information for coastal management and ecological protection.

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Data availability statement

Any data that support the findings of this study are included within the article.

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