A landscape approach for wetland change detection (1979-2009) in the Pearl River Estuary

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Abstract

Based on landscape data produced from integrated Landsat MSS/TM/ETM+ images and spatial metrics, this paper presented a synthesis of wetland landscape changes in the Pearl River estuary from 1979 to 2009, and explored the spatio-temporal characteristics of wetland change. The classified images were used to generate maps of wetland degradation, and spatial metrics were calculated and analyzed across class level every five years. Results indicated that (1) the main wetland types in study area were shallow marine water and irrigated land. The total area of wetlands in the study region decreased by a quarter (4598km²), and the area of irrigated wetlands decreased more than that of other wetland types. (2) Artificial wetland had higher fragmentation than natural wetland, coming from the increasing patch density, and a decreasing of edge density. (3) Most of natural wetlands changed to artificial wetland, and artificial wetland changed to urban land and other land. More than 50% of urban land came from changed wetland. Urban development, as a main reason, caused the reverse succession of wetland landscape in the Pearl River Estuary.

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Keywords: Remote sensing; Wetland change; Spatial metrics; Urban development; the Pearl River Estuary

1. Introduction

Estuarine wetland is an important kind of wetland and natural landscape with abundant natural resources and unique environmental effect [1, 2]. Human activities have changed the environment and caused a series of wetland changes, prolonging dry seasons, altering groundwater levels, and decreasing connectivity and habitat heterogeneity [3, 4]. Along with the rapid economic development in estuarine area, the damage caused by the interference of human activities is becoming more and more obvious [5]. Large areas of wetland are disappearing, and those remaining areas become vulnerable under anthropogenic impacts from industry, agriculture, aquaculture, urban development and domestic waste [6-8]. The wetland area greatly decreased in the past 50 years due to wetland...
reclamation, population pressure, water diversion, dam construction, pollution, resource over-excavation, biological invasion, desertification, climate change, and the misleading policies [5,9]. Therefore, the conflict between protection and exploitation is getting more and more irreconcilable [10].

At the same time advancements in Earth Observation coupled with geographical information analyses have provided opportunities for identifying, describing and mapping the distribution of wetlands at a range of scales from local to global [11]. A variety of remote sensing change detection methodologies have been developed and evaluated over the past twenty years [12,13]. Satellite imagery has been well utilized to measure qualitative and quantitative terrestrial land-cover changes [14]. Landsat MSS, TM, and SPOT are common data types for wetland classification and its temporal-spatial dynamic change [15-17]. Therefore, the study of qualitative and quantitative changes in wetland patterns and the reasons behind has become hotspot in wetland studies in recent years [7,16]. Qualitative changes in wetland landscapes can be attributed to either natural or human factors [18,19]. However, in many instances baseline wetland inventory is incomplete, and what has been collected is often inconsistent and/or is not readily accessible to those who need to use it [20]. The Ramsar Convention on Wetlands has long recognized the need to study development of artificial wetland [21-23]. Many researches of wetland focus on the status and characteristics of natural wetland [24-26]. So far, few researches have been carried out in estuarine area to study each type of wetland pattern and change, including artificial wetlands. The purpose of this paper is to reveals the qualitative and quantitative process of different type of wetland changes during the past thirty decades so as to find out the relations between landscape patterns and socio-economic activities. While a case studying both natural and artificial wetland, is provided by adopting remote sensing data, which benefits wetland resource management and monitoring.

2. Study site

The studied area, Pearl River Estuary, is located in the south-east coast of China (111°58’E to 114°38’E, 21°34’N to 23°56’N), covering an area of 31831 km² (Fig. 1). In the history, the studied area was called River Network Area, and rivers flowed communication with each other and formed a large number of the estuarine wetlands. The Pearl River is 2214 km long and has a catchment area of 453,690 km². It is the largest river in southern China, and has a

Fig. 1 Location of the study area
mean annual runoff of 326 billion m$^3$. The river is discharged to the South China Sea through Pearl River estuary with eight river branches, resulting in a complicated spatial distribution of natural and artificial wetlands [27].

The area is comparatively dense in population, with an average of 1209 persons /km$^2$ and its main industry is agriculture and industry. There are seven major cities in the delta, including Guangzhou, Foshan, Zhongshan, Dongguan, Jiangmen, Shenzhen, and Zhuhai. Over the last three decades, the whole estuary area has experienced rapid industrialization and urbanization, which has emerged as the prominent commercial, industrial and shipping centre. While there are national natural reserves, industrial areas, estuarine wetland and dense population in studied area. Detecting different types of wetland change in estuarine areas may help decision-makers to protect wetland in the areas with fast economic development.

3. Methods

3.1. Data source

Landsat data were searched for that represented the best match in time frame, and provided multispectral data from the early 1970s to the present. If possible, data were close to the same year of image acquisition in order to reduce seasonal effects. Data and information on wetland were extracted from Landsat Multispectral Scanner (MSS) images (1979), Landsat Thematic Mapper (TM) images (1986, 1990, 1995, 2005, 2009), Landsat Enhnace Thematic Mapper plus (ETM+) (2000) images. As the intent of this study was to reveal the general trends of spatial change of wetland pattern, the difference in spatial resolution between MSS and TM/ETM+ images was not a concern. Fifty-six scenes of Landsat images were acquired and processed, which were obtained from the China Remote Sensing Satellite Ground Station and the Global Land Cover Facility (GLCF) at the University of Maryland. These images were georeferenced to Universal Transverse Mercator projection and resampled to 30 m spatial resolution.

3.2. Methods

3.2.1 Wetland classification

Remote sensing data processing, including preprocessing and false color composite, was carried out by means of the software package of ENVI 4.4 (the Environment for Visualizing Images). The other processes using the masked images for wetland and the other land-use types were performed by software eCognition 5.0. The spatial distribution of the dominant wetland types across the site was classified from Landsat TM data using a decision tree classifier and a series of binary decision rules. Decision Tree classifiers allowed multistage classifications to be performed, recursively partitioning the input data set into increasingly homogenous subsets. A particular advantage of this approach was that data sets with different spatial resolutions, as well as ancillary data sets could be used together during the classification process. Global Positioning System (GPS) was used to record locations of field transects and points of interest, and classification results of land use were tested and verified.

The land use patterns in Pearl River Estuary were firstly divided into natural wetland, artificial wetland, urban land and other land. According to the Ramsar Convention on wetland conceptions [20] and local conditions, natural wetlands were then further divided into four types: Shallow marine water (NW1), River/stream/creek (NW2), Intertidal mud/sand (NW3), and Mangrove wetland (NW4); and artificial wetlands were classified into: Ponds/reservoir (AW1), Aquaculture pond (AW2) and Irrigated land (AW3). In view of the confusion over the definition of NW1, the scope of this study is limited to intertidal and shallow (<6 m at low tide) subtidal softsediment areas, with particular reference to estuarine wetlands, where urbanization pressure is usually most intense.

3.2.2 Spatial metrics analysis

FRAGSTATS is a spatial-pattern analysis program used to quantify the real extent and spatial configuration of patches within a landscape, and it is incumbent upon the user to establish a sound basis for defining and scaling the landscape (including the extent and grain of the landscape) and the scheme upon which patches are classified and delineated. Using FRAGSTATS (version 3.3) [28], five class-level metrics (Table 1) were computed in this study, which could serve as useful and essential tools for describing the characteristics of wetland pattern and their changes.
The metric of PLAND provided a general representation of landscape composition, specifically how much of the landscape comprised a particular patch type in the study area. PD frequently served as a general index of the spatial heterogeneity of the some landscape mosaic. ED standardized edge length to per unit area basis and served as a fundamental index of landscape shape. Both PD and ED provided fundamental aspects of wetland pattern that facilitated comparisons among landscapes of varying size. The metrics of SHAPE_AM were used to descript regularity and complexity of patch shape. The metrics of FRAC_AM were calculated to quantify the wetland configuration in terms of the complexity of patch shape.

3.2.3 Wetland change analysis

Two wetland change indexes, Wetland Change Speed (WCS) (Eq. (1)) and Wetland Change Intensity (WCI) (Eq. (2)), were used to compare the speed of wetland degradation or development at different time periods, and it could compare of wetland changes at different time periods.

\[
WCS_{i,t-\Delta t} = \left( \frac{WA_{i,t} - WA_{i,t-\Delta t}}{n} \right) \times 100
\]

\[
WCI_{i,t-\Delta t} = \left( \frac{WA_{i,t} - WA_{i,t-\Delta t}}{WA_{i,t}} \right) \times 100
\]

In Eq. (1) and (2), \(WCS_{i,t-\Delta t}\) represented an index of wetland change speed for spatial unit \(i\) during the time span \(t\) and \(t-\Delta t\); \(WCI_{i,t-\Delta t}\) represented an index of wetland change intensity for spatial unit \(i\) during the time span \(t\) and \(t-\Delta t\); wetland areas were normally presented in the form of grids, and calculated by ArcGIS 9.2.

Table 1 Spatial metrics selected in this study [28].

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Abbreviation</th>
<th>Calculating formula</th>
<th>Range&amp;Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of landscape</td>
<td>PLAND</td>
<td>(\sum \frac{a_{ij}}{A} \times 100)</td>
<td>0&lt;PLAND≤100; %</td>
</tr>
<tr>
<td>Patch density</td>
<td>PD</td>
<td>(\frac{n}{\sum a_{ij} \times 10000} \times 100)</td>
<td>PD&gt;0; number/km²</td>
</tr>
<tr>
<td>Edge density</td>
<td>ED</td>
<td>(\frac{\sum e_{ij}}{\sum a_{ij} \times 10000})</td>
<td>ED≥0; m/ha</td>
</tr>
<tr>
<td>Area weighted mean shape index</td>
<td>SHAPE_AM</td>
<td>(\sum \left( \frac{p_{ij}}{\min p_{ij}} \left( \frac{a_{ij}}{\sum a_{ij}} \right) \right))</td>
<td>1≤SHAPE_AM≤2; none</td>
</tr>
<tr>
<td>Area weighted mean patch fractal dimension</td>
<td>FRAC_AM</td>
<td>(\sum \left( \frac{2 \ln(0.25 p_{ij})}{\ln a_{ij}} \left( \frac{a_{ij}}{\sum a_{ij}} \right) \right))</td>
<td>1≤FRAC_AM≤2, none</td>
</tr>
</tbody>
</table>

Note: \(a_{ij}\) = area of patch \(j\) of land use type \(i\) (m²); \(p_{ij}\) = perimeter (m) of patch \(ij\); \(e_{ij}\) = length of patch \(ij\) (m); \(n\) = the number of patches of land use type \(i\) (class); \(m\) = number of patch types (class); \(A\) = total landscape area (m²); \(\min p_{ij}\) = minimum perimeter of patch \(ij\) in terms of number of cell surfaces.
Wetland change detection and monitoring involved the use of multi-date images to evaluate differences in wetland cover [14, 29], and the classification and post-comparison method were applied to analyze the changing condition of wetland. In post-comparison change detection two images from different dates were independently classified and labeled. The area of change was then extracted through the comparison of the classification results by spatial analysis module in Arcgis 9.2. The landscape maps were converted in vector format into gridded maps. The evolution of the gridded maps was chosen as 30 m to ensure that the smallest patch could be considered and computation efficiency was high.

4. Results

4.1. Area statistics

The Kappa parameter of the seven images on different dates was computed in the process of accuracy assessment, and the results are 0.75, 0.74, 0.75, 0.74, 0.75, 0.74, and 0.85, respectively. Based on the accuracy assessment, the results of the above classifications were presented by seven remote sensing images. The wetland area accounted for 53.36% (16981 km²) of the total area in 1979, and accounted for 38.91% (12383 km²) of the study area in 2009. So a decreasing trend of the total wetland area was shown from 1979 to 2009 in the Pearl River Estuary. Natural wetland (NW) accounted for one-third of the total wetland area, and mainly distributed in the seacoast; Artificial Wetland (AW) mainly located in the inland, and accounted for two-third of the total wetland area. The main wetland types were shallow marine water (NW1) and irrigated land (AW3), accounting for 13.48% and 33.95% of the total area in 1979, and 11.05% and 22.06% of the total area in 2009.

The period of 1979–2009 witnessed rapid massive wetland changes in the region according to WSC and WSI (Table 2). Areas of NW1, NW2, NW3, AW2, and AW3 showed a decreasing trend over thirty years, with WSC of -25.77 km²/a, -2.00 km²/a, -2.98 km²/a, -1.18 km²/a and -126.13 km²/a. However, NW4 and AW1 showed an increasing trend in total thirty year, with WSC of 0.22 km²/a and 4.53 km²/a. To every five years, WSC of NW1, NW2 and AW3 always shrunk with a small rate.

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<tbody>
<tr>
<td>NW1</td>
<td>-27.00</td>
<td>-0.63</td>
<td>-36.25</td>
<td>-0.87</td>
<td>-75.89</td>
<td>-1.91</td>
<td>-1.75</td>
</tr>
<tr>
<td>NW2</td>
<td>-7.56</td>
<td>-0.73</td>
<td>-2.25</td>
<td>-0.22</td>
<td>-4.25</td>
<td>-0.42</td>
<td>-3.87</td>
</tr>
<tr>
<td>NW3</td>
<td>-17.45</td>
<td>-10.02</td>
<td>3.68</td>
<td>4.24</td>
<td>39.64</td>
<td>37.66</td>
<td>-33.00</td>
</tr>
<tr>
<td>NW4</td>
<td>-0.08</td>
<td>-3.44</td>
<td>0.09</td>
<td>5.18</td>
<td>0.15</td>
<td>6.58</td>
<td>0.41</td>
</tr>
<tr>
<td>AW1</td>
<td>0.81</td>
<td>0.28</td>
<td>-20.33</td>
<td>-6.95</td>
<td>24.90</td>
<td>13.06</td>
<td>46.09</td>
</tr>
<tr>
<td>AW2</td>
<td>-49.27</td>
<td>-12.80</td>
<td>13.95</td>
<td>10.06</td>
<td>12.73</td>
<td>6.11</td>
<td>13.83</td>
</tr>
<tr>
<td>AW3</td>
<td>-199.45</td>
<td>-1.85</td>
<td>-211.92</td>
<td>-2.47</td>
<td>-100.87</td>
<td>-1.05</td>
<td>-60.58</td>
</tr>
</tbody>
</table>

**WCS**: wetland change speed, km²; **WCI**: wetland change intensity, %
- - : wetland decreasing, and no relationship with number; + : wetland increasing, and no relationship with number

4.2. Change maps

The change maps every five years (Fig 2-7) showed some land use changed to the wetland and the wetland changed to other land use. NW4 was not shown on the figures, because its area accounted for less than 0.02% of study area.

NW3 had a close and direct relationship with NW1, and a large number of NW1 was changed to NW3 at first. Then, NW3 was mainly changed to AW2 and AW3. Most shallow marine was enclosed tideland for cultivation, and
was changed as intertidal mud, paddy fields or fish pond, and the reclamation activity was intense in the first fifteen years. As a result, more than 70% of NW3 was changed during thirty years, and less than 30% of NW3 still kept its old location. NW2 had a similar transferring way with NW1, and NW2 gradually decreased and was changed to AW3 and UL1 in thirty years, with its occurring along Pearl River. The majority of NW2 was changed to AW3, and added up to 680 km² of within six periods; the minority of NW2 was changed to UL1, and added up to 257 km² of within six periods.

Fig. 2 Spatial changes of NW1 from 1979 to 2009
Fig. 3 Spatial changes of NW2 from 1979 to 2009

Fig. 4 Spatial changes of NW3 from 1979 to 2009
Fig. 5 Spatial changes of AW1 from 1979 to 2009

Fig. 6 Spatial changes of AW2 from 1979 to 2009
Fig. 7 Spatial changes of AW3 from 1979 to 2009
The majority of AW1 was changed to AW3, and the minority was changed to OL1 and UL1; the majority of AW2 was changed to AW3, and the minority was changed to OL3 and UL1; the majority of AW3 was changed to OL3 and UL1, and the minority was changed to OL1. In general, four types of natural wetlands mainly were changed to AW2 and AW3, and AW1 and AW2 were mainly changed to AW3, and finally AW3 was changed to UL and OL. More than 50% of urban land came from changed wetlands during 1979-1986, 1986-1990 and 1995-2000. Generally speaking, four types of natural wetland were mainly changed to AW2 and AW3, and then AW1 and AW2 were mainly changed to AW3, and finally AW3 changed to UL and OL. Most of natural wetland changed into artificial wetland, and then artificial wetland changed into UL and OL.

4.3. Spatial metrics

The synoptic analysis of selected metrics also provided the general representation of wetland patterns (Fig. 8). Landscape metrics helped in quantification of landscape structures and conveys the extent of changes and their effects. In the present study, landscape metrics have been calculated only at class level, because the main objective was to study the changes of wetland classes. Area/density metrics were used to study the extent of fragmentation in the area.

All types of PD_AW showed that the density of patches was increasing, though PD_NW had no unified order. Most metric values of PD_NW were less than those of PD_AW. These represented higher fragmentation of the artificial wetlands, coming from the increasing patches of AW in thirty years. The metric values of ED_AW exhibited a decreasing trend from 1979 to 2009. Thus, the patches of AW were becoming more vulnerable to undesirable changes due to increased edge effects.

The shape indices showed patch shape complexity, and the values of SHAPE_AM_NW2 were far more than those of other types, and decreased from 1979 to 2009. The metric values of FRAC_AM_NW2 exhibited a decreasing trend from 1979 to 2009, and values of other wetland type were less than 1.30. These indicated that patch shape of NW2 became simpler and regular, and the tortuosity of river was losing, and configurations of other wetland types were no complexity.

4.4. Wetland changes and urban land

All change area from wetland to urban land was added and shown on Table 3. More than 50% of urban land came from changed wetland during 1979-1986, 1986-1990 and 1995-2000. These showed change and change of wetland had the close relationship with urban land. The result indicates a strong spatial dependency of wetland changes on urban land.

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<tbody>
<tr>
<td>NW</td>
<td>AW</td>
<td>245.22</td>
<td>245.18</td>
<td>241.1</td>
<td>244.4</td>
<td>105.7</td>
<td>99.86</td>
</tr>
<tr>
<td></td>
<td>UL</td>
<td>74.71</td>
<td>162.2</td>
<td>105.38</td>
<td>81.5</td>
<td>41.86</td>
<td>53.3</td>
</tr>
<tr>
<td>AW</td>
<td>UL</td>
<td>752.6</td>
<td>899.22</td>
<td>1373.85</td>
<td>2338.54</td>
<td>1874.79</td>
<td>1002.24</td>
</tr>
<tr>
<td>NW+AW</td>
<td>UL</td>
<td>827.31</td>
<td>1061.42</td>
<td>1479.23</td>
<td>2420.04</td>
<td>1916.65</td>
<td>1055.54</td>
</tr>
<tr>
<td>PU (%)</td>
<td></td>
<td>70.40</td>
<td>54.81</td>
<td>45.45</td>
<td>52.27</td>
<td>37.85</td>
<td>17.42</td>
</tr>
</tbody>
</table>

PU: percent of wetland change area accounting for area of urban land

5. Discussion

5.1. Change trend of regional wetland
In the research, the changes of wetland area are studied by remote sensing data in order to analyze temporal and spatial changes, and there was a significant decrease in the amounts of natural and artificial wetlands in thirty years. Land use change has taken place in response to economic development [30]. Compared with other research of estuaries area [1, 4, 31, 32], the Pearl River estuary is characterized by high urbanization and dense population. Extensive urban expansion occurred between 1979 and 2009 in the study area, driven by human population increase,
industrial development, and residential spread. Urban land accounted for less than 2% of total area in 1979 and more than 18% of total area in 2009. The population number of 2009 was also four times of 1979 (Fig. 9 & 10).

Fig. 9 Changes of urban land (PLAND_U) in Pearl River Estuary     Fig. 10 Changes of population in Pearl River Estuary from 1979 to 2009

Occupying much wetland for rapid urbanization and economic development in the study area poses negative effect on the wetland protection. Estuaries wetlands are especially vulnerable to pressures from urban expansion, and their areas are decreased greatly. Aforementioned results were similar to the previous studies [7, 8, 19, 33] in urban wetland areas. Urban development caused the reverse succession of wetland landscape.

5.2. Natural wetland and urbanization

In the Pearl estuary, natural wetland landscape only accounted for one-third of the total wetland landscape, and overall trends of NW1, NW2 and NW3 were decreased in different scales. Under the pressure of urbanization, people often continue to exploit and utilize of natural wetland, such as reclamation to intertidal zone, construction of river channel and mass destruction to coastal mangroves [30, 34]. A major change is that natural wetland has been converted into artificial wetland or other land use for better revenue under the influences of market mechanism, and it would be very hard to be restored.

As the main way of obtaining extra land to coastal cities, internal migrations and external reclamations of NW3 went extraordinarily actively from 1979 to 2000 [20, 35], and only ten percent of the old NW3 was maintained at the original location. Since 2000, people have strengthened the consciousness of wetland protection, especially mangrove protection, so the reclamation activities were restrained and areas of NW3 begun to increase. While the destruction of mangrove wetland was banned and a series of nature reserves for mangrove wetland were established, the area of NW4 was added ($WCI>0$).

5.3. Artificial wetland and urbanization

Artificial wetland landscape accounted for two-thirds of the total wetland landscape. Artificial wetland plays an important role in the process of wetland degradation under the pressure of urbanization, and it would be the intermediate stage when natural wetland changed to urban wetland. Urban expanding and policy guidance determine the development trend of artificial wetland [8].

The main agricultural area is paddy field in study area, so the more artificial wetland landscape is AW3. AW in urban areas is often relatively small and linear in shape, and is thus not afforded the luxury of a core interior area spared from frequent disturbance. So landscape metrics of AW are especially higher fragmentation and vulnerable to pressures from urban expansion, and their area are decreased greatly.
6. Conclusions

The Pearl River estuary, a special and complicated wetland system, is closely related to the human activity which could play both a positive and a negative role in wetland evolution. This study only investigated characteristics of estuarine wetland, and analyzed the relationship between wetland change and urban land. Moreover, there exist many natural factors causing wetland transitions except artificial factors, such sea-level rising, climate change, human activities, and hydrologic factor etc. While further work is required to assess different influence of natural and artificial factors on estuarine wetlands, and to better understand evolutive form of estuarine wetlands.

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References


