Application of Markov model in wetland change dynamics in Tianjin Coastal Area, China

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Abstract

Wetland ecosystem is one of the most productive and most diverse ecosystems, which provides various important habitats for wildlife. However, the rapid urbanization caused wetland degradation. Thus, researchers all over the world pay attention to study on wetland dynamic changes in order to analyze the causes of wetland degradation. Tianjin Coastal Area is the center for the Bohai Bay. The government has prioritized integrating all the cities in the Bohai Bay Rim and fostering economic development in this area. Tianjin has various types of wetlands including coastal wetlands (estuarine waters, marshes, et al.), inland wetlands (rivers, lakes, et al.), and artificial wetlands (ponds, salt exploitation sites, et al.) according to classification in Ramsar Convention. The wetlands in Tianjin Coastal Area have high biodiversity and provide various ecological functions and values. With the development of this area, human disturbance have been increasing. The research on wetland change dynamics is the basic for wetland ecosystem protection and restoration.

This area is the site of an intense land-use conflict among urbanization and natural protection. Large scale spatial and temporal land-use data were used to investigate the dynamics of wetland change in this area. Markov software was applied based on the support of GIS and RS from 1979 to 2008. The Markov chain was used as a stochastic model to make quantitative comparisons of the wetland changes between discrete time periods extending from 1979 to 2008. The wetland dynamic changes have been predicted according the Markov chain model in 2015, 2020 and 2050. Three main conclusions have been drawn from the Markov model about the wetland change dynamics in this area. (1) A continuing 'exchange' of wetland area occurs between artificial wetlands and natural wetlands categories that has little effects on the net amount of wetland but could undermine the long-term ecological function of remaining natural wetland in this area. (2) The human induced factors such as pollution and construction were the predominant causes for wetland changes. (3) The natural wetlands will be in great decline in 2020 and 2050 without enhancing wetland protection policy and increasing restoration technology. It is hoped that the dynamic model will

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serve as a laboratory to study the different features of the wetland problem in coastal area and to analyses different policy alternatives with an integrated, systemic approach.

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Keywords: Tianjin Coastal Area; Markov model; wetland change; prediction

1. Introduction

Wetland is one of the most important ecosystems on earth and is described as ‘kidneys of the earth’, because it could provide many ecological functions such as cleaning the atmosphere, improving water quality, adjusting the floodwaters, recharging groundwater aquifers, protecting shorelines, providing various important habitats for wildlife, especially for threatened and endangered species [1]. Wetland ecosystem is one the most productive and most diverse ecosystems. However, in the last few decades, climate change and human activity have resulted in a rapid reduction in wetlands area and degradation in wetland quality in Bohai Bay. Since the Government of China had made important strategic planning to push forward the development of this area and made it included in the ‘National Eleventh Plan’. The government has prioritized integrating all the cities in the Bohai Bay Rim and fostering economic development in this area. Thus, the research on wetlands especially wetlands dynamic changes and the future change trends are important for understanding of wetland conservation and sustainable development [2, 3].

Remote sensing (RS) and geographic information systems (GIS) are essential tools for monitoring wetland distribution area, and spatial and temporal analysis of wetland dynamic change [4, 5]. The common application of RS and GIS technology is for wetland inventory, classification, and mapping. In recent decades, many studies focused on assessing wetland distribution patterns and dynamic changes [6], but fewer studies have been conducted to simulate wetland change trends. A Markov chain can be one of most convenient and accurate models for wetland change trends simulation. The Markov chain is mathematically and conceptually the most straightforward succession model presently in use [7]. Since scholars [8] had developed methods for estimating the transitive matrix from observing the states of a system through time, the methods have been widely used [9]. This has led to its application to vegetation restoration [10, 11], and land changes analysis [12, 13]. In addition, other scholar [14-16] integrated GIS, RS and the Markov chain model to simulate the land use changes in continuous time periods and discrete time periods.

From the reasons mentioned above, this paper integrates the RS, GIS, image classification and Markov chain to assess wetland dynamic changes in the past 30 years and forecast change trends in the future. The objective of this paper is to address three questions: (1) How the wetland categories changed during the past 30 years in TCA? (2) What factors caused the changes? (3) What will be the change trends for the wetland in TCA in the future? It is hoped that the dynamic model simulation will be conductive to better understand the wetland problems in coastal area and to analyses different policy alternatives with an integrated, systemic approach.

2. Study site

Tianjin Coastal Area (TCA) (38°40′N-39°00′N and 117°20′E-118°00′E) is located in the Northeastern China, and bounded to the east by the Bohai Bay (Fig.1). It is a coastal zone with coastal area of approximately 2,270 km² and near shore area of 3,000 km². Climatic conditions are characterized by a temperate, continental monsoon climate, distinct seasons, and contemporary conditions for rain and heat.
The annual average air temperature is 12.6°C, and total evaporation is about 1750–1840 mm, total precipitation is about 500–600 mm, most of which falls between June and August [17]. Tianjin is one of China’s developed cities and the center of Northern China. TCA is known as the emerging economic center of Northern China as one of the most important parts of ‘Bohai Economic Rim’ and has maintained rapid economic growth in recent years.

3. Methods

3.1. Data source

The data were collected based on two kinds of sources. Firstly, remote sensing image data were 1979, 1993, 1998, 2001, 2004 and 2008 from Tianjin Meteorological Bureau. Secondly, assistant data were also used, such as topographic maps (1:50 000 scale), Tianjin vegetation distribution maps, Tianjin soil type maps, and other social and economic statistical data.

3.2. Data processing and land categorization

Data collected for this study includes aerial photographs at 1:50 000 scale taken in 1979, 1993, 1998, 2001, 2004 and 2008. Geo-rectification, and mosaic of these images were conducted by using ERDAS image processing software and 1:50 000 scale topographic maps. The TM image has a resolution of 30 m, which could satisfy the precision required for mapping at a scale of 1:50 000. In this study, topographic maps, remote sensing image data and other supporting maps were analyzed by using field survey and GIS technology. The framework of flow diagram for data processing is shown as Figure 2. After the analysis, the wetland in TCA was categorized into five types prior to wetland-change analysis. For the study area, five wetland types were identified, including artificial wetlands, natural river wetlands, natural lake wetlands, natural coastal wetlands, and natural marshes (Table 3). Artificial wetlands included paddyfield, irrigation ditch, artificial reservoir, saline land, and artificial pond. Coastal wetland included intertidal zone wetland, subtidal wetland, tide pools, and tidal zone wetland. Natural river wetlands included permanent river, and floodplains. Natural lake wetlands included natural ponds, natural lakes, puddles, pools. Natural marshes included estuarine marsh, tidal marsh, shallow water with grasses, rushes, reeds, typhas, sedges, and other herbaceous plants.
Fig. 2. Framework of wetland change analysis

3.3. Markov chains

The Markov chain model was applied to forecast the wetland change in the future. Markov models can be used to describe the processes of wetland dynamic changes [18]. A Markov chain model could be described as a set of states, $X = \{X_0, X_1, X_2, \ldots, X_n\}$. The process starts from one of the states and moves successively to another. If it is currently in state $X_i$, then it moves to state $X_j$ at the next step with a probability denoted by transition probabilities $p_{ij}$. State $X_{i+1}$ in the system could be determined by former stage $X_i$ in the Markov chain. Their relationship could be getting in a general formula (1):

$$X_{i+1} = PX_i$$  \hspace{1cm} (1)

$X_i$ is state vector at stage $i$ in formula (1). $P_{ij}$ is designed in sequence to give the transition probability matrix $P$, which could be calculated by the formula (2).

$$P^n_{ij} = \begin{bmatrix}
  p_{11} & p_{12} & \cdots & p_{1n} \\
  p_{21} & p_{22} & \cdots & p_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  p_{n1} & p_{n2} & \cdots & p_{nn}
\end{bmatrix}$$  \hspace{1cm} (2)

Where, $n$ is the number of wetland type, $P_{ij}$ is the probability that change from type $i$ to type $j$. 
In accordance with the Markov stochastic process theory, we calculated the state transition probabilities (nth Markov state) by using the probability matrix from the initial state to the nth state. The nth state Markov transition probability was calculated as formula (3):

\[
P_{ij}^n = \sum_{k=0}^{m-1} P_{ik}P_{kj}^{(n-1)}
\]

(3)

where \( m \) is the number of columns or rows in the transition probability matrix. The nth transition probability matrix could be calculated by the initial transition probability matrix.

An initial probability distribution, which is defined as \( Y(0) \) is conducted by specifying a specific state as the starting state. Based on the initial matrix \( Y(0) \) and the transition probability of the nth stage \( P(n) \), wetland distribution area in Tianjin in the future can be calculated by using a Markov simulation. The Markov simulation model \( Y(n) \) is as follows:

\[
Y(n) = Y(n-1) \times P(1) = Y(0) \times P(n)
\]

(4)

4. Results

4.1. Dynamics changes for TCA wetlands from 1979 to 2009

The dynamics changes for TCA wetlands from 1979 to 2009 based on remote sensing image interpretation and overlay analysis were shown in Table 1.
The total area of wetlands in study area in 1979 was 2069.31 km\(^2\). The wetland area increased up to 2270.53 km\(^2\) in 1993, which is 1.09 times bigger than that in 1979. However, the total wetland area shows fluctuated trends and slightly changes during the 30 years. Since the area of artificial wetlands had increased sharply and artificial wetlands had big proportion of the total wetland area (Figure3). The proportion of artificial wetland had increased by an average annual rate of 3.02%. However, the other four types of wetlands decreased by 0.21% (river wetlands), 0.61% (lake wetlands), 1.63 (coastal wetlands), 0.57 (marshes). The coastal wetlands changed slightly from 1979 to 2001, but had decreased sharply after 2001. It is mainly due to the result of artificial reclamation based on our field survey. The artificial wetlands show dramatic decrease from 1993 to 1998, which is because that the drainage of paddy fields changed into upland. The artificial wetlands had a great increase rate from 2001 to 2004, since natural wetlands changing into artificial wetlands. The data of lake wetlands changes indicate that there was striking decrease from 2004 to 2008, which is because the biggest natural lagoon wetlands had development and destroyed in that period. The wetlands experienced serious fragmentation and reduced rapidly.

4.2. Prediction of dynamics of wetland change in 2020 and 2050

4.2.1 The initial state

Since the human activity disturbances in all periods are different, which lead to different transition probability. Therefore, we selected wetland changes from 2001 to 2009, which has consistent human and natural impact factors for forecasting wetland change. The initial state transition probability matrix from 2004 to 2008 (n=1) was calculated by wetland proportion of initial state (formula 5) and the results were shown in Table 2.

\[
Y(0) = \begin{bmatrix}
32.420 \\
4.403 \\
4.152 \\
24.300 \\
0.030 \\
34.400 \\
\end{bmatrix}
= \begin{bmatrix}
\text{Coastal wetlands} \\
\text{Lake wetlands} \\
\text{River wetlands} \\
\text{Artificial wetlands} \\
\text{Marshes} \\
\text{Upland} \\
\end{bmatrix}
\]  \hspace{1cm} (5)

Table 2. Initial state transition probability matrix from 2004 to 2008 (unit: km\(^2\)).
4.2.2 Forecast wetland change trends by simulation

The future wetlands change trends were calculated by using formula (4), formula (5) and Table 2. Specifically, we simulated the wetlands change trends in Tianjin by using the Markov model (Table 3). The results indicated that the wetlands area of coastal wetlands, lake wetlands, river wetlands, artificial wetlands, marshes and uplands will have different trends, but the total wetlands area show decreasing trends. The lake wetlands and marshes will be almost disappeared; the area of coastal wetlands will be decreased. However, the area of uplands will be increased, which will be as big as 1.8 times in 2050 as that in 2004. The artificial wetlands will be fluctuated slightly during these years.

Table 3. Percentage of wetland types predicted by using Markov chains (unit: %).

<table>
<thead>
<tr>
<th>Categories</th>
<th>2004</th>
<th>2015</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal wetlands</td>
<td>32.42</td>
<td>24.53</td>
<td>21.693</td>
<td>10.898</td>
</tr>
<tr>
<td>Lake wetlands</td>
<td>4.403</td>
<td>0.3653</td>
<td>0.132</td>
<td>0.03</td>
</tr>
<tr>
<td>River wetlands</td>
<td>4.152</td>
<td>4.865</td>
<td>5.303</td>
<td>7.544</td>
</tr>
<tr>
<td>Artificial wetlands</td>
<td>24.3</td>
<td>21.033</td>
<td>20.343</td>
<td>18.906</td>
</tr>
<tr>
<td>Marshes</td>
<td>0.03</td>
<td>0.8438</td>
<td>0.382</td>
<td>0.0634</td>
</tr>
<tr>
<td>Others</td>
<td>34.4</td>
<td>48.059</td>
<td>51.852</td>
<td>62.26</td>
</tr>
</tbody>
</table>
5. Discussions

We found that natural factors and human induced factors were responsible for the change of wetland ecosystem in Tianjin, which is consistent with Zhao and Lai’s [19] result that natural and anthropogenic factors contributed to the wetland changes. The natural factors that cause effects on wetland ecosystem, including climate change, diversion of precipitation and evaporation. The human induced factors affect wetland ecosystems are environmental pollution, and construction mainly due to economic development, population growth, social policies, and consumption styles and so on [19]. The factors of wetland change causes and the problems that be caused are shown in Figure 4.

Fig. 4. Causes and problems of dynamics of wetland change from 1979 to 2009

5.1. The influence of climate change to wetland changes

In recent years, global climate change has lead to an increase in the annual average temperatures and evaporation, which has resulted in decrease in the precipitation and the climate becoming drier in Tianjin (Figure 5). The decreasing trend in the natural wetland area is consistent with the decrease in the precipitation.

Fig. 5. Change tendency of precipitation and evaporation from 1964 to 2007 in TCA
5.2. The influence of construction to wetland changes

Population growth leads to increased amounts of constructions and rapid urban expansion. The area of urban construction land increased from 27881hm$^2$ in 2000 to 42915hm$^2$ in 2008, mainly due to the reclamation of coastal wetlands for construction use, and wetland drainage for agriculture. We selected statistic data from 2000 to 2004.

Table 4. Changes of the construction land from 2000 to 2004

<table>
<thead>
<tr>
<th>Types</th>
<th>Area (hm$^2$)</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction land</td>
<td>27881.26</td>
<td>37915.39</td>
</tr>
<tr>
<td>Undeveloped land</td>
<td>10080.22</td>
<td>4267.14</td>
</tr>
</tbody>
</table>

5.3. The influence of pollution to wetland changes

Economic development and population growth are the two main factors causing wetland degradation. The environment pollution especially low water quality of the wetlands or of water source of the wetlands is direct causes of the wetlands degradation (Table 4).

Table 5. Water quality of ten main rivers in TCA from 2001 to 2008
6. Conclusions

The RS and GIS provided systemic methods for identifying, classifying and analyzing the dynamic changes for wetlands in TCA. The Markov model provided a simple methodology for forecasting the wetland changes in the future based on the previous research based on RS and GIS. This study’s results revealed that the use of GIS and RS technology to establish the Markov model based on wetland type distribution in TCA is feasible. Forecasting the future change trends of wetland by using the Markov model is an effective ways of wetland resources conservation and an important reference for wetland management decision-making. According to the results of dynamic changes in past 30 years in TCA, the natural wetland area was showing a decreasing trend, while the artificial wetland area was showing an increasing trend. In view of the results of prediction in wetland change trends in TCA, the area of natural coastal and lake wetland are showing decreasing trend, while the marshes, artificial and river wetland area are showing an increasing trend. We also analyzed the causes of the wetland changes, and the results reveal that human activity and the climate change are predominant driving forces. The study indicates that the integration of RS, GIS and Markov model is accurate and reliable to establish prediction model. Thus, the application of the three methods could predict the wetland change trends in the future based on the current wetland management policies, therefore, the study could provide guidance for wetland conservation and sustainable development.

Acknowledgment
The authors thank the Tianjin Municipal Science and Technology Commission which provided financial support for this study under Tianjin Science and Technology Support Key Program (No.07ZCKFSF02000). Thank instructors in University of Wisconsin-Madison writing center for the language suggestions. We thank anonymous reviewers for their patience and time for reviewing this article.

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