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Using Markov chains to analyze changes in wetland trends in arid Yinchuan Plain, China

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ABSTRACT

Three wetland distribution maps were drawn using Two Land-sat 5 Thematic Mapper (TM) images from 1991 and 1999, and a China–Brazil Earth Resources Satellite (CBERS)-02B image from 2006. A transition probability matrix was constructed using two wetland distribution maps, one from 1991 and one 1999 and GIS (Geographic Information System). The trends in changes in wetland types and the distribution area were predicted using a Markov model. The prediction model was then tested for relative accuracy and the feasibility of a x^2 test. The prediction model's relative accuracy was 98.5%. The x^2 test results showed that both the simulated results and the actual wetland distribution area were in good agreement. Therefore, it is feasible to use the wetlands area transfer matrix to establish a transition probability matrix based on the Markov model and to predict the distribution pattern of the wetland in Yinchuan Plain. The results of this study may be helpful for local governments to develop wetland management policies.

1. Introduction

Wetlands are among the most important ecosystems on earth and are sometimes described as "the kidneys of the landscape" because they function as the downstream receivers of water and waste from both natural and human sources [1]. Wetlands are valued for their ability to store floodwaters, protect shorelines, improve water quality, and recharge groundwater aquifers [2]. Wetlands provide a habitat for fish and wildlife, supporting a rich biodiversity, including many threatened and endangered species [3]. The area of wetlands in arid and semi-arid areas is the basis of the maintenance of agricultural and oasis ecosystems [4]. In the last few decades, climate change and anthropogenic activity have resulted in a rapid reduction in the area of wetlands in Yinchuan plain. The degree and extent of wetland change over the last few decades has given a new urgency and relevance to the detection and understanding of wetland change [5]. Geographic information systems (GIS) and remote sensing (RS) are essential tools for monitoring the present wetland distribution area and spatial-temporal dynamic variety [6,7]. GIS also serves as a tool for predicting and analyzing wetland change and its underlying causes [8]. Other uses of GIS include determining methods of efficient storage, management, and analysis of spatial and non-spatial data [9].

Landscape ecology is an interdisciplinary study that includes geography and ecology. Some of the most important aspects of wetland change at the broad spatial level can be distinguished based on landscape pattern and structure [10]. However, it is necessary to monitor and assess wetland changes with a view toward the conservation and wise management of wetland resources [11]. The use of remote sensing technology for the identification, inventory, mapping, and classification of land wetlands has been a common application of satellite imagery [12,13]. In recent years, many studies have been conducted to

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Fig. 1. Location map of the study area.

evaluate wetland landscape pattern and structure change [8,3], but fewer studies have been conducted to evaluate wetland change trend simulation. A Markov process, like a Markov chain, can be thought of as a directed graph of states of the system. The difference is that, rather than transitioning to a new (possibly the same) state at each time step, the system will remain in the current state for some random (in particular, exponentially distributed) amount of time and then transition to a different state [14]. In principle, when a sequence of chance experiments is observed, all of the past outcomes could influence our predictions for the next experiment [15,16]. Thus, a continuous-time Markov process being suitable for wetland simulation of dynamic change, we can use two time-states showing the wetland distribution area to predict future wetland distribution areas.

In this study, we used three images (TM image from September 1991, TM image from September 1999, and CBERS-02B image from September 2006) for remote sensing wetland mapping. A Markov transition probability matrix was then built using the wetland distribution dates from 1991 and 1999 to predict wetland change trends in the future in Yinchuan Plain. The objective of this study was to apply the Markov model prediction to changes in wetland trends and to analyze the underlying causes of wetland change in the arid Yinchuan Plain, China.

2. Materials and methods

2.1. Study areas

Yinchuan Plain is located in the arid portion of western China (Fig. 1). The plain is approximately 165 km from south to north and 50 km from east to west, covering an area of about 7793 km^2. The elevation of the study area ranges from approximately 1000–1200 m, with a generally flat terrain that slopes from southwest to northeast. The Yellow River runs through Yinchuan Plain from south to north. The study area is subject to a temperate continental climate and has an annual average rainfall of 180–220 mm and an annual average evaporation of 1800–2200 mm. Some water is supplied to the Yinchuan Plain wetland from the Yellow River. Water is also provided by lateral groundwater infiltration, farmland water (runoff), torrent, and precipitation recharge. Before the formation of the Yellow River, the Yinchuan Plain was a landlocked lake. After the formation of the original Yellow River, the lake gradually evolved into a drainage basin with lakes distributed throughout the area [17]. However, due to global warming and unreasonable exploitation and utilization of wetlands in the Yinchuan Plain, the stability of the wetland ecosystem has been threatened over the past 50 years [18].

2.2. Wetland remote sensing mapping

Two Land-sat 5 Thematic Mapper (TM) images containing six bands from 1991 and 1999 with pixel resolutions of 57 m and 28.5 m, respectively, were acquired from Geographical Science and Natural Resources Research, Chinese Academy of Sciences. Additionally, a China–Brazil Earth Resources Satellite (CBERS)-02B image from 2006 with a pixel resolution of 19.5 m was provided by the China Resources Satellite Application Center. All images covered the area of Yinchuan Plain. The range of the study area in the remote sensing imageries was masked by a vector boundary for classification.

Wetlands in Yinchuan Plain were divided into wetland and non-wetland areas according to the wetland classification principles, wetland definition and the characteristics of the remote sensing imageries. Wetlands can be natural or constructed. Natural wetlands were formed naturally with little or no intervention of human activities, while constructed

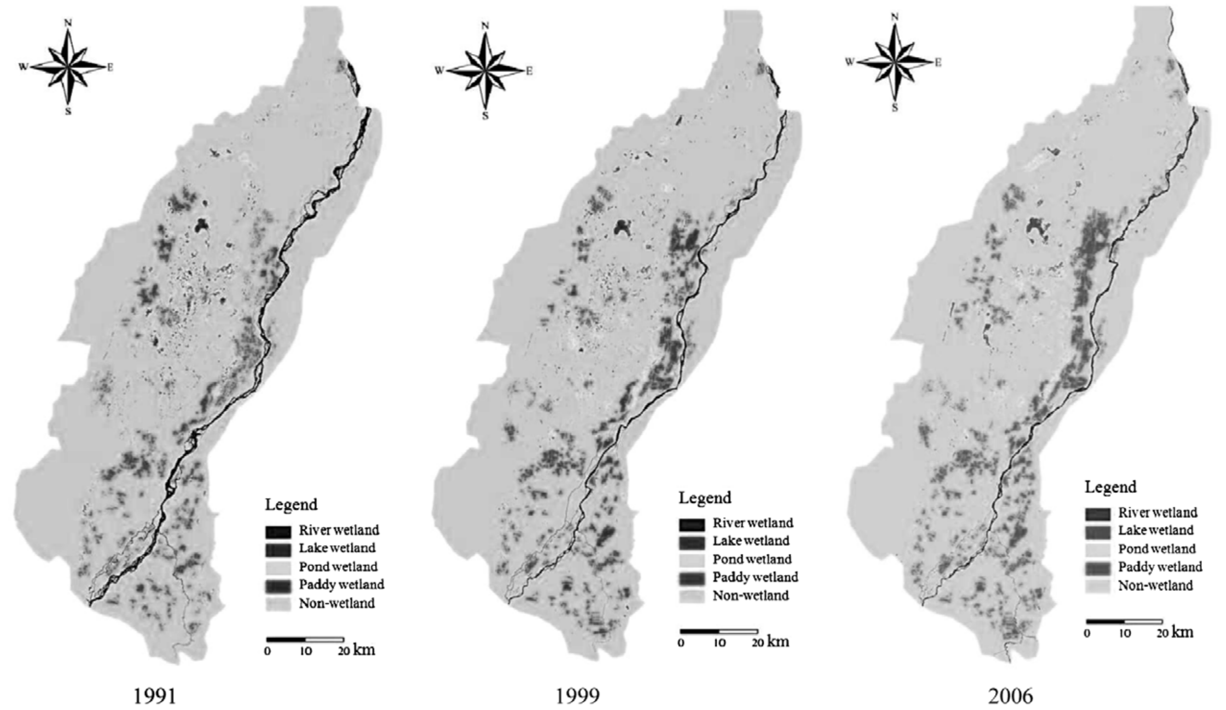

Fig. 2. Three time wetland distribution maps in Yinchuan Plain.

Table 1
Wetland distribution area in Yinchuan Plain (unit: km^2).

Year	River wetland	Lake wetland	Pond wetland	Paddy wetland	Non-wetland
1991	170.73	88.89	55.72	294.94	7159.85
1999	107.52	73.27	85.73	376.47	7127.14
2006	102.24	67.08	97.09	465.33	7049.38

wetlands have been strongly influenced by human activities. Based on the characteristics of the features displayed directly in the remote sensing imageries, such as shape, size, hue and texture, the natural wetlands were divided into river wetlands and lake wetlands, while the constructed wetlands included pond and paddy wetlands. The remaining land cover was designated as non-wetland, and included vegetation, building land and other uses land. Therefore, there were a total of four wetland types. The three wetland distribution maps and the distribution area information are presented in Fig. 2 and Table 1, respectively.

2.3. Markov chains

2.3.1. Markov process

A Markov chain can be described as a set of states, $S = \{s_0, s_1, s_2, \ldots, s_r\}$. The process starts in one of these states and moves successively from one state to another, and each move is called a *step*. If the chain is currently in state s_i, then it moves to state s_j at the next step with a probability denoted by p_{ij}, and this probability does not depend on which states the chain was in before the current state. The probabilities p_{ij} are called *transition probabilities*. The process can remain in the state it is in, and this occurs with probability p_{ii}. An initial probability distribution, defined as $S(0)$, specifies the starting state. Usually, this is conducted by specifying a particular state as the starting state.

2.3.2. Transition probability matrix

In a sequence of discrete time states, the probability of transitioning from state i in T_m to state j in T_{m+1} in a single step is p_{ij}. p_{ij} depends only on the state in T_m and T_{m+1}. p_{ij} are arranged in sequence to give the following transition probability matrix:

$$P = \begin{bmatrix} P_{00} & P_{01} & \cdots & P_{0m} \\ P_{10} & P_{11} & \cdots & P_{1m} \\ \cdots & \cdots & \cdots & \cdots \\ P_{m1} & P_{m2} & \cdots & P_{mm} \end{bmatrix} \tag{1}$$

Table 2
Wetland type area transition matrix for 1999 (km^2/8 years).

1991	1999					
	River wetland	Lake wetland	Pond wetland	Paddy wetland	Non-wetland	Area total
River wetland	58.3669	0.8845	0.0516	3.4565	107.9679	170.7275
Lake wetland	0.0641	22.4142	9.4832	0.4753	56.4543	88.8910
Pond wetland	0.0188	2.4155	28.2900	0.8144	24.1775	55.7162
Paddy wetland	0.0434	0.6674	1.2496	196.2779	96.7061	294.9445
Non-wetland	49.0256	46.8858	46.6600	175.4466	6841.8332	7159.8512
Area total	107.5188	73.2674	85.7345	376.4706	7127.1391	7770.1304

where p_{ij} is the transition probability of wetland types from type i to j. There are three assumptions: first, the Markov chain is stochastic. The probability of transition from state i to j is as follows: $P_{ij}1, j = 1, 2, 3, \ldots, m$. Second, Markov chains are usually assumed to be a first-order model so that the state of motion system in $T + 1$ depends only on that of T. Third, it is assumed that the transition probabilities do not change [19].

In accordance with the Markov stochastic process theory, we can use the probability matrix in the initial state to calculate the state transition probabilities given (here, we supposed it is the nth Markov state) from the initial state to the nth state and even a stable state. The formula of the nth state Markov transition probability was as follows:

$$P_{ij}^{(n)} = \sum_{k=0}^{m-1} P_{ik}^{(n-1)} P_{kj}^{(n-1)} \tag{2}$$

where m is the number of rows or columns of the transition probability matrix, and the nth transition probability matrix is equivalent to the nth power of the first transition probability matrix.

2.3.3. Markov prediction

According to the matrix of the initial $S(0)$ and the transition probability of the nth stage $P(n)$, we can calculate the wetland distribution area in Yinchuan Plain in the future by using a computer simulation. The Markov simulation model $S(n)$ is as follows:

$$S(n) = S(n-1) \times P^{(1)} = S(0) \times P^{(n)}. \tag{3}$$

3. Application of the model

3.1. The initial state

THe simulation steps are as follows: the first step is the determination of the initial state matrix. Dividing the wetland into a series of states evolving mutually based on the type of wetland landscape and building the initial state matrix with the areas of each wetland type for 1991 was as follows (p, unit: km^2):

$$S(0) = \begin{bmatrix} 170.73 \\ 88.89 \\ 55.72 \\ 294.94 \\ 7159.85 \end{bmatrix} = \begin{bmatrix} River\ wetland \\ Lake\ wetland \\ Pond\ wetland \\ Paddy\ wetland \\ Non\text{-}wetland \end{bmatrix}. \tag{4}$$

3.2. The transition probability matrix

The second step is to determine the transition probability matrix. The landscape types from 1991 and 1999 were set as the basic map. With the support of the Arc-View software, the two period wetland landscape raster maps were overlapped and the corresponding properties in the overlay map database PAT.DBF were extracted. The wetland type area transition matrix of the initial state (Table 2) was obtained from 1991 to 1999. Thus, we calculated the initial state transition probability matrix from 1991 to 1999 ($N = 0$) (Table 3) and the annual average transition probability matrix for calculating the prediction value of wetland type areas in 2006.

3.3. Evolution trends simulation

The future wetland distribution area of change trend was calculated using formula (3), formula (4) and Table 3. Specifically, we simulated the evolution trend of the wetland type distribution area in Yinchuan Plain using the Markov model (Table 4). The results indicated that the distribution area of river wetland, lake wetland, and pond wetland will be in a stable state after 2110. All wetland type and non-wetland distribution areas will be in a stable state after 2150.

Table 3
The initial state transition probability matrix from 1991 to 1999 ($n = 0$).

1991	1999				
	River wetland	Lake wetland	Pond wetland	Paddy wetland	Non-wetland
River wetland	0.341872	0.005181	0.000302	0.020245	0.632399
Lake wetland	0.000721	0.252154	0.106683	0.005347	0.635096
Pond wetland	0.000337	0.043354	0.507752	0.014616	0.433941
Paddy wetland	0.000147	0.002263	0.004237	0.665474	0.327879
Non-wetland	0.006847	0.006548	0.006517	0.024504	0.955583

Table 4
Wetland distribution area value predicted by using Markov chains (unit: km^2).

Year	River wetland	Lake wetland	Pond wetland	Paddy wetland	Non-wetland
2006	101.01	73.82	91.69	407.93	7095.68
2007	85.70	70.27	99.42	429.00	7085.74
2015	77.96	69.84	106.00	462.68	7053.64
2031	73.98	69.88	110.81	498.05	7017.41
2071	73.06	69.85	112.24	519.98	6995.00
2111	73.01	69.83	112.25	522.35	6992.69
2127	73.00	69.82	112.25	522.52	6992.53
2143	73.00	69.82	112.25	522.59	6992.47
2159	73.00	69.82	112.25	522.62	6992.44
2167	73.00	69.82	112.25	522.62	6992.43
2173	73.00	69.82	112.25	522.63	6992.43
$n \to \infty$	73.00	69.82	112.25	522.64	6992.42

Table 5
Prediction model x^2 test using the wetland distribution area in 2006 (unit: km^2).

Wetland types	Simulated value (Y')	Actual value (Y)	Absolute error $Y' - Y$	$(Y' - Y)^2$
River wetland	101.01	102.24	1.23	1.51
Lake wetland	73.82	67.08	−6.74	45.43
Pond wetland	91.69	97.09	5.40	29.16
Paddy wetland	407.93	465.33	57.40	32.95
Non-wetland	7095.68	7049.38	−46.30	21.45
x^2 test	$x^2 = \frac{\sum(Y'-Y)}{\bar{Y}} = 0.0084,$	$x^2_{(0.05)}(4) = 9.488$		

4. Results and discussion

4.1. Predictive model test

We used the simulated and actual values of wetland area in 2006 to test the precision of the Markov prediction model. The relative error of the simulation was about 98.5%, indicating that the wetland change trend was consistent in the beginning of the 21st Century and the end of the 20th century. In addition, we used x^2 to test the prediction model (Table 5). The test results were as follows:

$$x^2 = \frac{\sum(Y' - Y)/Y'}{5} = 0.0084, \qquad x^2_{(0.05)}(4) = 9.488, \qquad x^2 = 0.0084, \qquad x^2_{(0.05)}(4) = 9.488.$$

These findings show that the difference between the simulation results and the actual wetland distribution area was very small, and that both were in very good agreement. Therefore, it is feasible to use the wetland area transfer matrix to establish the transition probability matrix of the Markov chain and to predict the distribution pattern of the wetland in Yinchuan Plain.

4.2. Change trend analysis

According to the wetland distribution area predicted using the Markov model, if the level of wetland management of the last 20 years in Yinchuan Plain is maintained, the wetland distribution area will essentially be in a steady state in Yinchuan Plain in approximately 100 years. Once this condition is met, the total wetland area will be 777.71 km^2, accounting for 10.01% of total area of Yinchuan Plain. Additionally, there will be an increase of 2.16% in the total wetland area from 610.48 to 777.71 km^2, with a decrease in the natural wetland area from 259.82 to 142.82 km^2 and an increase in the artificial wetland area from 350.66 in the initial state (1991) to 634.89 km^2 in the stable state occurring (Table 6).

Table 6
Wetland distribution area and the percentage composition of the initial state and stable state in Yinchuan Plain (Unit: km^2, %).

Year	All wetland types		Natural wetlands		Artificial wetlands	
	Total area	Percentage (%)	Area	Percentage (%)	Area	Percentage
1991 initial state	610.48	7.85	259.82	3.34	350.66	4.51
$n \to \infty$ stable state	777.71	10.01	142.82	1.84	634.89	8.17
add (+) decrease (−)	+167.23	+2.16	−117	−1.50	+284.23	+3.66

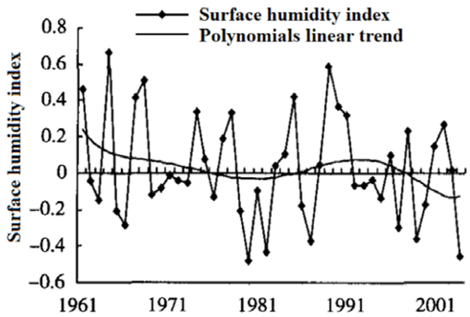

Fig. 3. Earth's surface humidity index and polynomial tendency in Yinchuan Plain.

4.3. Underlying cause analysis

4.3.1. The influence of climate

In recent decades, global climate change has included an increase in the annual average temperatures and evaporation, which has resulted in the climate becoming drier in Yinchuan Plain. Therefore, the environmental conditions responsible for maintenance of the wetland ecosystem health are deteriorating. We calculated the earth surface wetness index of Yinchuan Plain using the monthly mean temperature and monthly rainfall data collected from 1961 to 2004. Fig. 2 shows the earth's average surface wetness index and polynomials linear trend diagram. Fig. 3 demonstrates that the earth's surface wetness index declined, resulting in the surface becoming dry [18]. The decreasing trend in the natural wetland distribution area is consistent with the decrease in the earth's surface wetness.

4.3.2. The influence of human activity

In Yinchuan Plain, population growth increased from 149 to 255 million, while the GDP grew from 9.3 to 636 billion RMB from 1978 to 2006. Both population growth and economic development lead to increased amounts of water consumption, which causes groundwater levels to fall. Additionally, the increased population results in the need for increased food production; therefore, local residents drained lakes to expand the cultivated areas. In arid and semi-arid regions, shallow groundwater levels can easily cause soil salinization. As a result, lakes have been drained since the 1950s to control soil salinization, which has resulted in some loss of natural wetlands. Local residents also lack knowledge regarding the need for natural wetland protection and receive greater economic benefits from rice cultivation than other forms of agricultural farming. Thus, some wetland and flood land has been reclaimed into ponds and paddy fields. These areas consume a large amount of water each year, preventing water from being supplied to the wetlands and promoting the further shrinkage of the natural wetland.

4.3.3. Utilization of water resources

The wise use of water resources and optimal allocation of water resources is necessary to ensure sustainable wetland development in Yinchuan Plain. In China, traditional water management only considers the water allocation between economic development departments and people's daily lives, ignoring the water required to maintain ecosystem functions. The quota of water consumption from the Yellow River is 4.0 billion m^3 per year in Yinchuan Plain, with agricultural water consumption accounting for 95% and industrial water and living water accounting for 4%. This leaves less than 1% for the maintenance of wetland systems. This allocation of water resources is very dangerous when there is less than 200 mm of rainfall. Additionally, this water use distribution shows that greater attention to environmental protection is required in Yinchuan plain.

5. Conclusion

The transition probability of the Markov process simulation was determined according to the conversion rate between the actual value and the predicted wetland type distribution area in Yinchuan Plain in 2006. This model was then used to simulate the wetland type distribution area consistent with the actual situation in 2006. The results revealed that the use of RS (remote sensing) and GIS technology to establish the Markov model based on the distribution of wetland in Yinchuan

Plain is feasible. Using the Markov model to study wetland type distribution area change trends is a more effective means of protecting wetland resources and improving the standard of wetland management decision-making.

According to the prediction results of the wetland type distribution area change trends in Yinchuan Plain, the artificial wetland distribution area is showing an increasing trend, while the natural wetland area is showing a decreasing trend. If the current management condition of the wetland is maintained, the wetland distribution area will become stable in approximately 100 years. Once in the steady state, the river wetland area will be 73.00 km^2, the lake wetland area will be 69.82 km^2, the pond wetland area will be 112.25 km^2, the paddy wetland area will be 522.64 km^2, and the non-wetland area will be 6992.42 km^2. This indicates that human activity disturbance will remain the major cause of changes in the wetland distribution area in Yinchuan Plain.

Markov transition probability determination is an important part of the Markov process simulation; therefore, the transition probability should be accurate and reliable to establish the Markov prediction model. The high-precision data provided in wetland remote sensing mapping is the key process involved in the establishment of the Markov transition probability matrix. GIS provides technical support to set up the spatial transition probability matrix. Markov, while having no after-effects, can predict the wetland change trend in the future according to the current wetland management standard conditions, and can therefore provide guidance for wetland ecological system restoration and environmentally sustainable development.

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References

[1] Willian J. Mitsch, James G. Gosselink, Wetlands, third ed., John Wiley & Sons, Inc, New York, 2000 (in America).
[2] G.C. Daily, Nature's Services: Societal Dependence on Natural Ecosystems, Island Press, Washington, 1997 (in America).
[3] Stacy L. Ozesmi, Marvin E. Bauer, Satellite remote sensing of wetlands, Wetlands Ecology and Management 10 (2002) 38–402.
[4] De Zhou, Rongqun Zhang, Liming Liu, Liming Liu, Lingling Gao, Simin Cai, Evaluation of the sustainable land use status of the North China Plain, International Journal of Sustainable Development & World Ecology 16 (4) (2009) 253–259.
[5] Min Han, Yannan Sun, Shiguo Xu, Characteristics and driving factors of marsh changes in Zhalong wetland of China, Environmental Monitoring and Assessment 127 (2007) 363–381.
[6] Mostafa Emadi, Majid Baghernejad, Mojtaba Pakparvar, Sayyed Ahang Kowsar, An approach for land suitability evaluation using geostatistics, remote sensing, and geographic information system in arid and semiarid ecosystems, Environmental Monitoring and Assessment 164 (2010) 501–511.
[7] Rencai Dong, Lijun Yu, Guohua Liu, Impact of tourism development on land-cover change in a matriarchal community in the Lugu Lake area, International Journal of Sustainable Development and World Ecology 15 (1) (2008) 28–35.
[8] Hui Yuan, Rongqun Zhang, Changes in wetland landscape patterns on Yinchuan Plain, China, International Journal of Sustainable Development & World Ecology 17 (3) (2010) 236–243.
[9] Farooq Ahmad, GIS application for forest management in drylands of Pakistan, Journal of Food, Agriculture & Environment 6 (2) (2008) 388–392.
[10] K.H. Riitters, R.V. O'Neil1, C.T. Hunsaker, J.D. Wickham, D.H. Yankee, S.P. Timmins, K.B. JonesS, B.L. Jackson, A factor analysis of landscape pattern and structure metrics, Landscape Ecology 10 (1) (1995) 23–39.
[11] Liu Yang, Ke-Ming Ma, Qing-Hai Guo, Xue Bai, Evaluating long-term hydrological impacts of regional urbanisation in Hanyang, China, using a GIS model and remote sensing, International Journal of Sustainable Development and World Ecology 15 (4) (2008) 350–356.
[12] T.A. MacDonald, Wetland rehabilitation and remote sensing, in: E. Streever (Ed.), An International Perspective on Wetlands Rehabilitation, Kluwer Academic Publishers, Boston, 1999, pp. 251–264 (in America).
[13] Nina M. Kelly, Changes to the landscape pattern of coastal North Carolina wetlands under the Clean Water Act, 1984–1992, Landscape Ecology 16 (2001) 3–16.
[14] William J. Stewart, Introduction to the Numerical Solution of Markov Chains, Princeton University Press, 1994, pp. 17–23 (in America).
[15] B. García-Mora, C. Santamaría, E. Navarro, G. Rubio, B. García-Mora, et al., Modeling bladder cancer using a Markov process with multiple absorbing states, Mathematical and Computer Modelling (2010) doi:10.1016/j.mcm.2010.02.036.
[16] Carmen Armero, Anabel Forte, Antonio López–Quílez, Geographical variation in pharmacological prescription, Mathematical and Computer Modelling 50 (5–6) (2009) 921–928.
[17] De Zhou, Rongqun Zhang, Liming Liu, Lingling Gao, Simin Cai, A study on water resources consumption by principal component analysis in Qingtongxia irrigation areas of Yinchuan Plain, China, Journal of Food, Agriculture & Environment 7 (3–4) (2009) 734–738.
[18] Zhang Rongqun, Yuan Hui, Song Naiping, Lv Bo, Study on Wetland change detection and underlying causes analysis in Yinchuan Plain, China, Journal of Food, Agriculture & Environment 8 (2) (2010) 1109–1111.
[19] Li Sheng-Tun, Cheng Yi-Chung, A hidden Markov model-based forecasting model for fuzzy time series, WSEAS Transactions on Systems 5 (8) (2006) 1919–1924.