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ORIGINAL PAPER

Water surface variations monitoring and flood hazard analysis in Dongting Lake area using long-term Terra/MODIS data time series

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Abstract Dongting Lake is the second largest freshwater lake in China, and its water surface area varied very significantly during last decade. Remote sensing technology has more advantages in macro monitoring of lake water surface area than the traditional methods. In the paper, an integrated threshold method of water body extraction based on MODIS data is given, which synthesizes several factors, including vegetation index—NDVI, spectrum characters of water body, cloud and shadow, and the SRTM digital elevation information. With this method and 356 scenes MODIS 8-Day composite (MOD09Q1) image, water surface area of Dongting Lake was dynamically monitored from 2000 to 2009. The result shows that during 1 year, the water area variation in Dongting Lake area had a typical seasonal (monsoon) behavior, and during last decade, the water area decreased gradually and obviously. Based on variation monitoring, yearly max-submersion time index has been suggested to analyze flood hazard in study area. With the support of ArcGIS software, authors estimated the yearly submersion time of the Dongting Lake for each year separately and average submersion time from 2000 to 2009. The result shows 67.46% of study area is being with high flood hazard.

Keywords Terra/MODIS · Water area variations · Remote sensing monitoring · Dongting Lake area

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1 Introduction

Dongting Lake is the second largest freshwater lake in China. There are four main rivers (Xiang River, Zi River, Yuan River, and Li River) that flow into Dongting Lake from the south and one outfall that link it to the Yangtze River from the north. Like Poyang Lake, Dongting Lake acts as a huge retention basin for the Yangtze water during the flood season (Fang and Zhong 2001). The inflow from the Yangtze River carries a tremendous sediment load of 140,000,000 m^3/year on average. In flood season, vast volumes of water from the Yangtze River flow into the lake, and the lake's area, which normally is less than 500 km^2, may increase to 2,500 km^2. During the dry season, from October to April, more water is discharged from the lake than entered into, the water level falls, and a large part of the lake area becomes dry land. In the past 80 years, Dongting Lake has suffered several major floods, such as 1931, 1935, 1954, 1973, 1977, 1983, 1991, 1995, 1998, 2007, and the most severe ever recorded were in 1954 and 1998. The serious shrinkage of Dongting Lake has led to the deterioration of its flood diversion and storage capacity, and now, flood disasters happened more frequently.

As an important hydrological information, water area variation monitoring and the driving mechanism analysis is very important to a comprehensive understanding of the lake's change regularity and evolution tendency. Compared with traditional methods, remote sensing technology has more advantages in macro and dynamic monitoring of lake water surface area (Li and Huang 2003; Wang and Ma 2009). Many researchers had carried out lake water area monitoring based on remote sensing technology. Zhao (2009) analyzed Angulichuo Lake water area variation with MSS/TM/ETM and CBERS-2 images, Feng and Li (2006) studied Qinhai Lake water area variation characters during last two decades with TM images, Andreoli et al. (2007) carried out Poyang Lake monitoring with ENVISAT ASAR, and Satoshi et al. (2004) studied the dynamic variation of the surface water area and water storage in Dongting Lake with MODIS images. However, most of those studies are not long-term and long-interval monitoring due to lack of enough images.

Dongting Lake water surface area varied very significantly during last decade. In the paper, a long-term and short-interval series of MODIS datasets has been built and applied to monitoring water area variation from March 2000 to December 2009. In addition, yearly max-submersion time index (YMSTI) is suggested for flood hazard analysis.

2 Study area

Study area is composed of three parts: East Dongting Lake, West Dongting Lake, and South Dongting Lake. As Fig. 1 shows, the study area is surrounded by dike or natural coastline. The total area is about 2,629.23 km^2.

3 Remote sensing monitoring of water area variations during the last decade

3.1 Data

In order to monitor water surface variation of Dongting Lake, Terra/MODIS Data were selected as main data source. As a new type of remotely sensed resources, EOS/MODIS imagery has moderate spatial resolution, high temporal resolution, and high spectral resolution. In addition, it is free and easy to access. In this paper, MODIS Terra Surface

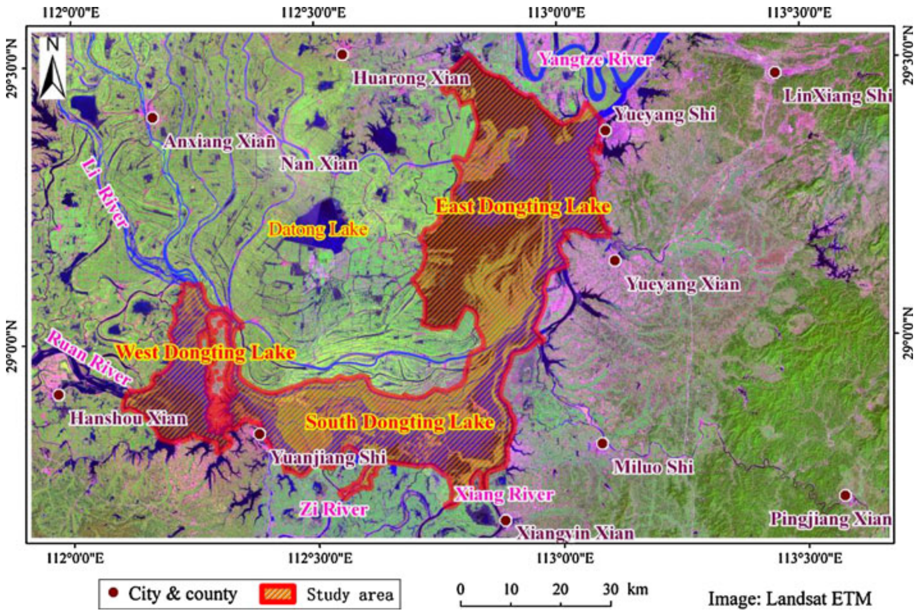

Fig. 1 Location of the Dongting Lake area

Reflectance 8-Day L3 Global 250 m(MOD09Q1) dataset were used to build Terra/MODIS Data Time Series from March 2000 to December 2009. MOD09Q1 provides Bands 1 (Red) and 2 (Near Infrared) at 250-m resolution in an 8-day gridded level-3 product.

Besides MODIS data, digital elevation model (DEM) data are also necessary. In the paper, SRTM DEM has been used to correct the water body extraction affected by shade. The SRTM DEM is publicly available through the Seamless Data Distribution System (SDDS) at two resolutions: 30 m for the United States and 90 m for the areas between 60°N and 56°S of latitude including the United States. In this research, 90-m resolution SRTM DEM of Dongting Lake area was got from Global Land Cover Facility (GLCF).

3.2 Method of water body extraction based on MODIS data

The principle for extracting the water body is based on the visible light and near-infrared band reflectance difference of water from other land cover types such as vegetation, soil, and resident region. Wu and Zhang (2005) analyzed the reflectance characteristics of water on different channel of MODIS imagery and claimed that band 2, 5, 6, 7, 16–19, 26, 27, and 18 are all well suited for extracting water body, and channel 2 is optimal for small water bodies. Min (2004) used NDWI, NDSI, and other kinds of indexes that were calculated with reflectance value from band 1–7 of MODIS 500-m resolution imagery to identify water body of the upper reach of Yangtze River. Satoshi et al. (2004) studied the dynamic variation of the surface water area and water storage in Dongting Lake by setting threshold with MODIS images derived from NDVI data.

In general, for water body extraction based on MODIS image, the threshold method of single band or index cannot effectively avoid the influence of mountain and cloud shadows, and the spectral relationship method will reduce the data's spatial resolution. In this paper, an integrated threshold method is adopted to extract surface water area. This method synthesizes several factors, such as vegetation index-NDVI, spectrum characters of typical ground objects, and the SRTM (Shuttle Radar Topography Mission) digital elevation information. In this research, method of water body extraction includes 5 steps as following.

Step 1 Data acquisition

MODIS 8-Day composite (MOD09Q1) data of the time span from 2000 to 2009 were downloaded from EOS data gateway (https://wist.echo.nasa.gov/api/) using the web-based search and FTP. Totally, 455 scenes images were acquired; because of too much cloud cover and bad data quality, 99 scenes image were deleted. At last, 356 scenes images were used for monitoring Dongitng Lake surface area.

Step 2 Data pre-processing

The MOD09Q1 images downloaded covers a large extent of southeast China and must be subsetted to extract the area of Dongting Lake. In addition, The MODIS land products are distributed by USGS in hierarchical data format (HDF) and projected into sinusoidal (SIN) projection. Neither the storing format nor the projection is well supported in conventional data-processing software. Thus, for the convenient further usage, each scene was re-projected to a more commonly used projection as Universal Transverse Mercator (UTM, WGS84) with nearest neighbor re-sampling method, and stacked into 250-m grid cell multi-layer images.

MODIS Re-projection Tool 1 developed by US Geological Survey was used to carry out this pre-processing. This software allows the user to read HDF metadata, resize and resample the data, and re-project to several different projections on a very simple user interface.

Step 3 Extraction of water body with integrated threshold method

In numerous scientific studies, NDVI has been proven to be one of the most successful indexes to identify water body simply and quickly. Generally, NDVI of water area is negative. However, for water area with water plant, the NDVI will be positive. During April to September, there are many water plants in Dongting Lake surface. In the paper, two rules were used to identify water body. One is NDVI $\leq$t1 and the other is DNband2 $<$t2. Threshold t1 between 0.1 and 0.2 and can be used to distinguish water from vegetations. Threshold t2 between 1,000 and 1,400 can be used to distinguish water from construction and bare soil. If a pixel's DN value was satisfied with the rule 1 or rule 2, then the pixel can be classified as water.

Step 4 Cloud effect elimination

Through above integrated threshold method, some cloud area may be recognized as water area. According to spectrum characters of cloud, it was thought that if DN band1 $>$2,000 and DN band2 $>$2,000, then the pixel can be classified as non-water directly.

Step 5 Shadow effect elimination

Shadow is another factor, which affects the accuracy of water body extraction. In order to eliminate the shadow effect, slope map is used to distinguish shadow with water. Generally, the slope of water area is below 1°, so the area with slope above 1° will not be water body. Slope map can be derived from SRTM DEM.

With above method, we got 356 temporal water body distribution maps from 2000 to 2009. In order to eliminate the effects from weather condition of the satellite flying

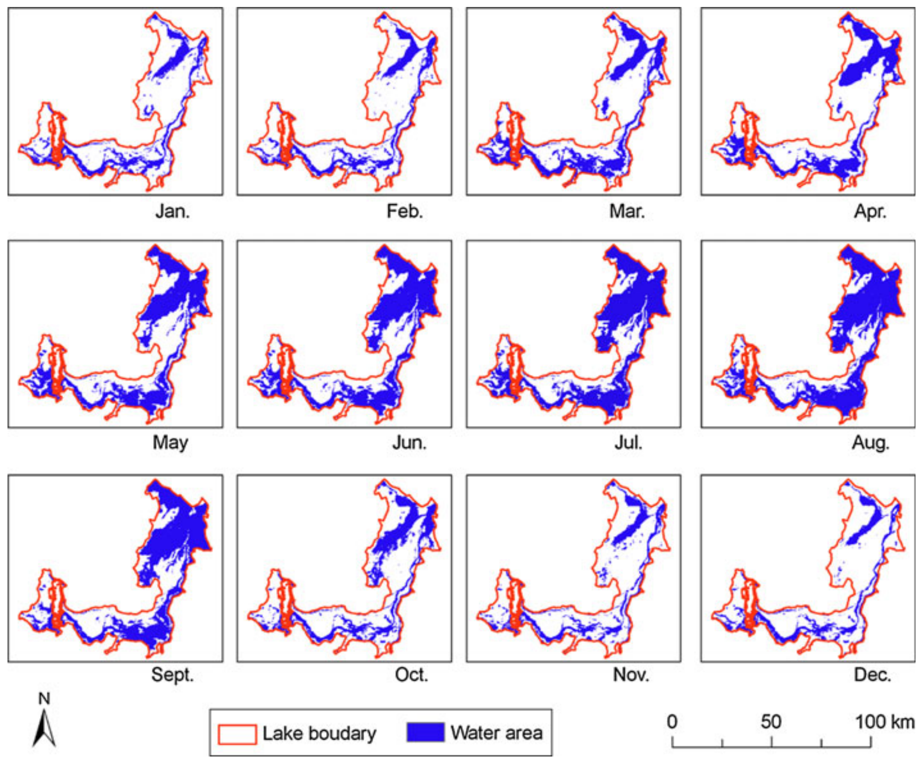

Fig. 2 Surface water dynamic variation of Dongting Lake in 2009 derived by Terra/MODIS MOD09Q1 data

overhead, clouds, data composing method, and etc., the MVC (maximum value composite) method was utilized to produce a water surface area monitoring result for every month in a year. At last, we got 118 monthly max-submersion area maps from March 2000 to December 2009. Figure 2 shows surface water dynamic variation of Dongting Lake in 2009.

3.3 Water surface variations analysis

Figure 3 shows variations of water area in the Dongting Lake area. From Fig. 3, several characteristics of the dynamic water extent can be found as follows:

1) The water extent variations during this 10-year period mostly followed a unimodal cycle with flood peaks centered during the monsoon season (June to September), except for 2002 when the highest water extent of the 10-year period was reached in May and 2005 when the variation showed a more undulating pattern.
2) During the period between 2000 and 2009, the maximal Dongting Lake water extent was reached in August 2002, with an area of about 2,400 km^2. And the minimal Dongting Lake water extent observed was around 440 km^2 in December 2007.
3) Seasonal variation characteristics: The water area change in Dongting Lake area had a typical seasonal (monsoon) behavior. On the whole, in the flood period, the lake was in a vast expanse of water, but in the dry season, it only remained a few ribbon waters.

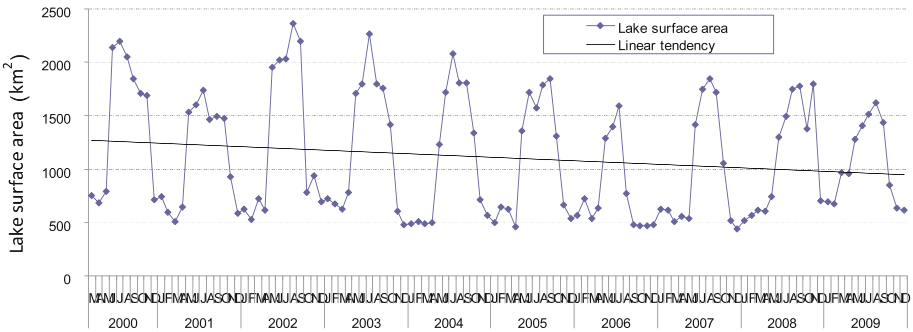

Fig. 3 Variations of water area in the Dongting Lake area observed by Terra/MODIS data time series acquired between March 2000 and December 2009

4) Year-to-year variation characteristics: During nearly 10 years, the water area of Dongting Lake area presented a declining trend to a certain extent.

The water area changes in Dongting Lake were mainly affected by the calculated water flow into lake from Dongting Lake basin and Yangtze River, in which the basin's precipitation and runoff conditions were the major drive forces.

4 Yearly max-submersion time index and flood hazard analysis in Dongting Lake area

4.1 Yearly max-submersion time index

To characterize the dynamic of Dongting Lake, YMSTI is defined as following:

$$F(W) = \frac{\sum_{i=1}^{12} (w_i \times n_i)}{N} \times 100 \quad (1)$$

where $F(w)$ is submersion time expressed in percent of year; N is number of days of the year; n_i is number of days of the month i; w_i is water extent layer extracted for the month; i, which can be selected from {0, 1}.

The index allows a quantitative description of lake temporal and spatial variations. We used ArcGIS software to calculate YMSTI, the procedure as following: first, monthly max-submersion area map should be transferred to ArcGIS GRID format, and water area will be assigned to "1", the other area will be assigned to "0"; second, using ArcGIS map algebra function, 12 monthly max-submersion area maps are overlaid according to the formula (1), and yearly max-submersion time map from 2000 to 2009 will be got; third, also using ArcGIS map algebra function, 10 yearly max-submersion time maps from 2000 to 2009 are overlaid, and average yearly max-submersion time map from 2000 to 2009 can be got.

4.2 Flood hazard analysis

According to the above method, estimation of water submersion time was calculated for each year from 2000 to 2009; and averaged Dongting Lake submersion time estimation was also produced (Figs. 4, 5).

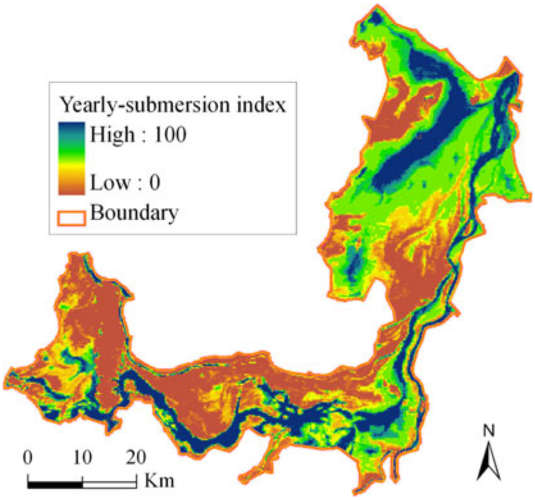

Fig. 4 The map of yearly max-submersion time index in the study area in 2005

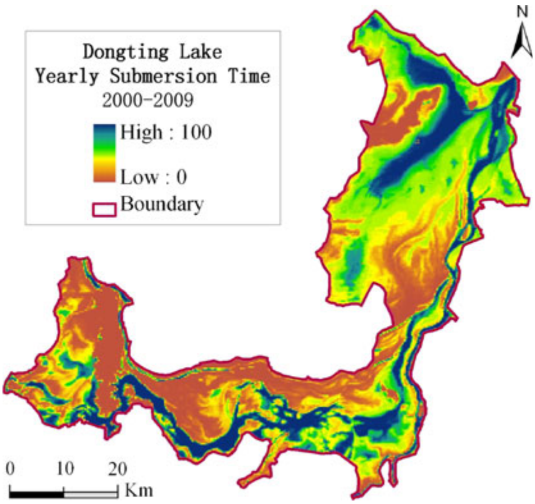

Fig. 5 The map of average yearly max-submersion time index in the study area from 2000 to 2009

Totally, due to water level changing with seasons, YMSTI of Dongting Lake decreases gradually from the center of inner lake and mainstream to outside. Topography is a main factor that affects the YMSTI. In the area with higher elevation, YMSTI is small, and in the area with lower elevation, YMSTI is larger, and flood hazard is higher.

According to spatial statistics of average yearly max-submersion time map, about 330 km^2 area (13.06% of study area) will be submerged for the whole year, the YMSTI is 100; About 493 km^2 area (19.48% of study area) will never be submerged for the whole year, the YMSTI is zero, and flood hazard is lowest; About 1,708 km^2 (67.46% of study area) will be sometimes submerged and sometimes not. In these areas, flood hazard is higher, and more attention should be paid to.

5 Conclusion and discussion

In the paper, based on analysis of MODIS data characters, a multi-source information method of water body extraction is given, which synthesizes several factors, including vegetation index—NDVI, spectrum characters of water body, cloud and shadow, and the SRTM digital elevation information. With this method and 356 scenes MODIS 8-Day composite (MOD09Q1) data, water surface area of Dongting Lake was dynamically monitored from 2000 to 2009. Seasonal variation characteristics and year-to-year variation characteristics were analyzed. Totally, the water area of Dongting Lake decreased gradually during last 10 years.

In addition, in order to analyze flood hazard in study area, YMSTI was suggested. With the support of ArcGIS, the yearly submersion time of the Dongting Lake for each year was estimated separately and average submersion time from 2000 to 2009. The result shows 67.46% of study area with high flood hazard. And with the topography changes, the flood hazard displays a gradual decreasing tendency from the center of inner lake and mainstream to outside. So far, in these higher flood hazard areas, an importance to prevention and control needs to be carried out from the departments or units responsible for flood control and flood fighting.

The study shows that inner lake monitoring and analysis using long-term Terra/MODIS data time series is feasible. However, lower spatial resolution of MODIS affected the accuracy of water body extraction and analysis. In order to improve the accuracy, higher resolution remote sensing image should be used. In the future, more satellites image with high resolution, such as Landsat TM, BJ-1, HJ-A/B, CBERS, and so on, will be used together to build long-term remote sensing data time series.

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