Monitoring Ephemeral Vegetation in Poyang Lake Using MODIS Remote Sensing Images

by
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Abstract

Poyang Lake is the largest freshwater lake in China and also one of the most important international wetlands which provides ideal habitat for overwintering birds. Water supply from five tributaries and the blocking effect of the Yangtze River make Poyang Lake a very complex aquatic-terrestrial ecosystem. The lake water level varies tremendously between flood season and low water season. Ephemeral vegetation, developed upon water recession in the central part of the lake is likely to green up in winter when water level is extremely low. This study aims to monitor change in area of ephemeral vegetation (AEV) by analyzing time series of Moderate-resolution Imaging Spectroradiometer (MODIS) imagery and to investigate whether this is related to change in hydrological conditions. The Poyang Lake water extent, area of ephemeral vegetation and central lake water area (CLWA) were extracted by masking and thresholding MODIS Terra MOD09Q1 and MOD09A1 images. After comparing various thresholds to visual interpretation, the NDVI threshold was set to 0.25 to identify vegetation, and NDWI was set to 0.001 to identify water. Areas were calculated from the extracted number of pixels and their sizes. Poyang Lake was monitored based on 229 MOD09A1 images over the 9-year period (2000 through 2008). AEV and CLWA were monitored based on 165 MODIS MOD09Q1 images and 165 MODIS MOD09A1 images respectively. Low water extent (below 1000 km^2) and longer low water season of Poyang Lake occurred in the winters of 2003-2004, 2006-2007 and 2007-2008, coinciding with low CLWA and high green up of AEV. The most remarkable low water and high green up of AEV was observed in 2006 and 2007. A strong linear relation (R^2=0.85, n=101) was established between Poyang Lake water area and water level measured at Duchang hydrological station, proving that lake level can be estimated by analysis of optical remote sensing imageries. Regression analysis showed that AEV and CLWA had strong negative exponential/logarithm relations in November, March and April (R^2= 0.91, 0.89 and 0.86, respectively), which suggests that lower water level was a major cause for the increase in ephemeral vegetation. Low spatial resolution, mixed pixels, and gaps in time series limited the accuracy and efficiency of area assessment and dynamics monitoring. Radar imageries, high spatial-temporal time series acquired from fusion techniques, and more hydrology information can be appropriate alternatives in further research.

Key words: Poyang Lake; ephemeral vegetation; MODIS image; NDVI; NDWI

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List of frequently used abbreviations

MODIS	Moderate-resolution Imaging Spectroradiometer
TM	Thematic Mapper
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
MNDWI	Modified Normalized Difference Water Index
EOS	Earth Observing System
NASA	National Aeronautics and Space Administration
HDF	Hierarchical Data Format
AEV	Area of Ephemeral Vegetation
CLWA	Central Lake Water Area
LEEV	Length of Emergence of Ephemeral Vegetation
R^2	Determination Factor
NIR	Near Infrared
MIR	Middle Infrared
MRT	MODIS Re-projection Tool
UTM	Universal Transverse Mercator
ROI	Region of Interest
SRES	School of Resources and Environmental Science
SCWP	Siberian Crane Wetland Project

1. Introduction

1.1. Research problem statement

Poyang Lake wetland is an internationally recognized wetland of great ecological value, providing habitat for fish, overwintering birds, and other wildlife species. However, this region is under environmental pressures, including erosion, soil degradation, water pollution and loss of bio-diversity (Huang et al. 2006). In recent years, the alarmingly low winter water level in Poyang Lake has raised concerns. There are fears that the drastic decrease of water level will become a tendency and that the lake will disappear in the near future (Tang 2008).

Various factors contribute to the fluctuation of water level of Poyang Lake, including the water level of the Yangtze and that of its tributaries, and human activities such as dredging, embankment and natural events such as climate change and flooding (Wu 2008). Water level fluctuation is conventional, but in recent years, the winter water level of Poyang Lake has dropped and sometimes in winter it no longer supplies water to the Yangtze River's middle reaches and the length of dry season also increases. The period of lowest water level usually concentrated in January or February, but nowadays it starts in December or even earlier. In December 2007 and January 2008, the water dropped to a historically extreme low level and the area covered by lake was reduced to only 40 km^2 (Li 2008).

The causes of this abrupt change are not known. Some argue that it is due to reduced rainfall which triggered historically low water level of the Yangtze River and other rivers which supply water to the lake (Tang 2008), an assumption which is not proven by solid evidence. Alternatively one might also speculate that the lowering of the bottom of the channel caused by dredging activities might have increased the ease of the lake discharging into the Yangtze and thus might have contributed to the change in winter water level (De-Leeuw et al. Submitted). A better understanding of underlying hydrological causes for the change in winter water levels might help the water department to define their strategy on how to deal with the drastically declining water level and properly manage the water resource of Poyang Lake. So far there has been no analysis of the year-to-year variation of winter water levels.

The declined winter water levels result in larger central lake areas being exposed for longer periods. And sediments emerged for longer periods develop a kind of ephemeral vegetation, which is productive in winter time and the adjacent parts of autumn and spring. Monitoring dynamics of this vegetation might give valuable information on the hydrological condition in Poyang Lake and could further help maintain the ecological safety of the region. We would expect that a lowering of water levels might also lead to increase of the extent of the areas with ephemeral vegetation. However, so far no such increase has been reported.

An analysis of the year-to-year variation of low winter water would require reliable time-series of water level data. It is usually difficult to get access to sound water level data held by Poyang Lake

Hydrology Office. But remote sensing provides the possibility to calculate water body area and there have been various studies about the relations between water body area and water level indicating that water body area is a very closely related variable to water level (Wei et al. 1999; Tan et al. 2006; Li et al. 2008).

MODIS (Moderate Resolution Imaging Spectro-radiometer) combines medium spatial resolution with high spectral resolution, high temporal resolution and accurate geolocation. It was frequently used for farmland detection; vegetation indices analysis and land cover dynamic monitoring (Brown de Colstoun et al. 2003; Lu et al. 2003). With tremendous volume of data production, advanced instrument calibration and characterization, MODIS provides accurate long term time-series products needed for global change studies (Justice et al. 2002) and thus offers possibility to monitor both the extent of the water area and the vegetated area in this research.

Because of its high spectral resolution, MODIS has great capability of differentiating land covers, especially water bodies, since the reflectance of water body differs a lot from vegetation, infrastructure and soil in visible and near infrared band (Ding, Wu et al. 2006). There are various methods for extracting the water body from multi-spectral optical imagery using different indices such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI) (Wang and Yi 2007). NDWI has proven to be an accurate index for water extraction and is defined as (GREEN-NIR)/(GREEN+NIR), where GREEN and NIR represent reflectance measured in green and near infrared channels, respectively (McFeeters 1996).

The widely used remotely sensed vegetation index NDVI can be derived from optical multi-spectral imagery data to extract ephemeral vegetation. The NDVI for MODIS is defined as: NDVI = $(Ch_2 - Ch_1)/(Ch_2 + Ch_1)$, where CH_2 and CH_1 represent the near infrared spectral band 2 and red band 1 respectively. The area covered by ephemeral vegetation could be extracted by setting NDVI threshold and area covered by water could be extracted by setting NDWI threshold. Then statistical analysis could be carried out to relate the water body area calculated from remote sensing imageries to the area covered by vegetation.

Finally, the time-series of all extracted areas of Poyang lake water areas, ephemeral vegetation and areas of central water could be analyzed in relation to water levels, climate, and water inputs to infer the relation between water level and ephemeral vegetation greenup.

1.2. Research objectives and research questions

The general objective of this study is to monitor change in area of ephemeral vegetation by analyzing time series of MODIS imagery and to investigate whether this is related to change in hydrological conditions.

Specific objectives (1, 2, 3 etc.), corresponding research questions (i, ii, iii etc.) are:

1. To determine NDVI threshold (T_v) for extracting ephemeral vegetation and NDWI threshold （T_w ）for extracting water body
   i. Which NDVI value should be set as threshold (T_v) to extract ephemeral vegetation?
   ii. Which NDWI value should be set as threshold (T_w) to extract water body?

2. To monitor the water area variation of Poyang Lake during 9 year period between 2000 and 2008
   i. What is the pattern of seasonal area variation in Poyang Lake?
   ii. What is the year-to-year change pattern in the area of Poyang Lake?
   iii. Can the water area be related to water level? If so, how is the relation between them?

3. To investigate whether there is evidence for a change of the areas of ephemeral vegetation in the central lake
   i. Is there a change in the central lake area with NDVI above a predefined threshold T_v?
   ii. If so, is this year-to-year variation in area with NDVI > T_v following a trend, has it been changing between years or is it abrupt?

4. To investigate whether there is evidence for a change in the central lake water body area in winter time
   i. Is there a change in the central lake area with NDWI above a predefined threshold T_w?
   ii. If so, is this year to year variation in area with NDWI > T_w following a trend, has it been changing between years or is it abrupt?

5. To relate changes in central lake water area to changes in ephemeral vegetation and infer causal relations
   i. Is there a relation between the central lake area with NDWI>T_w and the central lake area with NDVI>Tv?
   ii. Is there a relation between the central lake area with NDVI>T_v and meteorological condition?
   iii. Is there a relation between the central lake area with NDWI>T_w and rainfall?
   iv. Is there a relation between the central lake area with NDWI>T_w and the length of the emergence of ephemeral vegetation?

1.3. Research flow chart

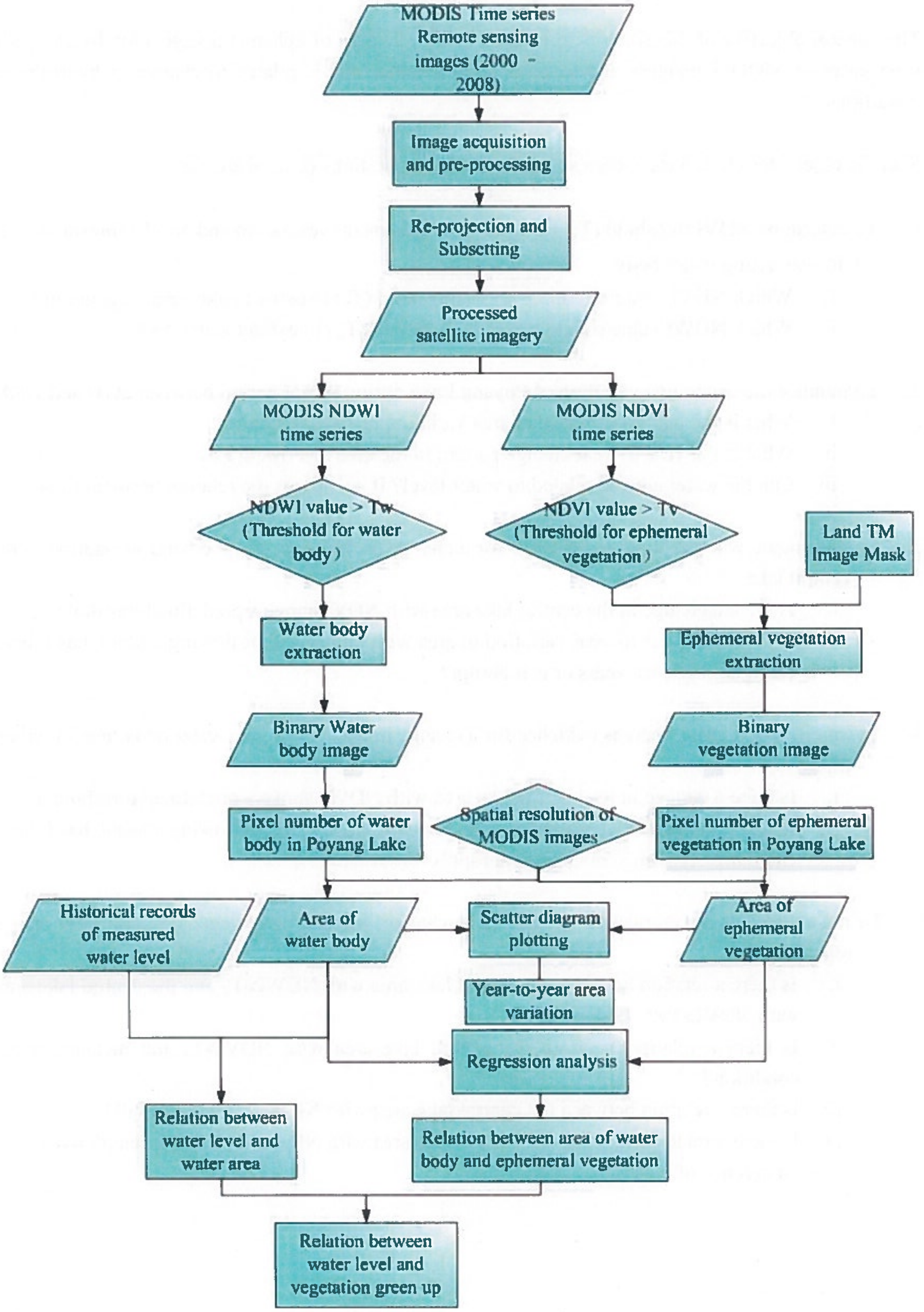

Figure 1-1 Flowchart for research methodology

1.4. Outline of the thesis

- Chapter 1: General introduction of the background, interesting phenomena, problem statement, general and specific research objectives, research questions and overview of methodology
- Chapter 2: A description of the study area that focused on vegetation structures, hydrological condition, environmental factors, and human activities in Poyang Lake
- Chapter 3: A literature review about MODIS, methods for vegetation extraction and methods for water extraction
- Chapter 4: Detailed research methods, which includes data collection and processing, images analysis and statistical analysis and modelling
- Chapter 5: Results obtained from this research, analysis and interpretation on the results and error analysis. Figures, graphs, and models were used to present the results.
- Chapter 6: Conclusions of this research and discussion including shortcomings and corresponding recommendations for further research

2. Study Area

2.1. General description of Poyang Lake

Poyang Lake is the largest freshwater lake in China, which situates in the northern part of Jiangxi Province and in a structural depression south of the Yangtze River. (Figure 2-1) It is located between 115° 49 ′ - 116° 46 ′ E, 28° 11 ′ -29° 51 ′ N in the middle reach of Yangtze River. It stretches to about 173 km from north to south, 50-70 km from east to west. According to the lake submersion time study, the lake could be divided into 3 sub-systems: The water channel in the north above Songmen Mountain; the main Poyang Lake and several lateral lakes such as Kangshan basin, Junshan and Qinglan Lakes (Andreoli et al. 2008).

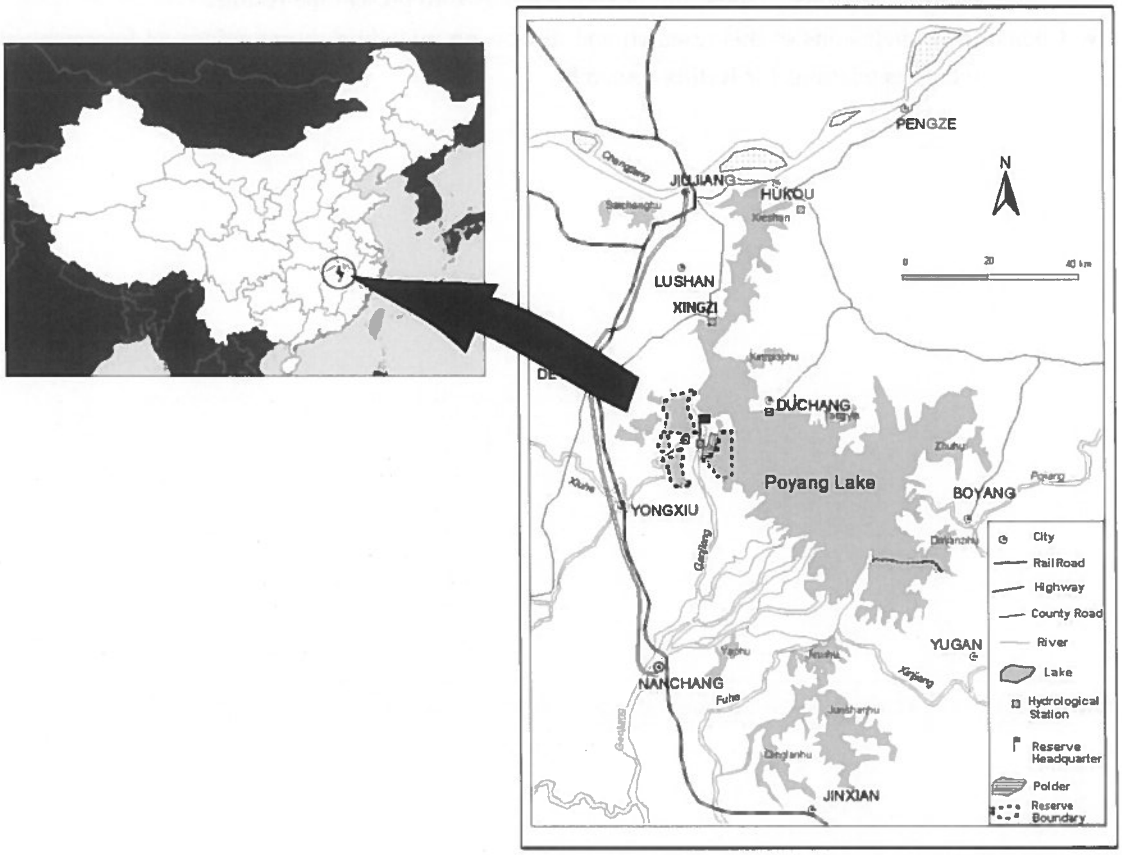

Figure 2-1 Map of study area (Right) and its location on the map of China (left) (Source: SCWP)

Poyang Lake exchanges water with Yangtze River through a 40 km long water channel. It serves as a flood regulator to this river by storing discharges from five tributaries: River Xiu, Gan, Xin, Fu and Rao and weakening the flood peaks. Interactions between the lake and rivers make Poyang wetland an aquatic-terrestrial ecosystem which is further complicated by various environmental factors as well as human activities such as dredging. Poyang Lake has always been put under spotlight by researchers; numerous studies have been done on the environmental issues on hydrology conditions, vegetation dynamics and other natural resources.

2.2. Hydrological characteristics

2.2.1. Historical water level seasonal variation

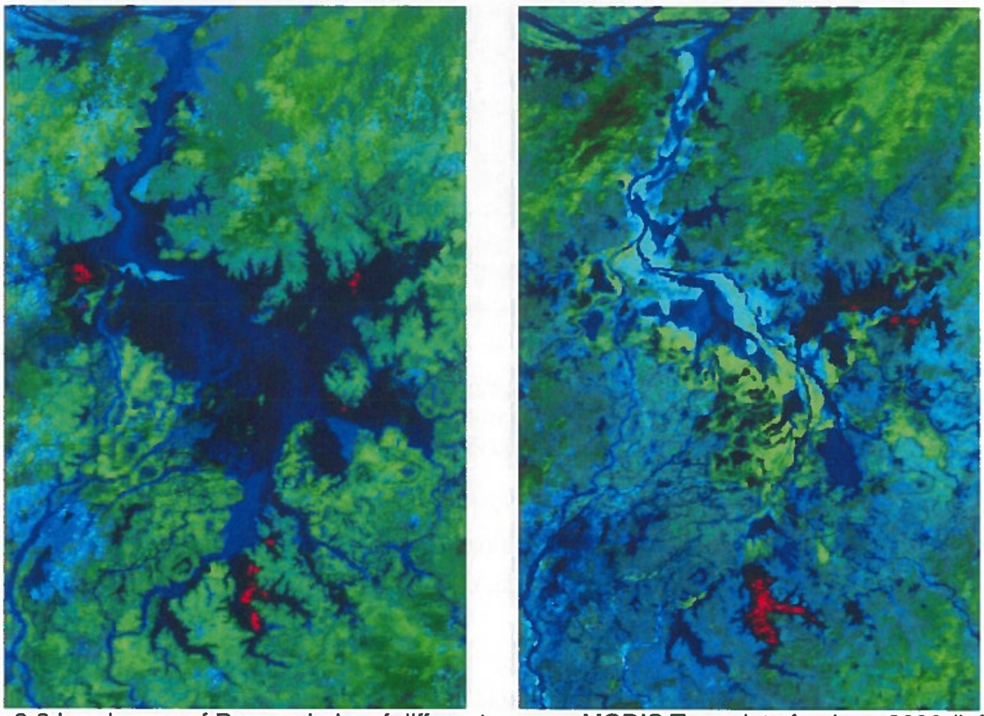

Figure 2-2 Landscape of Poyang Lake of different season MODIS Terra data for June 2006 (left) and November 2006 (Right)

The lake level is mainly influenced by the so called basin effect, which is the surface discharge from five river tributaries in Poyang Lake basin. However, this lake is unusual in that the Yangtze river into which it drains has a blocking effect on lake discharge when the lake water level is low; this effect is weakened when the lake level ascends due to large discharge received from the five rivers (Hu et al. 2007).

The magnitude of fluctuation is tremendous between high and low water level in Poyang Lake, the highest water level is 22.58 m and the corresponding water surface area is approximately 4070 km^2. The lowest water level is merely 5.9 m and the corresponding water surface area is only 30 km^2, the biggest fluctuation is 16.68 meter (Hu and Xiong 2002). Figure 2-2 shows different landscapes of Poyang Lake during high water season in June 2006 (left) and low water season in November 2006 (right). The appearance of the lake changes seasonally, the large lake during summer floods shrivels to a narrow river surrounded by marshland during lows in winter (Li, Li et al. 2008).

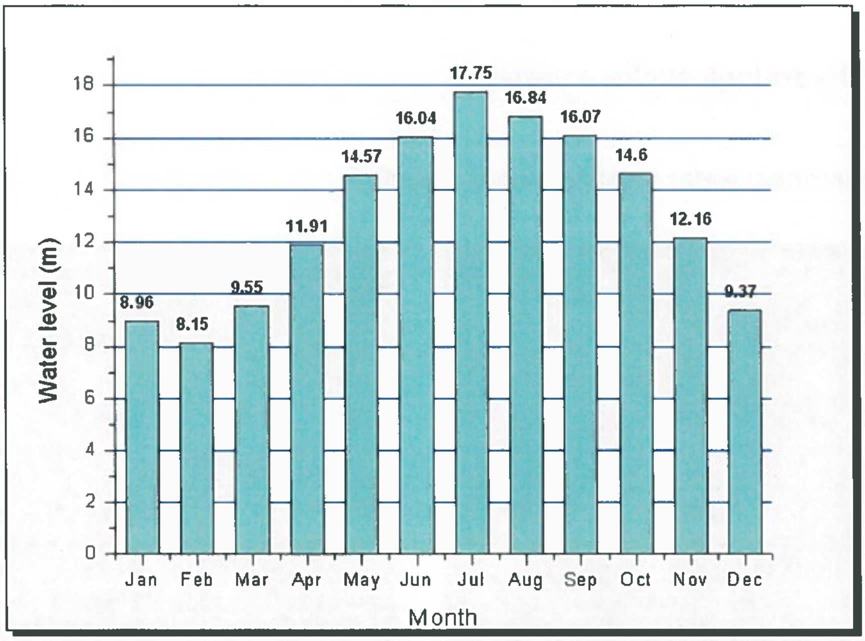

Figure 2- 3 Average monthly water level of nearly 50 years measured at Hukou hydrological station (Liu 2006)

Figure 2-3 shows the monthly average water level of Poyang Lake from 1956 to 2005 measured at Hukou hydrological station. The seasonal variation follows a cyclic pattern. According to historical water level records at Hukou hydrological station, extreme low water level (below 9 m) used to occur in January and February.

Due to the influence from both Yangtze River and five tributaries, Poyang Lake water level remains high for half a year from April to September. The period between April and June is the flood season for the five tributaries and Poyang lake area goes through concentrated rainfall; the lake water level swells up gradually but does not reach the highest. During the period between July and September, the water supply from five tributaries decreases, but Yangtze is in major flood season at the time, the water level is lifted by Yangtze and rises rapidly. The water supply from Yangtze makes water level of Poyang Lake reach the highest within a year.

According to the records from 1954 to 1998 at Hukou water level measuring station, the frequency that the highest water level occurs between July and September is 84.4%. Therefore the highest water level of Poyang Lake is mainly affected by flood in Yangtze River (Hu and Xiong 2002).

During the period between September and December, Poyang Lake recedes stably, since there are not enough water supplies from the five tributaries and Yangtze River is in recession, so the water level decrease correspondingly. In October, the water level may sometimes rise instead due to plenty rainfall. From September to December, the average water level in years measured at Hukou was between 9.37 and 16.07 meters.

2.2.2. Recent water level change

However, since 2000 the previous seasonal hydrological variation pattern has changed. The yearly water extent variation is even more extreme, lowest water level that used to occur in January could be observed in November and the dry season has been prolonged. In 2007, the lake suffered the biggest drought in 50 years, the water area shrunk to only 50 km^2 (Zhang et al. 2008). From Jul, 2006 to Nov, 2006, the water level at Xingzi water level station was 2 m lower than usual in previous years. The water level below 10 m appeared 75 days earlier than usual, In Oct, Nov and Dec,2007, the water level at Xingzi station are 2.38m, 3.11m and 2.3m lower than usual respectively. On Jan 18^{th}, 2008, the water level at Duchang station hit the historically lowest point at 8.05 m (Tan et al. 2008). The decrease of the water level has caused severe consequences, such as the loss of habitat for aquatic animals, lowering income of the fisherman, decrease of overwintering birds grazed on fish and vegetation tube, shortage of live water for the residents around the Poyang basin, inconvenience of shipping, etc (Tang 2008). Some (Li 2008) compare the low water level problem to the chronic disease that jeopardizes the lake eco-system's health gradually and imperceptibly.

2.3. Vegetation dynamics in Poyang wetland

The lake beach grassland constitutes an important sub-system in Poyang Lake wetland ecosystem. The area covered by lake beach grassland can reach up to 100,000 hm^2 (Hu 2007). The distribution of different grassland species like *Carex, Miscanthus* and *Cynodon* varies with elevation and water temperature discrepancy. The wetland grass grows at elevations between 13 and 17m. Lake water level is a primary determinant for wetland grass growth. Every year in flood season, some lake beach grassland species such as *Carex* have been submerged by water and goes into hibernation, other species with longer length stay emerged and aquatic vegetation community begins to dominate. Then in winter and early spring dry season, the sediment exposes and the submerged grass seeds start to germinate as the lake water level decreases and the lake beach would green up and flourish with grassland again (Hu and Xiong 2002). After water recedes, vast areas of grassland and various fragmented small shallow lakes form a unique ecosystem, providing an ideal habitat for overwintering birds grazed on wetland grass. Wetland vegetation in Poyang does not only serve as a very important environmental indicator and food for birds, but also have great economic values. It could be used for grazing livestock and producing fuels and fertilizers.

The term "ephemeral vegetation" refers to the flora species which emerge in temporary waters and dominate the amphibious areas of lakes with fluctuating water levels (Muller and Deil 2005). In aquatic environment, the development of this kind of vegetation is likely to have strong relations with water level. Thus, more insights on the dynamics of ephemeral vegetation in Poyang Lake give more information on the hydrological state.

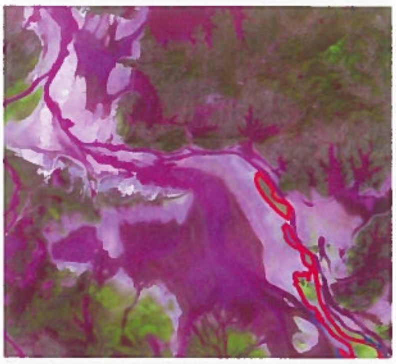

Figure 2- 4 Ephemeral vegetation observed (within the red frame) on Beijing1 30m remote sensing image (covering part of the study area) in winter (11th Nov) 2006

In high resolution satellite image observations, when the water level is extremely low in winter time, there is a mass area of vegetation greening up on the exposed sediment in the central part of the lake (Figure 2-4). And this kind of vegetation will continue to grow till early spring and be submerged when water level rise to normal, the growth of this vegetation is supposed to respond more sensitively to winter water level variation. The low water level hinders shipping at that time, thus makes this area very difficult to access.

2.4. Human activities in Poyang Lake

The abundant natural resources in Poyang Lake provide substantial benefits for the social-economic development in Jiangxi province. However, over-exploitation and over-use of these resources has greatly challenged the wetland ecosystem stability. In 1990s, the amount of zonal vegetation around Poyang Lake decrease due to unregulated logging, construction of embankments and urban development. This directly led to severe water and soil erosion in Poyang Lake region (Hu 2001). More sediment flux into the lake elevated the lake bottom and reduced the lake area causing the lowering of the lake flood storage capability. According to historical hydrological records, high water level above 20 m occurred in 15 years in the period from 1950 to 1998 and 6 years during the time from 1990 to 1998 (Shi et al. 2008).

Intensive dredging activities have taken place in Poyang Lake since 2001 after sand mining was banned from the lower Yangtze River (Zhong and Chen 2005). Dredging induced water turbidity might have many negative effects on the lake ecosystem causing loss of biodiversity. It is also suggested by De-Leeuw, et al. (Submitted) that the sediment balance of Poyang Lake is dominated by dredging activities and that sand mining changed Poyang Lake from a sediment accumulating system to an exporting one. And the bottom of the channel connecting the lake to Yangtze has been much more lowered than the main lake bottom by dredging. The deepening of channel bottom is likely to ease lake water outflow to Yangtze River and thus may result in lower water levels in winter.

3. Literature Review

3.1. MODIS application

Moderate-resolution Imaging Spectro-radiometer (MODIS) is the most comprehensive sensor carried on EOS Terra satellite, which was launched in December 18, 1999. MODIS has a 2330 km wide viewing swath and collects data across a wide spectrum of energy. It takes measurements of the earth in 36 spectral bands between 0.405 and 14.385 μm, and measures data at three different spatial resolutions: 250m (Bands 1-2), 500m (Bands 3-7) and 1000m (Bands 8-36). Table 3-1 shows the characteristics of MODIS medium resolution bands 1-7.

MODIS provides continuous data collection by extending the dataset derived from its heritage sensors launched by EOS, such as AVHRR, Landsat and HIRS. Its frequent (near daily) and wide coverage of the earth and substantial dataset allow for studies on global change dynamics. (Lindsey and Herring 2008) The MODIS science team of NASA have developed 44 MODIS data products (MOD01-MOD44) of four categories: calibration, atmosphere, land and ocean with different specific usage. Because the data products are freely distributed and convenient to acquire, they are frequently used for various environmental studies such as land-cover change, biophysical processes, eco-environmental monitoring. MODIS has been used for quantitative studies on vegetation index (Huete et al. 2002), leaf area index (Yi et al. 2008), biomass (Muukkonen and Heiskanen 2007), crop yield (Doraiswamy et al. 2005), desertification monitoring (Yan et al. 2005), forest and grassland fire monitoring (Wang et al. 2004), etc. have been carried out by scientists in recent years.

Band	Band width(nm)	Spatial resolution(m)	Spectrum Sensitivity	Signal/Noise Ratio
1	620−670 (Red)	250m	21.8	128
2	841−876 (NIR)	250m	24.7	201
3	459-479 (Blue)	500m	35.3	243
4	545-565 (Green)	500m	29	228
5	1230-1250 (NIR)	500m	5.4	74
6	1628-1652 (MIR)	500m	7.3	275
7	2105-2155 (MIR)	500m	1	110

Table 3-1 Characteristics of MODIS medium-resolution bands 1-7

3.2. Extraction of vegetation

Normalized difference vegetation index (NDVI) was initially proposed by Townshend and Justice (1986) to assess above-ground biomass and primary productivity of vegetation in 1986. Due to the fact that vegetation has higher near-infrared reflectance (NIR) and lower red light reflectance (RED), the presence of terrestrial vegetation could be greatly enhanced with NDVI calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED}.$$

Since then, it has been broadly used for remote sensing based vegetation studies.

It is commonly used with various sensors to study vegetation phenology, monitor spatial-temporal vegetation dynamic, generate vegetation maps, etc. Various scientific researches have extracted vegetation information using NDVI concerned methods. Cheng, et al. (2008) had used a NDVI fixed-thresholding method combined with a tasseled cap transformation and a designed image fusion method to generate a high-resolution vegetation maps using 126 IKONOS imageries. Yoshida (2005) use NDWI as a supplement for NDVI to synoptically observe the riparian vegetation distribution along ephemeral rivers in western Namibia. His results showed that NDVI threshold method worked well in extracting the overall distribution of vegetation but with errors, More detailed spatial pattern of coastal desert and dense vegetation in inland highland could efficiently observed by integrating NDVI and NDWI together. Pu (2008) carried out a change detection experiment for salt cedar - an invasive vegetation species in Nevada using classification and NDVI differencing methods with CASI hyper-spectral datasets. NDVI differencing method turned out to be more accurate than the classification method in this study. Susaki and Shibasaki (1999) characterized crop field with a crop field model developed with NDVI value and textual information (the density of straight lines which are extracted by wavelet transform). Among the NDVI threshold candidates determined by "scale-space filtering" method, the most appropriate threshold value was chosen by evaluating the line density of the area. The extracted crop field matched very well with visual interpretation. Danzeglocke and Menz (2004) studied the large-scale spatial distribution dynamics of timberline elevation by using filtering techniques and defining a threshold of NDVI calculated from MODIS surface reflectance data. He stated that despite numerous sources of error and uncertainty exist, NDVI is more suitable than SAVI (Soil-Adjusted vegetation Index) for reach his study purpose.

3.3. Extraction of water bodies

The principle for extracting the water 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. Satoshi (2004) studied the dynamic variation of the surface water area and water storage in Dongting Lake by setting threshold with MODIS images derived NDVI data.

NDWI was first used to delineate water body by McFeeters (1996), he calculated NDWI with reflectance of the green and NIR band from Landsat TM. It is also suggested by him that NDWI may provide possibility to assess water turbidity with remote sensed data. NDWI was defined as:

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

NDWI was developed using the similar principle with NDVI, it made use of the high reflectance figure of water within green light wavelength and low reflectance figure of water within NIR wavelength. On the other hand, soil and vegetation normally have higher reflectance of NIR than green light, so vegetation and soil information were effectively eliminated for having zero or negative value of NDWI.

Xu (2006) differentiated ocean, lake and river areas from various other types of land covers in Xiamen city with MNDWI calculated with band 4 (NIR) and 5 (MIR) of Landsat TM/ETM+ and proved that MNDWI worked better in extracting water bodies from built-up land dominated areas than NDWI in that case. Wang and Yi (2007) compared the accuracy of using five different feasible indices (RVI, NDVI, NDWI, MNDWI and NDSI) derived from MODIS imagery and suggested that MDNWI is the optimal index for extracting water body of Dongting lake. Min (2004) use NDWI, NDSI and other indices calculated with reflectance value from band 1-7 of MODIS 500m resolution imagery to identify water body of the upper reach of Yangtze river. Hui, et al. (2007) used NDWI and MNDWI derived from multi-temporal Landsat imagery to monitor the changing water extent and the temporal inundation of water over marshlands in Poyang Lake. It is concluded that multi-temporal images could be used to study the pattern of the varying water coverage in Poyang wetland, but not sufficient for accurate estimation of relation water inundation pattern. Zhang, et al. (2008) constructed a new water index: Normalized Difference water deviation Index (NDWDI) based on NDWI to extract the spatial temporal-characteristics of 2006 drought in Sichuan Basin using MODIS data. This new index proved to be very sensitive to regional drought.

4. Research Materials and Methods

4.1. Research Materials

MODIS imageries

8-day composite MODIS surface reflectance data MOD09A1 and MOD09Q1 were used to generate time series. MOD09Q1 provides Bands 1 (Red) and 2 (Near Infrared) at 250-meter resolution in an 8-day gridded level-3 product in the Sinusoidal projection. MOD09A1 provides Bands 1–7 at 500-meter resolution in an 8-day gridded level-3 product in the Sinusoidal projection. (More details specified in 4.2.1.1)

Landsat TM imageries

Landsat TM images of 28Oct, 2004 and 31 Oct, 2005 were shared by Wu (2008) from International Institute for Geo-information Science and Earth Observation in the Netherlands. They were originally acquired from Chinese Remote Sensing Satellite Ground Station. These images had been geo-referenced and atmospherically corrected by Wu (2008).

Meteorological data

Monthly temperature and rainfall data of January, 2000 to September, 2008 measured from eight meteorological stations located at Yongxiu, Hukou, Xingzi, Duchang, Poyang, Nanchang, Yugan and Jinxian around Poyang Lake.

Water level data

Monthly water level data of Duchang of January, 2000 to December, 2008 was acquired from Jiangxi Hydrological Bureau. Water level data was transferred to Wusong height datum.

Topographic map of Poyang Lake

1: 250000 topographic map of Poyang Lake Basin was obtained from staff working in Nanchang University.

4.2. General methods

4.2.1. Data acquisition and Data pre-processing

4.2.1.1. MODIS image acquisition

Remote sensing data sources were abundant, but certain factors were taken into account in choosing data products for this specific case: the accessibility of data; the expense for acquiring data; quality of data (resolution and noise). Long term monitoring of Poyang Lake water dynamics and vegetation dynamics require large volume of datasets, high temporal resolution and cost effective remote sensing images. Though imaging system like Landsat Thematic Mapper provides image data which reveals earth with finer spatial resolution, it only has an infrequent coverage of a given study of once per 16 days. And the expense of acquiring the data is too large.

MODIS satellite data was selected for studying the area variation of both vegetation and surface water. MODIS imageries have coarse spatial resolution of 250m, 500m and 1000m, which is a shortage in accurately identifying small land covers. However, the area of Poyang Lake is up to over 4000 km^2, corresponding to 16000 pixels on the 500 m image data. The resolution was good enough for displaying the study area.

MODIS 8-Day composite (MOD Q1/MOD A1) and daily surface reflectance (MOD GQ/ MOD GA) data of the time span from 2000 to 2008 were downloaded from EOS data gateway (https://wist.echo.nasa.gov/api/) using the web-based search and FTP. With the cloudy and noisy images excluded, 466 images (233 MODQ1 and 233 MOD A1 images) were acquired in this 9 year period. MODIS surface reflectance daily products MOD GQ contains two 250 m band (Bands 1-2), MOD GA consists of 7 medium resolution bands (Bands 1-7), for each band the surface spectral reflectance value was estimated assuming that there were no atmospheric scattering or absorption. It is the source data for generation of several other MODIS products such as the 8-day composite surface reflectance, Vegetation indices, etc using different algorithms. Each MODIS 8-day composite (MOD Q1/MOD A1) contains the best possible L2G daily observation during an 8-day period in terms of high observation coverage, low view angle, absence of clouds or cloud shadow, and aerosol loading.

4.2.1.2. Image subset and re-projection

The images downloaded were centered at 24.97° latitude, 116.55° longitude. Each scene covers a large extent of Southeast China. Hence, firstly raw data had to be subsetted to extract the area of interest. 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/500m grid cell multilayer images.

MODIS Re-projection Tool[1], developed by U.S. 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. Then all MODIS hdf files were imported into Erdas Imagine 8.7[2] to prepare for further image processing. Figure 4-1 shows one example of sub-setting and re-projecting the raw image downloaded from EOS data gateway into a scene of the area of interest using MRT.

[1] MODIS Reprojection Tool, USGS - NASA Distributed Active Archive Center http://igskmncnwb001.cr.usgs.gov/landdaac/tools/modis/index.asp

[2] Erdas Imagine 8.7 (ERDAS Inc., Atlanta GE http://www.erdas.com/)

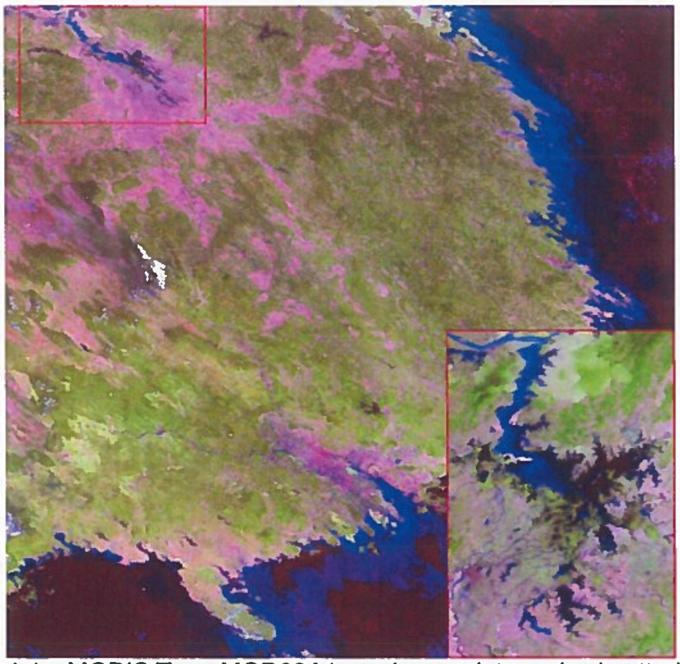

Figure 4-1 MODIS Terra MOD09A1 raw image data and subsetted image

4.2.2. Visual interpretation

Because the lack of in-situ information of the study area due to difficulties accessing the field and impossibility to test the historical remote sensing images, this study was carried out with the aid of visual interpretation of both current and historical images.

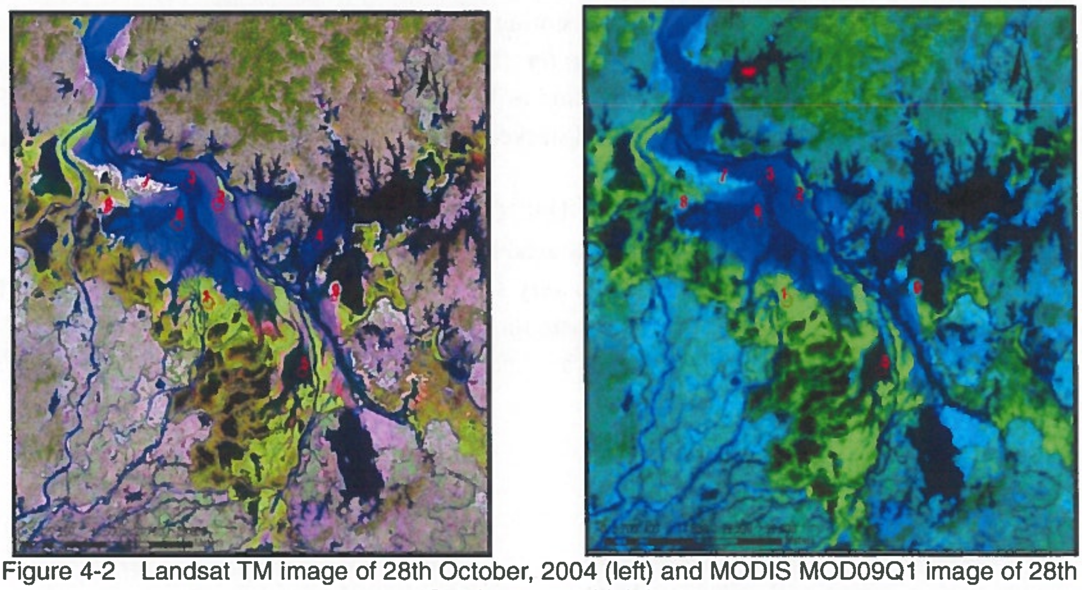

Figure 4-2 Landsat TM image of 28th October, 2004 (left) and MODIS MOD09Q1 image of 28th October, 2004 (right)

From Figure 4-2, we can see Landsat TM color composite image with band 5 (MIR), 4 (NIR), 3(Red) and MODIS color composite image with band 3 (quality control), 2 (NIR) and 1 (Red) best imitated the real color of the land cover. Landsat TM image provided more elaborate ground information because of finer spatial resolution and more spectral bands and can thus help validate the cover type revealed in coarser MODIS images. On the Landsat TM image, the bright greenish pixels (1) represent the non-zonal vegetation which exposes on the sediment when water level is low. The grayish pixels (2) represent the exposed sediments. Light and dark bluish pixels (3, 4, 5) represent water bodies. The pale bluish pixels (6) represent the mudflat among water areas. And the whitish pixels (7, 8, 9) represent sand and sand soil.

4.2.3. Determination of NDVI threshold

In numerous scientific studies, NDVI has been proven to be one of the most successful indices to simply and quickly identify vegetated areas. It was implemented on satellite images produced from different types of sensors including MODIS. An NDVI threshold is needed to delineate vegetated area, for instance, an area covered by dense vegetation canopy is likely to have an NDVI value of 0.3 to 0.8. The soil may reveal a rather small positive value of 0.1 to 0.2 and open water features have negative values. However, when using NDVI to do quantitative assessment, the threshold should be selected with caution and awareness of various factors that might influence NDVI value, such as atmospheric effects, clouds, soil effects and spectral effects. NDVI value derived from different sensors would yield to different results. Thus, in this study, an appropriate NDVI threshold needs to be determined to extract vegetated area with MODIS for each date. MODIS images are too coarse to precisely recognize the vegetated area, thus a high resolution Landsat TM image of 28Oct, 2004 providing more accurate land cover details and clearer spatial pattern of vegetation was used as a reference map to locate the vegetated area.

1) First this image was re-projected into UTM projection with WGS 84 datum to conform to the MODIS images.
2) 369 sample points were carefully selected, by visual image interpretation, within the vegetated area on Landsat image (Figure 4-3, left) and digitized using ArcGIS 9.0[3]. The sample points were saved in a point type shapefile.
3) The shapefile was opened in ENVI 4.5[4] and imported to an ENVI supported format evf Then the evf. file was exported as a ROI (Region of interest) layer.
4) An NDVI map was produced with MODIS image acquired on 28Oct, 2004 in ENVI using the band math tool.
5) ROI layer was associated with this NDVI map in ENVI. So that the sample points fit in this MODIS image. (Figure 4-3, right) In the ROI tool, we can view the attributes of the sample points and ROI statistics results showed the distribution of NDVI Value of vegetated area on this MODIS image.
6) 157, 123, 113 and 75 sample points were selected within the exposed sediment area, water area, mudflat area and sand area on this Landsat TM image, and step 2)-5) were repeated to understand the distributions of NDVI value of these areas on MODIS image.

[3] ArcGIS 9.0. ESRI Inc. USA http://www.esri.com/
[4] ENVI 4.5. ITT Visual Information Solutions Inc. USA http://www.ittvis.com/ENVI

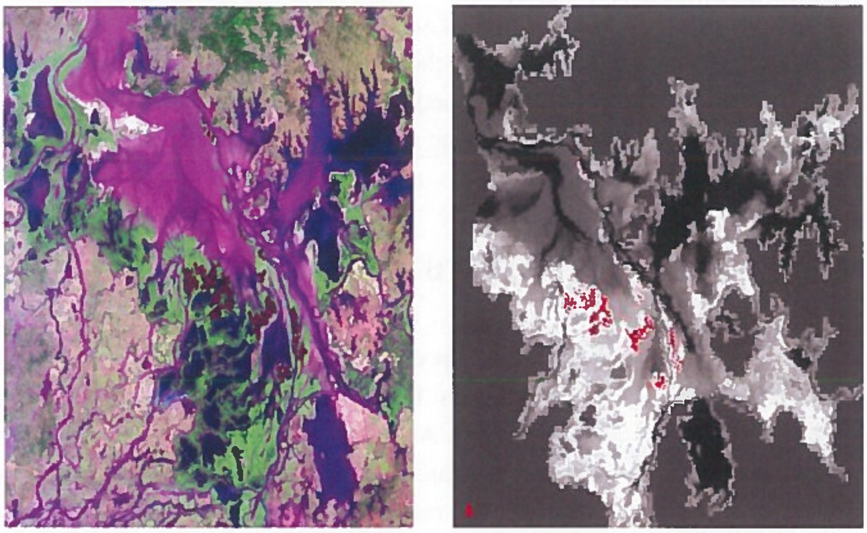

Figure 4-3 Sample points of vegetation extracted on Lantsat TM image of 28th Oct, 2004 (left) and associated with MODIS NDVI image on of 28th Oct, 2004 (right)

	Min	Max	Mean	Stdev
Vegetation NDVI	0.25366	0.85831	0.62823	0.11396
Sediment NDVI	0.08016	0.24463	0.13564	0.02434
Water NDVI	-0.5368	0.19931	-0.2724	0.1756
Mudflat NDVI	0.05492	0.17003	0.11927	0.02632
Sand NDVI	0.0226	0.23531	0.18597	0.07215

Table 4-1 Distribution of NDVI value of different land cover types on MODIS NDVI map of 28th Oct, 2004

The minimum NDVI value of vegetation shown in this Table 4-1 is 0.253655. This might suggest that 0.25 could be the NDVI threshold for this scene. For this scene we could decide the threshold more precisely, although there are still errors. However for other scenes, if the thresholds were determined solely by visual observation on the MODIS coarse image, it could lead to bigger error because of the mixed pixels and inaccurate interpretation.

Thus, we still used Landsat TM image of 28Oct, 2004 to derive 26 sample points within the greening up ephemeral vegetated area as virtual ground controls points and then attach these points to MODIS time series images between Nov, 2003 and Apr, 2004 to see the variation of the NDVI value (Figure 4-4, note that in this figure, the MODIS scenes are indicated by the year followed by the Julian date number).

MODIS date	Min	Mean	Max
2003321	-0.0249	0.255158	0.557265
2003329	0.02519	0.350552	0.701414
2003337	-0.01635	0.279911	0.573059
2003345	-0.25857	0.242844	0.646154
2003353	-0.09241	0.234877	0.480519
2003361	0.071448	0.301125	0.541109
2004001	0.01306	0.162761	0.35072
2004009	-0.09337	0.203128	0.446209
2004017	-0.14782	0.274361	0.536862
2004033	-0.10703	0.11929	0.247129
2004041	-0.07475	0.282335	0.498188
2004049	0.152416	0.367404	0.512166
2004057	0.051985	0.378497	0.572964
2004065	-0.15282	0.405857	0.696767
2004073	0.013761	0.32621	0.600463
2004081	0.02004	0.235647	0.524438
2004089	-0.16435	0.445956	0.723971
2004097	-0.19628	0.451552	0.71093
2004105	-0.13356	0.492792	0.752186
2004113	0.008731	0.438513	0.784143
2004121	-0.4589	0.182305	0.77959

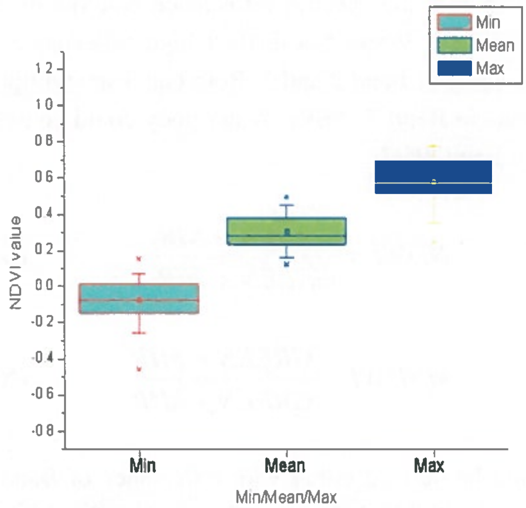

Figure 4-4 Table of temporal NDVI variation between Nov, 2003 and Apr, 2004 (left) and the corresponding Boxplot of NDVI distribution (right)

The temporal variation of NDVI value shown in Figure 4-4 might be caused by normal phenology development. The minimum NDVI value variation was likely to be strongly affected by water level fluctuation, hence not suitable as NDVI threshold. The central box of the mean NDVI boxplot spans about 0.24 and 0.38. The median value is about 0.28. Therefore the values between 0.24 and 0.28 were considered as good candidates for NDVI thresholds. We applied the threshold of 0.25 in all MODIS scenes and visually observed the extracted vegetated area, 0.25 worked quite well as threshold for all scenes. Because lack of *in situ* knowledge, low spatial resolution and existing image noise, the thresholds were determined with small errors that did not significantly affect the observation of overall spatial pattern of the ephemeral vegetation.

4.2.4. Determination of NDWI threshold

The land cover within the lake watershed could be mainly categorized into 4 types: vegetation, sediment water and mudflat. Spectral reflectance patterns of each cover type were observed.

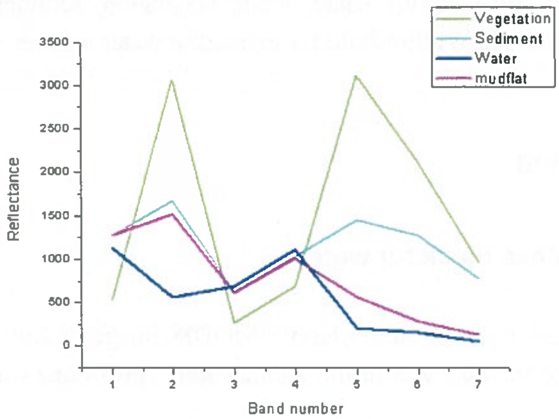

Figure 4-5 Spectral reflectance patterns of lake water, vegetation, sediment and mudflat in MODIS Image of Poyang Lake

Figure 4-5 reveals the spectral reflectance patterns of different land cover types on the 7 bands of MOD09A1 image. Water has distinct high reflectance value of Band 4 (Green) and relatively low reflectance value of Band 2 and 5. Both bands are within the NIR wave length. The lowest reflectance value appears in Band 7 (MIR). Water body could be extracted using the reflectance contrast between Band 4 and Band 2/5/7.

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \qquad \text{(McFeeters 1996)}$$

$$MNDWI = \frac{GREEN - MIR}{GREEN + MIR} \qquad \text{(Xu 2006)}$$

NDWI could be derived either with reflectance of Band 4 and Band 2 or reflectance of Band 4 and Band 5. But mudflat had similar reflectance of Band 5 with water. It is difficult to differentiate water from mudflat by using NDWI calculated with Band 4 and Band 5 in this study. MNDWI was proposed by (Xu 2006) and proven to be a better index for differentiating water from built-up areas. In Figure 4-5, we could see that the reflectance contrast between Band 4 and Band 7 was indeed the biggest. MNDWI greatly enhanced water body in MODIS images and small water bodies was distinctly recognized. However, sediment and mudflat reflectance of Band 7 were lower than that of Band 4. The MNDWI of sediment and mudflat appeared to be positive values. Sediment information was only suppressed by MNDWI, but not eliminated. And mudflat information also was enhanced by MNDWI as well as water. Thus, MNDWI was not a good option for extracting water in winter when lake water was mixed with marshland and mudflat.
NDWI was calculated as:

$$NDWI = \frac{CH4 - CH2}{CH4 + CH2}$$

where CH4 and CH2 represent reflectance value of Band 2 and Band 4 respectively.

Water features have positive NDWI value, while vegetation, sediment and mudflat have zero or negative value. Therefore, NDWI threshold for extracting water was set as 0.001.

4.2.5. Masking

4.2.5.1. Make mask for water

Unsupervised classification was used to classify MODIS image of July, 4th 2006, when Poyang Lake was in flood season and the lake was in full submersion. This image was classified to only 2 classes: land and water body.

The water-supplying inland rivers and small water bodies were excluded by using the ArcGIS raster to vector tool to convert the classified img file to a polygon shape file. Then the "erase" function in spatial analysis/overlay tool was used to eliminate the polygons representing the water bodies outside Poyang Lake watershed. The water body binary img mask was acquired in Erdas using the vector to raster tool. The "1" and "0" value represents areas to be extracted and to be excluded, respectively. Within the masked water body area, water surface area variation could be monitored by setting NDWI threshold.

4.2.5.2. Make mask for ephemeral vegetation

Comparing to water mask, vegetation mask should be more carefully made to extract area of interests. Landsat TM image of Oct. 28, 2004 was chosen to generate a classified NDVI map by setting NDVI threshold of 0.25 to identify vegetations.
The NDVI classified map could be generated by using the following formula in Erdas Imagine model maker:
($n1_20041028_atm_corrected(4)-$n1_20041028_atm_corrected(3))/($n1_20041028_atm_corrected(3) + $n1_20041028_atm_corrected(4)+0.0001)

The number 4, 3 in the brackets represent TM band 4 (NIR band) and 3 (Red band), respectively. The output type of NDVI map was defined as float single. Then the image was sliced into three classes by setting criteria (threshold) in the Model maker. Areas with pixel NDVI value above 0.25 were masked out. The perennial vegetation stretching along the lakeshore was excluded; the central area of the lake where ephemeral vegetation grows was extracted.

4.2.6. Calculation of vegetated area and water area

Once the thresholds were determined and images were masked, the NDVI and NDWI map of each MODIS image could be made (Appendix A). ENVI 4.5 provides a convenient band math tool to quickly calculate indices and generate maps. Band thresholds were input in the "band threshold to ROI" tool. The number of pixel with value above threshold for each image was extracted directly in the ROI tool. And vegetated area with pixel NDVI value above threshold T_v and water area with pixel NDWI value above threshold T_w were calculated as:

$S = NR^2$,
With N: number of pixels identified as vegetation/water
R: resolution of the data

In each month, 3 or 4 scenes of 8-day composite MODIS images were acquired. However, some images were either covered by clouds or contaminated by noise. Up to 4 good composite images were selected for area calculation. If there were 2 or more images chosen, we calculated the average value of areas calculated from these images for statistical analysis.

4.3. Time series analysis

4.3.1. Monitoring area variation

4.3.1.1. Poyang Lake area variation

In order to better understand the hydrological dynamics of Poyang Lake in recent years, we analyzed the Poyang Lake water surface area variation between 2000 and 2008 with MODIS data time series (Appendix B). First we used the mask made in 4.2.5.1 to extract water body covering the whole lake area which is submerged in summer flood season, including the water channel in the north, Poyang Lake main basin and small lateral lakes, such as Kangshan basin, Junshan and Qinglan lakes. With cloudy and heavily noisy data excluded, 229 MODIS MOD09A1 8-day composite 500 m images were used for monitoring, thus the average temporal resolution of this time series is approximately biweekly. The year 2007 was best covered with 30 data, while only 19 images were usable in 2000 because MODIS MOD09 data were not available until Mar, 2000. Water bodies were extracted inside the masked area with pixel NDWI value above 0.001. Then water extent was calculated by multiplying the number of these pixels with 0.25 km^2 (spatial resolution of the 500 m MOD09A1 data).

4.3.1.2. Variation of area of ephemeral vegetation and central lake water area

Both area of ephemeral vegetation (AEV) and central lake water area (CLWA) were extracted within the mask made in 4.2.5.2 (Appendix C). Ephemeral vegetation only appears in winter and early spring, so we limit the study time to the period between November and April in each year from March, 2000 (when MODIS started to be available) to January, 2009. 165 MODIS MOD09Q1 images and 165 MODIS MOD09A1 images were used to generate NDVI and NDWI maps respectively.

AEV was calculated as: $S_{AEV} = N_{NDVI>0.25} \times R_{MOD09Q1}$ (km^2), where $N_{NDVI>0.25}$ represents pixel number with NDVI value above 0.25, $R_{MOD09Q1}$ represents the resolution of MOD09Q1 data (250m × 250m).

CLWA was calculated as: $S_{CLWA} = N_{NDWI>0.001} \times R_{MOD09A1}$ (km^2), where $N_{NDWI>0.001}$ represents pixel number with NDWI value above 0.001, $R_{MOD09A1}$ represents the resolution of MOD09A1 data (500m × 500m).

1) Seasonal variation of AEV and CLWA in different years

AEV and CLWA were plotted against months from November to April in each year between 2000 and 2008 with CLWA on the left Y axis and AEV on the right Y axis. The temporal development of AEV and CLWA in these years can be observed from 8 graphs. And we can see whether there is a seasonal trend, whether there is a relation between the variation of AEV and variation of CLWA and how the timings of extreme large AEV and extreme low water vary between years.

2) Year-to-year variation of AEV and CLWA

AEV and CLWA of each month between November and April were plotted against different years between 2000 and 2008 in 6 graphs to learn if there's a trend of the inter-annual variation of AEV and CLWA, whether there's abrupt changes between years and how is the year-to-year change pattern.

4.3.2. Regression Analysis

Regression analysis was conducted to discover the relation between Poyang lake water extent and water level at Duchang, vegetated area and water area, etc.

Because for the analysis of the relation between CLWA and AEV, the sample size is relatively small: year-to-year analysis based on 9 year observations makes sample size n equal to 9. As a rule of thumb the number of variables for a regression model is one for every five degree of freedom. Hence we selected simple regression model that contains only one variable. The degree of freedom was then 8. The potential models were:

Linear model: $Y=a+b*X$
Logarithmic model: $Y=a+b*\ln(X)$
Power exponential model: $Y=a*e^{bX}$

Observing the data distribution or growth pattern helps us to choose and use the best fitting model. Linear model fits the study of straight line relation between variables or a variable that grows linearly over time ideally with a fixed increment added in each equal time period. It is well-suited for quantitative study of a steady trend. However, natural variables don't often grow in such a steady linear pattern. Sometimes we resort to logarithm or exponential models to study the changing growth pattern and the curved relationship between two variables. The Curve Expert[5] computer program, version 1.3 was used to develop different models and best-fitting model was selected in terms of having the bigger coefficient of determination ("R^2") and smaller standard error. SPSS[6] software version 15.0 was used to conduct multi-variate regression analysis and regression diagnostics.

4.3.2.1. Relation between water area and water level

Average water area of Poyang Lake was calculated on monthly basis with the observations and plotted against the monthly water level data measured from Duchang hydrological station. Duchang was located near the conjunction between the water channel and the main Poyang Lake. Water level measured at this station is representative of the average water level in Poyang Lake.

There were supposed to be 106 month observations in 9-year period, however in 5 months (June, 2002; August, 2003; February, 2005; February, 2006; May, 2008) during this period no cloud-free data was available. Therefore 101 observations were used to learn the relationship between water area derived from MODIS data and the actual water level.

4.3.2.2. Relation between area of ephemeral vegetation and central lake water area

The growth of ephemeral vegetation was prone to respond sensitively to the variation of water extent. Regression analysis was conducted to learn whether there was a relation between AEV and CLWA.

[5] CurveExpert 1.3 is a comprehensive curve fitting system for Windows. XY data can be modeled using a toolbox of linear regression models, nonlinear regression models, interpolation, or splines. http://userpages.xfoneusa.net/~dhyams/cmain.htm
[6] SPSS 15.0 (SPSS Inc., Chicago IL,http://www.spss.com/)

The sample size was small: 9 in Nov, Dec, Jan, Mar and Apr; 6 in Feb. Therefore, simple best-fitting linear/exponential/logarithm models were chosen to study the relation.

4.3.2.3. Relation between central water area and rainfall data

Lack of rainfall was considered as one possible cause for the low winter water level in Poyang Lake. In this session, the monthly average rainfall data was calculated with monthly rainfall data measured from 8 meteorological stations around Poyang Lake. A linear regression analysis was carried out to learn whether there was a relation between CLWA and rainfall data.

4.3.2.4. Relation between vegetated area and meteorological data

To study the relation between vegetated area and environmental factors, a multivariate model was established using AEV as dependent, CLWA, temperature and rainfall as explanatory variables in SPSS.

4.3.2.5. Relation between yearly mean central lake water areas and emergence of ephemeral vegetation

While observing the MODIS time-series images of Poyang Lake central area, we discovered that the timing of emergence and the submergence of the ephemeral vegetation varied between years. The variation of the length of emergence was likely to be related to the water area variation in the central area.

The minimal, maximal and mean NDVI value was calculated with ENVI ROI stats tool for 29 pixels selected in the central green up area (the area was observed as the earliest green up zone in the central lake in each year) on 28, October 2004 TM image. The emergence of ephemeral vegetation was defined by the time when maximal NDVI value of these 29 pixels exceeded the pre-defined threshold value 0.25. The submergence or end of the green season was defined by the time when the maximal NDVI value of these 29 pixels went below 0.25. The length of emergence of ephemeral vegetation was calculated by subtracting the date of emergence (onset of greening up) from the date of submergence.

5. Results and discussions

5.1. Monitoring area variation

5.1.1. Poyang Lake area variation

The total area of extracted region including perennial water bodies and area of water level variation was estimated to about 4040.19 km^2. The time interval with water area below 1000 km^2 was considered as low water level period. Figure 5-1 shows the variation of lake area in a typical year (2005).

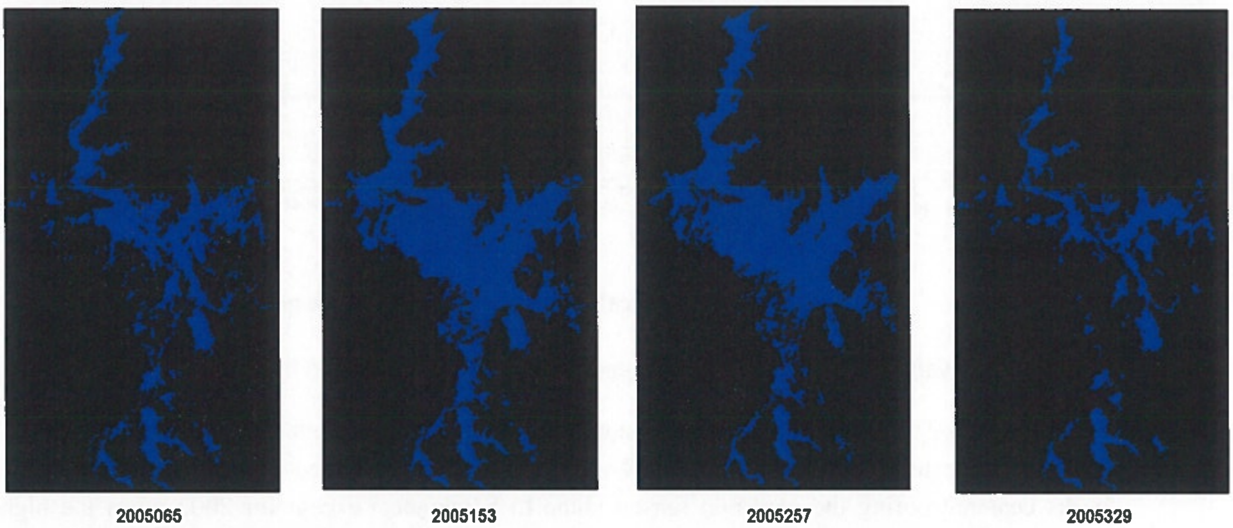

Figure 5-1 The extracted lake water bodies in different quarters of 2005

Though the temporal resolution varied among years, we could still observe a continuous 9-year Lake dynamic pattern through these 229 observations. The water extent variation of each month between 2000 and 2008 was plotted against month in Figure 5-2.

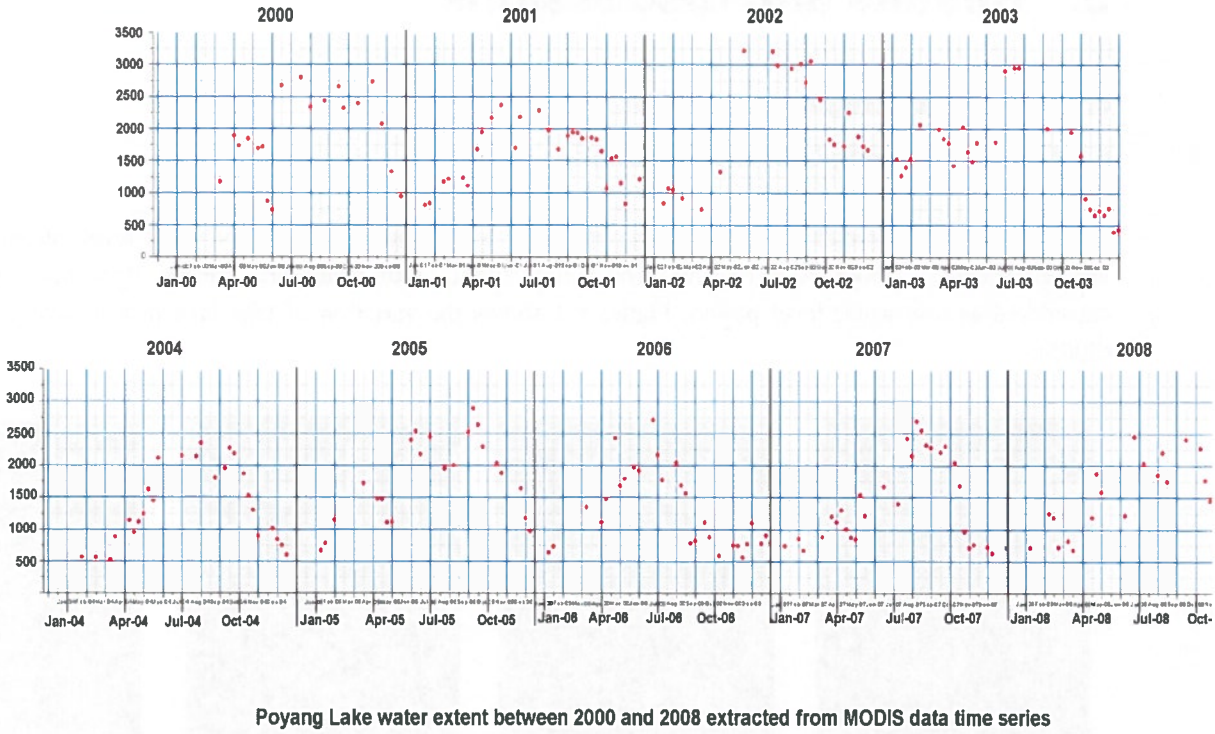

Figure 5-2 Poyang Lake water extent between 2000 and 2008 extracted from MODIS data time series

From Figure 5-2, some characteristics of the water extent dynamic were found as follows:

1) The water extent variations during this 9-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 9-year-period was reached in May and 2005 when the variation showed a more undulating pattern.

2) During the period between 2000 and 2008, the maximal Poyang Lake water extent was reached in May 2002 with an area of about 3200 km^2. And the minimal Poyang Lake water extent observed was around 400 km^2 in December 2003. Thus the water extent almost shrank by 90% of the total area in extreme low water season.

3) Before 2003, the winter water extent was generally higher than 1000 km^2. In 2000, the low water season occurred in late December and lasted only one month till January 2001. In 2001, the low water season lasted longer between December 2001 and March 2002. The water stayed high beyond 1500 km^2 in winter 2002.

4) After 2003, lower winter water extent and longer low water season was observed except in 2005. In winter 2003, the water extent dropped considerably and the low water period persisted from November 2003 to April 2004, which was almost half a year. In 2004, the low water season lasted three months between November 2004 and January 2005. However, the water extent stayed beyond 1000 km^2 in winter 2005.

5) One notable figure in water extent variation in 2006 was that the low water period started much earlier than before. In September, 2006, the water extent already dropped below 1000 km^2. And the low water period persisted from then until Mar, 2007. That counted for a time span of over 7 months of low water. The water extent rose back slightly in Apr, 2007 and gradually climbed to its peak at about 2,700 km^2 in August. Water extent stayed high between August and September and then went

down below 1000 km^2 in October. The low water period lasted between October, 2007 and March, 2008 except for two observations in February 2008. In winter 2008, the low winter water took place in late December.

5.1.2. Variation of area of ephemeral vegetation and central lake water area

5.1.2.1. Seasonal variation of ephemeral vegetation area and central lake water area in different years

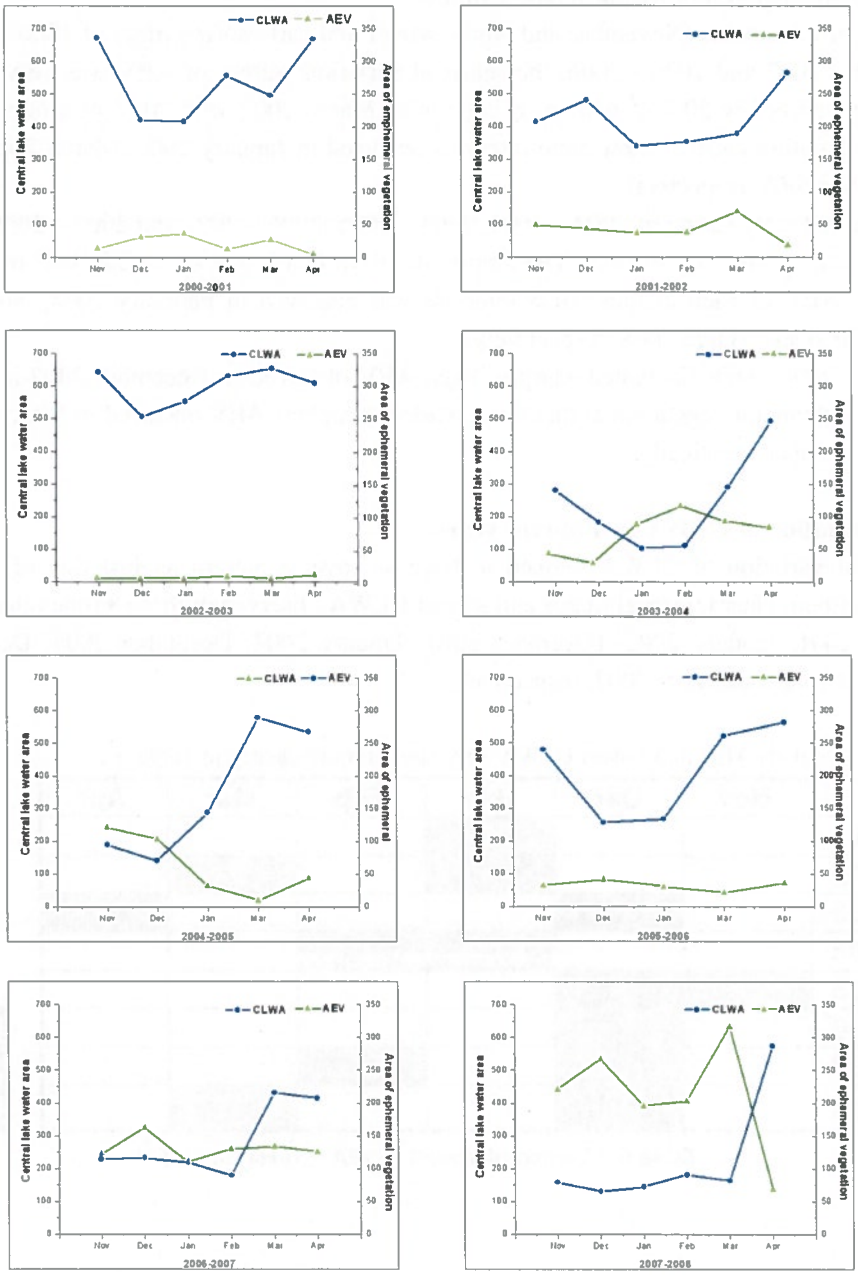

Figure 5-3 Seasonal variation of area of central lake water area (left Y axis with scale from 0 to 700 km^2) and ephemeral vegetation (Right Y axis with scale from 0 to 350 km^2)
CLWA: central lake water area; AEV: area of ephemeral vegetation

In figure 5-3, the area of ephemeral vegetation (AEV) and central lake water area (CLWA) were plotted against months from November to April in each year between 2000 and 2008 with CLWA on the left Y axis and AEV on the right Y axis. No monotonic trend was found in seasonal variation of either CLWA or AEV in all years.

Seasonal variation of AEV in different years:

1) In different years, the maximal and minimal AEV occurred in different months with different values. The fluctuation followed different patterns.

2) In time period between November and April (winter and early spring time) of 2000 – 2001, 2001 – 2002, 2002 – 2003 and 2005 - 2006, the seasonal variation pattern of AEV was very flat and AEV generally stayed below 50 km^2 with an exception in March 2002 with AEV of around 70 km^2. The highest AEV within each of these time intervals occurred in January 2001, March 2002, April 2003 and December 2005, respectively.

3) In winter and early spring of 2003 – 2004, 2004 – 2005, 2006 – 2007 and 2007 – 2008, AEV varied more significantly between months. The amplitude of variation was up to 250 km^2 in 2007 – 2008. The highest AEV of each of these time intervals was observed in February 2004, November 2004, December 2006 and March 2008, respectively.

4) In 2007 - 2008, AEV fluctuated sharply. High AEV observed in December 2007 indicated a vast green up of ephemeral vegetation at that time, while the highest AEV occurred in March 2008. In Apr 2008, AEV dropped drastically.

Seasonal variation of CLWA in different years:

The seasonal variation of CLWA seemed to have an inverse pattern against that of AEV. CLWA fluctuated without clear temporal trends and lowest CLWA observed in these 8 time intervals occurred in January 2001, January 2002, December 2002, January 2004, December 2004, December 2005, February 2007 and December 2007, respectively.

The timing of highest AEV and lowest CLWA were shown more clearly in Table 5-1:

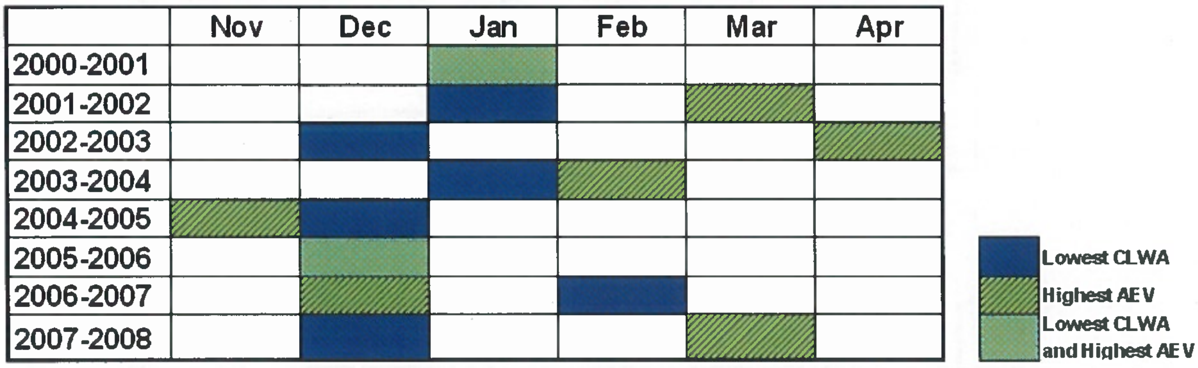

Table 5-1 Timing of lowest CLWA and Highest AEV

5.1.2.2. Year to Year variation of ephemeral vegetation area

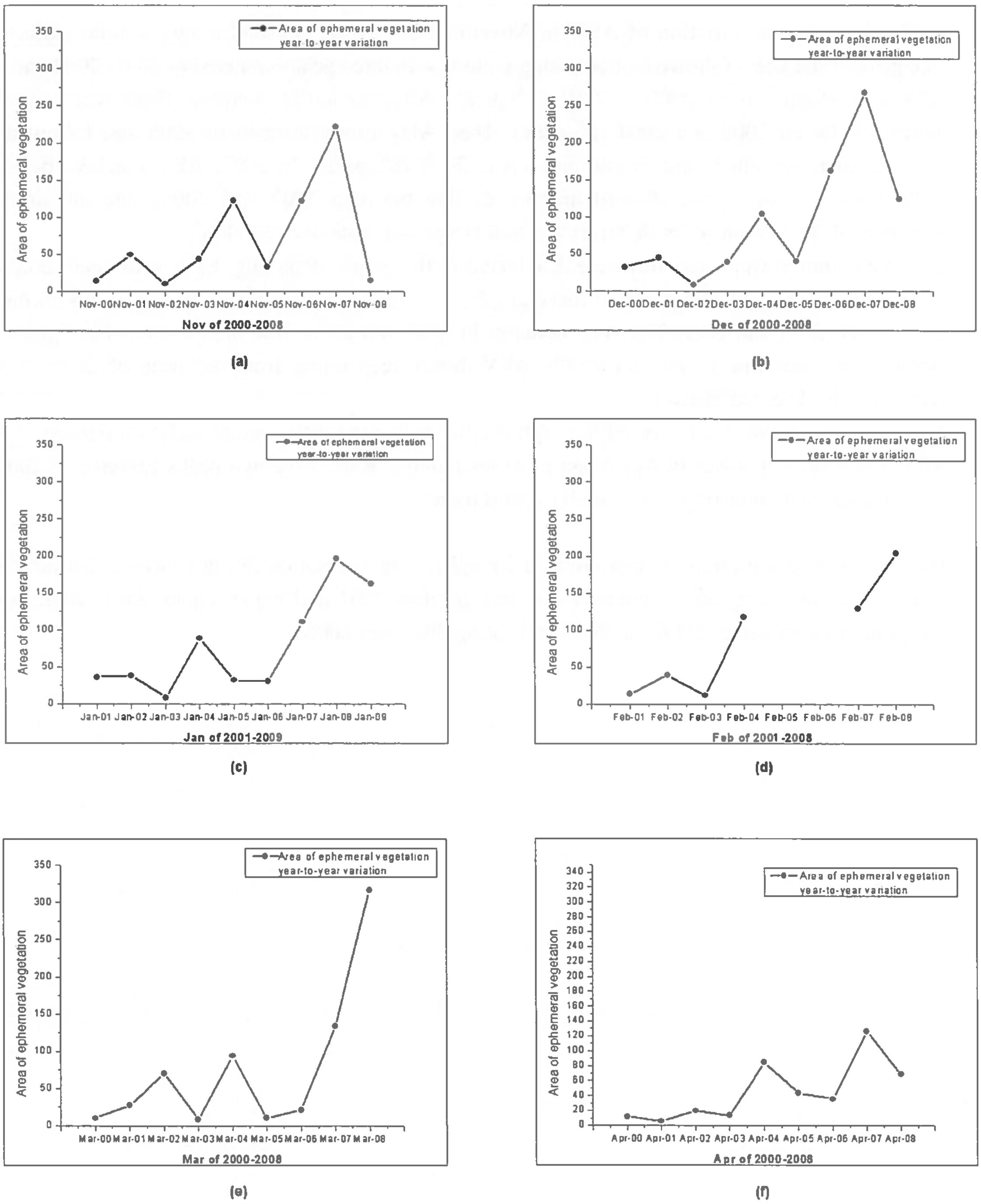

Figure 5-4 Year-to-Year variation of area covered by ephemeral vegetation (km^2) in Nov, Dec, Jan, Feb, Mar and Apr

In Figure 5-4 the area of ephemeral vegetation (AEV) was plotted against month (November, December, March and April) in the years between 2000 and 2008; January in the years between 2001 and 2009; February in the years between 2001 and 2008. The graphs demonstrated that while there was no distinct trend in the year-to-year variation of AEV, some patterns could be drawn as follows:

1) The year-to-year variation of AEV in November and December had a very similar pattern. The change over the years followed a fluctuating pattern with three peaks centered at 2001, 2004 and 2007. AEV rose slightly from 2000 to 2001 (1^{st} peak). After an initial decrease, there was a moderate increase between 2002 and 2004 (2^{nd} peak). Then AEV dropped again in 2005 and followed by a dramatic increase which was to continue up to 2007 (3^{rd} peak). In 2007, AEV reached the highest peak. However, the curve showed another decline between 2007 and 2008. The amplitudes of inter-annual fluctuations of both November and December were over 200 km^2.
2) Some common characteristics were discovered in the graphs depicting the year-to-year variation of January, February and March. In all these graphs, we could observe relatively large AEV in the year 2002, 2004, 2007 and 2008. The area increases in 2007 and 2008 were the most notable figures. And graph (c) showed that in January, 2009, AEV didn't keep rising from the peak of 2008. A slight decrease was observed instead.
3) A smoother curve was observed in graph (f) illustrating the inter-annual variation pattern of April. AEV was generally lower in April than previous months. Except for two peaks centered at 2004 and 2007, the curve demonstrated an overall upward trend.

The year-to-year variation of area covered by ephemeral vegetation doesn't have a distinct overall trend. Ephemeral vegetation generally greened up after 2001 and expanded in 2004. There was an abrupt increase in winter 2006 and 2007 and spring 2007 and 2008.

5.1.2.3. Year to Year variation of central lake water area

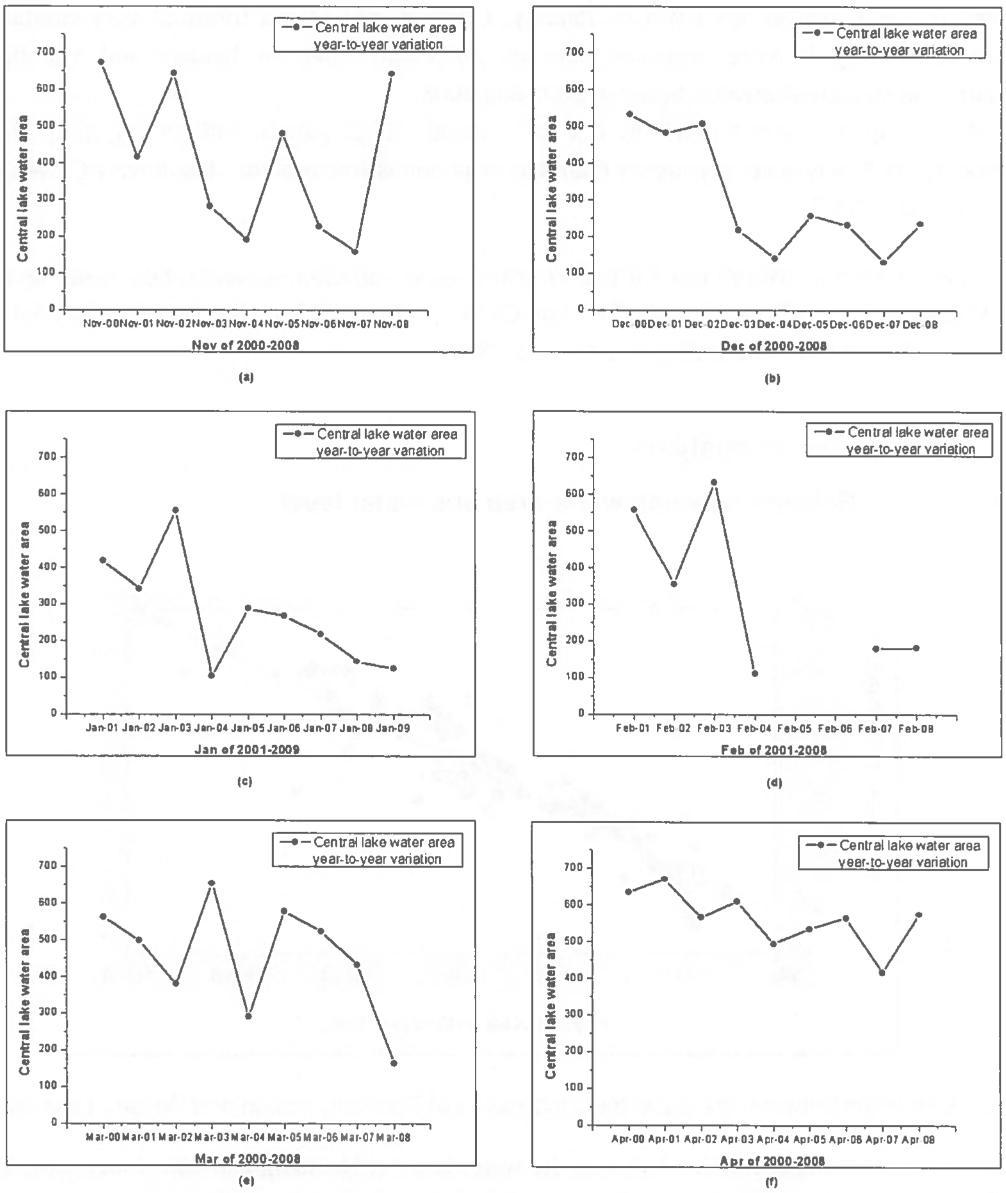

Figure 5-5 Year-to-Year variation of central lake water area (km^2) in Nov, Dec, Jan, Feb, Mar and Apr

In Figure 5-5 the central lake water area (CLWA) was plotted against month of November, December, March and April in the years between 2000 and 2008; January in the years between 2001 and 2009; February in the years between 2001 and 2008. No distinct overall trends were found in all the different months of observation, CLWA fluctuated between the years. However, some characteristics of variation could be drawn:

1) CLWA of November fluctuated tremendously between the years. The amplitude of fluctuation reached over 600 km^2. In 2000, 2002, 2005 and 2008, CLWA was very high exceeding 450 km^2. The extreme low CLWA below 200 km^2 occurred in 2004 and 2007. The curve depicting CLWA inter-annual variation in December fluctuated with a hidden downward trend. The CLWA of

December was generally smaller than in that of November. But like was observed in November, CLWA of December also dropped to extreme low points in 2004 and 2007.

2) Year-to-year variation of CLWA of January, February and March followed very similar pattern. The most striking decrease happened between 2003 and 2004. In January and March, CLWA gradually and steadily decreased between 2005 and 2008.

3) CLWA in April yielded a relatively flat inter-annual change pattern without any sharp increase or decrease. CLWA was generally higher than that of previous five months. The lowest CLWA in April was observed in 2007.

There was no obvious overall trend found in year-to-year variation of central lake water area in each month between November and April. The low CLWA below 200 km^2 was mostly observed in 2004, winter of 2006 and 2007 and spring of 2007 and 2008.

5.2. Regression analysis

5.2.1. Relation between water area and water level

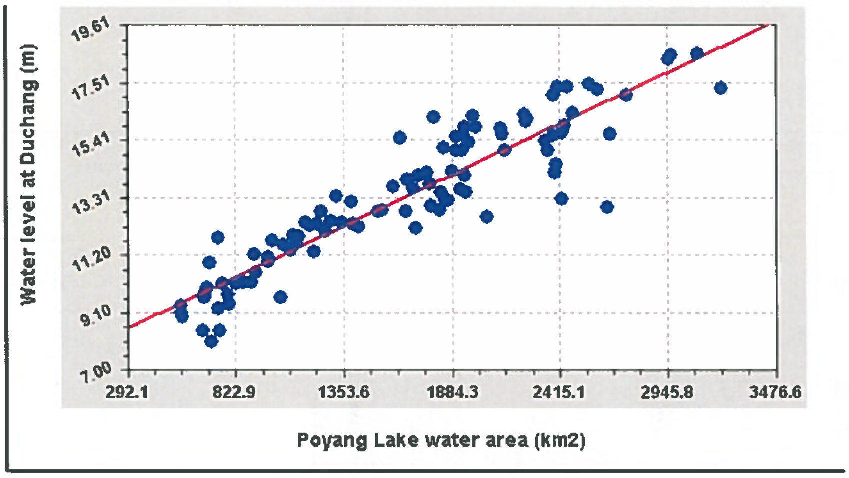

Figure 5-6 Relation between the water level measured at Duchang station and Poyang Lake water area

Figure 5-6 shows a linear relation between the water level at Duchang and lake water area. This was modelled by linear regression as:

$$Y=7.52+0.0035X$$

where Y represents water level of Poyang Lake at Duchang, X represents extracted water area of Poyang Lake ($R^2 = 0.85$, Standard Error 1.03, n = 101).

The linear regression model established indicated strong positive linear relationship between water area and water level (85% of variance in Poyang Lake water level explained).

Casewise Diagnostics(a)

Case Number	Month	Std. Residual	Water_level	Predicted Value	Residual
31	Oct-02	-3.824	12.94	16.8954	-3.95544
35	Feb-03	-2.098	12.60	14.7698	-2.16980
38	May-03	2.145	15.46	13.2413	2.21872
52	Aug-04	2.303	16.22	13.8383	2.38172
74	Aug-06	-2.739	13.25	16.0833	-2.83335

Table 5-2 Residual casewise diagnostics generated in SPSS

a Dependent Variable: Water_level

Table 5-2 shows the Residual casewise diagnostics results. The outliers were defined as cases that have residuals reached outside 2 standard deviations. Five cases that are the predicted water levels of October 2002, February 2003, May 2003, August 2004 and August 2006 were considered as outliers. The biggest residual observed in October 2002 was -3.96 meters; this relative error was 30.6%. The possible reasons for the errors might be as follows: 1) Water levels vary spatially in Poyang Lake. Water level measured at Duchang, though representative, doesn't mean the accurate average water level; 2) Unusual events happened in those time intervals such as sudden increase or decrease of water supply from five tributaries, sudden change of the Yangtze water level; 3) Inaccurate estimation of water area due to low spatial resolution of MODIS.4) Asynchronous dates of measuring and imagery. But overall there is a consistent positive relationship between water levels and Poyang Lake water area. Remote sensed images can be used to reach water level by estimating water areas.

5.2.2. Relation between ephemeral vegetation area and central lake water area

The growth of ephemeral vegetation may be expected to respond sensitively to the variation of water extent. In discussion section 5.1.2.2 and 5.1.2.3, we could see that year-to-year variation of AEV and CLWA seemed to have an inverse relation with each other; here we test that impression. A regression between all month's AEV and CLWA was attempted and regression analysis was conducted to learn whether there was a negative relation between AEV and CLWA.

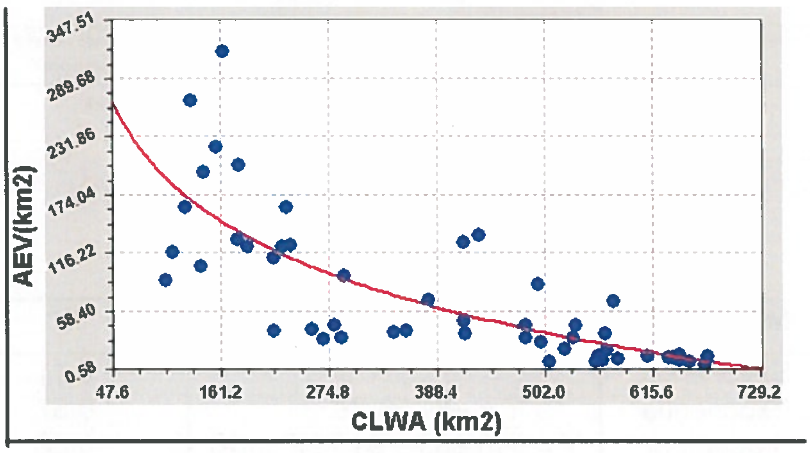

Figure 5-7 Best fitting regression line for the relation between CLWA and AEV of all months

Figure 5-7 shows a logarithm relation between AEV and CLWA. It was modelled by logarithm regression as:

$$Y = 644.13 - 97.65 * \ln(X)$$

Where Y represents AEV, X represents CLWA. (R^2=0.58, standard error 47.92, n=51). This model indicates a negative relation between AEV and CLWA as expected. But only 58% of variance in AEV can be explained by CLWA. We then analyze the relation between AEV and CLWA on monthly basis to test if the relations vary between months. (Figure 5-8)

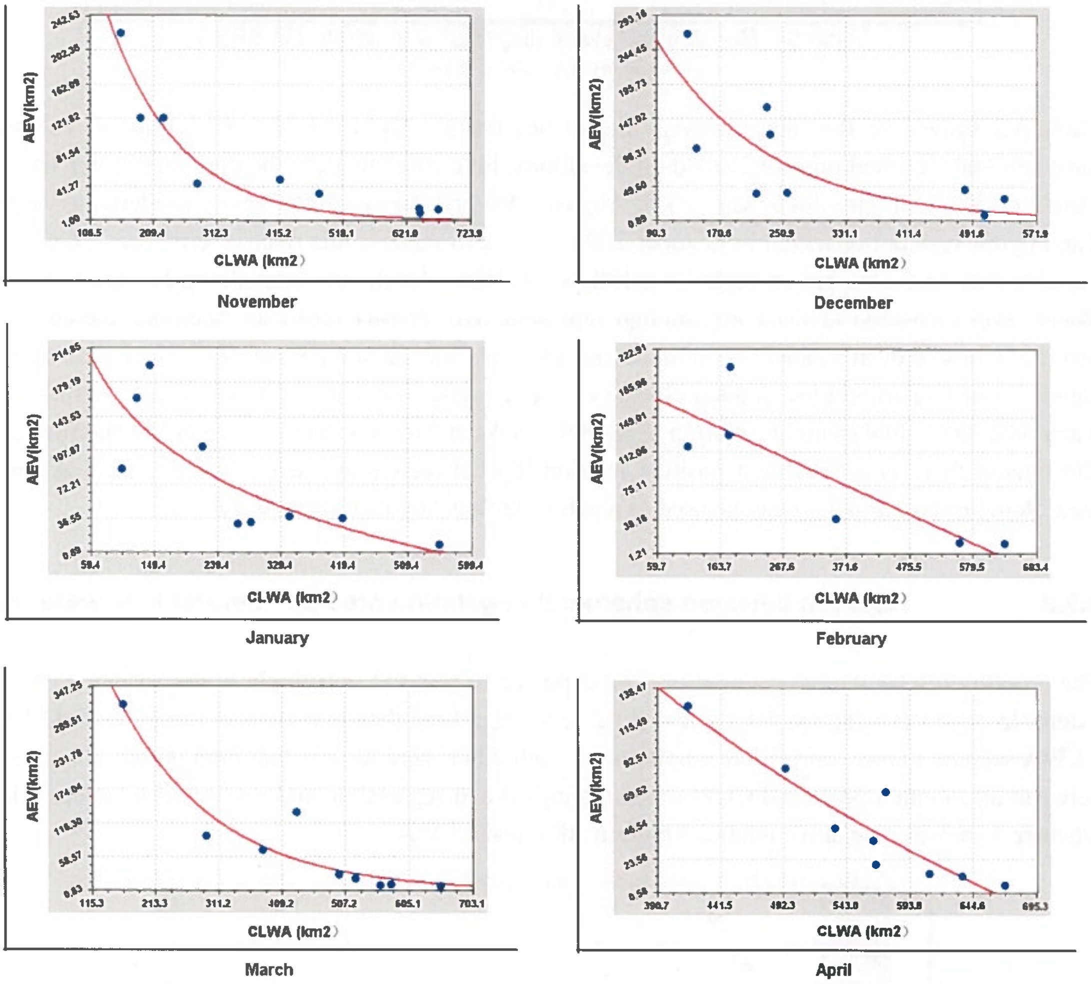

Figure 5-8 Best fitting regression lines for the relations between CLWA and AEV in each month based on year-to-year analysis

Month	Model type	Regression Model	R^2	Ste
Nov	Exponential	$Y = 785.234*e^{-0.0086X}$	0.91	22.643
Dec	Exponential	$Y = 484.669*e^{-0.0070X}$	0.57	58.051
Jan	Logarithm	$Y = 580.855 - 91.797* \ln(X)$	0.62	43.136
Feb	Linear	$Y = 187.131-0.301*X$	0.72	45.529
Mar	Exponential	$Y = 906.055*e^{-0.0066X}$	0.89	35.054
Apr	Logarithm	$Y = 1713.113-263.682*\ln(X)$	0.86	16.332

Table 5-3 Description of the best fitting regression models
(Y: AEV; X:CLWE; Ste: Standard error; R^2: squared correlation coefficient)

Figure 5-8 shows the best-fitting regression lines and Table 5-3 shows more information of the regression models. For each month, a best fitting regression model was chosen simulating the relations between AEV and CLWA. In November, March and April, the regression coefficients (R^2) were 0.91, 0.89 and 0.86, respectively. These R^2 may indicate some reasonable relations, but with large Standard errors. And the sample size was too small to conduct a proper regression diagnosis. But these regression models provided some evidence that AEV might be negatively correlated to CLWA. Different environment conditions such as climate, water dynamics in different months may contribute to the variance in relations. We then carried out regression analysis between CLWA and rainfall, AEV and meteorological (5.2.3 and 5.2.4) to learn whether there are some relations between these variables.

5.2.3. Relation between central lake water area and rainfall data

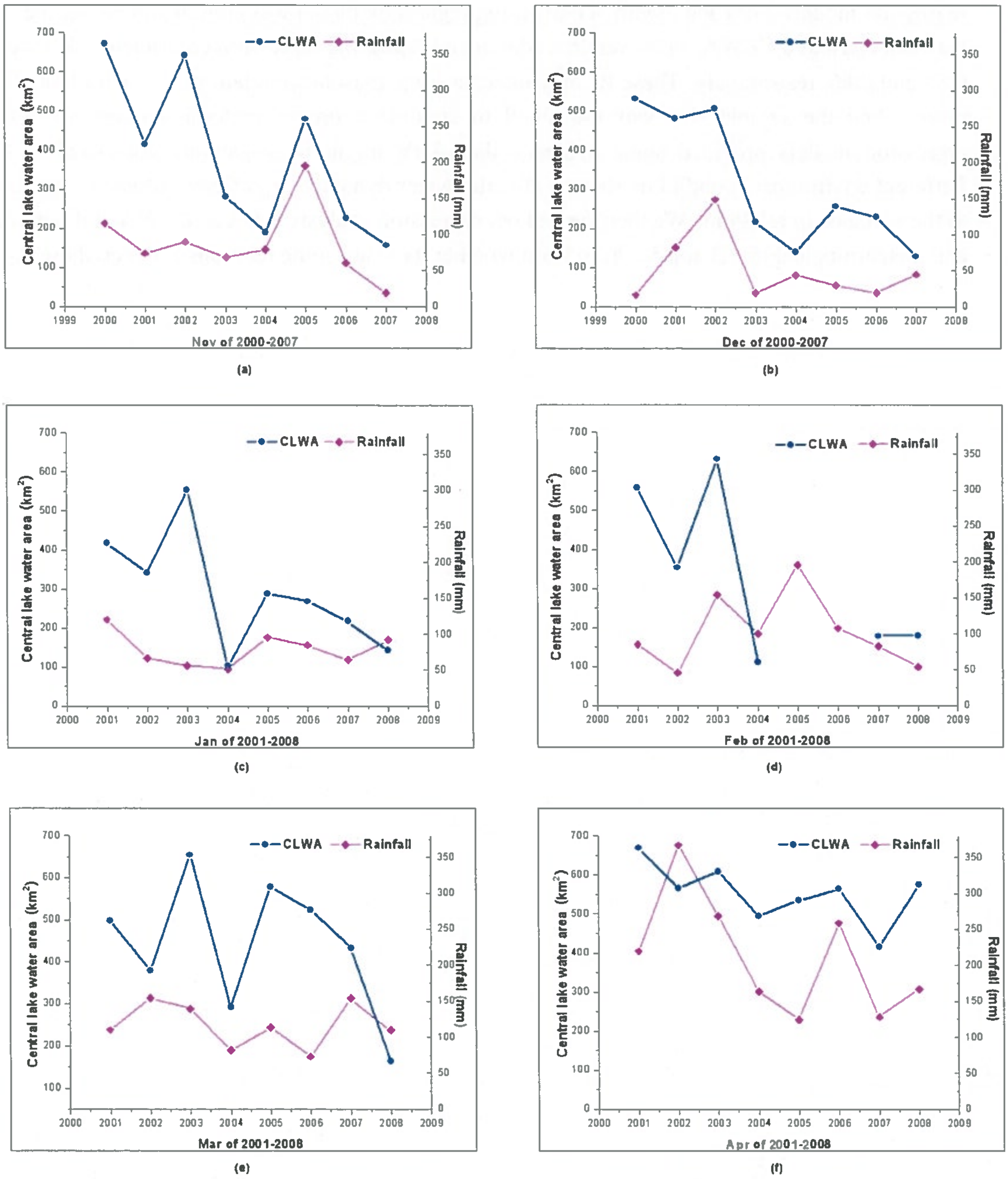

Figure 5-9 Year-to-year variation of Central lake water area (left Y axis with scale from 0 to 700 km^2 and rainfall (right Y axis with scale from 0 to 350 mm)

Figure 5-9 demonstrated monthly average rainfall year-to-year variation patterns compared with CLWA variation pattern in each month between November and April in six graphs (a – f)

The aim of this comparison is to visually inspect whether rainfall had an effect on central lake water area, how rainfall affect the water area.

We see in graph (a) of Figure 5-9 inter-annual variation of rainfall in November show some very similar pattern with that of CLWA, especially in the years between 2004 and 2007. The decrease of CLWA in December between 2002 and 2003 concurred with the reduction of rainfall. In January, the rainfall inter-annual variation pattern was similar with that of CLWA, except for 2003 and 2008. In February, despite gaps in the time series, we could observe some common characteristics between CLWA fluctuations and rainfall fluctuations. In March and April, the variation pattern of rainfall differed a lot from the pattern of CLWA. We could still observe some concurrence in March of 2003-2005, 2007-2008 and Apr of 2003 - 2004, 2006-2008.

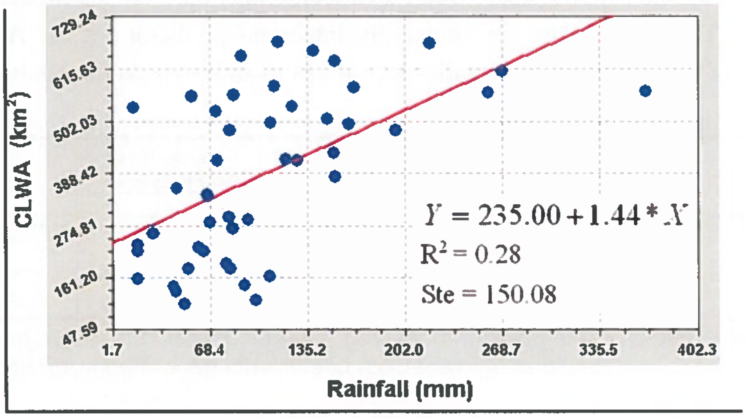

Figure 5-10 Linear regression model for the relation between CLWA and Rainfall

We attempted to simulate relation between CLWA and rainfall with linear regression model shown in Figure 5-10 for all events. However, this relation turned out to be rather weak with regression coefficient R^2 of only 0.28 and large standard error. This means that the local rainfall cannot satisfactorily predict lake level. Thus upstream rainfall or Yangtze backflow are more likely to be major contributors to the lake water.

Though it's not possible to assess relation between rainfall and CLWA with the presented curve patterns, those concurrences still indicated the inter-annual rainfall variation might have positive impact on CLWA especially in November and January.

5.2.4. Relation between vegetated area and meteorological data

In sections 5.2.2. and 5.2.3., we discussed the relation between water area and vegetated area and relation between water area and rainfall. In this session, we put water area, rainfall and temperature as explanatory variables and vegetated area as dependent variable to study whether a regression model could be established to study the relation between AEV and these variables.

All monthly observations (from November to April of 2000-2008) were used as samples. The sample size was n = 48. A linear regression model was developed as:

$$Y = aX_1 + bX_2 + cX_3 + d$$

Y represents AEV, X_1, X_2, X_3 represent CLWA, rainfall and temperature respectively.

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	156.823	21.023		7.460	.000
	Water_area	-.336	.048	-.836	-7.000	.000
	Rainfall	-.023	.142	-.022	-.160	.874
	Temporature	4.555	1.934	.288	2.355	.023

Table 5-4 Regression summary for model (veg_area as dependent, water_area, rainfall and temperature as explanatory variables) coefficients generated in SPSS

Table 5-4 shows the two variables: water area and temperature are significant at the .000, .023 level, respectively. This means they are potentially important predictors of the AEV. But rainfall, with a significance of 0.874 doesn't much influence on this model, so it can be omitted from the model.

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	157.451	20.428		7.708	.000
	Water_area	-.340	.042	-.844	-8.005	.000
	Temporature	4.403	1.666	.279	2.642	.011

Table 5-5 Regression summary for model (veg_area as dependent, water_area, and temperature as explanatory variables) coefficients generated in SPSS

Table 5-5 shows the regression model could be written as:

AEV = 157.451-0.34CLWA+4.403Temp

This multivariate model only considers the influences of water extent and temperature. The variance of AEV can be explained partially (59%, as assessed by R^2) by these environmental factors. There are many more environmental variables that were related to area of ephemeral vegetation, such as evaporation, insolation, and soil condition. It is possible that more reliable model could be established if we had these data.

5.2.5. Relation between yearly mean central winter water areas and emergence of ephemeral vegetation

Year	Emergence Date	Submergence Date	Length
2000	2000337	2001073	97
2001	2001273	2002073	161
2002	2003017	2003041	24
2003	2003321	2004121	161
2004	2004289	2005025	97
2005	2005329	2006097	129
2006	2006225	2007185	321
2007	2007305	2008153	209

Table 5-6 Emergence date (Julian day), submergence date and length of the emergence of ephemeral vegetation between 2000 and 2007

The yearly average central winter water areas were calculated with the mean value of CLWA of the six months between November and April (Table 5-7).

Year	2000	2001	2002	2003	2004	2005	2006	2007
Average CLWA	557.917	423.5792	599.8675	250.3492	346.593	418.9358	283.97	225.4203

Table 5-7 Yearly average central winter water areas

Length of the emergence of ephemeral vegetation and yearly average central winter water areas between 2000 and 2007 were plotted against year in one graph.

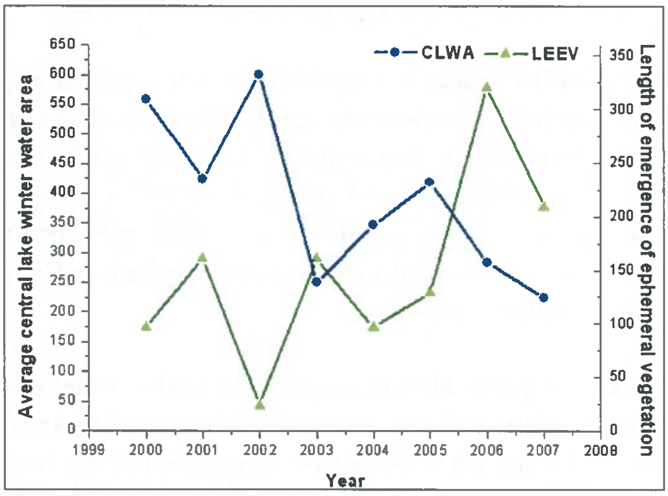

Figure 5-11 Year-to-year variation of average central lake water area (left Y axis with scale from 0 to 650 km^2) and length of emergence of ephemeral vegetation (right Y axis with scale from 0 to 350 d)
CLWA: Central Lake Water Area LEEV: Length of emergence of ephemeral vegetation

From Figure 5-11, we can see the variation patterns of CLWA and LEEV were generally inversed, as expected: less water means longer vegetation emergence. However, the relation explains only half the total variation (53%) (Figure 5-12).

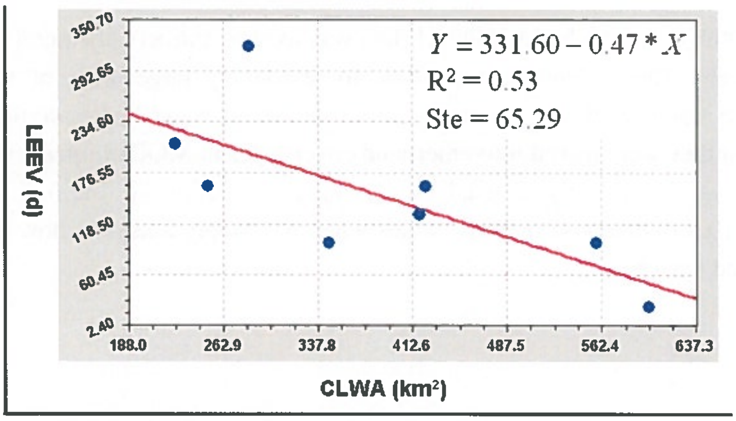

Figure 5-12 Linear regression model for the relation between CLWA (km^2) and LEEV (d)
CLWA: Central Lake Water Area; LEEV: Length of emergence of ephemeral vegetation

5.3. Error analysis

Certain sources of errors can affect the accuracy of the assessment of vegetation and water area: The areas were calculated by multiplying the spatial resolution of MODIS images and number of pixels above the defined NDVI and NDWI thresholds. The area estimates generated by this method would be prone to random error between dates without atmospheric correction, since the surface reflectance value of land covers might be affected by different atmospheric condition on different dates. MOD09 products have already been corrected for the effects of atmospheric gases, aerosols, and thin cirrus clouds. Therefore, the random error caused by these effects was diminished.

Each pixel in the remote sensing images is a combination of the spectral response of all the objects covered by the instantaneous field of view of the sensor. Therefore, coarse spatial resolution images like MODIS images are dominated by mixed pixels, especially pixels representing areas on the boundary between water and mudflat, grassland and small mountains in the lake and areas along the lake bank. In this study, every pixel was assigned to one single land cover type. For example, one pixel with NDVI value above 0.25 was simply categorized as vegetation. Thus, the existence of mixed pixel was another source of random error.

In this research, 165 8-day composite MODIS images were used to monitor the vegetation dynamics and water extent variation in winter and early spring (From November to April) during the time period between January 2000 and January 2009. The temporal resolution of this time series dataset is about one data per 13-day. The monitoring was carried out on monthly basis. There was on average of 2 data per month. Up to four 8-day composite data could be acquired in one month, but due to the restrictions of cloud cover and data quality, lesser data was available in some months. There were no cloud free data in February 2005 and 2006, which caused gaps in the time series. Sometimes vegetation and water evolves rapidly in Poyang Lake even in one month. The area estimated for each month was the mean area averaged from the available data. The varying amount of data would affect the monthly area estimation.

The 250m MOD09Q1 and 500m MOD09A1 data was used to extract ephemeral vegetation and water bodies respectively. These resolutions are fine for extracting large areas of vegetation and water bodies. But when water level was extremely low, some small water bodies could not be classified as water and instead they were mixed into other land cover types in MODIS image. Thus, the accuracy of area estimation may be severely affected by the coarse resolution but the bias was the same in the various images used to compose the time series when we simply analyzed how the water area varies between years and seasons.

6. Conclusions and Recommendations

6.1. Conclusions

The general objectives of this study were to monitor changes in the area of ephemeral vegetation greening up on the exposed sediment in the central part of the lake in winter and early spring, and to determine whether the changes can be related to the changes in the lake water level..

While monitoring Poyang Lake for 9-year period between 2000 and 2008, we observed that lower water extent and longer low water duration of Poyang Lake in winters of 2003-2004, 2006-2007 and 2007-2008. While monitoring seasonal and year-to-year variation of AEV and CLWA, we discovered that both AEV and CLWA fluctuated seasonally without clear temporal trends and the variation patterns of AEV and CLWA seemed inversed against each other. The timing of lowest CLWA and highest AEV varied between the years. The year-to-year variation of both AEV and CLWA don't have a distinct overall trend, either. While low CLWA below 200 km^2 occurred in 2004, 2007 and 2008, vast AEV greening up was observed in the same years. The most remarkable low water and massive green up of AEV was observed in 2006 and 2007.

Regression analyses carried out to further study relation between water area and water level, AEV and CLWA, CLWA and rainfall, vegetated area and meteorological data and yearly mean central winter water areas and length of emergence of ephemeral vegetation show:

- Strong linear relation between water area of Poyang Lake and water level measured at Duchang (R^2=0.85) based on all 101 monthly observations throughout the 9-year period. Such relation suggested that there is a consistent relation between water area and water level.
- In each monthly inter-annual observation between November and April, a linear, logarithmic, or exponential regression model was established; strong negative relations between AEV and CLWA with R^2 of 0.91, 0.89 and 0.86 were observed in November, March and April, despite the limited sample size.
- The linear relation between CLWA and rainfall was weak (R^2=0.28), thus rainfall doesn't satisfactorily predict lake level.
- The linear regression model established between AEV and CLWA and temperature with R^2=0.59 suggested that 59% of variance of AEV can be explained by two environmental factors: water extent and temperature.
- Only half of the variance (R^2=0.53) in LEEV can be explain by the lake water extent.

The strong linear relation proved that lake water level can be reached by analysis of optical remote sensing imageries. Strong negative relations between AEV and CLWA suggested that lower water level might be one major cause for the increase in ephemeral vegetation. The linear relations between CLWA and rainfall, AEV and CLWA, temperature, LEEV and CLWA are not well-enough modelled to draw firm conclusions for the underlying explanations for the changes.

6.2. Recommendations

1) Poyang Lake region is mainly located in the sub-tropics. The climate conditions hinder the utility of optical remote sensing images because this area is more or less covered by clouds for almost half a year. This will lead to uneven observations between different seasons, gaps in the time series dataset and further affect the efficiency of dynamic monitoring and accuracy of area estimation. Radar sensors have the capability to take measurements in presence of cloud cover, dust, haze, and rain. And they can operate both day and night without an external energy source. Thus, Radar image dataset can provide a continuous time series for monitoring. High resolution SAR imageries and medium resolution Envisat imageries are potential alternatives, since they have already been used for wetland vegetation mapping (Martinez and Le Toan 2007), vegetation properties studies (Grippa and Woodhouse 2003; Dabrowska-Zielinska et al. 2007), water extent monitoring (Andreoli, Li et al. 2008) and water level estimation (Medina et al. 2008), respectively.

2) Higher spatial resolution remote sensing imagery can more accurately extract different land covers and assess the area variation. However, infrequent coverage and high expense usually diminish its utility in long term monitoring. Some fusion techniques have been suggested to produce high spatial-temporal resolution time series by blending MODIS imageries with other high spatial resolution imageries such as Landsat TM and Aster imageries (Gao et al. 2006; Wan et al. 2007). Those techniques can be considered in future quantitative researches of biophysical processes.

3) Remote sensing imageries have provided clear overview of the temporal evolution of water dynamics and vegetation dynamics. However the complicated hydrological process of Poyang Lake can not be fully understood solely by image data time series analysis. Future researches aiming at building process-based hydrological models would require more data such as DEM, topographic contour map of the Lake Bottom and daily water level and information such as detail knowledge of hydro-processes from five tributaries and Yangtze River, water mechanics in the lake and Lake Bottom conditions.

4) The spatial distribution and temporal development of vegetation are affected by many environmental factors such as insolation, water temperature, evaporation, climate, sediment composition and inorganic carbon availability. In this research, we have only time series climate (temperature and rainfall) data available. More time series data of environmental variables are needed to understand the ecological cause for vegetation dynamics.

5) Three Gorges Dam in Yangtze River has been under construction since December 1994. It has been predicted that after completion, Three Gorges reservoir will have great influence on the water level, flood control capability, sediment flux and marshland emergence in Poyang Lake. And the influence on water level will be bigger in low water season than that of flood season (Jiang and Huang 1997). Thus future studies can be carried out to further assess those impacts if more water level data and hydro-dynamic models are available. It was suggested by Tan, Tan et al. (2008) that dredging may induce the lowering bathymetry of the channel linking Poyang lake to Yangtze. It is logical to expect that reduced water levels in the lake could also be caused by the lower bathymetry if we had evidence proving that the sediment in the channel previously restricted the discharge of water out of Poyang Lake. This possible effect of dredging on the low water level can be considered in future research.

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Appendix A: NDVI maps and NDWI maps of January between 2001 and 2009

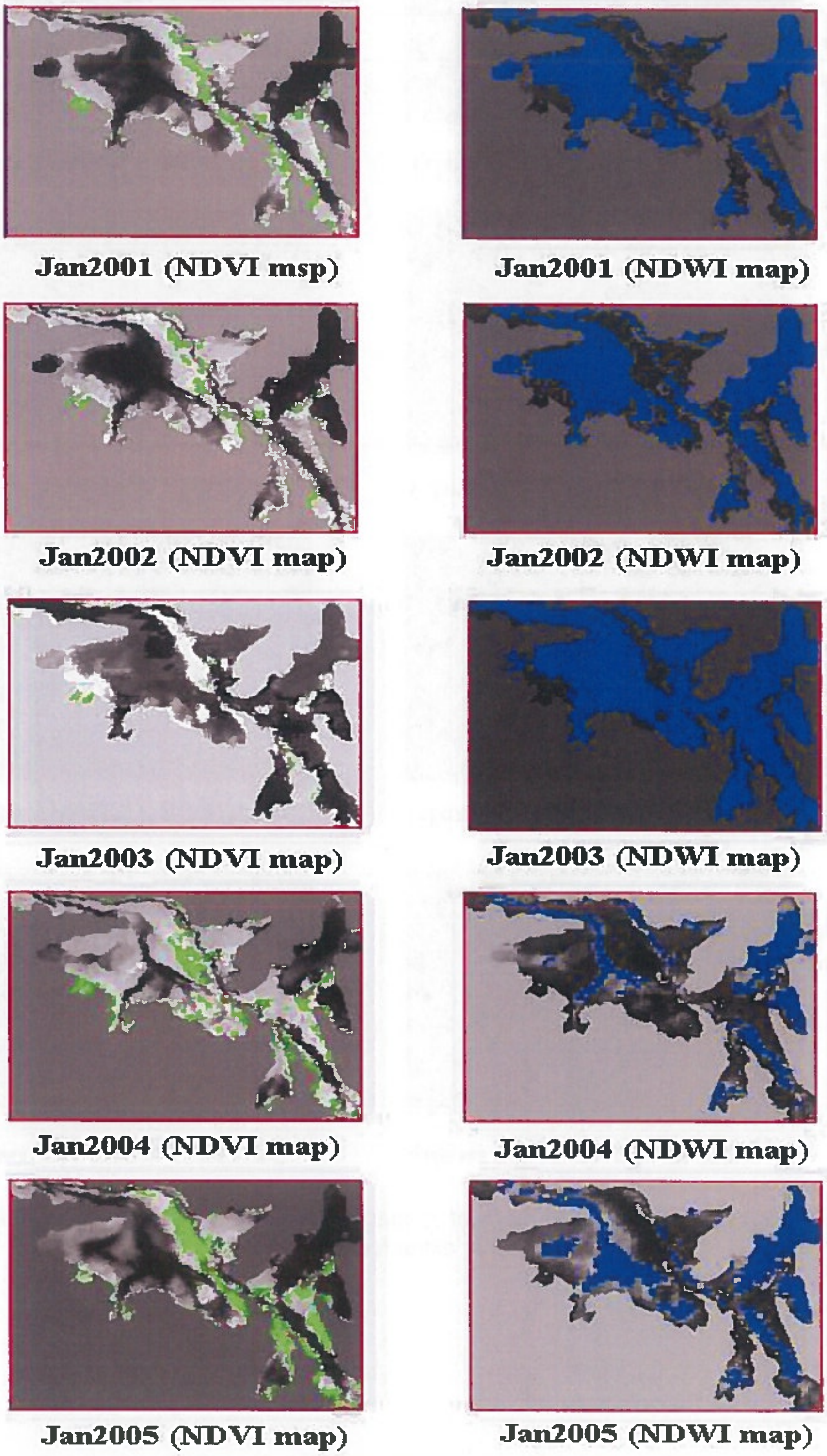

Figure A-1 NDVI maps and NDWI maps of January between 2001 and 2005 (extracted ephemeral vegetation: green; extracted water: blue)

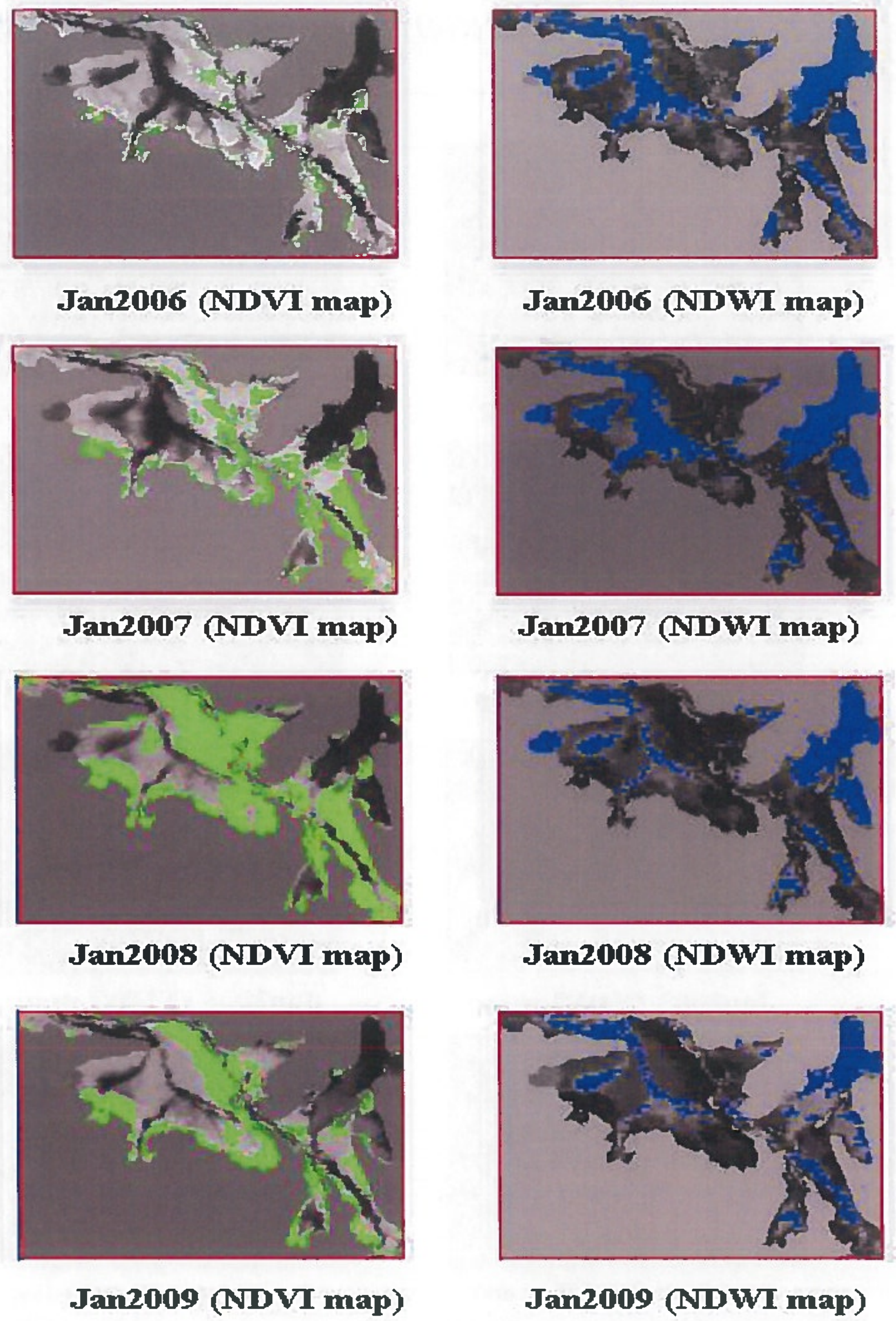

Figure A-2 NDVI maps and NDWI maps of January between 2006 and 2009 (extracted vegetation: green; extracted water: blue)

Appendix B: Poyang Lake water areas between 2000 and 2008 using MODIS MOD09A1 500m data

Table B-1 Poyang Lake water areas in 2000

2000

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Mar-00	26feb 04mar	2000057	1,167	1526.84
	21mar 28mar	2000081	1,886.38	
Apr-00	29mar 05apr	2000089	1,729.38	1786.22
	14apr 21apr	2000105	1,843.06	
May-00	30apr 07may	2000121	1,690.56	1248.27
	08may 15may	2000129	1,711.19	
	16may 23may	2000137	862.94	
	24may 31may	2000145	728.38	
Jun-00	09jun 16jun	2000161	2,669.50	2669.50
Jul-00	11jul 18jul	2000193	2,794.25	2564.34
	27jul 03aug	2000209	2,334.44	
Aug-00	20aug 27aug	2000233	2,430.63	2430.63
Sep-00	13sep 20sep	2000257	2,649.31	2482.63
	21sep 28sep	2000265	2,315.94	
Oct-00	07oct 14oct	2000281	2,388.19	2388.19
Nov-00	01nov 08nov	2000305	2,731.00	2400.81
	17nov 24nov	2000321	2,070.63	
Dec-00	03dec 10dec	2000337	1,327.63	1132.81
	19dec 26dec	2000353	938.00	

Table B-2 Poyang Lake water areas in 2001

2001

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-01	09jan 16jan	2001009	806.50	1094.46
	17jan 24jan	2001017	837.00	
	25jan 01feb	2001025	1,639.88	
Feb-01	10feb 17feb	2001041	1,171.88	1192.75
	18feb 25feb	2001049	1,213.63	
Mar-01	06mar 13mar	2001065	1,230.31	1169.44
	14mar 21mar	2001073	1,108.56	
Apr-01	30mar 06apr	2001089	1,680.81	1929.25
	07apr 14apr	2001097	1,945.13	
	23apr 30apr	2001113	2,161.81	
May-01	09may 16may	2001129	2,362.63	2362.63
Jun-01	02jun 09jun	2001153	1,694.25	1936.19
	10jun 17jun	2001161	2,178.13	
Jul-01	04jul 11jul	2001185	2,275.63	2124.56
	20jul 27jul	2001201	1,973.50	
Aug-01	13aug 20aug	2001225	1,673.50	1780.59
	29aug 05sep	2001241	1,887.69	
Sep-01	06sep 13sep	2001249	1,944.81	1909.33
	14sep 21sep	2001257	1,938.69	
	22sep 29sep	2001265	1,844.50	
Oct-01	30sep 07oct	2001273	1,862.19	1603.84
	08oct 15oct	2001281	1,833.19	
	16oct 23oct	2001289	1,652.06	
	24oct 31oct	2001297	1,067.94	
Nov-01	01nov 08nov	2001305	1,535.50	1268.64
	09nov 16nov	2001313	1,563.31	
	17nov 24nov	2001321	1,148.06	
	25nov 02dec	2001329	827.69	
Dec-01	19dec 26dec	2001353	1,211.56	1211.56

Table B-3 Poyang Lake water areas in 2002

2002

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-02	09jan 16jan	2002009	836.50	984.71
	17jan 24jan	2002017	1,068.13	
	25jan 01feb	2002025	1,049.50	
Feb-02	10feb 17feb	2002041	916.13	916.13
Mar-02	06mar 13mar	2002065	738.31	738.31
Apr-02	07apr 14apr	2002097	1,321.63	1321.63
May-02	17may 24may	2002137	3,211.19	3211.19
Jul-02	04jul 11jul	2002185	3,202.69	3094.44
	12jul 19jul	2002193	2,986.19	
Aug-02	05aug 12aug	2002217	2934.75	2969.25
	21aug 28aug	2002233	3011.938	
	29aug 05sep	2002241	2718.88	
Sep-02	06sep 13sep	2002249	3,052.94	2749.97
	22sep 29sep	2002265	2,447.00	
Oct-02	30sep 07oct	2002273	1,827.69	1770.73
	08oct 15oct	2002281	1,754.88	
	24oct 31oct	2002297	1,729.63	
Nov-02	01nov 08nov	2002305	2,253.06	1952.98
	17nov 24nov	2002321	1,879.88	
	25nov 02dec	2002329	1,726.00	
Dec-02	03dec 10dec	2002337	1,662.88	1662.88

Table B-4 Poyang Lake water areas in 2003

2003

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-03	09jan 16jan	2003009	1,525.75	2094.19
	17jan 24jan	2003017	1,266.00	
	25jan 01feb	2003025	1,396.63	
Feb-03	02feb 09feb	2003033	1,525.50	1792.94
	18feb 25feb	2003049	2,060.38	
Mar-03	06mar 13mar	2003065	1,987.25	1867.08
	14mar 21mar	2003073	1,838.63	
	22mar 29mar	2003081	1,775.38	
Apr-03	30mar 06apr	2003089	1,423.31	1695.35
	15apr 22apr	2003105	2,025.19	
	23apr 30apr	2003113	1,637.56	
May-03	01may 08may	2003121	1,483.69	1632.00
	09may 16may	2003129	1,780.31	
Jun-03	10jun 17jun	2003161	1,789.38	2344.00
	26jun 03jul	2003177	2,898.63	
Jul-03	12jul 19jul	2003193	2,951.94	2951.25
	20jul 27jul	2003201	2,950.56	
Sep-03	06sep 13sep	2003249	2,001.81	2001.81
Oct-03	08oct 15oct	2003281	1,948.31	1764.94
	24oct 31oct	2003297	1,581.56	
Nov-03	01nov 08nov	2003305	913.188	760.44
	09nov 16nov	2003313	752.938	
	17nov 24nov	2003321	651.438	
	25nov 02dec	2003329	724.188	
Dec-03	03dec 10dec	2003337	657	557.48
	11dec 18dec	2003345	758.938	
	19dec 26dec	2003353	391.813	
	27dec 03jan	2003361	422.188	

Table B-5 Poyang Lake water areas in 2004

2004

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-04	17jan 24jan	2004017	563.125	563.13
Feb-04	10feb 17feb	2004041	557.5	557.50
Mar-04	26feb 04mar	2004057	518.063	698.84
	05mar 12mar	2004065	879.625	
Apr-04	29mar 05apr	2004089	1,137.00	1106.97
	06apr 13apr	2004097	945.875	
	14apr 21apr	2004105	1,109.88	
	22apr 29apr	2004113	1,235.13	
May-04	30apr 07may	2004121	1,621.44	1725.04
	08may 15may	2004129	1,442.81	
	16may 23may	2004137	2,110.88	
Jun-04	25jun 02jul	2004177	2,144.31	2144.31
Jul-04	19jul 26jul	2004201	2,134.69	2242.31
	27jul 03aug	2004209	2,349.94	
Aug-04	20aug 27aug	2004233	1,799.31	1799.31
Sep-04	05sep 12sep	2004249	1,944.38	2133.04
	13sep 20sep	2004257	2,272.19	
	21sep 28sep	2004265	2,182.56	
Oct-04	29sep 06oct	2004273	1,862.94	1393.31
	07oct 14oct	2004281	1,521.00	
	15oct 21oct	2004289	1,299.56	
	22oct 31oct	2004297	889.75	
Nov-04	17nov 24nov	2004321	1,012.75	926.50
	25nov 02dec	2004329	840.25	
Dec-04	03dec 10dec	2004337	746	671.66
	11dec 18dec	2004345	597.313	

Table B-6 Poyang Lake water areas in 2005

2005

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-05	01jan 08jan	2005001	666.813	862.17
	09jan 16jan	2005009	774.813	
	25jan 01feb	2005025	1,144.88	
Feb-05	06mar 13mar	2005065	1,711.81	1711.81
Apr-05	30mar 06apr	2005089	1,475.88	1290.05
	07apr 14apr	2005097	1,467.19	
	15apr 22apr	2005105	1,104.44	
	23apr 30apr	2005113	1,112.69	
May-05	25may 01jun	2005145	2,395.38	2395.38
Jun-05	02jun 09jun	2005153	2,534.19	2383.19
	10jun 17jun	2005161	2,173.81	
	26jun 03jul	2005177	2,441.56	
Jul-05	20jul 27jul	2005201	1,947.69	1947.69
Aug-05	05aug 12aug	2005217	1,997.75	2257.75
	29aug 05sep	2005241	2,517.75	
Sep-05	06sep 13sep	2005249	2,889.50	2605.31
	14sep 21sep	2005257	2,635.63	
	22sep 29sep	2005265	2,290.81	
Oct-05	08oct 15oct	2005281	2,026.31	1950.19
	16oct 23oct	2005289	1,874.06	
Nov-05	17nov 24nov	2005321	1,636.50	1402.13
	25nov 02dec	2005329	1,167.75	
Dec-05	03dec 10dec	2005337	970.563	907.10
	11dec 18dec	2005345	884.938	
	19dec 26dec	2005353	865.813	

Table B-7 Poyang Lake water areas in 2006

2006

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-06	01jan_08jan	2006001	637.563	683.75
	09jan_16jan	2006009	729.938	
Mar-06	26feb_05mar	2006057	1,346.13	1226.88
	22mar_29mar	2006081	1,107.63	
Apr-06	30mar_06apr	2006089	1,467.69	1856.98
	15apr_22apr	2006105	2,426.44	
	23apr_30apr	2006113	1,676.81	
May-06	01may_08may	2006121	1,787.50	1889.83
	17may_24may	2006137	1,966.38	
	25may_01jun	2006145	1,915.63	
Jun-06	18jun_25jun	2006169	2,710.88	2438.81
	26jun_03jul	2006177	2,166.75	
Jul-06	04jul_11jul2006	2006185	1,771.88	1905.97
	28jul_04aug	2006209	2,040.06	
Aug-06	05aug_12aug	2006217	1,689.81	1214.25
	13aug_20aug	2006225	1,566.19	
	21aug_28aug	2006233	780.56	
	29aug_05sep	2006241	820.44	
Sep-06	14sep_21sep	2006257	1,100.94	988.78
	22sep_29sep	2006265	876.63	
Oct-06	30sep_07oct	2006273	584.81	667.97
	24oct_31oct	2006297	751.13	
Nov-06	01nov_08nov	2006305	741.25	790.63
	09nov_16nov	2006313	562.563	
	17nov_24nov	2006321	768.625	
	25nov_02dec	2006329	1,090.06	
Dec-06	11dec_18dec	2006345	781.438	825.96
	19dec_26dec	2006353	907	
	27dec_03jan	2006361	789.438	

Table B-8 Poyang Lake water areas in 2007

2007

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-07	01jan_08jan	2007001	737.125	794.13
	25jan_01feb	2007025	851.125	
Feb-07	02feb_09feb	2007033	668.313	668.31
Mar-07	26feb_05mar	2007057	879.75	1063.40
	14mar_21mar	2007073	1,197.06	
	22mar_29mar	2007081	1,113.38	
Apr-07	30mar_06apr	2007089	1,299.94	1006.13
	07apr_14apr	2007097	1,003.00	
	15apr_22apr	2007105	872.938	
	23apr_30apr	2007113	848.625	
May-07	01may_08may	2007121	1,532.06	1121.71
	09may_16may	2007129	1,207.94	
	17may_24may	2007137	625.125	
Jun-07	10jun_17jun	2007161	1,668.19	1668.19
Jul-07	04jul_11jul	2007185	1,403.00	1988.54
	20jul_27jul	2007201	2,413.75	
	28jul_04aug	2007209	2,148.88	
Aug-07	05aug_12aug	2007217	2,693.44	2457.64
	13aug_20aug	2007225	2,542.44	
	21aug_28aug	2007233	2,318.38	
	29aug_05sep	2007241	2,276.31	
Sep-07	14sep_21sep	2007257	2,199.44	2249.34
	22sep_29sep	2007265	2,299.25	
Oct-07	30sep_07oct	2007273	2,042.00	1346.95
	08oct_15oct	2007281	1,674.50	
	16oct_23oct	2007289	962.25	
	24oct_31oct	2007297	709.063	
Nov-07	01nov_08nov	2007305	761.75	740.56
	25nov_02dec	2007329	719.375	
Dec-07	03dec_10dec	2007337	626.188	667.41
	27dec_03jan	2007361	708.625	

Table B-9 Poyang Lake water areas in 2008

2008

Month	Time span	Composite date	Lake water extent (km^2)	Monthly average lake water extent (km^2)
Jan-08	01jan 08jan	2008001	708.625	708.63
Feb-08	02feb 09feb	2008033	1,246.19	1047.46
	10feb 17feb	2008041	1,178.56	
	18feb 25feb	2008049	717.625	
Mar-08	26feb 04mar	2008057	820.875	745.53
	05mar 12mar	2008065	670.188	
Apr-08	06apr 13apr	2008097	1,185.06	1542.94
	14apr 21apr	2008105	1,865.69	
	22apr 29apr	2008113	1,578.06	
Jun-08	01jun 08jun	2008153	1,213.94	1829.75
	17jun 24jun	2008169	2,445.56	
Jul-08	03jul 10jul	2008185	2,031.56	1941.50
	27jul 03aug	2008209	1,851.44	
Aug-08	04aug 11aug	2008217	2,199.94	1971.81
	12aug 19aug	2008225	1,743.69	
Sep-08	13sep 20sep	2008257	2,407.25	2407.25
Oct-08	29sep 06oct	2008273	2,268.31	1827.04
	07oct 14oct	2008281	1,767.31	
	15oct 21oct	2008289	1,445.50	
Nov-08	01nov 08nov	2008305	1,793.19	1847.73
	17nov 24nov	2008321	1,966.88	
	25nov 02dec	2008329	1,783.13	
Dec-08	03dec 10dec	2008337	1,493.81	972.13
	19dec 26dec	2008353	751.5	
	27dec 03jan	2008361	671.063	

Appendix C: Areas of ephemeral vegetation and central lake water areas

Table C-1 AEV and CLWA estimated between 2000 and 2002

Month	Time span	Comsite Julian Date	AEV (km2)	Monthly Average AEV (km2)	CLWA	Monthly Average CLWA (km2)
2000						
Feb-00	26feb 05mar	2000057	14.75	9.9375	462.625	561.9065
	22mar 29mar	2000081	5.125		661.188	
Mar-00	30mar 06apr	2000089	9.938	11.969	623.688	635.563
	16apr 22apr	2000105	14		647.438	
2000-2001						
Nov-00	31oct 07nov	2000305	14	14.125	681.188	672.438
	16nov 23nov	2000321	14.25		663.688	
Dec-00	02dec 09dec	2000337	32.125	32.125	531.75	531.75
Jan-01	01jan 08jan	2001001	38.563	36.3755	339.5	417.9377
	09jan 16jan	2001009	20.813		275.125	
	25jan 01feb	2001025	13.375		639.188	
Feb-01	10feb 17feb	2001041	13.438	13.438	557.75	557.75
Mar-01	26feb 05mar	2001057	16.438	27.479333	477.25	497.6877
	06mar 13mar	2001065	31.875		519.5	
	14mar 21mar	2001073	34.125		496.313	
Apr-01	07apr 14apr	2001097	5.75	5.75	669.938	669.938
2001-2002						
Nov-01	01nov 08nov	2001305	49.438	49.250333	520	416.3333
	09nov 16nov	2001313	43.938		475.875	
	25nov 02dec	2001329	54.375		253.125	
Dec-01	19dec 26dec	2001353	44.375	44.375	481.563	481.563
Jan-02	01jan 08jan	2002001	24.375	38.094	297.625	342.1408
	09jan 16jan	2002009	44.188		271.75	
	17jan 24jan	2002017	35.875		402.813	
	25jan 01feb	2002025	47.938		396.375	
Feb-02	10feb 17feb	2002041	39.313	39.313	355.5	355.5
Mar-02	06mar 13mar	2002065	58.188	70.219	325.688	379.438
	14mar 19mar	2002073	82.25		433.188	
Apr-02	07apr 14apr	2002097	19.5	19.5	566.5	566.5

Table C- 2 AEV and CLWA estimated between 2002 and 2004

Month	Time span	Comsite Julian Date	AEV (km2)	Monthly Average AEV (km2)	CLWA	Monthly Average CLWA (km2)
2002-2003						
Nov-02	01nov 08nov	2002305	5.438	10.0005	677.75	643.344
	09nov 16nov	2002313	14.063		628.563	
	17nov 24nov	2002321	8.188		657.313	
	25nov 02dec	2002329	12.313		609.75	
Dec-02	27dec 03jan	2002361	8.875	8.895	506.75	506.75
Jan-03	01jan 08jan	2003001	2.125	8.875	618.25	554.3908
	09jan 16jan	2003009	6.5		566.875	
	17jan 24jan	2003017	11.875		483.375	
	25jan 31jan	2003025	15		549.063	
Feb-03	02feb 09feb	2003033	17.938	12.1255	595.063	631.469
	18feb 25feb	2003049	6.313		667.875	
Mar-03	06mar 13mar	2003065	5.563	8.313	658.875	654.094
	14mar 21mar	2003073	11.063		649.313	
Apr-03	30mar 06apr	2003089	14.188	13.344	591.625	609.1565
	23apr 30apr	2003113	12.5		626.688	
2003-2004						
Nov-03	01nov 08nov	2003305	48.563	43.9065	314.563	281.594
	09nov 16nov	2003313	32.438		291	
	17nov 24nov	2003321	45.375		258.063	
	25nov 02dec	2003329	49.25		262.75	
Dec-03	11dec 18dec	2003345	38.938	38.938	218.25	218.25
Jan-04	01jan 08jan	2004001	85.375	88.5	106.438	104.396
	09jan 16jan	2004009	104.375		95.375	
	17jan 24jan	2004017	75.75		111.375	
Feb-04	10feb 17feb	2004041	65.875	117.5	111.688	111.688
	18feb 25feb	2004049	169.125		111.68	
Mar-04	26feb 04mar	2004057	92.063	93.8755	198.813	291.813
	05mar 12mar	2004065	95.688		384.813	
Apr-04	29mar 05apr	2004089	103.875	84.521	484.375	494.3543
	14apr 21apr	2004105	94.875		460	
	22apr 29apr	2004113	54.813		538.688	

Table C- 3 AEV and CLWA estimated between 2004 and 2006

Month	Time span	Comsite Julian Date	AEV (km2)	Monthly Average AEV (km2)	CLWA	Monthly Average CLWA (km2)
2004-2005						
Nov-04	31oct 07nov	2004305	104.688	121.86	160.63	190.3598
	08nov 15nov	2004313	111.25		108.06	
	16nov 23nov	2004321	133.813		283.94	
	24nov 01dec	2004329	137.688		208.81	
Dec-04	02dec 09dec	2004337	110.5	103.59	158.13	141.625
	10dec 17dec	2004345	96.688		125.13	
Jan-05	01jan 08jan	2005001	12.063	32.271	184.5	287.8543
	09jan 16jan	2005009	22		216.63	
	25jan 01feb	2005025	62.75		462.44	
Mar-05	06mar 13mar	2005065	10.625	10.625	578.56	578.563
Apr-05	30mar 06apr	2005089	31.438	43.891	590.5	534.5628
	07apr 14apr	2005097	50.438		551.19	
	15apr 22apr	2005105	78.313		475.63	
	23apr 30apr	2005113	15.375		520.94	
2005-2006						
Nov-05	17nov 24nov	2005321	31.75	32.532	577.44	480.813
	25nov 02dec	2005329	33.313		384.19	
Dec-05	03dec 10dec	2005337	45.438	40.605	289.75	257.6877
	11dec 18dec	2005345	36.938		246.63	
	19dec 26dec	2005353	39.438		236.69	
Jan-06	01jan 08jan	2006001	26.188	30.792	171.31	268.5003
	09jan 16jan	2006009	27.125		161.81	
	17jan 24jan	2006017	39.063		472.38	
Mar-06	26feb 05mar	2006057	27.625	21.407	518.81	522.9065
	22mar 29mar	2006081	15.188		527	
Apr-06	30mar 06apr	2006089	36	35.479	580.13	564.771
	07apr 14apr	2006097	55.063		488	
	23apr 30apr	2006113	15.375		626.19	

Table C- 4 AEV and CLWA estimated between 2006 and 2008

Month	Time span	Comsite Julian Date	AEV (km2)	Monthly Average AEV (km2)	CLWA	Monthly Average CLWA (km2)
2006-2007						
Nov-06	01nov 08nov	2006305	131.75	122.04	148.563	227.0213
	09nov 16nov	2006313	114		114.563	
	25nov 02dec	2006329	120.375		417.938	
Dec-06	11dec 18dec	2006345	187.313	162.19	221	231.396
	19dec 26dec	2006353	162		273.063	
	27dec 03jan	2006361	137.25		200.125	
Jan-07	09jan 16jan	2007009	124.063	110.91	203.188	218.188
	25jan 01feb	2007025	97.75		233.188	
Feb-07	02feb 09feb	2007033	129.625	129.63	179.063	179.063
Mar-07	26feb 05mar	2007057	201.375	134.15	340.813	432.042
	14mar 21mar	2007073	128.188		461.563	
	22mar 29mar	2007081	72.875		493.75	
Apr-07	30mar 06apr	2007089	80.875	126.41	545.813	416.1098
	07apr 14apr	2007097	134.75		405.063	
	15apr 22apr	2007105	157		318.875	
	23apr 30apr	2007113	133		394.688	
2007-2008						
Nov-07	01nov 08nov	2007305	187.25	221.48	177.688	157.969
	09nov 16nov	2007313	209.188		152.125	
	17nov 24nov	2007321	251.938		154.375	
	25nov 02dec	2007329	237.563		147.688	
Dec-07	03dec 10dec	2007337	239.625	267.31	116.688	130.469
	27dec 03jan	2007361	295		144.25	
Jan-08	01jan 08jan	2008001	196.125	196.13	144.25	144.25
Feb-08	02feb 09feb	2008033	118.75	203.75	238.125	181
	10feb 17feb	2008041	207.563		144.75	
	18feb 25feb	2008049	284.938		160.125	
Mar-08	26feb 05mar	2008057	267.938	316.44	187.938	164.313
	14mar 21mar	2008073	364.938		140.688	
Apr-08	07apr 14apr	2008097	110.25	68.667	516.813	574.521
	15apr 22apr	2008105	40.625		605	
	23apr 30apr	2008113	55.125		601.75	

Table C- 5 AEV and CLWA estimated between 2008 and 2009

Month	Time span	Comsite Julian Date	AEV(km2)	Monthly Average AEV (km2)	CLWA	Monthly Average CLWA(km2)
2008-2009						
Nov-08	09nov 16nov	2008313	21.875	14.95867	638.938	642.542
	17nov 24nov	2008321	7.313		641.813	
	25nov 02dec	2008329	15.688		646.875	
Dec-08	03dec 10dec	2008337	78.188	123.9065	475.625	235.5003
	11dec 18dec	2008345	118.188		203.313	
	19dec 26dec	2008353	136.125		153.625	
	27dec 03jan	2008361	163.125		109.438	
Jan-09	01jan 08jan	2009001	163.188	161.313	109.688	125.469
	09jan 16jan	2009009	159.438		141.25	