Chapter 17
Multitemporal Remote Sensing for Inland Water Bodies and Wetland Monitoring

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Abstract Remote sensing is critically important in monitoring inland water and wetlands for protecting the related environments and ecosystems. This chapter summarizes remote sensing applications in water and wetland monitoring, in particular in the subject areas of monitoring water quality, water surface areas and water fluctuation in wetland areas. The chapter then introduces two cases of monitoring studies in the Poyang Lake, the largest fresh water lake in China, in terms of monitoring of fluctuation and variation of water surface areas using MODIS data product, and monitoring of variation of natural wetlands corresponding to the changing water levels of Poyang Lake using Landsat data.

17.1 Introduction

Inland water bodies and wetlands are essential nature resources for human beings in terms of providing multiple ecosystem services (Costanza et al. 1998). However, inland lakes, rivers and wetlands are threatened by many environmental problems

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caused by various natural and anthropogenic factors, such as eutrophication, other organic and inorganic pollution, acidification, spread of invasive species and climate change. Therefore, monitoring of inland water and wetland are critically important for the protection of related environments and ecosystems (Wang 2012). Remote sensing science and technologies, with the ability of covering large spatial areas at frequent temporal intervals, have been broadly applied in monitoring of inland and coastal waters and wetlands (Wang 2009). In particular, remote sensing is the most effective in monitoring of water and wetland environments with significant dynamic fluctuation and inundation hydrological patterns.

17.1.1 Monitoring of Water Quality

Water with different constituents has different spectral characteristics. Spectral reflectance of water body in visible spectrum provides effective information on optically significant materials present in water (Le et al. 2011), which makes it possible to use remote sensing techniques to monitor water quality.

With research development in understanding of inland water spectral characteristics, improvement of inversion algorithms and new sensor technology, the accuracy of remote sensing monitoring of inland water quality has been continuously improved (Palmer et al. 2015a; Ogashawara and Moreno-Madriñán 2014; Jaelani et al. 2015; Matthews and Odermatt 2015; Wu et al. 2014). In general, the techniques in retrieval of chlorophyll-a (Chl-a) and total suspended solids (TSS) are relatively mature in practical remote sensing applications of inland water bodies (Kutser et al. 1995; Le et al. 2011; Yu et al. 2012; Palmer et al. 2015a; Guo et al. 2015). Also, the retrieval of colored dissolved organic matter (CDOM) in inland water has gained attentions (Kutser et al. 2005; Kutser 2012; Jiang et al. 2014b). Other studies about indicators of remote sensing of water quality have been developed and reported, such as monitoring of dissolved organic carbon (DOC) (Kutser et al. 2015), particulate organic carbon (POC) (Duan et al. 2014), water surface temperature (Korosov et al. 2007), water transparency (Kutser et al. 1995), phycocyanin (PC) (Song et al. 2013), total nitrogen and total phosphorus (Kutser et al. 1995).

Applications of multitemporal remote sensing in monitoring of inland water quality have been reported. For example, a study of monitoring of a massive blue-green algae bloom in Taihu Lake of China presented an analysis with contrasting of Chl-a concentrations between the days before and after throughout the event (Wang and Shi 2008). Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) data were used to monitor seasonal and interannual variabilities and spatial distributions of water properties in Taihu Lake as well (Wang et al. 2011). Recently, 10 years (2002–2012) of Medium Resolution Imaging Spectrometer (MERIS) data over South Africa was employed to study the 50 largest standing water bodies in South Africa to obtain the time series of Chl-a, cyanobacteria and surface scum area coverage (Matthews 2014). Long-term distribution patterns of Chl-a concentration were also analyzed using MERIS full-resolution scenes of 10-year period for the Poyang Lake, the largest freshwater lake of China (Feng et al. 2014). Chl-a concentration mapping using MERIS data has been used to evaluate spatiotemporal dynamics of bloom event for Lake Balaton (Palmer et al. 2015b). Study also reported temporal and spatial distributions of total suspended solids in the Poyang Lake using MODIS medium-resolution (250 m) data from 2000 to 2010 (Feng et al. 2012a). Shi et al. (2015) integrated MODIS-Aqua medium-resolution (250 m) data gathered from 2003 to 2013 and in situ data collected from a number of cruise surveys to estimate the concentrations of total suspended matter in Taihu Lake. Kutser (2012) evaluated suitability of Landsat archive for mapping CDOM changes in Swedish lakes over the last 30 years. Multitemporal remote sensing of inland water can provide immediate and accessible information in monitoring of concentrations of water constituents, which is critically important for establishing an early warning system for emergency management and governance of natural resources.

17.1.2 Monitoring of Water Area

Dramatic changes in the size and morphology of inland water, such as lakes and reservoirs, have occurred around the world in recent decades. For instance, lakes in arid regions have shrunk or vanished due to changes in precipitation/evaporation conditions (Awange et al. 2008). On the other hand, ice melting from mountain glaciers caused significant changes of lakes in the Tibet Plateau, Arctic coastal plain, and Western Siberia in recent decades (Kropácek et al. 2012; Yang and Lu 2014; Sheng and Li 2011; Wang et al. 2012; Smith et al. 2012). There are lakes, such as Poyang Lake in China, that have significant large and rapid water level variations controlled by monsoon climate and the hydrological conditions, which brings increasingly severe floods or droughts.

Remote sensing is extremely effective for monitoring of dynamics of areas of water surface. Landsat images have been used to monitor water environments (Plug et al. 2008; Ma et al. 2010). MODIS data have been used to study the short- and long-term characteristics of Poyang Lake inundation (Feng et al. 2012b) and the regional differences of water inundation duration in different geographic regions (Wu and Liu 2015). Meanwhile, satellite radar altimeter data have been used to monitor the water level and water area (e.g., Jarihani et al. 2013; Liao et al. 2014). Recently, new Sentinel-1 data were evaluated for monitoring of reservoirs (Amitrano et al. 2014). The monitoring results are valuable for hydrological safety and provide information for preparation and precautions against extreme harmful hydrological events.

17.1.3 Monitoring of Water Fluctuation in Wetland Areas

Wetland degradation has aroused widespread concerns. Monitor of water fluctuation in wetland areas is among important practices for conservation and management of wetland resources. Landsat and SPOT images are among major data sources that have been used in monitoring of water fluctuations in wetland areas. Multi-temporal data are very effective in extraction of wetland information when combined with elevation and topography data (Ozesmi and Bauer 2002).

Early research employed Landsat and SPOT HRV multispectral data to evaluate aquatic macrophyte changes within the Florida Everglades (Jensen et al. 1995). Gong et al. (2010) identified changed areas in China's wetland between 1990 and 2000 and analyzed potential uncertainties in the wetland change mapping based on Landsat data acquired around 1990 and 2000. Landsat data have been used on Poyang Lake of China for monitoring of water inundation of wetland (Hui et al. 2008), and for monitoring of suitable habitat for Siberian cranes (Jiang et al. 2014a).

17.2 Multitemporal Remote Sensing of Poyang Lake, China

Poyang Lake is situated at the lower Yangtze River basin and it is the largest fresh water lake in China. Poyang Lake is fed by tributaries of five rivers of Gan, Fu, Xin, Rao and Xiu and it is connected and exchange water with Yangtze River through lake mouth in the north (Fig. 17.1). As controlled by water from the five tributary rivers as well as the Yangtze River, the Lake's highly dynamic and seasonal variations in water level present a unique landscape of fresh water lake-wetland ecosystem. The variation of the size of the lake is illustrated as an ocean when flooded during the wet season and as a line of river when withered during the dry season. The Poyang Lake wetland is a key habitat site for wintering migratory birds with global importance. The lake plays an irreplaceable role for flood control, river shipping, city water supply and conservation of biological diversity of middle and lower reaches of Yangtze River (Gao et al. 2014).

Poyang Lake is affected by subtropical monsoon climate with a mean annual precipitation of 1632 mm (Xu and Qin 1998), about 60 % of the annual rainfall happened in flood season during April to August within the Poyang Lake watershed. It was estimated that approximately 1.43×10^7 tons of sediments with nutritive materials were carried from the five tributary rivers and deposit in the floodplain each year. The sediment loaded by water discharge was deposit and formed fertile deltas. Lake sediment is important for a biologically productive lake-wetland system such as the Poyang Lake wetland. There are about 102 vegetation species of aquatic vascular plants and freshwater organisms presented in the fertile floodplain. Poyang Lake wetland was first selected as the protected area under the international Ramsar Convention in China because of its biological productivity, species richness and being a critical wintering habitat for rare and endangered migratory bird species such as the Siberian crane (Grus leucogeranus). The lake area has a long history of agricultural and fishery practices. The lake and associated wetlands support a high population densities of about 400–800 persons/km^2 (Shankman et al. 2006).

The area and shape of Poyang Lake were affected by natural deposition and erosion in the past decades. Increased human population and economic growth induced activities such as sand mining (Feng et al. 2011), reclamation for agriculture,

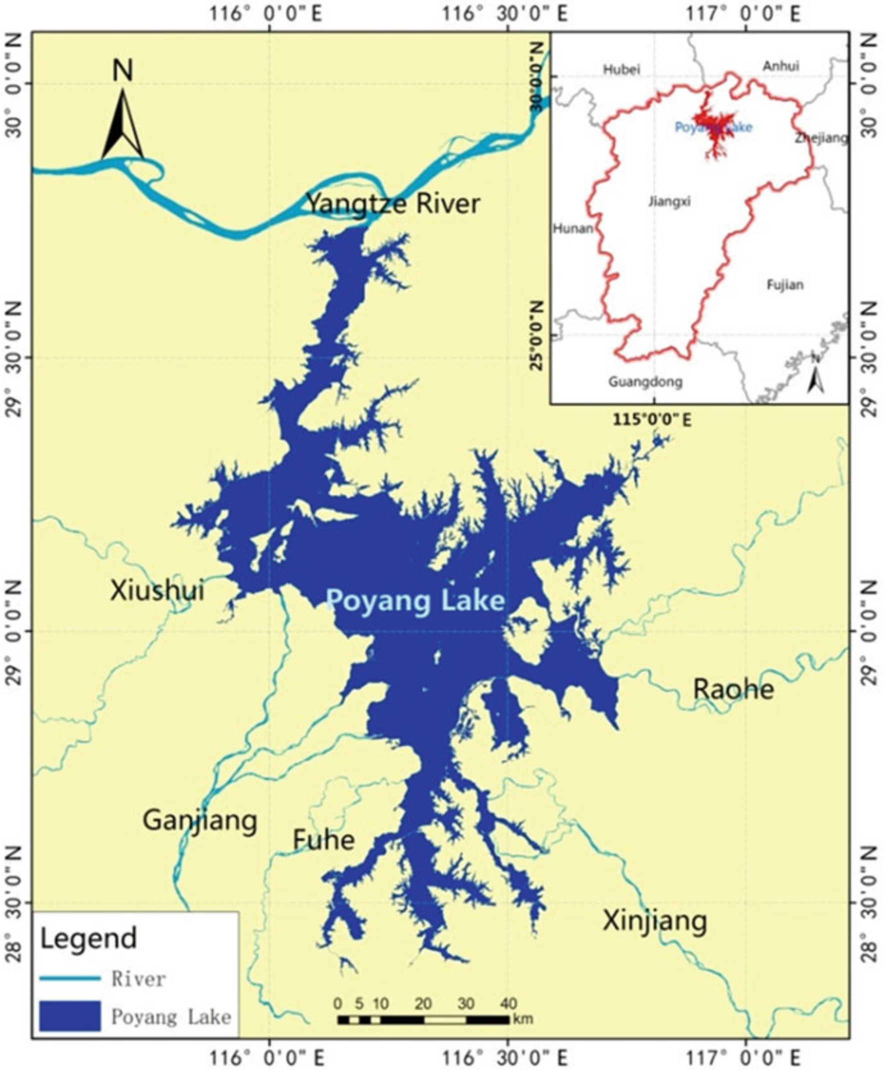

Fig. 17.1 Location of Poyang Lake

fishery, aquaculture and settlements (Qi et al. 2009; Min 1999), which also affected areas and surrounding landscape of the lake. It is estimated that area of Poyang Lake was reduced from 5160 km^2 in 1954 to 3860 km^2 in 1998 (Shankman and Liang 2003). Reclaiming farmland was the most significant activity changing the morphology of Poyang Lake dramatically before 1998. However sand dredging in the Poyang Lake water system was intensified since 2001 because of the demand of raw materials in the rapid urbanization in the lower Yangtze River valley, as well as that sand dredging was banned in the Yangtze River in 2000. Lured by high profits, sand dredging business developed quickly with hundreds of large sand vessels assembled and operated in the Poyang Lake water system. Poyang Lake has attracted wide attention of the international and scientific communities (Jiao 2009; Yésou et al. 2011; Dronova et al. 2011; Zhang et al. 2014). We report two case studies in monitoring of water and wetland of Poyang Lake, respectively, in the follow sections.

17.2.1 Monitoring of Inundation Areas Using MODIS Data

The Poyang Lake experiences the most significant flood and drought rotation each year. The inundation with dynamics of water levels occurs in both short term on weekly and monthly basis and in long term with annual variations. In monitoring of inundation, time series MODIS data were employed.

17.2.1.1 Data Acquisition

The 8-day MODIS Surface Reflectance data (MOD09Q1) collected between 2000 and 2014 were obtained from an open source (https://ladsweb.nascom.nasa.gov/data.html). There are 46 scenes of MOD09Q1 images during every year, i.e., every 8 days to cover one image. Due to the missing of six scenes in 2000 and one scene in 2001, a total of 683 scenes of MOD09Q1 images were acquired between 2000 and 2014. MOD09Q1 contains 3 data layers, surface reflectance for band 1 (620–670 nm), surface reflectance for band 2 (841–876 nm) and surface reflectance quality control flags, all with 250 m spatial resolution.

17.2.1.2 Data Processing and Result

All the collected MODIS images were resampled using nearest neighbor method, and geometrically rectified to WGS84 datum with Universal Transverse Mercator (UTM) coordinate system. Then all the images were clipped by the boundary of the Poyang Lake using mask calculation. The water surface areas were extracted from other features using the normalized difference vegetation index (NDVI) threshold:

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \tag{18.1}$$

Where, VIS and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively. Normally, the value of NDVI for water is less than 0. However due to the existence of large amount of aquatic vegetation in Poyang Lake, which affects the absorption, reflection and transmission of visible and near-infrared spectrum on water surface. A modified NDVI threshold of less than 0.1 was applied to extract the water surface areas. For those MOD09Q1

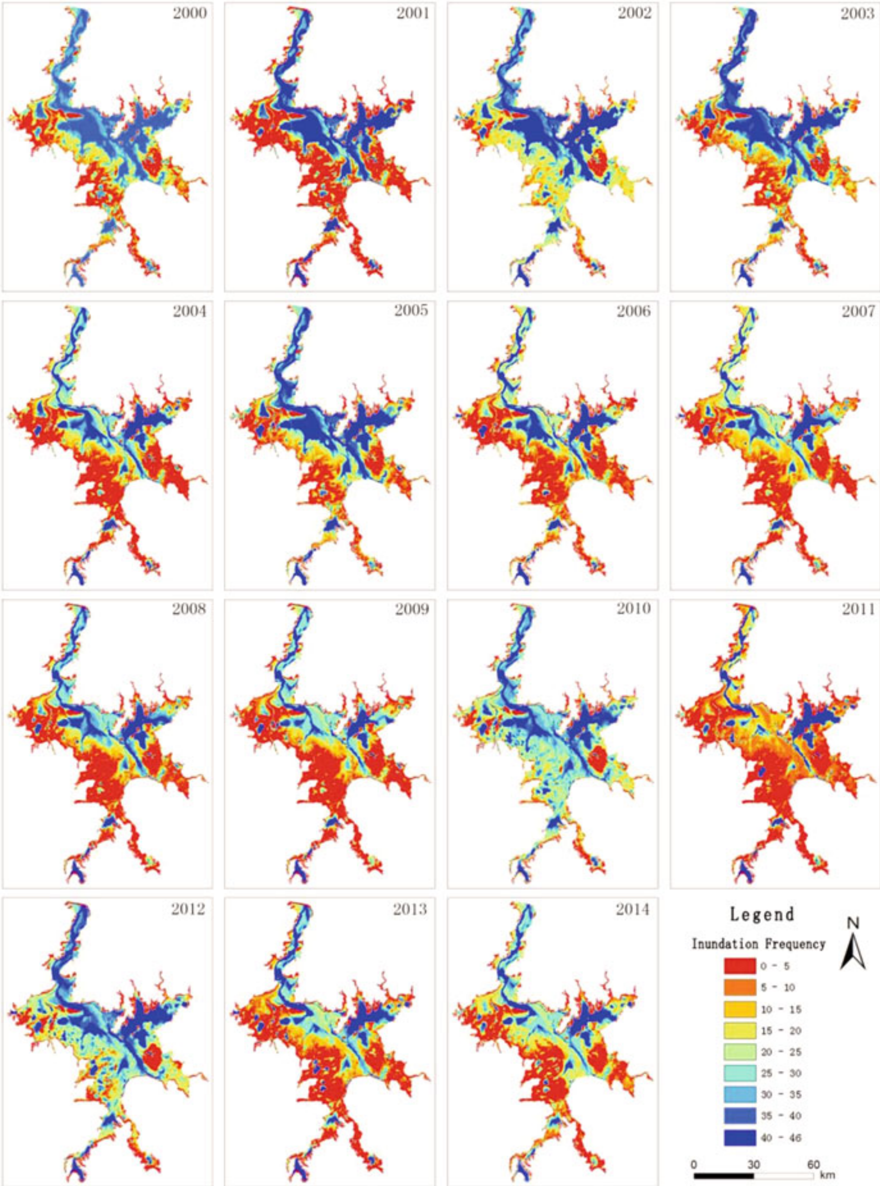

Fig. 17.2 Variation of inundation areas in Poyang Lake during each year between 2000 and 2014

images that have thick cloud covers, MODIS09Q1 images acquired in similar date were applied instead. At last, the extracted water surface images were added together for each year to obtain the inundation variation of water surface areas in Poyang Lake between 2000 and 2014 (Fig. 17.2). According to the extents of inundation areas, the maximum flooding time lake area was about 3400 km^2, while

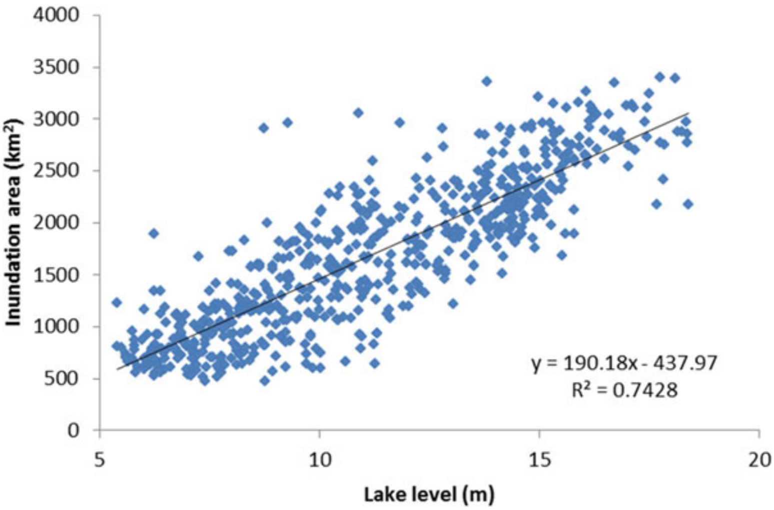

Fig. 17.3 The inundation area of Poyang Lake at different lake water level

Table 17.1 Annual maximum and minimum inundation area of Poyang Lake during 2000–2014

Year	Annual maximum inundation area (Km2)	Annual minimum inundation area (Km2)	Annual maximum Water level (m)	Annual minimum Water level (m)
2000	3363.44	1068.00	16.23	7.11
2001	2650.50	1183.38	15.14	7.67
2002	3396.88	941.94	18.36	6.51
2003	3241.31	799.38	17.49	6.07
2004	2526.44	614.75	15.53	5.23
2005	3104.50	1045.38	17.15	6.37
2006	2915.75	617.69	14.82	5.91
2007	3045.63	623.81	16.59	5.40
2008	2399.44	560.94	15.78	5.48
2009	2137.13	472.25	15.27	5.60
2010	2881.31	526.25	18.38	5.85
2011	2457.69	512.19	15.50	6.22
2012	2905.13	556.69	17.75	5.90
2013	2280.31	585	15.06	5.54
2014	3040.56	616.81	16.70	5.41

the minimum inundate area of the lake was only about 470 km^2. The largest annual variability ratio between maximum and minimum water surface areas was 5.48 that occurred in year 2010. Together with water level records measured at a gauging station on the lake, a strong correlation existed between inundation areas and water levels (Fig. 17.3). A decreased trend is evident between maximum and minimum water levels since 2000 (Table 17.1).

17.2.2 Monitoring of Wetland Fluctuation Using Landsat Data

Poyang Lake wetlands provide wintering habitats for most of the estimated existing population of Siberian cranes. Hydrological regime of Poyang Lake is a dominant factor controlling the quality of the habitats. However the hydrological process in Poyang Lake wetland has been changing especially in recent decades due to human activities. Abnormal low water level in Poyang Lake occurred more frequently in autumns and winters in recent 10 years. In this case study, the fluctuation of Poyang Lake wetland areas in different water levels were extracted based on multitemporal Landsat images.

17.2.2.1 Data Selection

Twelve scenes of Landsat images (path 121/Row 40) with no or little cloud cover were selected (Table 17.2). Among those images, 10 scenes were acquired from October to March in different years, reflected different water levels with about 1 m interval. The images were select to evaluate habitat vulnerability to water levels with analysis on landscape configuration by land-cover types derived from imagery classification process. The image acquired in 5 July 2000 corresponded to the time that the lake water level was 15.6 m above a mean sea level. This image was selected as a surrogate of the water level controlled at 15.5 m as the proposed hydrologic engineering project of Poyang Lake Dam for analyzing the effects of water variation to wetland landscape. The image acquired in 8 July 1998 corresponded to the time that the lake water level was 19.6 m above a mean sea level. This image was used only for defining the boundary of the natural wetland areas of the Poyang Lake.

Table 17.2 Landsat TM/ETM+ images and water level in Xingzi gauging station

No.	Date of imagery acquisition (DD-MM-YYYY)	Satellite/Sensor	Water level (m)	Purpose of usage in this study
1	15 February 2004	Landsat 5/TM	5.3	*a*
2	6 January 2007	Landsat 5/TM	5.9	*a*
3	15 December 2004	Landsat 5/TM	7.1	*a*
4	27 January 2000	Landsat 7/ETM+	7.9	*a*
5	10 December 1999	Landsat 7/ETM+	8.8	*a*
6	5 March 2005	Landsat 5/TM	10.1	*a*
7	16 November 1999	Landsat 5/TM	11.1	*a, b*
8	2 November 1994	Landsat 5/TM	12.1	*a*
9	5 October 2007	Landsat 5/TM	13.0	*a*
10	9 October 2000	Landsat 7/ETM+	14.2	*a*
11	5 July 2000	Landsat 7/ETM+	15.6	*a*
12	8 July 1998	Landsat 5/TM	19.6	*c*

Note: *a* – land-cover classification, *b* – defining the boundary of inner-lakes of the Poyang Lake, *c* – defining the boundary of natural wetlands of the Poyang Lake

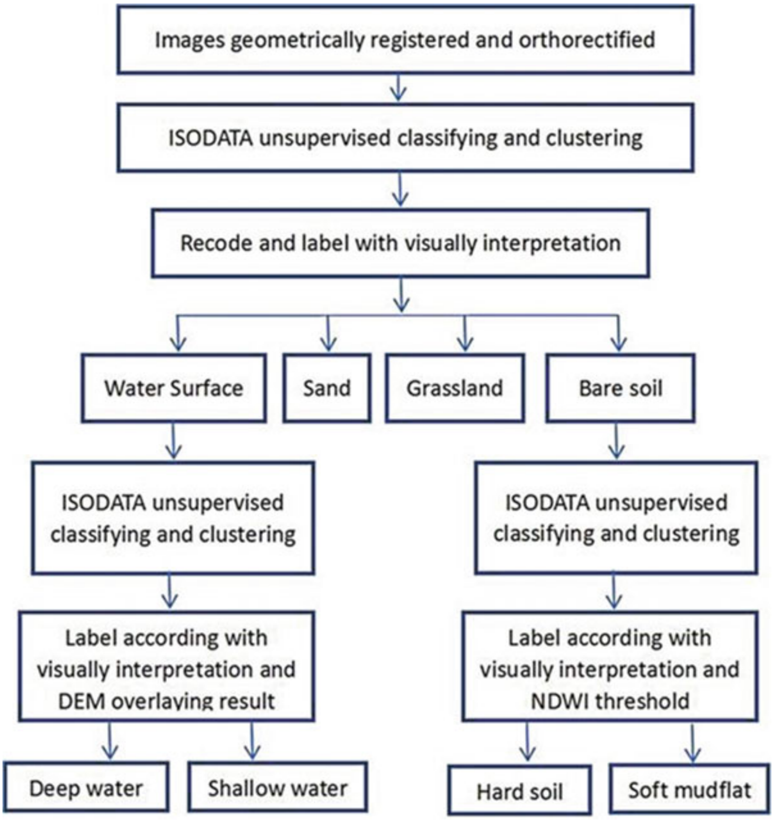

Fig. 17.4 The technological process of land-cover classification

17.2.2.2 Data Processing and Result

All Landsat images were geometrically rectified to WGS84 datum with UTM coordinate system and orthorectified using a digital elevation model (DEM). Eleven scenes of Landsat images were used to map six land-cover categories including deep water, shallow water, soft mudflat, hard soil, grassland and sand (Fig. 17.4).

Unsupervised classification by ISODATA algorithm was used to produce 10 clusters of pixels with corresponding spectral similarities. At first, the spectral clusters were recoded and labeled as four land-cover categories of water surface, sand, bare soil and grassland with visual interpretation. Unsupervised classification was applied again on pixels of water surface and bare soil categories, respectively. The water surface was then divided into deep and shallow water areas according to visual interpretation and estimation of water depth. Bare soil was divided into hard soil and soft mudflat by referencing to visual interpretation and NDWI threshold:

$$NDWI = \frac{(r2 - r5)}{(r2 + r5)} \quad (18.2)$$

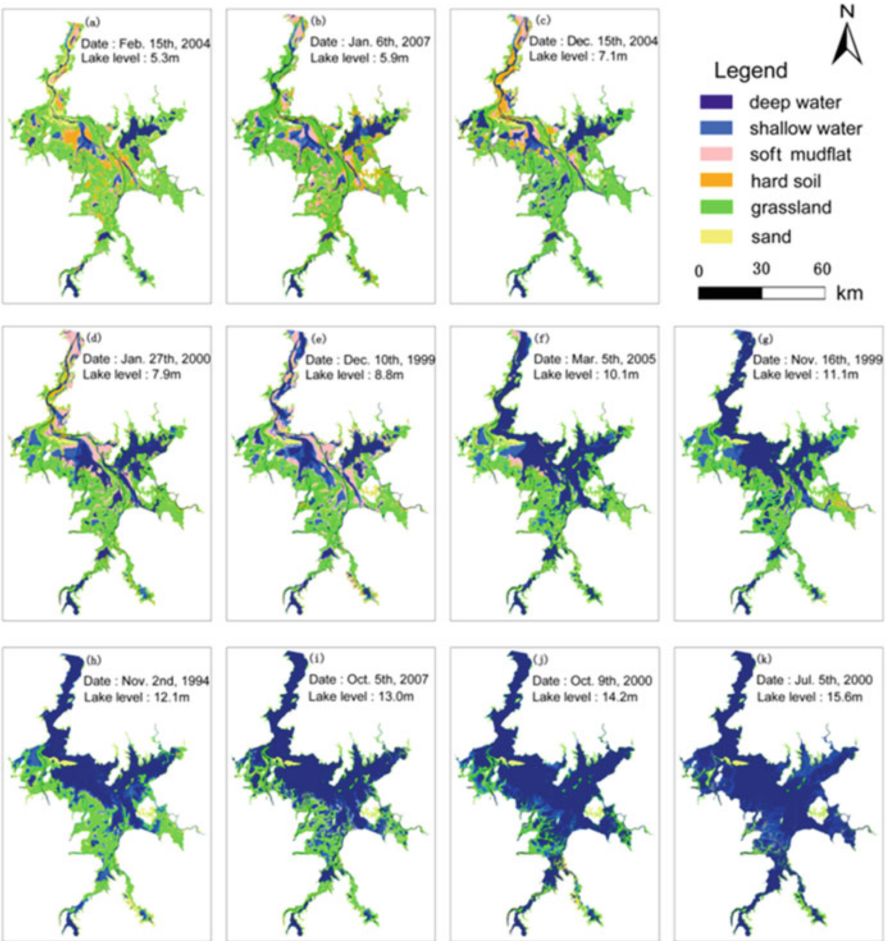

Fig. 17.5 Land-cover maps of Poyang Lake natural wetland in different water levels

where *r2* and *r5* refer to the at-sensor reflectance for Landsat TM/ETM+ band 2 and band 5, respectively. According to the GPS-guided field sampling, the NDWI threshold (=0.65) was applied to distinguish the categories of hard soil and soft mudflat. Additionally, the burned grassland area was also classified as hard soil because the post-fire grassland area was deprived of habitat function with drier soil for the year.

The land cover types of natural wetlands of the Poyang Lake were extracted from 11 Landsat scenes and illustrated as Fig. 17.5. Considering that the Landsat imagery acquired 15th December 2004 was coincident with lake water level of 7.1 m, which is very close to the water level of 7.06 m of our third field survey day, the land cover map derived from classification of 15th December 2004 image was assessed by 126 GPS-guided samplings sites during the field survey. According

Table 17.3 Error matrix and classification accuracy assessment

	G	S	HS	SM	SW	DW	Row total
G	35	0	0	0	0	0	35
S	0	12	0	0	0	0	12
HS	0	0	17	3	0	0	20
SM	0	0	2	12	1	0	15
SW	0	0	0	3	23	2	28
DW	0	0	0	0	0	16	16
Column total	35	12	19	18	24	18	126

Overall accuracy = 115/126 = 91 %, kappa = 0.89
G Grassland, *S* Sand, *HS* Hard soil, *SM* Soft mudflat, *SW* Shallow water, *DW* Deep water

Table 17.4 Area of potential suitable habitat for Siberian cranes with different water level in Poyang Lake wetland (km^2)

WL	SW	SM	G	DW	HS	S
5.3 m	182.09	599.9	1510.62	414.72	451.35	147.34
5.9 m	229.39	547.81	1525.51	509.6	444.37	49.34
7.1 m	301.34	446.04	1262.75	735.72	392.33	167.84
7.9 m	230.52	658.38	1247.46	887.17	232.56	49.93
8.8 m	399.6	538.43	1068.4	779.38	340.23	179.98
10.1 m	291.03	246.24	1179.26	1400.1	85.04	104.35
11.1 m	397.93	257.37	1100.23	1341.56	152.63	56.3
12.1 m	404.35	186.7	908.11	1489.84	82.77	234.25
13 m	359.35	210.45	664.76	1866.13	25.71	179.62
14.2 m	246.76	87.05	418.24	2389.01	22.8	142.16
15.6 m	241.34	91.71	197.48	2660.32	18.4	96.77

WL Water level, *SW* Shallow water, *SM* Soft mudflat, *G* Grassland, *DW* Deep water, *HS* Hard soil, *S* Sand

to the error matrix (Table 17.3), all reference sites for grassland and sand types were classified correctly, but confusions existed between shallow and deep water, and soft mudflat and hard soil categories. Accuracy assessment results indicate of 91 % overall accuracy and 0.89 kappa coefficient for the land cover map of 2004. It was conclude that the total area of glassland, soft mudflat and shallow water areas that could be used as habitat for migrate birds in Poyang Lake was decreased with water level increasing (Table 17.4).

17.3 Conclusion Remarks

As the largest freshwater lake in China with the greatest variation in water level and inundation extent, multitemporal remote sensing plays a key role in monitoring of water quantity and quality, as well as the associate wetlands as critical habitats of a global significance in biodiversity conservation. Time-series MODIS data products were very effective to capture the change of water surface areas due to the hydrologically sensitive nature of the Poyang Lake. MODIS data reveal that the largest annual variability ratio between 2000 and 2014 and between maximum and minimum water surface areas was 5.48 which occurred in year 2010. Together with water level records measured at a gauging station on the lake, a strong correlation existed between inundation areas and water levels. A decreased trend is evident between maximum and minimum water levels since 2000. On the other hand, finer spatial resolution multitemporal Landsat data are much appreciated for monitoring of the wetlands that are routinely affected by the dynamics of water levels of the Poyang Lake. Landsat data reveal that the total areas of suitable habitats for migrate birds in Poyang Lake, i.e., glassland, soft mudflat and shallow water areas, were decreased as water level increased. This may provide an important piece of information about the hydrological effects on key habitats conditions of the key migratory birds for planning and management actions in conservation of biodiversity of the Poyang Lake region. The data process and analysis approaches are applicable to most of the situations for monitoring of the changing environment, in particular, for the subjects of inland water and wetland monitoring.

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