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ARTICLE

Assessment of Alpine Wetland Dynamics from 1976–2006 in the Vicinity of Mount Everest

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Abstract Wetlands provide a range of critically important ecosystem services. However, a lack of reliable wetland data limits the efficacy of wetland management in remote mountainous areas. To optimize the management of wetlands in the vicinity of Mount Everest we created a new classification system for high alpine wetlands. Object-oriented image classifications and geographical information systems were used to extract wetland information for 1976, 1988, and 2006 from remote sensing data and field surveys. The results show that total area of wetlands in the vicinity of Mount Everest in 2006 was 1663.5 km^2 mainly found 4100–4800 m above sea level. Wetlands had changed, and the changing area (expansion and contraction) added up to 94.5 km^2 or 5.6% from 1976–2006. Temporal-spatial variation in wetlands and land cover imply that regressive succession has occurred in some areas. Natural driving forces are key factors. Data suggest that creation of the Mount Qomolangma (Everest) National Nature Preserve in 1988 positively impacted wetland conservation.

Keywords Lands cover change · Qomolangma · Remote sensing · Tibetan Plateau

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Introduction

Wetlands perform vital functions such as water storage, water purification, biodiversity conservation, storm protection, flood mitigation, erosion control, and eco-environmental improvement. These ecosystems are of tremendous economic benefit to fisheries and agriculture, and are an important component of the cultural heritage of many areas (Davis 1994; Mitsch and Gosselink 2000; Ramsar Convention Secretariat 2006; Pan and Wang 2009; McCarthy et al. 2010). Wetlands are considered to be one of the most sensitive ecosystems to changes in the global climate (Keith et al. 2010). Earth observation technologies have enabled the implementation of the Ramsar Convention on wetlands (Jones et al. 2009; MacKay et al. 2009) as assessment and monitoring at different spatial and temporal scales informs wetland management. Remote sensing (RS) has proved to be useful in wetland resource monitoring, especially across large areas (Ozesmi and Bauer 2002). RS images such as Landsat (MSS, TM, ETM), synthetic aperture radar (SAR), airborne light detection and ranging (LiDAR), and systeme probatoire d'observation de laterre (SPOT) have been used in mapping and monitoring of wetlands worldwide (Prigent et al. 2001; Hess et al. 2003; Wright and Gallant 2007; Liu et al. 2008; Papastergiadou et al. 2008; Castañeda and Ducrot 2009; Lang and McCarty 2009; Bwangoy et al. 2010; Davranche et al. 2010; Gondwe et al. 2010; Grapentine and Kowalski 2010). Objective, rapid, precise, and quantitative extraction of wetland attributes based on RS and geographic information systems (GIS) are essential to assess carbon balance and cycling under a changing climate (Kayranli et al. 2010). Collectively, these tools aid land managers in the protection and sustainable management of wetlands.

The Tibetan Plateau is a unique and sensitive environment particularly vulnerable to global climate change. The 10 largest rivers in Asia, in terms of length and volume, originate from the Plateau (Qiu 2008), making it an area rich in aquatic ecosystems and wetlands. The Tibetan Plateau is of high economic and ecological importance due to the value of its ecosystem services, and the human populations that rely on its waters (Xie et al. 2003). Research in this region has mainly focused on the source areas for the Yangtze, Yellow, and Roige Rivers (Shen et al. 2005; Wang et al. 2007), and the Lhasa River basin (Zhang et al. 2010). Data involving tempo-spatial changes in the distribution, total area, structure, and function of wetlands of the Tibetan Plateau, especially in the vicinity of Mount Everest (or Qomolangma locally) are lacking.

The absence of reliable data on the wetlands surrounding Mount Everest has constrained their protection. The objectives of our study were to identify wetland types across this region, and characterize the distribution and temporal change in wetlands within this part of the central Himalayas. Landsat RS images and field surveys were used to quantitatively analyze the spatial distribution of wetlands, as well as temporal variation. To our knowledge, this is the first large scale assessment of wetland change conducted in this important region, and may promote the conservation and restoration of high alpine wetland ecosystems.

Study Area

Mount Qomolangma (Everest) National Nature Preserve (QNNP) is located within China's borders (27°48′–29°19′N, 84°28′E–88°23′E), was founded in 1988, and is the highest altitude protected area in the world (Cidanlunzhu 1997; Zhang et al. 2007). Its location makes it a useful place to conduct research on water and energy budgets, as well as differences in ecosystem structure and function under a changing global environment. The region addressed in this study is a 36594.6 km^2 area, ranging in altitude from 1460–8844 m above sea level (asl), comprising the whole of QNNP plus some surrounding unprotected areas (Fig. 1). The study region has four major river basins: Pengqu, Gyirong Zangbo, Poiqu, and Yarlung Zangbo. Soils shows distinct vertical zonation (from bottom to top): mountain yellow brown soil, mountain acid brown soil, mountain bleached podzolic soil, subalpine meadow soil, alpine meadow soil, subalpine steppe soil, and alpine meadow-steppe soil (Tibetan Scientific Expedition Team of Chinese Academy of Sciences 1975). Meteorological data show that the annual mean air temperature is 3.0°C

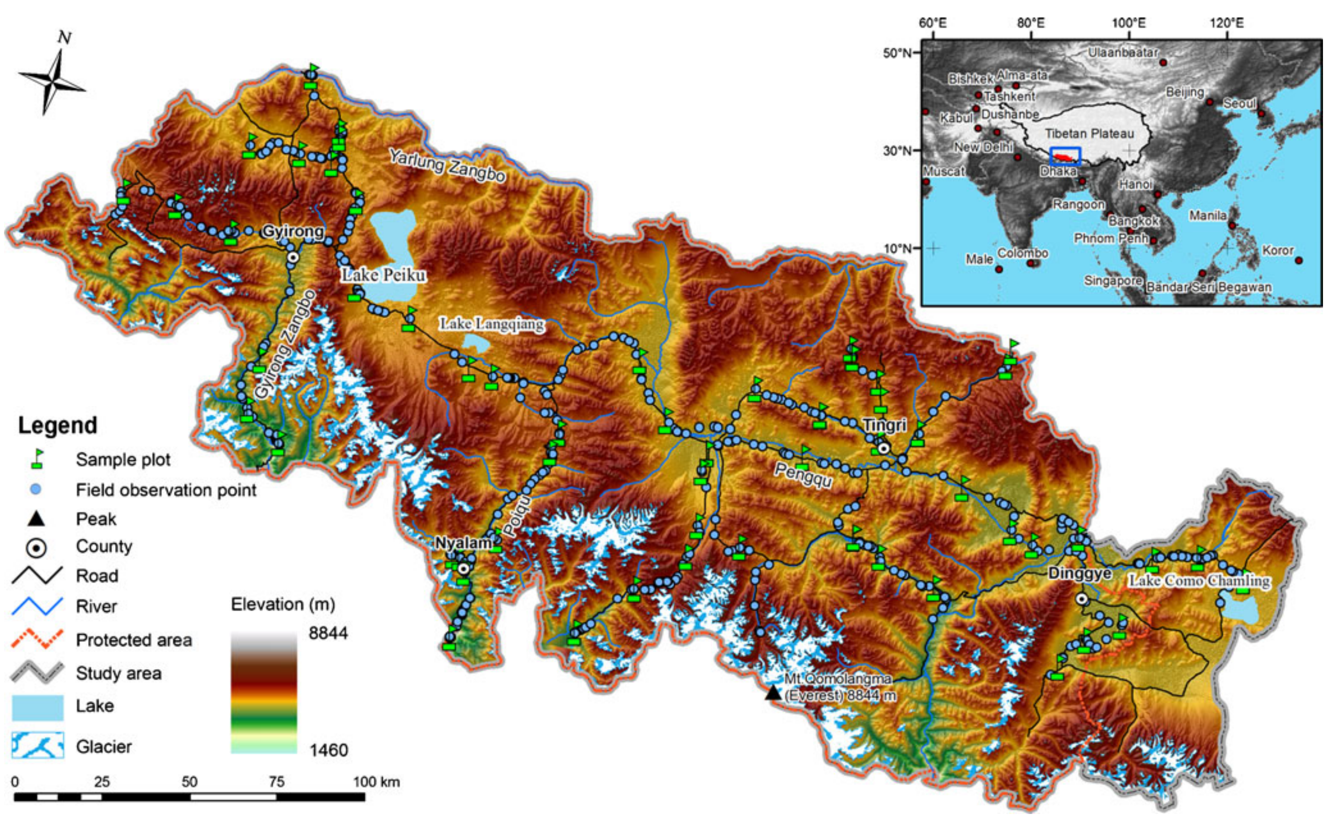

Fig. 1 Location of the Mount Qomolangma (Everest) National Nature Preserve and study area

and precipitation is 286.3 mm in Tingri, and 3.8°C and 658.8 mm in Nyalam (Nie et al. 2010). Altitudinal vegetation zonation occurs on both southern and northern slopes (from bottom to top): mountain subtropical evergreen broad-leaved forests, mountain warm-temperate needle-leaved and broad-leaved mixed forests, mountain cold-temperate needle-leaved forests, subalpine frigid shrubs and meadows, alpine frigid meadows and cushion vegetation, and alpine frigid moraine lichens are found on southern slopes; and plateau frigid semi-arid steppes, alpine frigid meadows and cushion vegetation, and alpine frigid moraine lichens are found on northern slopes (Comprehensive Scientific Expedition Team of Chinese Academy of Sciences in Qinghai-Tibet Plateau 1988). Agriculture is the predominant human activity in the area and the total human population across the study area was approximately 97,000 in 2008 (Tibet Bureau of Statistic 2009).

Methods

Remote Sensing and Ancillary Data

Frequent cloud cover across the Tibetan Plateau affects the quality of optical RS data and reduces the capability of monitoring wetlands using this technology. The images we used were of the highest available quality and sourced from Landsat satellites, which are a combination of data from the Global Land Cover Facility (GLCF) and the US Geological Survey (USGS), and have been precisely geo-rectified. The high probability of cloud cover over the Tibetan Plateau meant that suitable Landsat remote sensing data with low cloud coverage were limited (Li et al. 1999). Therefore it was not possible to select the same acquired time images to monitor wetland change. In order to reduce errors resulting from differences in the time of acquisition, data from similar seasons for 1976, 1988, and 2006 were selected, focusing on October to January (Table 1). On the Tibetan Plateau, the plant growing season is from May to September (Yang and Piao 2006), and the rainy season is from June to August. Thus wetland change over the October to January non-growing season is modest, so differences in the time of acquisition on the wetland change should be negligible. The original spatial resolution of MSS and TM was 79 and 30 m, which was resampled to 57 and 28.5 m, respectively, by GLCF. Most images were cloud free except for Path141/Row40 (2006-10-14), Path141/Row41 (2006-10-14), and Path140/Row41 (2004-11-02) that contained spotty clouds. Cloudy zones were replaced by other cloudless images.

Other data used included land cover data from 1976, 1988, and 2006, using 73 representative sample plots and hundreds of field observation points during the field investigations in QNNP from 2007 and 2008 (Fig. 1). Field survey data on wetlands was provided by scientific expedition teams of the Chinese Academy of Sciences (1959–1960, 1966–1968, 1975, and 2005). Annual mean air temperature and precipitation data from five meteorological stations (Tingri, Nyalam, Xigaze, Lazi, and Gyantse) were provided by the National Meteorological Information Center, China Meteorological Administration. Topographic maps at a scale of 1:100 000 were used. An ASTER Global Digital Elevation Model (ASTER GDEM) with spatial resolution of 30 m was released jointly by the Japanese Ministry of Economy, Trade and Industry (METI) and the National Aeronautics and Space Administration (NASA).

Table 1 Landsat images and their acquisition dates

Order	Path	Row	Date	Sensor	Resolution/m	Order	Path	Row	Date	Sensor	Resolution/m
1	151	41	1975-10-15[a]	MSS	57	13	140	41	1992-11-17	TM	28.5
2	151	40	1976-12-02[a]	MSS	57	14	140	40	2004-11-2	TM	30
3	152	40	1976-12-03	MSS	57	15	140	41	2004-11-2	TM	30
4	150	40	1976-12-19	MSS	57	16	140	40	2005-11-05[a]	TM	30
5	150	41	1976-12-19	MSS	57	17	140	41	2005-11-05[a]	TM	30
6	151	40	1977-01-07	MSS	57	18	139	40	2005-11-14	TM	30
7	151	41	1977-01-07	MSS	57	19	139	41	2005-11-14	TM	30
8	141	40	1988-10-12	TM	28.5	20	142	40	2006-02-07[a]	TM	30
9	139	40	1989-11-10	TM	28.5	21	141	41	2006-10-14	TM	30
10	139	41	1989-11-10	TM	28.5	22	141	40	2006-10-14	TM	30
11	142	40	1990-11-10	TM	28.5	23	142	40	2006-11-22	TM	30
12	140	40	1992-11-17	TM	28.5						

[a] selected as ancillary data

Wetlands Classification System

A global standard for the classification of wetland systems is not available (MacKay et al. 2009). However, many site-specific classification systems across different spatial and temporal scales have been developed (Hess et al. 2003; Zhu et al. 2003; Bai et al. 2004; Yu et al. 2004; Cozar et al. 2005; Wright and Gallant 2007; Castañeda and Herrero 2008; Jones et al. 2009; Lang and McCarty 2009; Niu et al. 2009; Zhang et al. 2009; Bwangoy et al. 2010; Zhang et al. 2010). A unique classification system was developed based on Ramsar guidelines for wetlands, field surveys in the study area, RS images, and wetland research in the Lhasa River basin (Zhang et al. 2010). This classification system included seven categories based on morphology, hydrological characteristics, and vegetative attributes (Table 2).

Wetland Information Retrieval

Traditional classification methods such as human visual interpretation (Yu et al. 2004; Papastergiadou et al. 2008; Niu et al. 2009) and supervised classification (Zhang et al. 2009; Bwangoy et al. 2010) were used for wetland classification. However, these methods lacked location accuracy and created 'salt and pepper' effects that largely constrained their application to our study. Alongside the development of RS techniques, rule-based automatic classification methods have been made available to obtain better outcomes (Ozesmi and Bauer 2002). Ancillary data (such as DEM) and expert knowledge have been applied to novel rule-based methods of decision tree (Wright and Gallant 2007; Liu et al. 2008; Bwangoy et al. 2010) and object-oriented classification (Frohn et al. 2009). The object-oriented classification method was initially used for high spatial resolution images (Blaschke and Hay 2001; Radoux and Defourny 2007). However this advanced method was also suitable to Landsat images (Mitri and Gitas 2004; Watts et al. 2009). Object-oriented classification has been successfully applied to wetlands mapping (Frohn et al. 2009; Reif et al. 2009), and is especially effective in restraining 'salt and pepper' effects and improving extraction accuracy (Reif et al. 2009; Blaschke 2010; Nie et al. 2010).

Object-oriented image interpretation methods and post classification of visual inspection and modification were employed to extract wetland information. We adopted a rule-based classification for object-oriented feature extraction (Jin and Paswaters 2007) to map wetlands in the study area using the platform ENVI ZOOM (ITT Visual Information Solutions, Boulder, USA). Wetlands extraction workflow included segmenting images, merging segments, rule-building, and exporting vectors. First, all bands of MSS or TM, Normalized Difference Vegetation Index (NDVI) (Epting et al. 2005), Normalized Difference Water Index (NDWI) (McFeeters 1996), DEM, and slope were stacked as one dataset. Second, thresholds for segmentation and merging segments were determined to find objects. Third, rule-building was developed primarily based on expert opinions and samples from field surveys and images. Parameters such as NDVI, NDWI, DEM, slope, object-based spectral, textural, and neighborhood attributes were selected as key factors for rule-building to extract wetland types. For example, wetlands did not occur above 6000 m asl, and *Kobresia humilis, Carex moorcroftii* wet meadow in images had a higher NDVI numeric value. Fourth, the extracted wetlands were exported into shapefile formats. Wetland information in images from different acquisition dates were extracted individually. The numeric values of each rule varied and were reselected based on the image dates. However, extraction workflows and rules were the same for TM and MSS. Following this, manually attributive, spatial inspection and correction for each exported shapefiles was done using ArcGIS software (Environmental Systems Research Institute, California). We mosaicked the corrected shapefiles to contrast wetland data from 1976, 1988, and 2006. Wetland conversions from 1976–2006 and 1988–2006 were calculated using the UNION command in ArcGIS. To ensure the accuracy of wetland change, the conversions were checked individually, and errors were corrected. Features of the same attributes were aggregated using the DISSOLVE command to generate final reliable wetland data.

A random stratified sampling method was used to assess accuracy. A total 150 sample points were randomly selected for analysis. Results indicated that weedy wet meadows and gravel floodplain had a relatively low producer's and user's accuracy (but still >87%) because they were easily confused due to similar spectral characteristics. Overall classification accuracy for 1976, 1988, and 2006 was >95%, and kappa coefficients were >94% (Table 3).

Results and Discussion

Distribution and Characteristics of Wetlands

Data indicate the total area of wetland in the vicinity of Mount Everest was 1663.5 km^2 in 2006, accounting for 4.5% of the whole study area. Major wetland types were *Kobresia humilis* and *Carex moorcroftii* wet meadow (667.4 km^2), lacustrine wetland (481.7 km^2), weedy wet meadow (319.2 km^2), and gravel floodplain (119.4 km^2) (Fig. 2, Table 4).

Wetlands in the vicinity of Mount Everest had distinct altitudinal distributions. The majority of wetlands in our study area (83.6%) occurred between 4100–4800 m asl (Fig. 3). For example, 82.1% of *Kobresia humilis* and

Table 2 Classification system of high alpine wetland in the vicinity of Mount Everest

Classification system of wetland		Characteristics and interpretation criterion	Image	Photograph
Geomorphic class	Vegetative sub-class			
Riverine wetland		Permanent or intermittent moving water bodies. It appears as black or blue-black in images.		
Floodplain wetland	Weedy wet meadow	Floodplain or ait dominated by *Kobresia, Carex*, and/or *Gramineae*. Plant height and coverage varied regionally. It usually appears as light pink in images.		
	Hippophae rhamnoides scrub	*Hippophae rhamnoides* is the dominant plant species, with tree heights from 1-3 m and coverage of 90%. It appears as copper brown in images.		
	Gravel floodplain	Floodplain or ait with vegetation coverage <5%, It appears as light blue or white with relative consistent texture in images.		
Lacustrine wetland		Water surfaces of lakes and glacial lakes. It appears as blue or black in images, with irregular but clear boundaries with land.		
Palustrine wetland	Aquatic weedy marsh	Dominant plants are *Hippuris vulgaris, Eleocharis vulgaris*, and/or *Polygonum lapathifolium* with heights from 30–50 cm and cover from 65–90%. Water levels were low. Images were light red with black water rings.		
	Kobresia humilis and *Carex moorcroftii* wet meadow	Dominant plant species are *Kobresia humilis, K. littledalei,* and/or *Carex moorcroftii* with 25–45 cm height and ~90% coverage. Typically distributed in the middle of wide valleys. It appears as dark red or deep brown in images.		

Table 3 Accuracy assessments of derived wetland types

Type	1976		1988		2006	
	Producer's (%)	User's (%)	Producer's (%)	User's (%)	Producer's (%)	User's (%)
Riverine wetland	100.0	100.0	100.0	100.0	100.0	100.0
Lacustrine wetland	100.0	97.4	100.0	97.4	100.0	100.0
Kobresia humilis and *Carex moorcroftii* wet meadow	96.0	98.0	96.0	96.0	98.0	100.0
Weedy wet meadow	90.3	90.3	96.7	93.5	96.7	90.6
Gravel floodplain	87.5	87.5	88.2	100.0	88.2	93.8
Hippophae rhamnoides scrub	100.0	100.0	100.0	100.0	100.0	100.0
Aquatic weedy marsh	100.0	100.0	100.0	100.0	100.0	100.0
Overall accuracy (%)	95.3		96.7		97.3	
Kappa (%)	94.0		95.7		96.6	

Carex moorcroftii wet meadow was found from 4100–4900 m asl, 74.4% of lacustrine wetland occurred between 4400–4700 m, and 96.3% of weedy wet meadow occurred between 4100–4700 m. Most lacustrine wetland occurred around Lake Peiku. The clear majority of wetlands (91.9%) occurred on slopes less than eight degrees.

Changes in Wetlands: Dynamics

Wetland distribution in the vicinity of Mount Everest has changed since 1976. The total area of wetland decreased by 15.3 km^2, however, because some wetland increased, the area of change added up to 94.5 km^2 or 5.6% from 1976 to 2006. Each wetland type was affected differently. The loss of weedy wet meadow was most severe (37.5 km^2), while *Kobresia humilis* and *Carex moorcroftii* wet meadow declined only slightly. Lacustrine wetland increased by 22.2 km^2, probably from a rapid expansion of glacial lakes (Table 4).

The area of aquatic weedy marsh doubled in total area over the last 30 years, with aquatic weedy marsh at Lake Kaju in 1976 covering 0.8 km^2, expanding to 1.4 km^2 in 1988, and then to 1.6 km^2 in 2006 (Fig. 4).

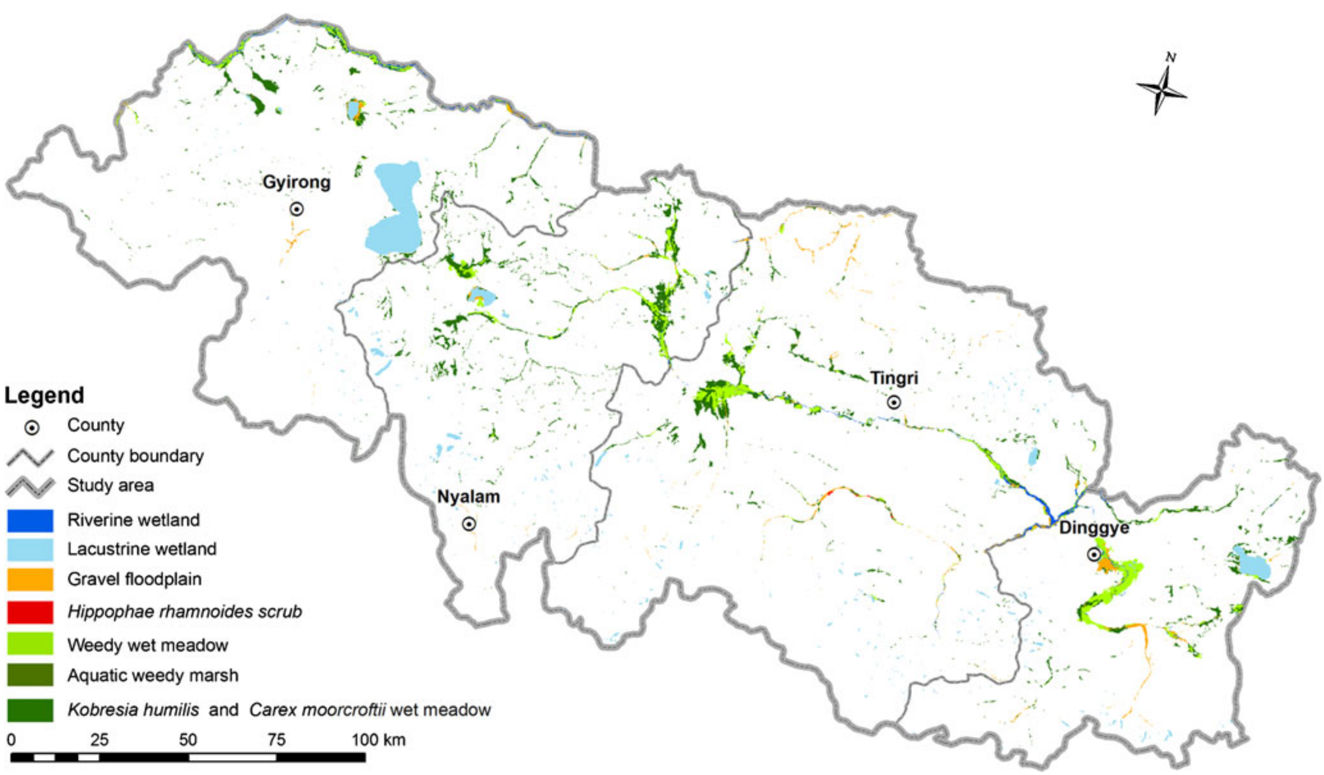

Fig. 2 Wetland distribution within study area in 2006

Table 4 Wetland areal change in the vicinity of Mount Everest from 1976–2006

Type	1976	1988	2006	1976–2006	
	km^2	km^2	km^2	km^2	% change
Riverine wetland	85.7	92.5	71.3	−14.4	−16.9
Lacustrine wetland	459.5	468.0	481.7	22.2	4.8
Kobresia humilis and *Carex moorcroftii* wet meadow	670.2	668.4	667.4	−2.8	−0.4
Weedy wet meadow	356.7	333.0	319.2	−37.5	−10.5
Gravel floodplain	103.6	113.6	119.4	15.8	15.3
Hippophae rhamnoides scrub	2.3	2.1	2.1	−0.2	−7.5
Aquatic weedy marsh	0.8	1.4	2.4	1.6	208.4
Total	1678.8	1679.0	1663.5	−15.3	−0.9

Changes in Wetlands and Other Land Cover Types

Temporal-spatial variation in wetlands and land cover revealed that conversion and succession among riverine wetland, lacustrine wetland, *Kobresia humilis* and *Carex moorcroftii* wet meadows, and weedy wet meadows occurred from 1976–2006. *Kobresia humilis* and *Carex moorcroftii* wet meadow converted into weedy wet meadow and in turn evolved into forbs grassland (*Artemisia wellbyi*, *Orinus thoroldii*) in some areas. This conversion proved that regressive succession had occurred.

From 1976 to 1988, weedy wet meadow (26.4 km^2) mainly converted to river (7.4 km^2), bare soil (5.6 km^2), cultivated land (4.9 km^2), and lake (4.2 km^2). *Kobresia humilis* and *Carex moorcroftii* wet meadow decreased by 10.1 km^2, with 3.3 km^2 inundated by lake and 4.9 km^2 reclaimed as

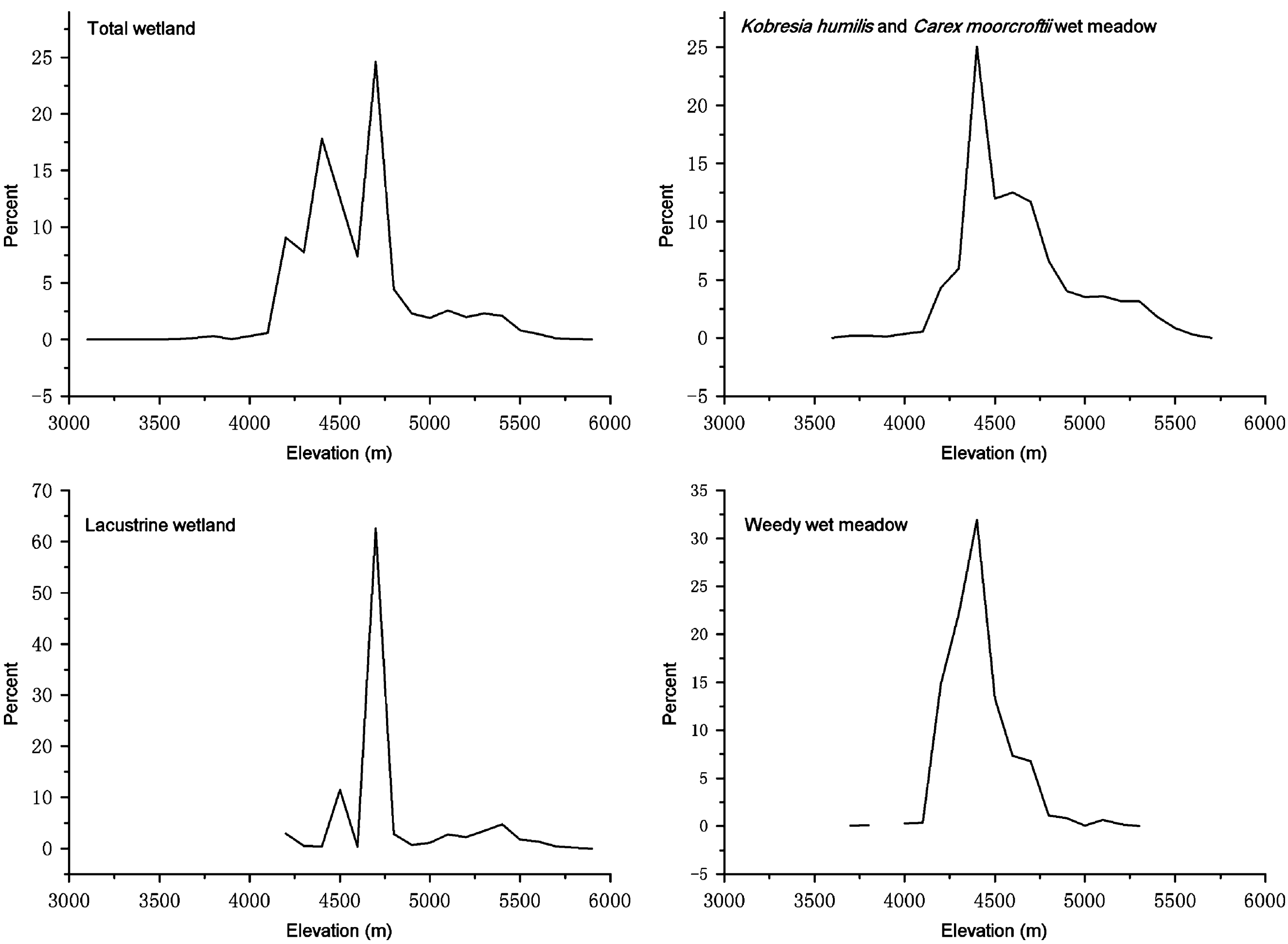

Fig. 3 Distribution of wetlands across different elevations

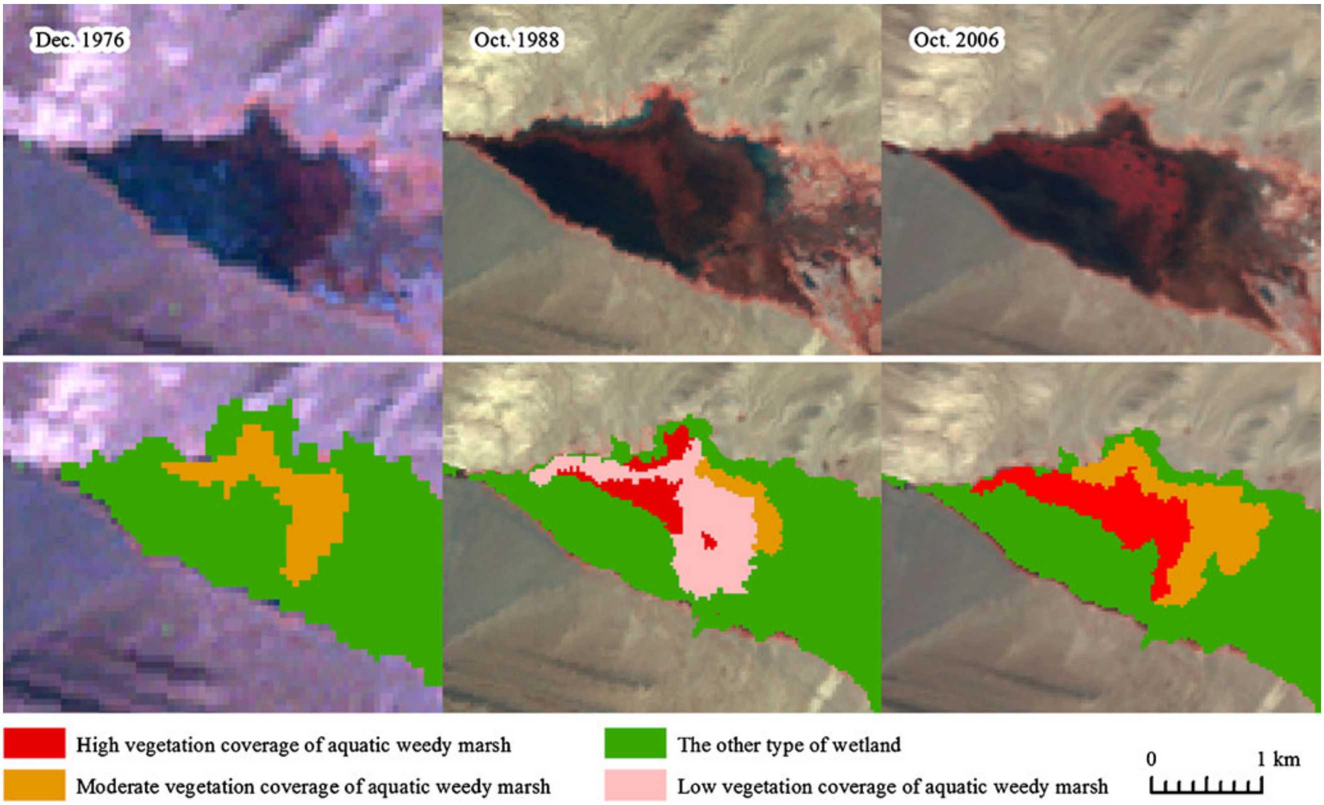

Fig. 4 Change in aquatic weedy marsh from 1976 to 2006

cultivated land. Meanwhile, *Kobresia humilis* and *Carex moorcroftii* wet meadow increased by 8.2 km^2, mainly from lake (3.1 km^2) and gravel floodplain (1.9 km^2).

From 1988 to 2006, weedy wet meadows reduced by 32.0 km^2, with 13.1 km^2 converted to forbs grassland. *Kobresia humilis* and *Carex moorcroftii* wet meadow decreased by 13.7 km^2, mainly converted into forbs grassland (3.8 km^2) and weedy wet meadow (3.0 km^2), and inundated by lake (2.3 km^2). Meanwhile, *Kobresia humilis* and *Carex moorcroftii* wet meadow increased by 12.7 km^2 mainly from cultivated land, rivers, and lakes. Weedy wet meadow increased by 18.3 km^2 mainly from lake and river.

Changes in Wetlands: Implications

Natural driving forces are key factors for wetland evolution in this study area. A total 9.8 km^2 of wetlands were reclaimed as cultivated land from 1976–1988, while only 1.8 km^2 were reclaimed from 1988–2006. There were 31.9 km^2 (from 1976–1988) and 48.6 km^2 (from 1988–2006) of wetlands converted into other non-cultivated land cover types. From 1976–1988, a percentage of wetland reclaimed as cultivated land was 23.5% of the total wetland contraction, while this percentage fell to 3.6% from 1988–2006. The conversion from wetlands to cultivated lands demonstrated the strong influence of human activities across this region. The decreasing area and less percentage of reclaimed cultivated land from wetlands revealed that wetlands in the vicinity of Mount Everest were principally under a natural ecological succession, and the creation of the QNNP was significant in maintaining this process.

Increases in air temperature and decreases in precipitation were important natural driving forces of wetland changes. The annual mean temperature of the study area increased by 0.4°C $(10a)^{-1}$ from 1976 to 2006 and glaciers continued to retreat (Nie et al. 2010). Climate research from 1971 to 2004 suggested that warming at the Mount Everest region occurred earlier, and exceeded the mean rate of increase across China and the global average (Yang et al. 2006). Meteorological data and ice core studies showed annual precipitation in this region had decreased in recent decades (Duan et al. 2002; Duan et al. 2007; Nie et al. 2010). Under changing climate, change in lacustrine wetland appeared complex, and was affected by the expansion for glacial lakes and shrinkage for non-glacial lakes. Climate change resulted in glacial retreat and directly led to the expansion of glacial lakes in a short period. However, non-glacial lakes were shrinking in this region. Overall, climate change played an important role. In sensitive areas such as the Tibetan Plateau, effects of climate change on wetlands require urgent attention.

QNNP positively impacted environmental protection since 1988, but measurements on wetland conservation fell behind. One urgently required activity is to assess the effect of fences on the Tibetan Plateau (Fox et al. 2009). Whether fences will promote or hinder wetland conservation needs to be examined at regular time intervals. Alpine wetlands in the source areas for the Yangtze and Yellow River decreased by >10% from 1969–2000. Comparatively, wetland changes in the vicinity of Mount Everest were slight. However these wetlands merit concern because of their uniqueness and importance, especially under increasing pressure from rapid development by the local populous and their livestock. Hydrologic monitoring for large lakes, site-specific planning, and financial support are required for wetland conservation within QNNP.

The quality of Landsat images is strongly affected by weather conditions. As the world's highest region, low availability and poor continuity of RS data restrain the ability of dynamic monitoring for wetlands. Impacts of images from different acquisition dates on wetland change at large area are inevitable. In this study, object-oriented classification method and post classification of visual modification were employed to minimize these effects. The wetland data were extracted effectively to support the policy making for wetland management in the vicinity of Mount Everest.

Our study is a preliminary report that highlights the need for more and in-depth studies on wetland change in alpine regions. Further studies on the mechanisms of wetland change and the effects of management strategies within the QNNP are necessary in order to maintain this fragile and unique ecosystem.

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