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Dynamics and Driving Forces of the Alpine Wetlands in the Yarlung Zangbo River Basin of Tibet, China

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***Abstract*—**Based on the field investigation and long term remote sensing data, the dynamics of the alpine wetland in the river basin and their response to climate change were studied. Results showed the alpine wetlands accounted for 3.73% of total basin in 2010. Lake and river appeared an increasing trend in the past 30 years, with an increase of 34.36 % and 24.57%. However, swamp exhibited a tendency of decreasing with 233.74 km^2. Annual average temperature, maximum temperature, minimum temperature and precipitation in the river basin all exhibited an increasing trend, whereas relative humidity exhibited a decreasing trend. Ice and snow melting are main reasons of lake and river area enhancement and swamp area descend. There existed 91.78%-97.86% of reduced swamp converted into lakes on the basis of remote sensing image interpretation. China's government policy of implementing development in the river basin is the major driving force of artificial wetland growth.

***Keywords*—**alpine wetland dynamics, climate change, Yarlung Zangbo River basin

I. Introduction

As a unique geographical region with the highest elevation, the Qinghai-Tibetan plateau has great ecological meanings for global climate changes in South Asia and even the whole world [1]-[2]. It is also one of areas which is less disturbed by human activities on the surface of the earth, serving as a foreboding or early-warning area for global changes. Distributed mainly in Qinghai-Tibet Plateau of China, the alpine wetland is not only the birthplace of large rivers, such as the Yangtze River, the Yellow River and Lancang River, in China [3], but also is a unique habitat for many rare wildlife species and migratory birds [4]. Originated from the Chamyungdung glacier at an elevation of 5200 m in southwestern Tibet on the northern slope of the Himalayas [5], stretching across the southern part of the Tibetan Plateau from the west to the east, the Yarlung Zangbo River is about 2229 km long in China, with a mean elevation of over 4000 m a.s.l. (above sea level) and a total drainage area of 2.4 ×10^5 km^2 [6]. After outflowing Chinese territory through Pasighat into India, the river is known as the Brahmaputra River, and it is called the Jiamu River when flowing through Bangladesh. The river finally flows into the Bay of Bengal, confluencing the Ganges.

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The scientific research work carried out in the Yarlung Zangbo River Basin was relatively poor due to the harsh geographical conditions and historic reasons. In order to understand the present status, spatial distribution and dynamics of the alpine wetland in the river basin in the past 30 years, on the basis of field investigation, we identified different wetland types in the river basin in 1980-2011 from high precision remote sensing data using method of visual interpretation and manual delineation of remotely sensed imagery. The climate changes in the river basin and its influence on the alpine wetlands are also analyzed.

II. Study Area

The Yarlung Zangbo River basin stretches over large areas of the Lhasa, Shigatse and Shannan regions of Tibet and over small areas within the Ngari, Nagqu and Qamdo regions, including 41 counties (cities) (Fig. 1). Himalayas Mountain located in the south of the river basin, with Gangdese Mountains and Nyainqentanglha Mountains standing in the north.

The topography of the Yarlung Zangbo River basin is high in the west and low in the east, high in the north and south, but low in the central reaches. At the boundaries between Zhongba and Saga counties, Ngamring and Lhaze counties, and Sangri and Gyaca counties, the river basin can be divided into four ecological regions: the source region, and the upper, middle, and lower reaches of the river (Fig. 1). Differences in climatic factors (particularly precipitation and temperature) create large differences environment among the four regions of the river basin [7].

The Yarlung Zangbo River has the highest source region in the world, at an altitude ranging from 5100 to 5200 m a.s.l. The source region is a typical arid to semiarid frigid plateau zone characterized by an abundant light supply, high irradiance intensity, distinct wet and dry seasons, a cool summer, and a frigid winter. The number of days with a wind speed of 20 m s^{-1} or more ranges from 112 to 150 days per year [8]. The high elevation, combined with strong winds, creates freeze-thaw erosion and wind erosion throughout most of the source region. Thus, the ecological environment is extremely fragile in the source region.

The average elevation in the upper reaches is more than 4600 m a.s.l., and the main landform is alpine valleys [8]. These valleys are mainly sunken rift valleys, but there are large areas of moraine hills and mesas, mounds, and proluvial fans in the foothills of the mountains. The valley floors are broad fluvial plains. The upper reaches are a semiarid sub-frigid plateau zone. The average annual temperature ranges from 0 to 3°C, and annual precipitation ranges from 150 to 250 mm.

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Precipitation mainly occurs during the growing season, from June to September. Soil erosion occurs throughout the region, and mainly results from freeze-thaw erosion and water erosion [9].

The topography of the middle reaches are mostly valleys, which is high in the west and low in the east, high in the north and south, but low in the central region. The climate is semiarid, with cool humid summer and dry windy winter. Sandstorms are frequently happened in this region, causing greatly harm to local residents. The number of sandstorms per year with a wind speed greater than 4 m/s is 56.4, and maximum wind speeds during these storms can reach 15 m/s. About 80% of the windy days occur during the dry season, from November to January. The expansion of aeolian desertified land occurs mainly during the dry season, when large areas of sediments are exposed in riverbeds [10]-[11].

The climate of the lower reaches ranges from a humid to sub-humid temperate plateau climate to a subtropical mountain climate. The average temperature in the warmest month is 8-20°C, versus about 0°C during the coldest month. Annual precipitation is greater than 600 mm, and some areas such as Pasighat can reach more than 3000 mm annually. The lower reaches of the Yarlung Zangbo River is a place with high species differentiation and abundant flora.

III. Materials and Methods

A. Data

The four sets of remote-sensing data was used in this study included , America's Landsat MSS, TM, ETM data and China's environment satellite HJ-1 data in 1980, 1990, 2000 and 2010. Among the data, the MSS data is 21 scenes from the year of 1980s, with 60 m spatial resolution. The TM images came from the year of 1990, with 21 scenes, 30 m spatial resolution. The ETM data in 2000s was acquired by 21 scenes with 30 m spatial resolution. The HJ-1 image in 2010 was 6 scenes with a spatial resolution of 30 m. It was difficult to acquire cloud-free images that covered the whole study area within a given year because of the large geographical area covered by the study region. Therefore, some images from previous or subsequent years were used as replacements. Prior to image interpretation, remote sensing data was geo-referenced through the use of 1: 100000 land use maps. The distortion of the images of greatly undulate terrain was corrected with the help of DEM data with 30 m spatial resolution. 1: 1000000 vegetation types of Tibetan Plateau were also used in the study. Meanwhile, field geological surveys were conducted in the key areas and field-measured photos located with GPS coordinates were collected across the study region to contrast verifications.

The daily air temperature, maximum temperature, minimum temperature, precipitation, relative humidity data were recorded at eight meteorological stations in the Yarlung Zangbo River basin during the 1970-2010 period, including Gyangzê, Shigatse, Lhasa, Nyingchi, Zetang, Bomê, Damxung, Lhari stations. The all data were provided by the National climatic centre (NCC) of China meteorological administration (CMA).

B. Methods

1) Types of the alpine wetland in the Yarlung Zangbo River basin

Referencing to the Ramsar Convention and Chinese wetland classification system[4], considering the actual situation of Yarlung Zangbo River basin, the wetland classification system of Yarlung Zangbo River basin was established, in which the wetlands of the river basin were divided into two major categories, natural wetland and artificial wetland. The former included river, lake, *Carex* swamp, *Kobresia* swamp, and the latter consisted of reservoir and rice paddy (Table1).

2) Wetland information extraction

ERDAS software of version 9.3 was used to conduct pre-processing of the four sets of remote-sensing images. We used the geometric correction, mosaic cutting, optimum band combination and image enhancement functions to modify the images.

The images produced using R, G and B false-color composites on the 4, 3 and 2 band of remote-sensing images. Using 1:100,000 topographic maps, the four sets of images were geometric corrected and 30 to 40 ground control points (GCPs) were selected for each image to ensure the corrected accuracy in the range of one or two pixel.

Due to the dynamic nature of this analysis, the Alberts coordinate system was used. The geometrically corrected remote-sensing images were conducted combining a treatment and histogram match to obtain four sets of remote-sensing images for the basin with a consistent tone.

Using a large amount of in situ field surveys, according to various types of wetland landscape spectrum and geometric features, the locations, distribution and textures of different types of alpine wetland were verified, the remote-sensing image data were compared and the remote-sensing interpretation marks of alpine wetlands were established (Table 1).

The alpine wetlands were interpreted manually from the composite false-color images by means of a visually interactive interpretation method, according to the criteria shown in Table 1. Due to using different resolution remote sensing images in the wetland information extraction, we unified the river width no less than 2 pixels (60 m-120 m), the lake area of no less than 3×3 pixels (that is 0.09-0.36 km^2). The interpretation results of imagery in 2000 year were used as a reference to compare and examine the interpretation in 1980s, 1990s, 2010s. Although the water levels of the lakes, rivers underwent seasonal variation, the amplitudes are generally rather small at no more than 50 cm during a year [12].

Therefore, although the data are limited and there are certain seasonal differences between contrast images, the results of the discussion are little affected.

TABLE I
TYPES OF THE ALPINEWETLANDS IN THE YARLUNG ZANGBO RIVER BASIN

Types			Characteristic	Interpretation mark	Remote sensing image
Natural Wetland	River		permanent or temporary river and its tributaries, also including flood area and flood river valley	using the 432 band synthesis, the river is black or blue brown, appeared as long and narrow	
	Lake		with an area of more than 1 km^2, perennial or seasonal lake	using the 432 band synthesis, the lake appeared as dark blue, with clear boundaries	
	Swamp	*Carex* swamp	the grass mound and puddle interphase distributed, average plant coverage is about 90%, with the dominant species of *Carex*	interpretation is mainly based on the type of vegetation, using the 753 band synthesis, exhibited as green or gray-green, sometimes densely packed small area of water surface	
		Kobresia swamp	plant coverage is about 90%, with the dominant species of *Kobresia*	interpretation is mainly based on the type of vegetation, using the 753 band synthesis, appeared as a dark green, rough texture	
Artificial Wetland	Reservoir		human build or development water area	using the 432 band synthesis, geometry boundary of smaller bodies of water	
	Rice paddy		rice planting area	using the 753 band synthesis, appeared as bright green, small distribution range, around the area of farmland	

3) Dynamic analysis of the alpine wetland

We use dynamic degree for determining dynamic changes of different alpine wetland types, the formula is as follows:

$$WD = \frac{U_b - U_a}{U_a} \times \frac{1}{t} \times 100\% \quad (1)$$

Where, WD indicates dynamic change, U_a indicates wetland area in the starting year, U_b indicates wetland area in the ending year, t is the interval time.

4) Climate factor driving force

We used a linear regression model to define the trends in annual mean air temperature, maximum temperature, minimum temperature, precipitation and relative humidity. The Mann-Kendall non-parametric test was used to evaluate significance. In addition, we did some correlation analysis using the wetland area and meteorological statistical data to find the main factors that dominated alpine wetland changes in the last 30 years.

5) Grey relational analysis

Impacts of climate factors on the dynamic change of alpine wetland is comprehensive process with uncertainty, consequently, utilizing grey system theory to evaluate different climate factors on wetland change is appropriate. Grey system theory is an interdisciplinary scientific area that was first introduced in late 1980s. During the last two decades, it has been developed to study the incomplete information system .Grey relational analysis (GRA) aims to find relationship for the various factors through analyzing systematic statistical sequence. GRA determined correlation between numerous factors using sequence's geometric relations comparison, in fact, is essentially a curve shape difference among various factors [13]. In this study, we use GRA to correlate various climate factors with alpine wetland dynamics. Calculation is as follows:

$$R_{OM} = \frac{1}{N} \sum_{t=1}^{1} R_{OM}(t) \quad (2)$$

Where, R_{OM} indicates two sequence correlation, N indicates the length of the sequence, Rom (t) indicates correlation coefficient at t time.

$$R_{OM(t)} = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{OM(t)} + \rho\Delta_{\max}} \quad (3)$$

Where, Δmin and Δmax indicates the minimum and maximum of absolute difference for two sequences. Δ_{OM} (t) indicates absolute difference of two sequences at t time. ρ indicates distinguishing coefficient, generally it takes 0.1 - 0.5. In this paper, we set it as 0.5.

IV. RESULTS AND DISCUSSION

A. Composition and Dynamic Characteristics of the Alpine Wetlands

In 2010, there were 9033.53 km^2 of the alpine wetlands in the Yarlung Zangbo River basin, occupying 3.73% of total river basin. The largest wetland type was swamp, up to 5370.94 km^2 (Fig. 1), accounting for 59.46% of the total area of wetlands, followed by river, with an area of 2726.81 km^2, accounting for 30.19% of the total area of wetlands. Lake area was 915.46 km^2, accounting for 10.13% of the total area of wetlands. Artificial wetland was less smaller than natural wetland. The area of reservoir was 5.66 km^2, whereas rice paddy was 14.67 km^2. Total artificial wetlands was 20.33 km^2, accounting for 0.23% of the total alpine wetlands in the Yarlung Zangbo River basin. The alpine wetlands in the source region of Yarlung Zangbo River basin was 2994.81 km^2, accounting for 33.15% of total basin wetlands. Rivers and lakes, occupying more than 90% of wetlands in the source region (Fig. 1), were the two most important wetlands. Area of the alpine wetland in the upstream region was 3300.58 km^2, accounting for 35.43% of the total area of the whole basin wetlands. Among them, marsh occupied 1910.17 km^2, was the most widely distributed wetland, occupying 59.68% of wetland in upstream reach, followed by the river, which was 1051.75 km^2, accounting for 32.86% of wetland in upstream reach.Swamp and rivers constituted the main body of the wetlands in upstream reach. In the middle reach of Yarlung Zangbo River basin, there were 1535.52 km^2 of wetlands, accounting for 17% of the whole basin wetlands.

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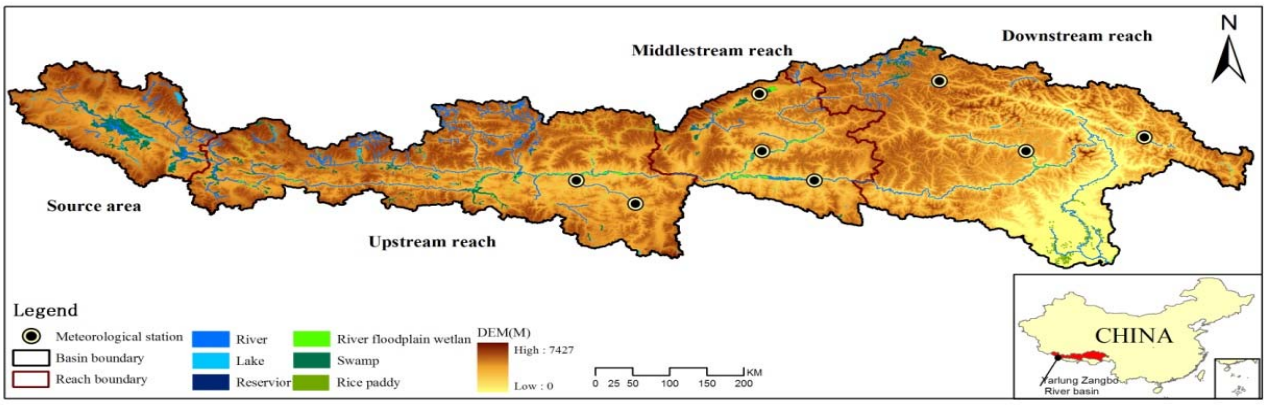


Fig. 1 Alpine wetlands in the Yarlung Zangbo River basin in 2010

Rivers and marshes occupied 60.53% and 37.35%, respectively. Area of total wetlands in downstream is 1302.62 km^2, far less than those in upper and middle reaches. Marsh and river accounted for 45.76% and 38.53% of total wetland area in downstream reach. Rice paddy was only found in Mêdog and and Zayü county, located in the downstream region with area of 14.67 km^2 (Fig. 1). The result of remote sensing data prevail that the alpine wetlands in Yarlung Zangbo River basin are in the trend of expansion during the past 30 years. The areas of the alpine wetland in the river basin were 8331.18, 8504.04, 8404.28, 90 33.53 km^2 in 1980s, 1990s, 2000s and 2010s, respectively (Table 2).

Among the four typical wetland types, artificial wetland has been raised its area by 12.64 km^2 in the past 30 years, with dilation dynamic change rate by 5.48%. And these increase occurred mainly during the period of 1990-2000, with the dynamic change degree up to 4.81% (Table 2). This is also human activities strongly disturbed period since China has implemented development project in the middle reaches of the Yarlung Zangbo River and its tributaries Nianchu River and Lhasa River in 1991. Farming, agriculture, road construction, building dam and reservoir were given priority development in the region [14]. Consequently, reservoir and rice paddy exhibited steadily increasing trend.

Swamp has reduced its area by 81.74 km^2 in the past 30 years (Table 2). During the first decade (1980-1990), the change of swamp area was the greatest by 30.17 km^2. Through analyzing matrix of area conversion between various types of wetlands, we found that there were 27.69 km^2 swamp converted into lake, accounting for 91.78% of reduced swamp area. For the period of 1990 to 2000, swamp has reduced its area by 29.05 km^2, among which there are 98.76% conversion into lake. During the recent decades (2000-2010), swamp decreased its area by 22.52 km^2, including 20.83 km^2 swamp conversion to lakes, accounted for 92.50% of its reduced area.

In the past 30 years, lake in general exhibited increasing trend with a dynamic increase change of 1.14%. During 1980 to1990, lake area has increased from 681.85 km^2 to 709.32 km^2, with dynamic change degree of 0.4% (Table 2).

Number of lakes has increased from 167 to 172, mainly smaller than 30 km^2. For 1990-2000, lake area declined with dynamic change degree of - 0.68%. The number of lakes reduced from 172 to 160, among which there were 11 lakes smaller than 10 km^2. From 2000 to 2010, lake area represented a substantial growth, increasing by 254.68 km^2 with dynamic degree of 3.85%. The number of lakes increased from 160 to 198, the majority of which less than 10 km^2.

The overall growing trend in the past 30 years, the river has increased its area by 537.84 km^2, with a dynamic change rate of 0.82%. Between 1990 and 2000, river shrinked slightly by reducing its area of 27.11 km^2. After the period of 2000, river area resumed growth by 392.02 km^2 till 2010. In the past 30 years, the five largest tributaries of the Yarlung Zangbo River were also appeared the trend of increasing, the main stream of Lhasa River has increased its length from 333.17 km in 1980 to 432.08 km in 2010. Niyang River, Parlung Zangbo River and Dogxung Zangbo River also grew 90.58 km, 50.39 km, 75.93 km, and 95.81 km respectively in the past 30 years.

TABLE II
DYNAMIC CHANGES OF THE WETLANDS IN THE YARLUNG ZANGBO RIVER BASIN DURING THREE PERIODS

Year	Wetland type				
	River	Lake	Swamp	AW	Total
1980	2188.97	681.85	5452.67	7.69	8331.18
1990	2361.90	709.32	5422.50	10.31	8504.04
2000	2334.79	660.77	5393.45	15.26	8404.28
2010	2726.81	915.46	5370.94	20.33	9033.53
dynamic change in 1980-1990	0.79	0.40	-0.06	3.41	0.21
dynamic change in 1990-2000	-0.11	-0.68	-0.05	4.81	-0.12
dynamic change in 2000-2010	1.68	3.85	-0.04	3.32	0.75
dynamic change in 1980-2010	0.82	1.14	-0.05	5.48	0.28

Note: AW=Artificial wetland
Data in the top four rows is with unit of km^2, the following is with unit of %

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B. Alpine Wetland in the Response to Climate Change

Because of the scarcity of meteorological stations in Tibet, we can only use limited data from eight meteorological stations in the upper, middle, and lower reaches of Yarlung Zangbo River Basin. Source region due to scarcity of meteorological data was not discussed in this study. The daily air temperature, maximum temperature, minimum temperature, precipitation, relative humidity data were recorded for upper reach (representing as Gyangzê, Shigatse meteorological stations), middle reach (representing as Lhasa, Zetang, Damxung meteorological stations), lower reach (representing as Nyingchi, Bomê, Lhari meteorological stations). Annual average temperature, maximum temperature, minimum temperature and precipitation all exhibited an increasing trend, whereas relative humidity exhibited a decreasing trend (Fig. 2). The annual mean temperature has increased by 1.69 °C in the past 30 years with the remarkably increase happened in the middle reach by 2.31°C. For the average maximum temperature, there existed an increase rate of 13.29% from 1980 to 2010, of which the largest increase was in the middle reach of the river basin, by 21.13%. Extreme value of annual maximum temperature was 17.74°C, recorded in lower reach in 2009. Average annual mean minimum temperature has elevated 7-folds in the past 30 years from 0.28 °C to 1.96°C. Particularly, annual minimum temperature rose up from 0.98°C in 1980 to 1.46 °C in 2010, with an increase rate of 249%. Annual precipitation showed rising trend from upper reach to middle and lower reach. Annual precipitation in lower reach was increased by 123.8%, 81.97% higher than in upper reach. The annual precipitation in the whole basin exhibited an obvious fluctuating and increasing trend and was found to be significant increase in lower reach, with a dilation rate of 5.28%. Average relative humidity in the whole basin decreased by 6.74% in recent 30 years, whereas it was significantly higher than that of upper and middle reaches. No significant difference was found between upper and middle reaches.

There showed increased temperatures and precipitation but decreased relative humidity trend in the whole Yarlung Zangbo River Basin in the past 30 years. Gray relational analysis was used to analyze relationship between various meteorological factors and wetland dynamic changes. The original data during different temporal period of the alpine wetlands and meteorological factors were standardized in order to eliminate the possible impact caused by different dimensions. Results of gray relational analysis showed that average temperature, maximum temperature and minimum temperature were the most correlated factors with river area change (Table 3). Temperatures has been increasing in the past 30 years which may bring the glaciers shrinking, ice and snow melting, and water supplies in near river and length of river have been increased consequently. The most remarkable dynamic change rate for river was 1.68 % in the period of 2000 to 2010.The average temperature and maximum temperature were the most correlated factors with lake area change (Table 3). With the temperature rise in the river basin, it resulted in ice and snow melting thus leading to lake area increase.

Remote sensing image interpretation reveals that there existed 91.78%-97.86% of reduced swamp converted into lakes.

Average temperature, maximum temperature and relative humidity were found the highest correlation with swamp area change (Table 3). There exhibited negative correlation between increased temperature and decreased swamp area. The main way of water consumption in Tibet is evaporation and evapotranspiration [15]. Relative humidity is the most directly related factor with evaporation and evapotranspiration. Decreased relative humidity indicated the air humidity saturation difference amplified, resulting in more evapotranspiration in the growth season. Consequently, decreased relative humidity also resulted in swamp degradation.

TABLE III
GRAY RELATIONAL ANALYSES BETWEEN ALPINE WETLAND AREAS AND CLIMATE FACTORS

Gray relational analysis coefficient		Annual mean temperature	Annual mean maximum temperature	Annual mean minimum temperature	Relative humidity	Annual mean Precipit-ation
Upstream reach	River	0.8684*	0.9346 *	0.6154	0.8262	0.6869
	Lake	0.8723*	0.8835*	0.6757	0.8263	0.7223
	Swamp	0.8281*	0.9103*	0.6166	0.8233*	0.6690
	AW	0.8119*	0.8771*	0.6508	0.7931*	0.6639*
Middle stream reach	River	0.8652*	0.8977*	0.5649	0.8192	0.6964
	Lake	0.8284*	0.8990 *	0.5618	0.8012	0.7173
	Swamp	0.7609	0.8395*	0.5004	0.8063*	0.6667
	AW	0.7957*	0.7428*	0.6211	0.7160	0.6844
Down stream reach	River	0.7013*	0.6824 *	0.7450*	0.6825	0.7242
	Lake	0.7873*	0.8437*	0.6508	0.7410	0.5757
	Swamp	0.8023*	0.8606*	0.6586	0.7406	0.5733
	AW	0.6708	0.6601	0.7042	0.6570	0.7103

Note: AW=Artificial wetland
* Single asterisk in the same row indicated significant difference at $\alpha = 0.05$

V. CONCLUSIONS

There was a total of 9033.53 km^2 of alpine wetland in the Yarlung Zangbo River basin in 2010, accounting for 3.73 % of total basin area. Swamp is accounting for 59.46% of the total alpine wetland, followed by river (30.19%), lake (10.13%) and artificial wetland (0.23%). Swamp, river and lake constitute the main wetland types in the overall basin.

There experienced increased temperature and precipitation but decreased relative humidity in recent 30 years in the Yarlung Zangbo River basin. Dynamic change of the alpine wetlands was closely related to climate changes, especially the temperature rise. The remote sensing image interpretation reveals that during the past 30 years, alpine wetland in the Yarlung Zangbo River basin was in the trend of expansion, with a 6.49% growth. The river area has increased by 392.02 km^2 in the period of 2000 to 2010, with a growth proportion of 1.68 %.



The river area of the five largest tributaries of the Yarlung Zangbo River had increased by 10%-29.69% in the past 30 years. The areas of lake have experienced an overall increase and areas of swamp have steadily decreased in the past 30 years.

Lake and river areas enhancement were directly correlated to the change of glacier melting in the basin with the air temperature rise. The remote sensing data demonstrated that during the past 30 years 91.78%-97.86% of reduced swamp converted into lake resulting from increasing glacier melting water. The implementation of the developing plan in the middle reaches of theYarlung Zangbo River and its tributaries by the government of Tibet Autonomous Region is the major driving force of artificial wetland growth.

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