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Topographic Influence on Wetland Distribution and Change in Maduo County, Qinghai-Tibet Plateau, China

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Abstract: Accurate information on the spatial distribution and temporal change of wetlands is vital to devise effective measures for their protection. This study uses satellite images in 1994 and 2001 to assess the effects of topography and proximity to channels on wetland change in Maduo County on the Qinghai-Tibet Plateau, western China. In 1994 wetlands in the study area extended over 6,780.0 km². They were distributed widely throughout the county, with a higher concentration in the south, and were especially prominent close to streams. The pattern of wetlands demonstrated a bell-shaped distribution curve with elevation, ranging over hill slopes with gradients from 0-19°, the commonest gradient being around 3°. Although the aspects of these hill slopes range over all directions, there is a lower concentration of wetlands facing east and southeast. The extent of wetlands in 2001 decreased to 6,181.1 km². Marked spatial differentiation in the pattern of wetlands is evident, as their area increased by 1,193.3 km² at lower elevations but decreased by 1,792.2 km² at higher ground, resulting in a net decrease of 598.8 km². In areas with a gradient <2° or >9° the area of wetlands remained approximately consistent from 1994-2001. Newly retained wetlands are situated in relatively flat lowland areas, with no evident preference in terms of aspect. Wetlands on north-, east- and northeast-facing hillslopes with a bearing of 1-86° were more prone to loss of area than other orientations. The altered pattern of wetland distribution from higher to lower elevation on north-facing slopes coincided with the doubling of annual temperature during the same period, suggesting that climate warming could be an important cause.

Keywords: Wetland change detection; Topographic influence; Remote Sensing; GIS; Qinghai-Tibet Plateau

Introduction

Wetlands are unique land feature whose surface is covered by water either seasonally or permanently, or is fully saturated with moisture. Aquatic plants or water tolerant vegetation may form swamps, marshes and bogs alongside pools of water. Collectively, these are important components of terrestrial ecosystems. Wetlands provide many ecological services including important habitat and biodiversity functions, and regulation of water flows and water quality. However, wetlands may be ecologically fragile and are degraded easily by environmental change and anthropogenic activities.

Across the world there has been a concerted effort to monitor changes in wetlands to assist efforts to understand prospects for their restoration. Remote sensing techniques provide an effective means to identify, classify and monitor wetlands over extensive geographic areas, providing a basis to appraise measures of

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ecological functionality through biomass assessments (e.g. Butera 1983; Jensen et al. 1986; Johnston & Barson 1993; Chopra et al. 2001; Rundquist et al. 2001; Ozesmi & Bauer 2002; Rebelo et al. 2009; Bwangoy et al. 2010).

Inventorying wetlands from satellite images is usually accomplished by using a combination of visual interpretation and automatic classification. For example, Xing et al. (2010) visually interpreted TM, ETM+ and China and Brazil Earth Resource Satellite images to analyze changes in wetland area in the Qinghai-Tibet Plateau. Although the automatic unsupervised or supervised methods of image classification are much faster than visual interpretation, inaccuracy has arisen because of spectral confusion of wetlands with other land covers and among different types of wetlands. Mean error rates are as high as 7.8% for palustrine wetland/upland models and 17.0% for palustrine wetland type models obtained with classification trees incorporating all available predictors (Wright & Gallant 2007). For emergent wetlands, classification and regression tree and multinomial logistic regression analysis achieved accuracies of 57.1% and 40.7%, respectively (Pantaleoni et al. 2009). The corresponding accuracies for woody wetlands were 68.7% and 52.6%. The overall accuracy of only 54.1% achieved by the supervised classification approach from Landsat TM images prompted Feng et al. (2008) to use the visual interpretation method to map marsh wetland. Visually interpreted results tend to be more accurate owing to the use of several properties of wetlands in the decision making, such as texture, color, pattern, situation, and shape, even though it is slower than automatic classification.

Mapping and monitoring of changes in wetland area is commonly achieved using multi-temporal change detection techniques (e.g. Jensen et al. 1995; Brivio and Zilioli 1996; Haack 1996; Schmid et al. 2004; Gong et al. 2010; Teferi et al. 2010). Cai and Guo (2008) determined the spatial extent and changes of wetlands in Maqu County from multi-temporal Landsat TM and ETM+ data using geographic information system (GIS) and stepwise discriminant analysis. After land covers were mapped from satellite images, hotspots of marsh landscape change were detected in a post-classification session in a GIS (Munyati 2000; Zhang et al. 2009). To date, however, appraisals of these changes in wetland area have not been framed in relation to topographic setting. This issue is particularly important in assessing the wellbeing and evolution of plateau wetlands that are recharged mainly by water from snow-melting, permafrost thawing, and percolated rainwater on the Qinghai-Tibet Plateau. Topographic factors such as elevation and slope gradient dictate the (re)distribution of moisture and water on a hill slope and over the landscape. With a low water reserve, plateau wetlands are prone to change and degradation induced by climate change and anthropogenic activities. Significant concern for these issues is evident for highland marshes on the Qinghai-Tibet Plateau at elevations above 3,200 m asl. An understanding of topographic influence on the distribution and evolution of plateau wetlands is a prerequisite to their effective management and protection.

This study assesses the influence of topographic variables on the changing distribution of wetlands on part of the Qinghai-Tibet Plateau from 1994-2001. Specifically, this research aimed to (1) explore the topographic characteristics of plateau wetland distribution in Maduo County, Qinghai Province; (2) examine the spatial extent and temporal dynamics of wetland evolution; and (3) identify the possible relationship between wetland change and topographic settings and proximity to water sources.

1 Methods

1.1 Study area

Maduo County (33°50'-35°40'N and 96°50'-99°20'E), situated in the northwestern Guoluo Prefecture, Qinghai Province, covers an area of 25,253 km^2 (Figure 1). It has a population of 11,000, of whom 85% are Tibetan. This county has a frigid alpine climate with annual temperature averaging only −4.1°C. Most of this low relief landscape lies between 4,500 and 5,000 m asl. Given the high altitude, only warm and cold seasons can be differentiated, with the warm season lasting only two months each year. Grassland makes up 87.5% of the vegetation cover across the county, for grazing by sheep and yaks.

Maduo County receives an annual rainfall of 303.9 mm, far less than the annual evaporation of over 1,260 mm. Despite this water deficit, Maduo County has abundant water resources. There are 13 relatively large rivers, the most important being the Yellow River (Figure 1). In addition, thousands of freshwater lakes, with a combined surface area of 1,674 km², dot the county. As an important contributor to the "Water Tower of China", Maduo County contributes 1.4 to 2 billion m³ of surface water to the river system. Associated with these rivers and lakes are plateau wetlands of various types and sizes, all associated with productive grassland. In the past, wetlands on the Plateau experienced decline, but they have showed signs of recovery over recent years (Wang et al. 2007).

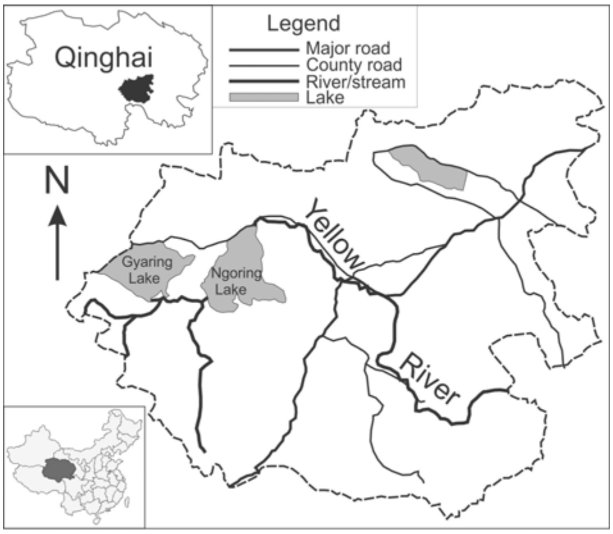

Figure 1 Location of Maduo County in Qinghai Province, China

This county was selected for study because it contains a huge amount of wetlands that have experienced dynamic changes. The area may be representative of other plateau areas, such as those in the Andes (Peru-Bolivia). Plateau wetlands provide significant economic benefits and valuable services to the local ecosystem, and beyond.

1.2 Data used

Three types of data were used in this study: remote sensing, topographic, and hydrologic. Remotely sensed data are the primary data source. Two Landsat TM/ETM+ satellite images were downloaded from the Global Land Cover Facility website (http://glcf.umiacs.umd.edu/index.shtml) at the University of Maryland. The first image was recorded on 24 July 1994 (row–36, path–134) and the second on 4 July 2001 separated by 20 Julian days from the first. Both images with a spatial resolution of 28.5 m have been geo-referenced to the UTM coordinate system (zone 47 north).

Topographic data were downloaded from NASA's EOS data website (http://asterweb.jpl.nasa.gov/gdem.asp). These archived global digital elevation model (GDEM) data are a product of METI and NASA, and are publicly accessible free of charge. They cover the Earth's land surface between 83°N and 83°S. GDEM is produced at 30 m resolution from stereoscopic ASTER VNIR bands, and is available in 1 by 1° tiles in the GeoTIFF format. Each GDEM tile is accompanied by a quality assessment file, either giving the number of ASTER scenes used to calculate a pixel's value, or indicating the source of external DEM data used to fill the ASTER voids. Stream data were extracted from the Digital Charts of the World at http://www.maproom.psu.edu/dcw/ in the ERSI interchange format. The data used in this study have a scale of 1:1 million (version 1993).

1.3 Wetland mapping

The color composites of both satellite images were displayed onscreen and visually interpreted in ArcGIS. In the literature, TM bands 3, 4 and 5 are reportedly the most informative in studying wetlands (Zhang et al. 2000). However, the combination of bands 5 (red), 4 (green) and 2 (blue) was found to be the best for the 1994 image while bands 4 (red), 7 (green) and 2 (blue) were superior for the 2001 image. Two interpretation clues or keys are critical for delineating wetlands in the plateau environment: grassland health and presence of water bodies. Owing to the availability of abundant water resources, wetlands are healthier than normal grassland. In the 1994 composite they appeared to have a saturated dark green color in contrast to the light green color of normal grassland. On the 2001 composite, healthy wetland had a bluish dark red colour while regular grassland had a light red color and degraded wetland appeared to be reddish grey. The presence of water in ponds is also critical to the differentiation between wetlands and ordinary grassland. However, water bodies are not routinely included in wetlands unless they are so small that separate delineation becomes impossible (i.e., lakes are not included in wetlands). All the wetlands were delineated as polygons on screen in ArcGIS. At the end of interpretation these polygons were saved as a vector shape file. Two wetland distribution maps were produced, both sharing the same ground coordinate system as that of the raw images. The interpretation results were validated in the field in July 2010 and August 2011. Field checks confirmed that the maps were mostly accurate except for the omission of saturated alpine wetlands. Such omission was remedied in another session of interpretation. After appropriate symbols were assigned to wetland polygons, both maps were then visualized to illustrate the spatial pattern of wetland distribution. They were also rasterized at a spatial resolution of 30 m, the same as that of the DEM, in preparation for subsequent analyses.

1.4 Spatial analyses

Change detection for the two wetland distribution maps was performed using the union function in ArcGIS. The newly derived layer was then queried aspatially to detect changes between wetlands and non-wetlands. The resultant wetland change map was then queried. Conversion between wetland and non-wetland classes was quantified. After the extent of wetland change was recalculated to a new value of 1, maps showing wetland gain and loss were rasterized at 30 m scale.

As wetlands are nourished by water, they are prone to degradation and may eventually disappear unless sufficient water supply is maintained. Therefore, it is important to assess their proximity to channels. To assess this factor, buffers with a width ranging from 10 to 1000 m were generated around streams and channels. After these buffers were dissolved, they were overlaid on the 1994 and 2001 wetland distribution maps individually to study the relationship between wetlands and their proximity to water sources. The proportion of wetlands within the buffers was queried and the results were exported to MS Excel for further processing.

Hillslope aspect and gradient (in degrees) were derived in ArcGIS from the DEM. Aspect affects the distribution of solar energy on the terrain, thus influencing snow melt and permafrost. Also, aspect influences rainfall pattern. It is calculated from the four cell heights surrounding the one under consideration and expressed as a value from 0 to 359° continuously from the magnetic north. Values were rounded up to the nearest integer and aggregated at 5°intervals. The flat surface without a definite aspect was assigned a value of －1. The DEM layer, the slope gradient and aspect layers were overlaid with the two rasterized wetland distribution maps and the wetland change maps individually using masking in order to relate wetland changes to elevation, slope, and orientation. The overlaid results were queried to determine the topographic characteristics of wetlands. All results were converted to text format and imported to MS Excel for processing (see Figure 2).

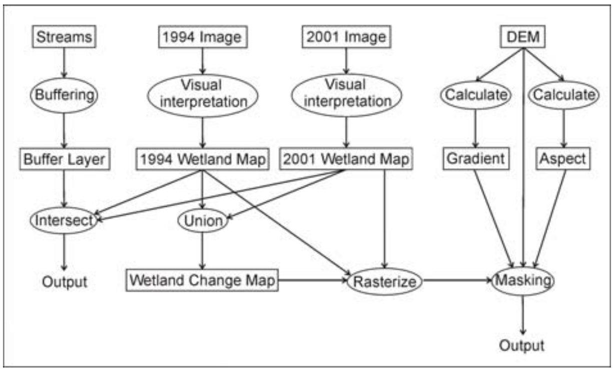

Figure 2 Flowchart illustrating the procedure of data processing and analysis undertaken in this study

2 Results

2.1 Wetland dynamics

In 1994, wetlands amounted to 6,780.0 km^2 inside the study area. They were distributed widely throughout the County but were more concentrated in the south than in the north (Figure 3). The more extensive wetlands were confined to the southwest while wetlands were nearly absent from the northwestern corner. Moreover, most of the wetlands in the north were small in size, elongated in shape, situated along valley bottoms and in upland concave slopes. The larger areas in the north were associated with lakes. In contrast, wetlands in the south tended to have a larger patch size. The large and extensive patches in this region

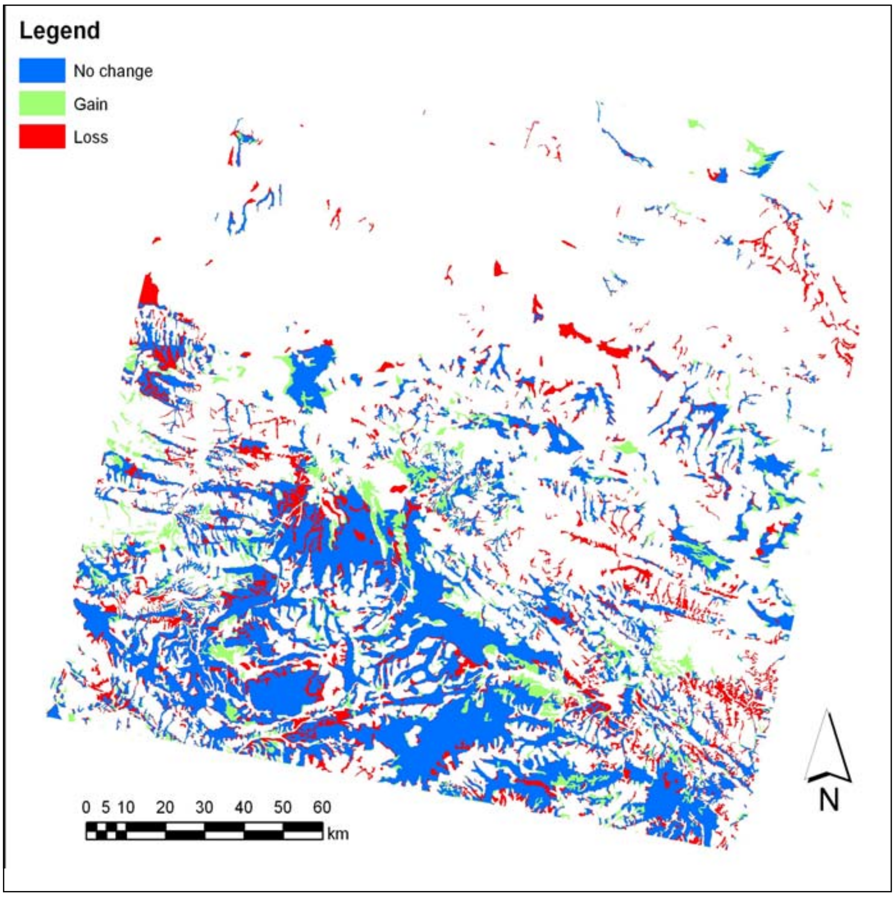

Figure 3 Distribution of wetlands inside the study area and its change from 1994 to 2001

were located on mountain sides where small water bodies accumulated on the surface. This pattern seems to reflect the dominance of tall mountains in the south and the plateau landform in the north.

Total wetland area in 2001 was 6,181.1 km². Their spatial distribution closely followed the pattern in 1994 (Figure 3), with more wetlands in the south than in the north. There were far fewer wetlands in the northeast because of the disappearance of quite a few long and narrow patches.

Marked spatial variability in the pattern of wetland gain and loss is evident in the study period. Although 4,987.8 km² or 73.6% of the wetlands were unchanged, some areas of the remainder increased by 1,193.3 km² and other areas decreased by 1,783.7 km², resulting in a net loss of 590.4 km². This translates into an annual rate of loss of 84.3 km². This decline in some areas is consistent with findings in the source region of the Yangtze and Yellow Rivers reported by Pan et al. (2007), and the severe decline of wetlands in the source region of the Yangtze and Zoige Rivers reported by Wang et al. (2007).

Wetland loss occurred across the study area (Figure 3). Many patches that used to be wetlands vanished. Most of the lost wetlands were small, linear in shape and distant from large wetland patches. These large patches of river and lake wetlands had also shrunk, an outcome attributed to the fall in water level. All these polygons have a clustered distribution. The added wetlands were small in size. Their distribution was confined to a few locations adjacent to extensive patches of wetlands. This was especially true for the large patches that tend to congregate around the largest wetlands. This spatial relationship suggests they originated from the outward expansion of existing wetlands. Incidentally, these newly gained wetlands did not intermix with the lost wetland in their spatial arrangement. Of the two processes, wetland shrinkage appeared to be the dominant process throughout the study area, whereas expansion was largely limited to highland locations.

2.2 Topographic influence on wetland distribution

2.2.1 Elevation

In 1994 wetlands occurred at elevations ranging from 4,033 to 5,089 m, most commonly around 4,540 m (Figure 4, A). A plot of their distribution demonstrated a near bell-shape curve, but it showed an asymmetric distribution with elevation with a few sub-peaks towards lower elevations. The first peak, at around 4,100 m, corresponds to lowland wetlands associated with lakes and rivers. The next two peaks of almost equal magnitude occur at 4,220 and 4,300 m, respectively. These correspond to floodplain and piedmont wetlands. The last minor peak takes place at 4400m, corresponding to valley wetlands. The right tail of the curve (higher elevations) is much lower but longer and without peaks, suggesting a uniform type of wetlands. The amount of wetlands decreased markedly above 4,600 m.

2.2.2 Hillslope gradient

Wetlands whose surface was usually covered with water were flat without any gradient. This applied to less than 4% of the wetlands found in this plateau environment in 1994 (Figure 4, B). Plateau wetlands saturated with moisture were also found on sloped surfaces, most of which had a gradient ranging from 0 to 13°. The proportion of wetlands increases markedly at a gradient up to 3°. Afterwards, it started to decrease rapidly initially but levelled off at a gradient >20°. The long right tail of the curve suggests that a minority of alpine wetlands do occur on precarious slopes. The prominence of wetlands on hillslopes of around only 3° suggests that piedmont and valley wetlands are the most common in the study area. In relative terms, there is a disproportionately large area of wetlands on hillslopes < 6°, while the converse is true for hillslopes > 6°.

2.2.3 Aspect

Wetlands are found in all geographic orientations, but they were more prominent in some directions than in others (Figure 4, C). This pattern followed closely the general topography, characterized by an uneven distribution with respect to aspect. The curves for 1994 and 2001 differ from each other only in the quantity of wetlands (e.g., a lower curve) in certain directions, such as those facing the north. The range of percentage was much smaller for the general topography except over aspects <8°.

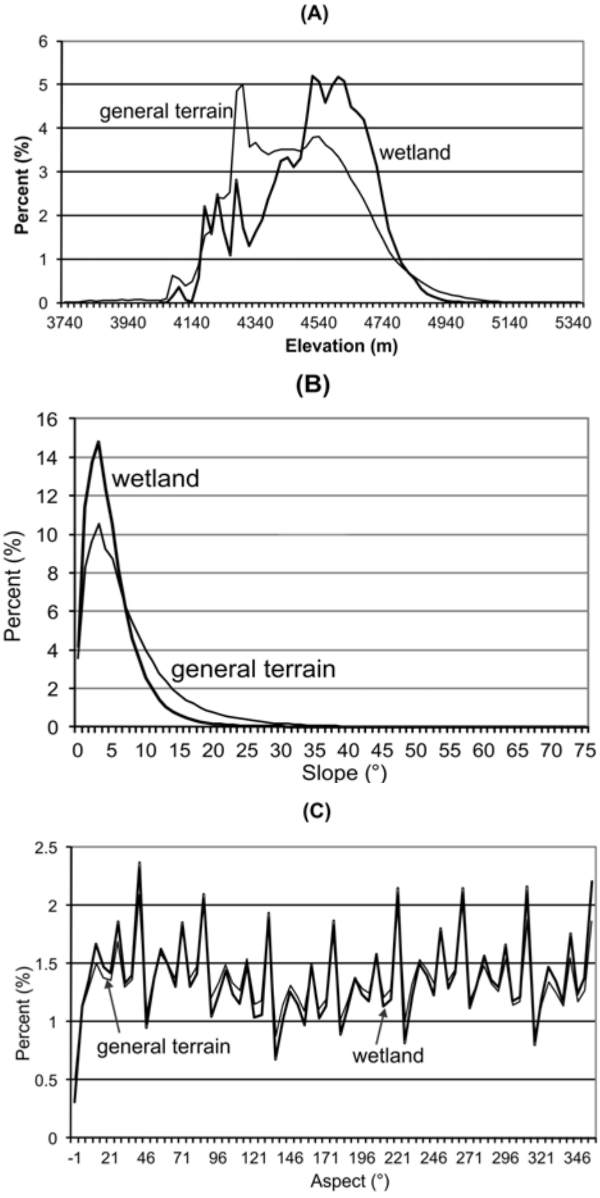

Figure 4 Relationship between wetland distribution and general topography. (A) Elevation; (B) Slope gradient, and (C) Slope aspect in degrees measured from the magnetic north.

2.2.4 Proximity to channels

The relationship between the amount of wetlands and their distance to a channel was nearly linear (Figure 5, note the logarithmic scale of the horizontal axis). In other words, wetlands were not closely associated with channels in the plateau setting. The patterns were very similar in 1994 and 2001. Wetlands further away from a channel had decreased more in 2001 than those close to the channel. Those within 100-150 m of a channel did not decrease probably because they were recharged by river water. This finding may indicate that the majority of wetlands were nourished by water from snow melt over a slope.

2.3 Topographic influence on wetland changes

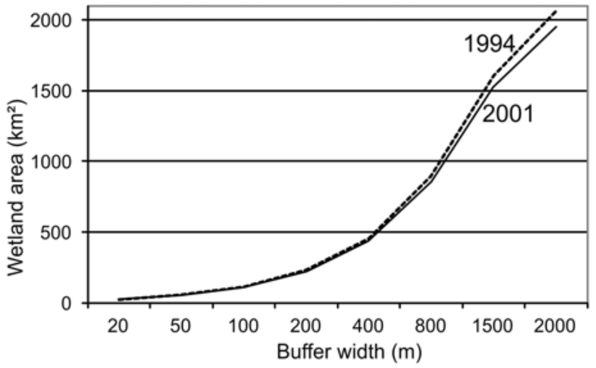

Figure 5 Relationship between wetland dominance and its distance to channel which is half of the buffer width

2.3.1 Elevation

A plot of elevation and topography for those wetlands that vanished during the study period showed a bell-shaped distribution (Figure 6, A). This curve has three distinct small peaks on the lower side of the mode at around 4,460 m while there was a less distinct pattern for wetlands above the mode altitude. Although wetlands throughout the range of 4,033 to 5,089 m experienced decline, the magnitude of reduction was small towards extreme low or high elevations. This curve indicates that wetlands at an intermediate elevation, especially over the 4,420-4,480 m range, were the most vulnerable to decline due probably to the fact that outflow was high while inflow was low at these elevations.

The distribution of the added or increased wetlands with elevation also had a bell-shaped curve, bearing a close resemblance to the general trend of the loss curve except for a few minor peaks lower than the mode around 4,500 m, slightly higher than that for the vanished wetlands. Of these sub-peaks, the two most important ones occurred around 4,080 m and 4,180 m. Around 4,080 m, the gain curve was above the loss curve, suggesting that wetland increase exceeded decrease at the lower elevations. Around 4,180 m, the peak for the gain was much lower than that for the loss. The same is also true for the nearby trough and the third sub-peak at 4,300 m. Thus, losses of wetlands at a higher ground are greater than the gains. This was reversed towards lower elevations. The overall

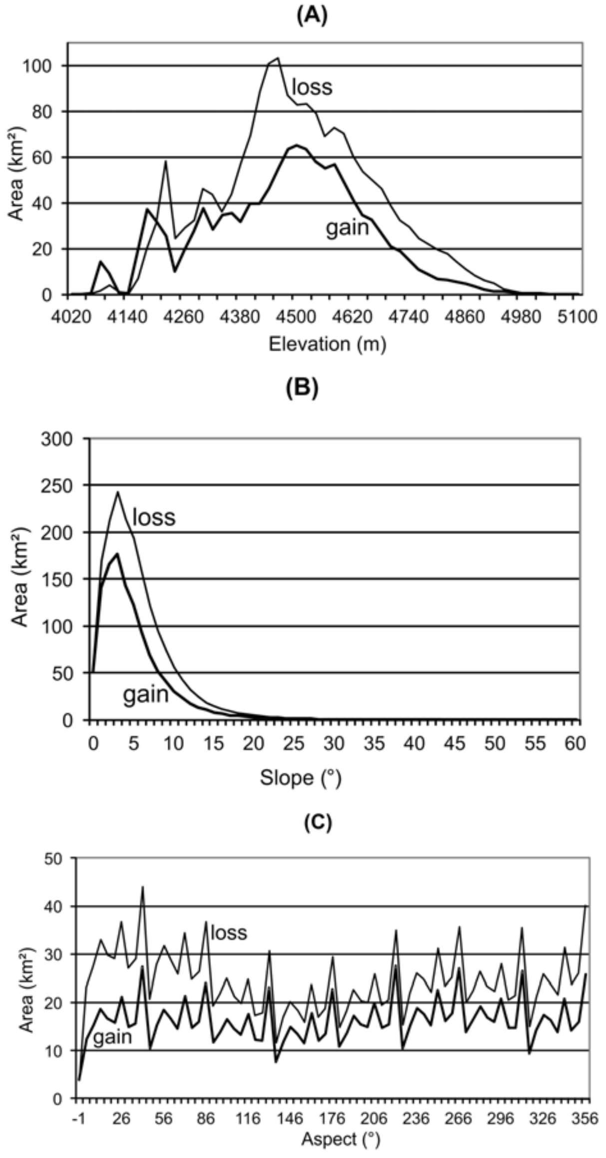

Figure 6 Relationship between changes in wetland and topography. (A) Elevation; (B) Slope gradient; and (C) Slope aspect in degrees measured from the magnetic north (-1 – flat surface)

consequence was a gradual shift in the remaining wetlands towards a lower elevation. However, over the elevation range of 4,500-4,820 m, the two curves are almost parallel to each other, suggesting a uniform rate of change.

2.3.2 Hill slope gradient

Wetlands inside the study area were not equally vulnerable to decline across the whole spectrum of gradients. They decreased with slope gradient in a bell-shaped manner (Figure 6, B). Although wetlands of both a flat surface and a steep surface up to 59° experienced decline, the most common hill slope gradient centered around 3°, beyond which the proportion dropped rapidly. Few wetlands were on slopes with a gradient of 15°. In general, gentler slopes were more prone to wetland disappearance.

Wetlands were gained mostly on slopes gentler than 10° with the most gain occurring at around 3°, but a very small number were on slopes as steep as 60°. On both flat (e.g., gradient <2°) and steep (e.g., gradient >10°) slopes the amount of gain was similar to the amount of loss. It was only on slopes with a gradient around 3° that the difference was the greatest. The gap between gain and loss gradually narrowed from 3° to 18°, beyond which there is hardly any disparity between them. The fact that the gain curve always lies underneath the loss curve indicates that wetland disappearance was a more dominant process than wetland creation.

2.3.3 Hillslope aspect

The amount of wetland loss has a periodic distribution with slope aspect, suggesting certain slope aspects are more prone to decline than others. The slopes that lost the most wetlands were confined to 36°-41°, followed by those between 11° and 86° with a deep trough around 46° (Figure 6, C). Although the amount of wetlands lost in other orientations also exceeded 30 km^2, these orientations were not adjoining each other. In other words, the southeast, south, southwest, west and northwest directions were noticeably less prone to wetland decline. Between the orientation of 91° and 216°, the amount of wetland loss fluctuated around 20 km^2. This preferential association of wetland disappearance with slope aspect is explained by the differential distribution of solar energy over the terrain.

Similar to the lost wetlands, the newly gained wetlands also have a periodic distribution with slope aspect, even though the magnitude of fluctuation was limited to between 10 and 27 km^2 (Figure 6, C). The quantity of newly gained wetlands was not related to a particular slope orientation, even though there was a noticeably smaller amount of wetlands on flat surface (aspect = －1). The gain curve always lies below the loss curve, but the two curves are close to each other within the direction of 136° to 216°, suggesting a small margin of wetland gain. Outside this range, the gap between the two curves widens. Of particular note is the much larger margin between the loss curve and its gain counterpart within 1°-86°. Hence, the north-, northeast-, and east-facing slopes lost much more wetlands than they gained.

3 Causes of Wetland Loss

Wetland degradation in the Upper Yellow River has resulted from both natural factors, such as climate warming, precipitation reduction, groundwater level decline, and soil change, and the influences of human activities, including overgrazing, excessive excavation, and frequent rodent outbreaks (Qi & Li 2007). Similar circumstances have contributed to wetland degradation in Maqu County (Cai & Guo 2008), and the observed wetland loss in our study area, where human influences include engineering works that diverted channel flow for irrigation and power generation. Channel flow may also have been reduced by intercepting water for human consumption. Overgrazing may have reduced ground biomass and caused more rainwater to enter the channel directly rather than through percolation to recharge wetlands (cf., Harris 2010; Li et al. 2011). Wetlands in the plateau environment have not been reclaimed for farming due to the cold climate.

Of the natural variables, rainfall and temperature have the greatest impact on the health of plateau wetlands. Rainfall directly influences the amount of water available to the wetland system, but in the plateau setting it is less important than temperature change or climate warming. Figures 3, 6A and 6C indicate that wetland changes can be related to a warming temperature regime. Climate warming increases evaporation on the one hand, and accelerates melting of snow and permafrost on the other. Findings from this study indicated that north-facing slopes lost more wetlands than those with other orientations, likely in response to the increased evaporation. This is in contrast to the newly gained wetlands that were almost evenly distributed among all slope aspects. North and northeast slopes receiving more solar radiation lost more moisture than other slopes. Similarly, increased evaporation explains the disappearance of wetlands at a higher elevation. Those at a lower elevation were recharged by snow-melted water. Indeed, the study area experienced climate warming with annual temperature rising by 0.25°C each decade during 1959-1999 and annual precipitation decreased by 2.81 mm (Wang et al. 2007). Associated with this warming is the increase in annual evaporation at a decadal rate of 5.8 mm during the same period.

Further analysis of natural and anthropogenic factors, using techniques such as principal component analysis, is required to unravel underlying causes of wetland change, but findings from this study indicate that the relative influence of these factors may vary with topography.

4 Conclusions

In 1994 6,780.0 km² of wetlands were widely distributed throughout Maduo County, with a higher concentration in the south. Wetland patches varied widely in size, with small and narrow patches mostly in valley wetlands, while more extensive wetlands were associated with alpine settings in the south. The mapped wetlands have a bell-shaped distribution with elevation with a mode of around 4,540 m. Although wetlands can be situated on slopes of 0 to 19°, they were most prominent on hill slopes around 3°. These slopes faced all directions with fewer oriented to the east and southeast. There was an almost linear relationship to the distance from channels up to 1,500 m, beyond which wetlands occurred at any location.

The wetland area in 2001 became 6,181.1 km². While 4,987.8 km² of the wetlands remained unchanged, 1,193.3 km² of wetlands were gained and 1,792.2 km² were lost, causing a net loss of 598.8 km², and an average loss rate of 85.5 km² per annum. Spatially, most wetland loss was in small patches in all parts of the County while large losses were associated with lakes in the south.

Topography exerts a significant control on wetland evolution. While most newly gained wetlands were at lower elevations, those at higher elevations tended to remain in balance, i.e. the increase was equal to the decrease. The overall trend is that the wetlands shifted towards a lower elevation over time. The majority of the new or increased wetlands were on slopes having a gradient < 10°, the commonest being 3°. Within the gradient range of < 2° and > 9°, wetland loss far outstripped wetland gain. Outside this range, however, wetland areas tend to be in balance. Slope orientation did not exert any consistent impact on wetland gain. However, north-, east- and northeast-facing slopes up to 86° lost more wetlands than other orientations. The loss far exceeded the gain. In other slope aspects, the amount of loss was only slightly greater than the gain. This pattern of change suggests that the main cause of wetland evolution in Maduo County is climate warming, which accelerated snow melt and evaporation.

Acknowledgements

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