

Investigating marsh sediment dynamics and its driving factors in Yellow River delta for wetland restoration



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ABSTRACT

The wetlands of the Yellow River delta play important roles for Asian and west Pacific birds during migration. Marshes are the main component of wetlands in the delta, and their coverage area has experienced a decreasing trend for the last few decades. Wetland changes in the Yellow River delta have been analyzed in previous studies; however, those studies only partially analyzed the causes of the decline. Using statistical and spatial analysis based on observational data and remote sensing imagery for the period of 1986–2005, we found that the annual mean temperature and annual precipitation tended to increase, and the evapotranspiration and the moisture index tended to decrease. Consequently, these climate factors led to a significant decrease in river runoff, which resulted in decreased water supply for the marshes in the delta. A Wetland Restoration Project was launched in 1992, and it successfully conserved marshes within a relatively small area. However, the inadequate water supply still resulted in an overall decrease in marsh area over the entire study area. These results provide more insights into managing wetlands eco-restoration.

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1. Introduction

The wetlands of the Yellow River delta represent one of the most important transfer stations for Asian and west Pacific birds during migration. Many migratory bird species such as red-crowned cranes, storks, white-spoonbills, geese, and ducks stop to replenish their foods and energy in the wetlands of the delta, then fly to other Asian and western Pacific areas (Cui et al., 2009a; Li et al., 2011; Wang et al., 2014; Liu et al., 2015). Wetlands in the area are mainly composed of marshes. However, the area of marshes has decreased due to climate change and human activities in recent decades. Engineering projects could affect the status of eco-systems (Shao et al., 2012a,b, 2015; Shao, 2014; Xu et al., 2013; Verhoeven, 2014; Joyce,

2014; Postila et al., 2015). Some engineering projects have successfully improved the wetland functions, but some failed. The main reason is that whether the managers could understand the mechanisms of changes before launching those projects. Therefore, we conducted this study for the driving changes in the marsh in order to find solutions that may lead to conservation and eco-restoration of marshes in the delta.

Marshes are covered by saturated soils and standing water during certain periods of the year. Therefore, maintaining water balance in the marsh is the key to conserving existing marsh coverage (Zhang and Shao, 2013). Precipitation, evapotranspiration, and runoff are the main factors that affect the marsh water balance. In addition, sediment discharge and human activity also play important roles in changes in marsh coverage.

Wetland changes in Yellow River delta have been analyzed in previous studies (Ye et al., 2004; Li et al., 2009; Wang et al., 2012; Chen et al., 2016). However, those studies only partially analyzed the causes of decline in marsh area. Cui et al. (2009a,b) demonstrated that maintaining adequate water is vital to sustaining wetland ecosystems; however, the interaction among precipitation, evapotranspiration, riverine water supplies, and marsh

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dynamics were not analyzed (Cui et al., 2009b; Zhang et al., 2011a,b). Therefore, the purpose of this study was to analyze the role of precipitation, evapotranspiration, river water supply, sediment load, and human activity in the marsh dynamics of the Yellow River delta for providing detailed principles for wetland eco-restoration.

2. Study area

The Yellow River delta is located on the estuary of the Yellow River near Dongying City, northeastern Shandong Province, China. Our study area was composed of the Yellow River Delta Nature Reserve and its surrounding areas, with an area of 284,260 ha. Sediment deposited from the Loess Plateau is continually expanding the delta, making the Yellow River delta a typical integrated marsh ecosystem. Elevation in our study area ranges from 0 to 37 m above sea level. Climate in this area is controlled by Asian monsoon systems. Summer is warm and wet, while winter is cold and dry.

The Yellow River Delta Nature Reserve was established in 1992, and is one of 13 key protected marshes of the world according to United Nations Environment Programme (Gao et al., 2010; Huang et al., 2012). It is composed of two separate parts: the Diaokouhe Nature Reserve and the Yellow River Mouth Nature Reserve. The current Yellow River course lies in the Yellow River Mouth Nature Reserve, and the old course is within the Diaokouhe Nature Reserve. Farmlands, oil fields, marshes, meadows, and residential areas are the main land use types in the Yellow River delta (Fig. 1).

3. Data and methodology

3.1. Data sources

Three datasets were used to analyze the interaction among precipitation, evapotranspiration, river runoff, sediment discharge, and changes in marsh coverage area. Runoff and evapotranspiration data were derived from observed data. The observed data used in our study included daily runoff, daily maximum and minimum temperature, daily precipitation, wind velocity, actual water vapor pressure, runoff, and sediment discharge from 1986

to 2005. Runoff and sediment load data were collected from the Yellow River Conservancy Commission of the Ministry of Water Resource (www.yellowriver.gov.cn). Weather data were obtained from the Dongying weather observation station and recorded by the State Meteorological Bureau. River and marsh data were interpreted from Thematic Mapper (TM) images for 1986, 1992, and 2005 downloaded from the United States Geological Survey (USGS) (www.usgs.gov). An administrative map of the Yellow River Delta Nature Reserve was obtained from local government agency and digitalized by the research team.

3.2. Methodology

The evapotranspiration at Dongying station for each year was obtained by calculating daily evapotranspiration according to the improved Penman–Monteith equation (Eqs. (1)–(7)) (Allen et al., 1998):

$$PET = \frac{0.408\Delta(R_n - G) + r(900/(T + 273))U_2(e_s - e_a)}{\Delta + r(1 + 0.34U_2)} \quad (1)$$

$$R_n = R_{ns} - R_{nl} \quad (2)$$

$$R_{ns} = (1 - \alpha)R_s \quad (3)$$

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (4)$$

$$R_a = F_{(G_{sc}, d_r, \delta, \varphi, J, L_m)} \quad (5)$$

$$R_{nl} = F_{(T_{max}, T_{min}, e_a, R_s)} \quad (6)$$

where PET is potential evapotranspiration (mm d^{-1}), R_n is net canopy radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$), T is air temperature at 2-m height ($^{\circ}\text{C}$), U_2 is wind velocity at 2-m height (m s^{-1}), e_a is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve ($\text{kPa}^{\circ}\text{C}^{-1}$), r is the psychrometer constant ($\text{kPa}^{\circ}\text{C}^{-1}$), and MI represents the moisture index. The values of T , U_2 , and e_a were obtained from daily weather station data. R_{ns} is net shortwave radiation ($\text{MJ m}^{-2} \text{day}^{-1}$); α is Albedo R_s is shortwave radiation ($\text{MJ m}^{-2} \text{day}^{-1}$); n is the actual duration of sunshine (h); N is maximum possible duration of sunshine or daylight hours; a_s and b_s are the fraction of extraterrestrial radiation

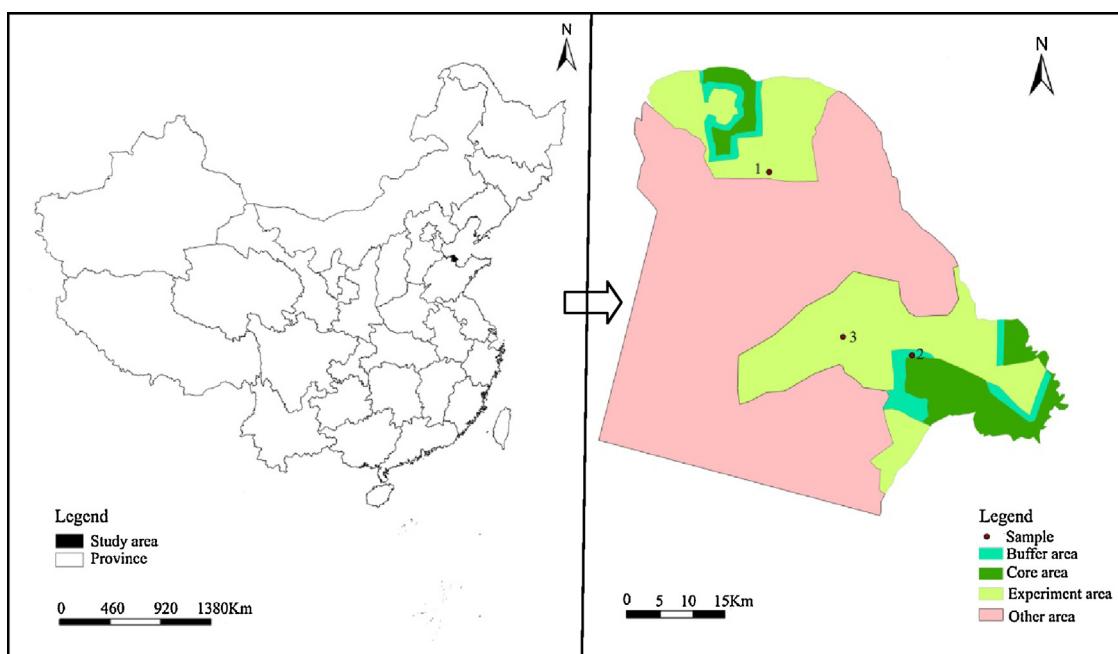


Fig. 1. Location of study area.

reaching the Earth on clear days ($n = N$); R_a is extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$); C_{sc} is the solar constant ($0.082 \text{ MJ m}^{-2} \text{ min}^{-1}$); d_r is the inverse relative distance Earth–Sun; J is the number of the days in the year between 1 and 365 (or 366); δ is solar declination (rad); φ is latitude (rad); L_m is longitude (degree); T_{\max} is maximum absolute temperature during a 24-h period; T_{\min} is minimum absolute temperature during a 24-h period; and e_a is the actual vapour pressure(kPa). Recommended Food and Agriculture Organization (FAO) values for α , G , Δ , and r were used. These values have been widely used for calculating PET.

Moisture index (MI) was calculated according to the following equation (Eq. (7)):

$$\text{MI} = 100\% \times \left(\frac{\text{Precipitation}}{\text{PET}} - 1 \right) \quad (7)$$

where MI is the moisture index, PET is potential evapotranspiration (mm y^{-1}), and precipitation is the annual precipitation(mm y^{-1}).

Land use and land cover in the Yellow River delta were classified into four classes: oil fields, marshes, water bodies, and others. Three cloud-free, Landsat TM images recorded in early May, August/September, and late October were selected from the USGS website. Each image was rectified in ArcGIS software with terrain maps at the scale of 1:100,000 and projected to the same standard coordinate system. The false-colour composite images were produced from bands 4, 3 and 2 of the TM images. A field survey was completed in August 2013. Interpretation samples for each class were set up from false-colour composite images according to the field survey and Google Earth. Visual interpretation was used to extract marshes, water bodies, rivers, and other land-use classes in 1986, 1992, and 2005. Visual interpretation has been widely used in extraction of land use and land cover types in previous studies and the accuracy of extracted results is above 90% (Liu et al., 2010; Gong et al., 2010). Spatial analysis and statistical methods were applied to analyze changes in the river and marshes.

4. Results and analysis

4.1. Trends in temperature, precipitation, evapotranspiration, and MI

Fig. 2 shows the trends of annual mean temperature during the period from 1986 to 2005. Annual mean temperature tended to increase at the Dongying Weather Station during our study period. The slope of annual mean temperature was 0.056. Annual mean temperature was 12.6°C in 1986, and it increased to 13.4 and 13.5°C in 1996 and 2005, respectively.

According to **Fig. 3**, annual precipitation at Dongying Weather Station also tended to increase during the study period. The slope of

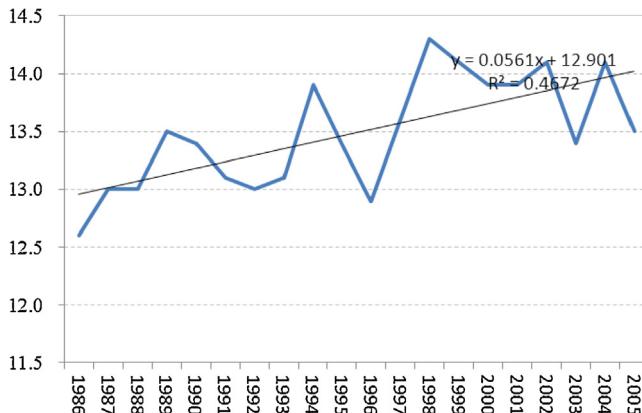


Fig. 2. Trend of annual mean temperature during 1986–2005.

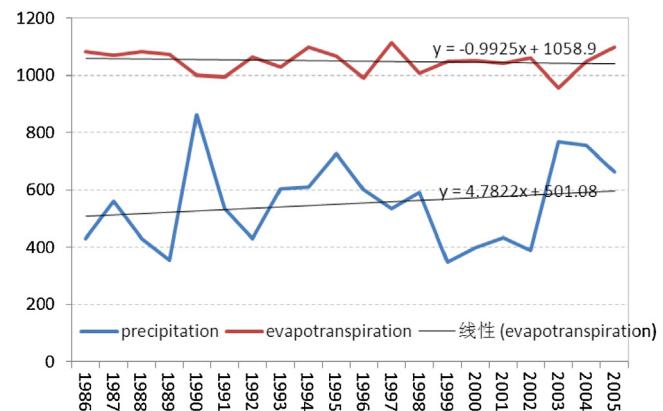


Fig. 3. Trends of annual precipitation and evapotranspiration.

annual precipitation was 4.782. Annual precipitation was 429.7 mm in 1986, and it increased to 605.0 and 663.0 mm in 1993 and 2005, respectively. However, annual evapotranspiration showed a slight decreasing trend. The slope of annual evapotranspiration was -0.992 . Annual evapotranspiration was 1082.0 mm in 1986, and it decreased to 1063 and 1048 mm in 1992 and 2004, respectively.

According to **Fig. 4**, the moisture index tended to increase from 1986 to 2005. The MI was -72 in 1986, and it increased to -55 in 1995 and -42 in 2004, respectively. The slope of MI was 0.515. This indicates that the Yellow River delta tended to become more humid. A more humid climate would help to prevent the decrease in area of marshes.

4.2. Runoff, sediment discharge, and river courses

The Yellow River delta is located in a semi-humid zone in which annual evapotranspiration is larger than annual precipitation. Therefore, an adequate water supply is the key factor determining the current status of marshes in the Yellow River delta. Runoff from the Yellow River is the only water source for marshes in the study area. Therefore, the amount of runoff in Yellow River determines marsh status.

The trend of annual runoff in the Yellow River observed in the Lijin Hydrologic Station is shown in **Fig. 5**. Annual runoff tended to decrease from 1986 to 2002. After 2002, runoff tended to increase. Annual runoff at Kenli Hydrologic Station was more than $200 \times 10^8 \text{ m}^3$ in 1986, decreasing to 18.6×10^8 and $34.6 \times 10^8 \text{ m}^3$ in 1997 and 2002, respectively. Although climate change has led to increased moisture index, a significant decrease of runoff in the Yellow River still resulted in an inadequate water supply.

The sediment load from the Yellow River also tended to decrease during this period (**Fig. 6**). The sediment load was slightly lower

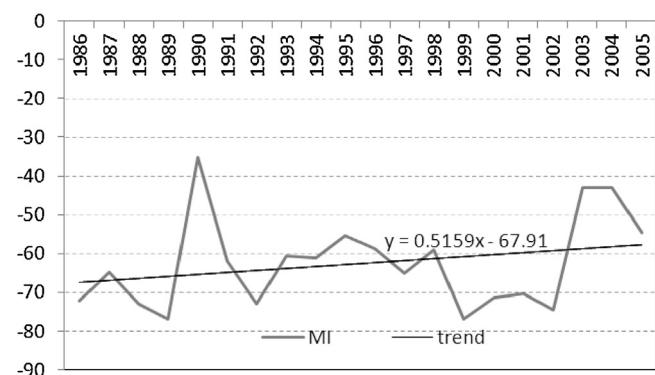


Fig. 4. Trend of moisture index (MI).

Table 1

River course length in Yellow River delta in 1986, 1992 and 2005 (m).

| Year | Nature reserve (south) | | | Nature reserve (north) | | | Others | Total |
|------|------------------------|----------|------------|------------------------|----------|------------|-----------|-------------|
| | Core | Buffer | Experiment | Core | Buffer | Experiment | | |
| 1986 | 148,648.6 | 55,075.0 | 299,842.2 | 17,698.5 | 24,626.8 | 141,754.3 | 914,591.2 | 1,602,236.6 |
| 1992 | 40,605.0 | 15,106.6 | 214,313.4 | 17,232.4 | 22,363.8 | 103,999.1 | 631,726.6 | 1,045,346.9 |
| 2005 | 150,819.7 | 32,605.0 | 227,929.6 | 12,390.1 | 10,483.3 | 53,815.0 | 401,289.3 | 889,332.0 |

Table 2

Changes of marsh area in our study area from 1986 to 2005.

| Year | South | | | North | | | Other | Total |
|------|--------|--------|------------|-------|--------|------------|----------|-----------|
| | Core | Buffer | Experiment | Core | Buffer | Experiment | | |
| 1986 | 7181.0 | 3509.0 | 22,972.0 | 505.0 | 1271.0 | 12,658.0 | 67,577.0 | 115,673.0 |
| 1992 | 5587.0 | 3589.0 | 16,057.0 | 331.0 | 750.0 | 10,491.0 | 59,403.0 | 96,208.0 |
| 2005 | 2546.0 | 1133.0 | 8483.0 | 1.0 | 129.0 | 5780.0 | 41,003.0 | 59,075.0 |

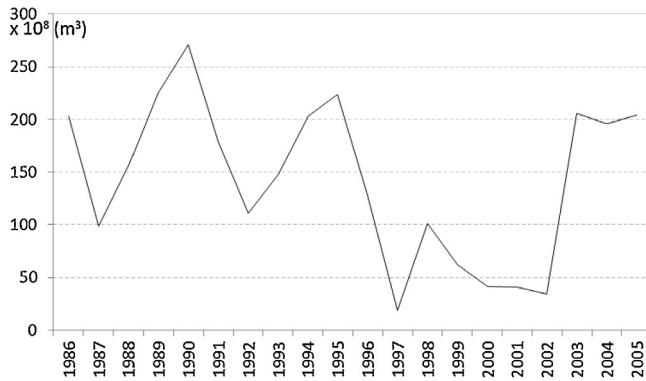


Fig. 5. Runoff in Yellow River at Lijin Hydrologic Station.

than $8 \times 10^8 \text{ t}$ in 1988, and it decreased to $1.91 \times 10^8 \text{ t}$ in 2005. The decreased sediment load led to less mud and sand deposited in marsh area, which would have helped to maintain stable marsh coverage.

The total length of the river was 1,602,236.6 m in 1986. A significant decrease in runoff in the Yellow River caused some river courses to dry up. Afterwards, local farmers began to reclaim the dried courses for cultivation. This caused the total length of the river course length to decrease from 1,602,236.6 m in 1986 to 1,045,346 m in 1992. The decreased length of the river course made it harder for marshes to obtain an adequate water supply and further worsened marsh coverage status.

The Yellow River Natural Reserve was established in 1992 to improve marsh status. However, only the length of river in the

southern portion of the reserve increased from 1992 to 2005, and in other areas it tended to decrease. The river length in the core, buffer, and experimental areas in the southern portion of the reserve increased from 40,605.0, 15,106.6, and 214,313.4 m in 1992, to 150,819.7, 32,605.0 and 227,929.6 m in 2005, respectively. In contrast, the river length in core, buffer, and experimental areas in the northern portion of the reserve and in other areas decreased from 17,232.4, 22,363.8, 103,999.1, and 631,726.6 m in 1992 to 12,390.1, 10,483.3, 53,815.0, and 401,289.3 m in 2005 (Table 1).

4.3. Human activities

According to our analysis, annual evapotranspiration is larger than annual precipitation in the Yellow River delta, and a decreased water supply from the Yellow River has caused the marsh coverage area to decrease. In addition, human activities have also played an important role in marsh changes.

Table 3 shows three samples that were collected from false-colour composite images in 1986, 1992, and 2005. The areas in dark red are marshes, and areas in white are bare land. According to Fig. 5, we know that decreased water supplies from the Yellow River caused some areas in dark red to turn into bare land (areas in white) during 1986–1992. No roads were built during this process. At that point, some of the bare lands were converted into farmland (areas with regular stripes) and roads were built in the area

Table 3
Selected samples from images in 1986, 1992 and 2005.

| | 1986 | 1992 | 2005 |
|---|------|------|------|
| 1 | | | |
| 2 | | | |
| 3 | | | |

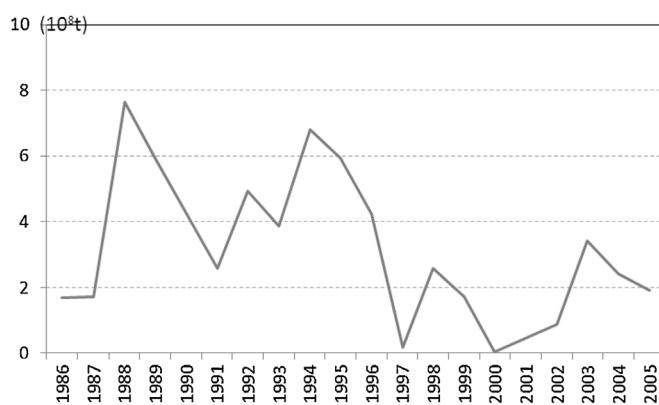


Fig. 6. Trend of sediment discharge at Lijin hydrologic station.

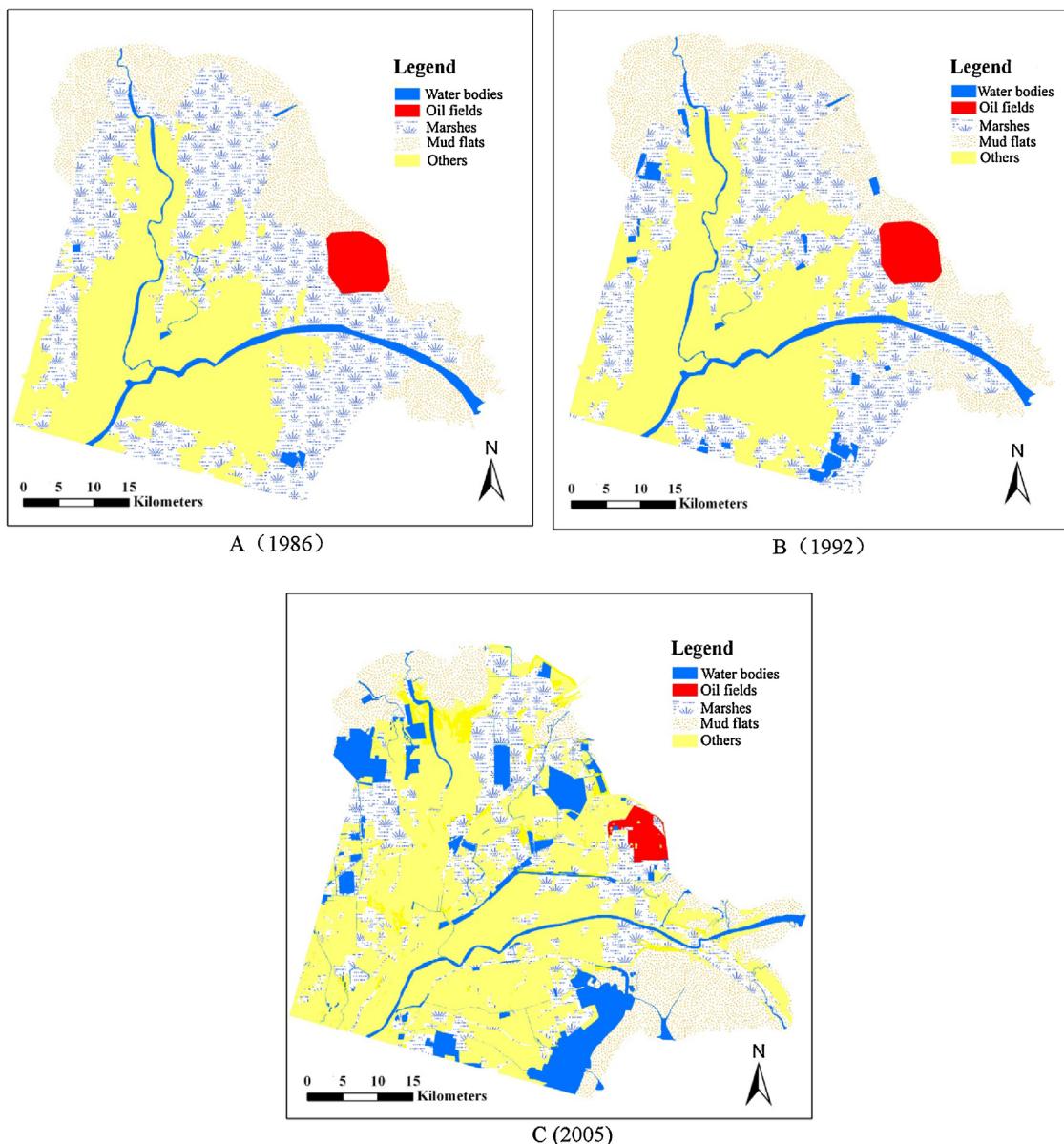


Fig. 7. Marsh area in our study area from 1986 to 2005.

from 1992 to 2005. In addition, bridges were often constructed if roads crossed river courses in which the water supply temporarily reestablished the river flow. Therefore, we concluded that the conversion of marshes to other land use types was affected by water supply and human activities.

4.4. Marsh changes

The spatial datasets of marshes in our study area were obtained from visual interpretation of remote sensing images. The results are shown in Fig. 7 and Table 2. The marsh area in our study area was 115,673 ha in 1986. Decreased runoff led to a reduced water supply from the Yellow river. This caused the marsh to become drier, and then human activities caused the marsh area to decrease. In addition, a continuous decrease in the length of the river by human activities also accelerated the rate of marsh shrinkage. With a combination of decreased runoff and increased human activity, the marsh area decreased to 96,208 ha in 1992.

To improve marsh conservation, the Chinese government established the Yellow River Delta Nature Reserve in 1992. However,

a continuous decline in Yellow River runoff was not able to satisfy with the minimum water demand for marsh maintenance, and marsh area continued to decrease. In 2000, the Chinese government launched a marsh restoration project in one of the core areas in the southern portion of the Yellow River Nature Reserve in 2000. New river courses and reservoirs were constructed. The water supply was improved and marsh coverage area began to expand. Yellow river runoff also increased in response to government regulation policies established in 2003.

The overall marsh coverage area in the study area still showed a decreasing trend from 1992 to 2005. In 1992, the marsh area was 96,208 ha in our study area, and it decreased to 59,075 ha in 2005. The marsh area in core, buffer, and experimental areas of the southern portion of the reserve was 5587, 3589 and 16,057 ha in 1992, and decreased to 2546, 1133, and 8483 ha in 2005, respectively. The marsh area in core, buffer, and experimental areas of the northern portion of the reserve was 331, 750 and 10,491 ha in 1992, and decreased to 129, 5780 and 41,003 ha in 2005, respectively. The marsh area in other areas was 59,403 ha in 1992 and this decreased to 41,003 ha in 2005. The reason for this declining trend was that

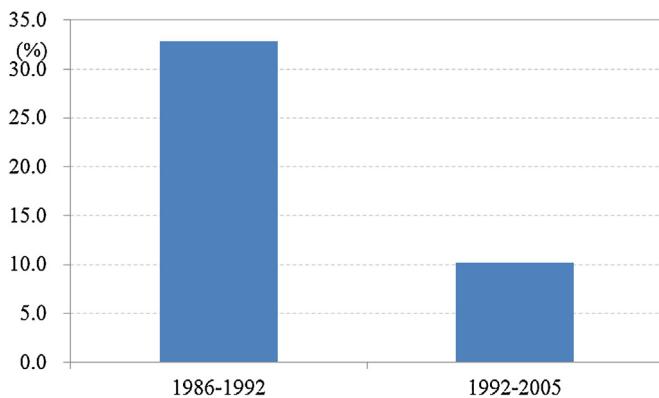


Fig. 8. Bare land within farmlands that were converted from marshes.

the area implemented for the restoration project was too small. To restore the marsh area in our study area, government agencies should further expand the extent of the project.

5. Discussion

Due to the high level of grain production in the Yellow River delta, it has been described as “China’s barn.” Since grain production is one of the primary missions of the central and local governments, marsh reclamation is one option for increasing grain production. However, the groundwater table is very shallow in our study area, irrigation is irregular, and annual evapotranspiration is larger than annual precipitation. Marsh reclamation would likely result in higher soil salinity. Higher salt content will further impair plant growth, and when soil salinity accumulates to a certain level, the reclaimed lands would convert to bare land.

The bare land identified within reclaimed lands in 2005 was extracted from remote sensing images that are produced during the vegetable growing season. We classified the bare land into two classes: bare land occurring in farmlands converted during 1986–1992, and bare land occurring on farmlands converted during 1992–2005. The results are shown in Fig. 7. Fig. 7 indicates that there was a higher percentage of bare land within farmland that was converted during the earlier period than that converted during the later period. The percentage of bare land in farmland converted in the first period was 32.8%, and that in farmland converted in the second period was 10.1%. This shows that the salt content was higher in farmlands that are converted in the earlier period (Fig. 8).

The government has been using soil desalinization to increase grain production, and many projects have been launched to analyze soil salt content since the late 1980s (Wu et al., 1993; Yang and Yao, 2007; Xie et al., 2011). Some studies (Cui et al., 2009a; Zhang et al., 2012) had found out that reasonable engineering projects could improve eco-system functions. The higher salt content in farmlands converted in the earlier period indicates that more engineering projects will be needed to improve soil salt content in the Yellow River delta.

6. Conclusions

Evapotranspiration was calculated from observation data from the Dongying Weather Station. The trend of MI was obtained according to Eq. (7). Marsh changes from 1986 to 2005 were extracted from Landsat TM images. By statistical and spatial analysis, we found out that climate change caused the temperature and precipitation to increase, but caused evapotranspiration to decrease. The moisture index (MI) tended to increase from 1986 to 2005. These climate factors led to a decrease in runoff in the Yellow River, and this decrease in runoff resulted in a reduced water

supply for marshes in the Yellow River delta. In addition, human activities converted some marsh area into farmland. Climate factors and land use conversion led to a decrease in marsh area from 1986 to 1991. The Wetland Restoration Project was launched in 1992, and it prevented the decreasing trend in a small area, but overall, an inadequate water supply to marshes still resulted in a rapid decrease of the marsh coverage area in the entire study area. Reclaimed marshes could lead to soil salinization, and engineering projects will be required to prevent soil salinization (Shao et al., 2012a,b, 2015; Shao, 2014; Liu et al., 2015).

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