Chin. Geogra. Sci. 2020 Vol. 30 No. 1 pp. 170–179
https://doi.org/10.1007/s11769-020-1103-6

Springer Science Press
www.springerlink.com/content/1002-0063

Effects of Tidal Channels and Roads on Landscape Dynamic Distribution in the Yellow River Delta, China

YU Xiaojuan[1,2], ZHANG Zhongsheng[2], XUE Zhenshan[2], WU Haitao[2], ZHANG Hongri[1]

(1. *Shangdong University of Science and Technology*, *Qingdao* 266590, *China*; 2. *Northeast Institute of Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 1301012, *China*)

Abstract: Landscape characters in estuarine regions generally controlled by tidal regimes and human activities like road construction. In this work, tidal channels and road construction in the Yellow River Delta (YRD) were extracted by visual interpretation methods so as to decipher impacts of tidal channel development and road construction on landscape patch change during 1989–2016. Spatial distribution history of three wetlands, which covered by *Phragmites australis* (freshwater marsh, FM), *Suaeda salsa* (salt marsh, SM), and mudflats (MD) were also established. Results indicated that tidal channel, number, frequency, and fractal dimension were all the maximum in 2003, and the minimum in 1998, respectively. Road length, number, and density showed increasing trend during 1989–2016. MD were the predominant landscape type, followed by FM and SM during 1989−2016. Principal component analysis implied two extracted factors, F1 and F2, which could represent 91.93% of the total variations. F1 mainly proxied tidal channel development, while F2 represented road construction. A multiple linear regression analysis showed positive effects of both F1 and F2 on FM patch numbers and negative impacts on SM patch areaes with R^2 values of 0.416 and 0.599, respectively. Tidal channels were negatively related to MD patch numbers, while roads were positively related to that. In any case, road construction showed larger impacts on landscape type shifting than that of tidal channel development in the YRD.

Keywords: tidal channel development; road construction; principal component analysis; multiple linear regression analysis; the Yellow River Delta

Citation: YU Xiaojuan, ZHANG Zhongsheng, XUE Zhenshan, WU Haitao, ZHANG Hongri, 2020. Effects of Tidal Channels and Roads on Landscape Dynamic Distribution in the Yellow River Delta, China. *Chinese Geographical Science*, 30(1): 170–179. https://doi.org/10.1007/s11769-020-1103-6

1 Introduction

Tidal channels are controlled by interactions between reiver flow and tides (Yin, 1997), and are unique geomorphologic components in delta regions. They usually serve as important pathways of matter, energy and information exchanges between ocean and land (Teal, 1962). Tidal channels are ecotones where fresh and salt water meet each other. Tidal channel connectivity mirrors hydrologic connectivity patterns to some extend in estuary areas (Naiman et al., 1993). Tidal channels with complex but good connectivity could favor organism colonization and diffusion. Maintainging hydrologic connectivity in fluent is essential for stabilizing population of biota communities, improving ecological resistance to external disturbances, and promoting ecological sustainability (Paillex et al., 2009; Obolewski, 2011; Isbell et al., 2015). Tidal channels shape water flow pathway by their distribution patterns, spatial-temporal changes, and geometric structure characteristics, and thereby govern, at least partly, nutrient bioavailability, sedimentation, and biota

Received date: 2018-12-04; accepted date: 2019-02-18
Foundation item: Under the auspices of National Key Research and Development Project (No. 2017YFC0505901)
Corresponding author: XUE Zhenshan, E-mail: xuezhenshan@iga.ac.cn

colonization and propagation in estuaries (Wolaver et al., 1985; Chrzanowski and Spurrier, 1987; Spurrier and Kjerfve, 1988; Zhao et al., 2010). Hydrological regimes greatly regulate the stability, biodiversity and ecological functions of coastal wetlands, and have vital impacts on sustainable development and utilization of resources from estuarine delta (Lerberg et al., 2000; Mallin and Lewitus, 2004). Tidal flats are usually characterized by lots of tidal channels in spatial. Wetland vegetation diffusion and colonization are closely related to geometric features of tidal channels. Vegetation propagule migrate with water to where tidal channel occurrence, and thereby, hydrologic connectivity of tidal channel is vital to vegetation succession in coastal wetlands (Luo et al., 2018). Salt-marsh vegetation growth could increase tidal channel curvature and then affect its connectivity (Kearney and Fagherazzi, 2016). In the Yancheng coastal wetland, tidal channels accelerate *Spartina alterniflora* (SA) expansion landwards to where occupied by salt marsh (SM) initially (Hou et al., 2014). SA expansion rates depend on tidal channel development because its propagule is dispersed by tides (Hou et al., 2014). In the Jiuduansha wetland, when grade of tidal channels changed to the first-order from the fourth-order, native plant species were gradually replaced by SA (Chen et al., 2011). Road construction also has important impacts on vegetation shift and wetland ecological functions. Road construction could leds to wetland fragmentation (Qin, 2012), not only cause areas loss but also alter predominant vegetation species (Wang, 2008).

The Yellow River Delta (YRD) is one of the youngest wetlands in China but has been suffering increasing anthropogenic and natural pressure. Road construction for oil exploitation has shown deleterious effects on coastal wetlands by fragmenting wetlands to samll isolated patches. Animal migration and plant diffusion are greatly restriced by low habitat connectivity caused by road construction. Meanwhile, soil accretion in estuarine are governed sediment discharge from the river and regulated by tidal scour. A 44-year data record measured by Lijin Hydraulic Station on the Yellow River showed increasing sediment concentrations but decreasging river discharge into the delta since 1970s (Li et al., 1998). More sediment but fewer discharge input has greatly affected wetland development and changed shorelines in the YRD. The YRD coastline has changed frequentely and rapidly from 1992 to 2014, which were mainly influenced by the flow path of the Yellow River and human activity (Wang, 2019). During 1973−2013, wetland areas in the YRD have reduced by 683.12 km^2 and the trend of loss continues now (Zhu et al., 2018). Besides area loss, tidal channel development in the YRD has been greatly affected by natural and anthropogenic disturbances. Previous work carried out in the YRD often concerned with spatial-temporal dynamics of tidal channels (Sun et al., 2001; Huang and Fan, 2004; Yu et al., 2018), or impacts of roads on vegetation changes. In fact, vegetation changes in the YRD are regulated by both tidal channel and roads together. However, there is still little information available on this point, and this has greatly restricted our knowledge on community succession of coastal wetland in the YRD.

In this study, spatial-temporal dynamic changes and of tidal channels and roads were studied 1989–2016 in the YRD. Their morphological feathers were also mirrored by some parameters including length, density, number, frequency, curvature, fractal dimension and network indices like network roundness (α), node connection rate (β) and connectivity (γ). Three marsh types, freshwater marsh (FM) covered by *Phragmites australis*, salt marsh (SM) covered by *Suaeda salsa,* and mudflats (MD) without vegetations, were extracted by visual interpretation method. It is aimed to decipher effects of tidal channel development and road construction on landscape patch change of these three wetlands over the past 27 yr, and then to provide scientific basis for guiding wetland restoration in the YRD.

2 Materials and Methods

2.1 Study area

The YRD locates at the entry of the Yellow River in the northeast of the Dongying City, Shandong Province, China (Fig. 1). It spans to Bohai in north, to Laizhou Bay in south. It reaches the Song Chunrong ditch to the south, extends about 30 km to the north (end of the tidal flat), meets the sea to the east, and uses the internal boundary of the tidal flat in 1989 as the boundary in the west. The Yellow River was diverted due to the implementation of the Qing 8 Project in August 1996 (Wang et al., 2016), which performed by the Yellow River Conservancy Commission of the Ministry of Water Resources in 1996 and resulted in the shift of Yellow

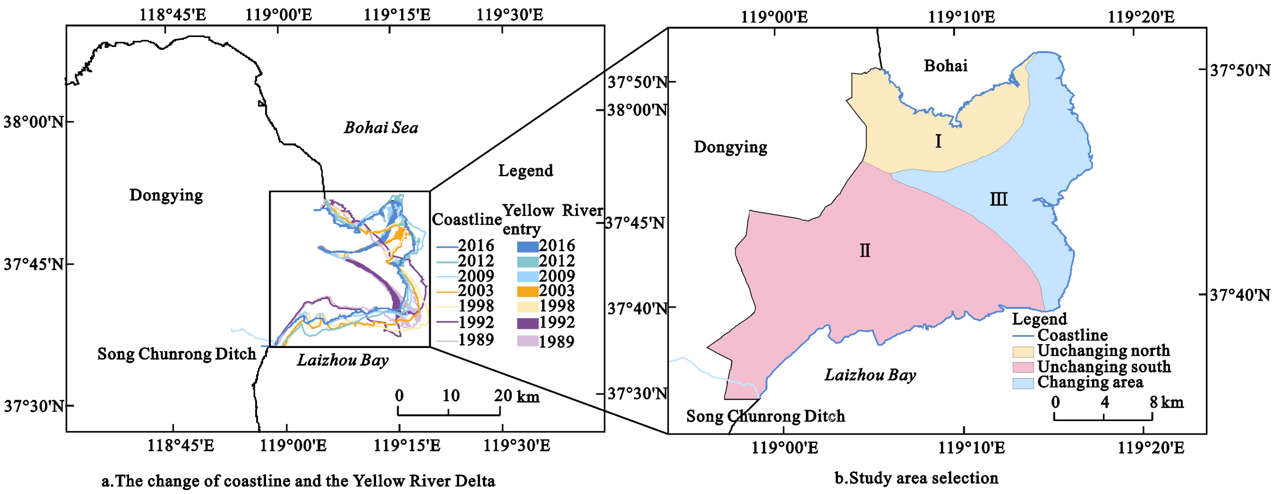

Fig. 1 Location of the study area coastline changes in the Yellow River Delta during 1989–2016. Three regions were divided in the Yellow River Delta according to main stream location and durative swing areas of the Yellow River, which were the unchanging north region (Ⅰ), the unchanging south region (Ⅱ) and the changing region (Ⅲ)

River's route. This had caused sedimentation decreasing in the original estuary and increasing in the new estuary, and coastlines changed greatly (Gu et al., 2000) (Fig.1a). Based on the Yellow River estuary shifting location, the study area is further divided into the northern region of the river (the unchanging North: Ⅰ), the southern region of the river (the unchanging South: Ⅱ) and the variable region of the estuary (the changing region: Ⅲ) (Fig.1b) for the subsequent discussion.

2.2 Materials

Based on seven remote SPOT images during 1989–2016 (Table 1), tidal channels, roads and wetlands (FM, SM and MD) were extracted by visual interpretation with ArcGIS10.3 software. Spatial and temporal resolution of SPOT images is 20 m × 20 m and 26 d, respectively. Data of 2016 from Landsat 8 OLI (operational land imager) images were transformed to produce a spatial resolution of 20 m × 20 m using the Gram-Schmidt algorithm to fuse the multispectral band sensing image (30 m × 30 m) and high resolution spatial panchromatic image (15 m × 15 m). Considering that acquisition time of SPOT images does not match plant growth period, TM/ETM/OLI images from the end of August to the beginning of October (http://earthexplorer.usgs.gov/), with a resolution of 30 m × 30 m and 16 d, were used to obtain landscape type information. By ENVI5.3 software, all images were pre-processed by conducting radiation calibration and FLAASH atmospheric correction and followed by geometric correction using remote sensing image in 2016 as the reference (root mean square (RMS) < 1).

Information of normalized difference vegetation index (NDVI) was extracted according to pervious work (Zhao, 2003). Tidal channels, roads and wetlands (FM, SM, MD) were extracted by visual interpretation in ArcGIS10.3 software environment from 1989 to 2016 (Fig. 2). Indices were calculated using polyline data of tidal channels and roads (Table 2). Buffer zones were created to reveal impacts of tidal channels and roads on wetland fragmentation in the YRD. In June, 2018, field investigation was performed to test the accuracy of visual interpretation results. Interpretation accuracy was estimated to be over 70%, which was acceptable.

Table 1 Basic information of remote sensing images used in the present work

Interpretation	Year	1989	1992	1998	2003	2009	2012	2016
Tidal Channels/roads	Type	SPOT1	SPOT2	SPOT4	SPOT4	SPOT4	SPOT4	OLI
	Date	08-08	02-05	04-25	10-18	12-07	05-01	08-26
Landscape types	Type	TM	TM	TM	ETM+	ETM+	ETM+	OLI
	Date	10-03	08-24	09-10	08-31	09-31	08-23	08-26

Notes: SPOT, high-resolution images, SPOT 1 launched February 22, 1986 with 10 panchromatic and 20 meter multispectral picture resolution capability, withdrawn December 31, 1990; SPOT 2 launched January 22, 1990 and deorbited in July 2009; SPOT 4 launched March 24, 1998. Stopped functioning July, 2013. OLI is from the operational land imager, TM is from the thematic mapper, and ETM+ is from the enhanced thematic mappter plus

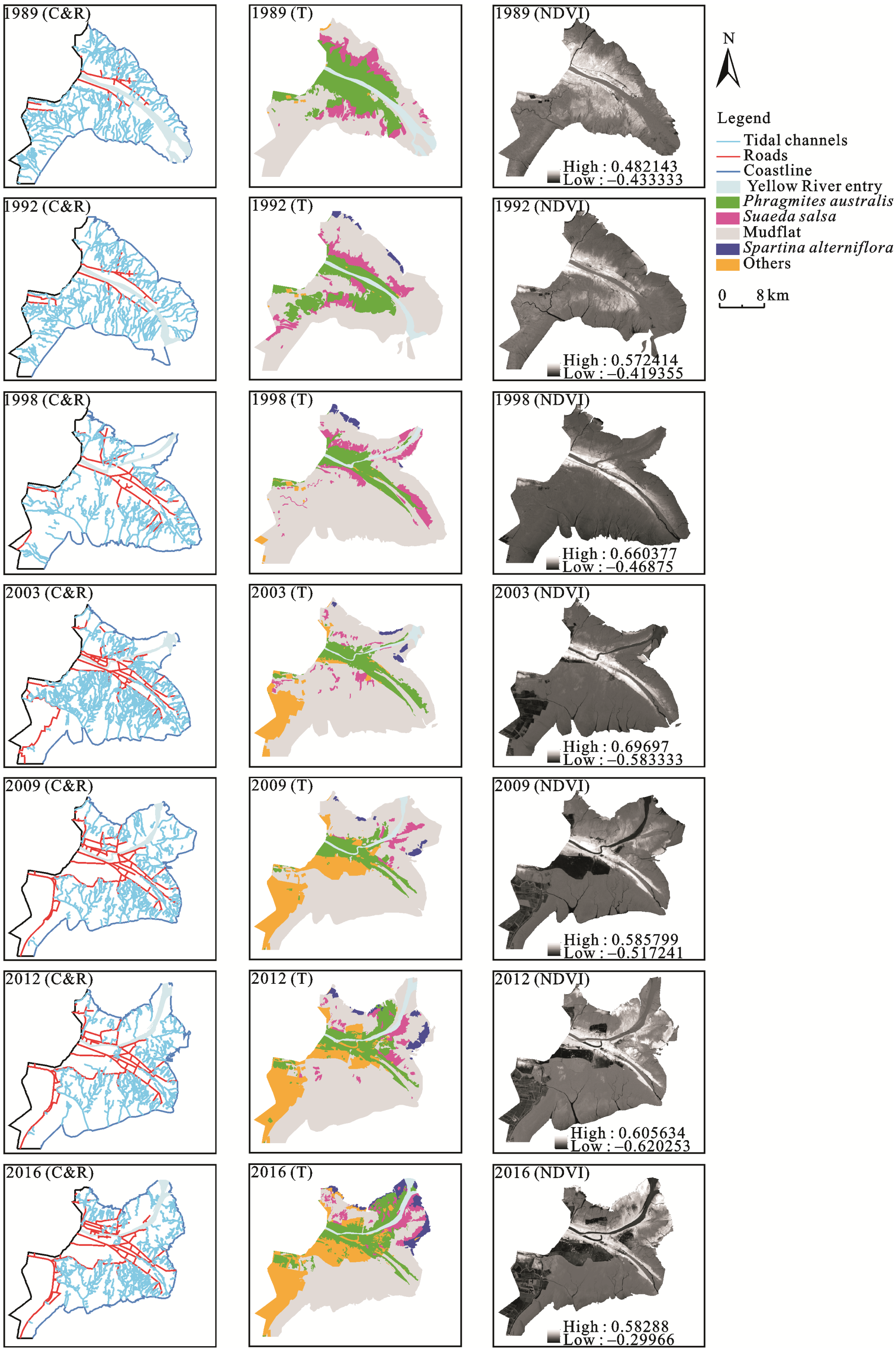

Fig. 2 Spatial distribution of tidal channels and roads (C&R), landscape types (T) and NDVI (NDVI) in the Yellow River Delta during 1989–2016

2.3 Methods

Different indices of tidal channels and roads were calculated to show their morphological characteristics and network connectivity, which were tidal channel length, number, density, frequency, curvature, fractal dimension and network connectivity (α, β and γ). There were only three indices representing road construction due to data limitation, namely, road length, number and density (Table 2).

Principal component analysis (PCA) is used to reduce original multiple variables into fewer principal components that describe or explain the multivariate variance-covariance structure features (Chen, 2011; Xu, 2014). It is an effective dimensionality reduction and statistical simplification process. A multiple linear regression analysis was used to construct the regression model. That is to say, each principal component was used as a new independent variable for model establishment. All statistical analysis was performed by SPSS 22.0, where $P < 0.05$ was considered as the threshold value for significance.

3 Results

3.1 Morphological change of tidal channels

Tidal channel length (L_t) ranged from 400.752 km (in 2012) to 624.389 km (in 2003), with the average of 474.116 km during 1989–2016. The extreme high value in 2003 was ascribed to the first water and sand regulation project on July 4, 2002. This project was carried out at the Xiaolangdi and Sanmenxia reservoirs on the upper and middle Yellow River (Xu et al., 2005). This project has greatly altered the unreasonable ratios of water to sediment in the Yellow River, scoured river channels, and reduced sediment deposition on the estuarine regions (Xu et al., 2005; Jiang et al., 2015). The average tidal channel density (d_t) was 1.074 km/km^2 during 1989–2016, with the maximum and minimum ,1.378 km/km^2 and 0.814 km/km^2, in 1989 and in 2012 respectively (Table 3).

The average number (N_t) and frequency (f) were 293 and 0.659 per kilometers in the YRD. Both the maximum and the minimum N_t (427 vs. 233) and f (0.911 vs. 0.472) were observed in 2003 and 1998, respectively. High N_t and f in 2003 related to well developed tidal channels in this period. Besides 2003, N_t and f decreased during 1989–1998 and then fluctuated. N_t in 2016 was larger than that in 1989, which indicated improvement of tidal channel development in the YRD over the last 30 yr.

Table 2 Basic information of different indices

Indices	Description	Symbol	Formula	Unit	Application	References
Length	—	L_t/L_r	—	km	Tidal channels (L_t) /roads (L_r)	—
Number	—	N_t/N_r	—	per	Tidal channels (N_t) /roads(N_r)	—
Density	the total length of tidal channels or roads per unit area of tidal flat	d_t/d_r	$d=\sum L/A$	km/km^2	Tidal channels (d_t) /roads (d_r)	Marani et al., 2003; Wu et al., 2013; Shi et al., 2016
Frequency	number of tidal channels per unit area of tidal flat	f	$f=\sum N/A$	per/km^2	Tidal channels	Horton, 1945
Curvature	the ratio of tidal channel length to straight line distance between its two ends	c	$c=L/L'$	—	Tidal channels	Ichokuand Chorowicz, 1994; Wu et al., 2013
Fractal Dimension	the slope of ln$N(n)$ and ln $1/r$,	D	$D=\lim_{r\to 0}\frac{\ln N(n)}{\ln 1/n}$	—	Tidal channels	Sun et al., 2001
Network Connectivity	the ratio of the actual number of loops to the maximum number of possible loops	α	$\alpha=(N-V+1)/(2V-5)$ $(V\geq 3)$	—	Tidal channels	Cui et al., 2009; Li et al., 2018
	the average channel number of connections per node in the network	β	$\beta=N/V$	—	Tidal channels	Lu et al., 2008; Li et al., 2018
	the ratio of the actual number of tidal channels to the maximum number of possible tidal channels	γ	$\gamma=N/N_{\max}=N/3(V-2)$ $(V\geq 3)$	—	Tidal channels	Cook, 2002; Xia et al., 2017

Notes: L is the length of tidal channels (t) or roads (r); A is the area of tidal flats; N is the number of tidal channels (t) or roads (r); L' is straight line distance between tidal channels' two ends; $N(n)$ is the number of non-empty boxes that completely cover the entire figure using the same small box; n is the same side length of the box; V is the number of nodes; N_{max} is the maximum number of possible tidal channels

Table 3 Results of different index of tidal channels in the Yellow River Delta

Year	L_t (km)	N_t	d_t (km/km^2)	F (per/km^2)	c	D	α	β	γ
1989	500.580	276	1.378	0.760	1.141	1.047	0.068	1.131	0.380
1992	532.872	249	1.301	0.608	1.160	1.040	0.054	1.102	0.371
1998	428.147	233	0.868	0.472	1.130	1.037	0.124	1.239	0.418
2003	624.389	427	1.332	0.911	1.128	1.079	0.025	1.047	0.351
2009	411.224	272	0.871	0.576	1.147	1.044	0.143	1.277	0.430
2012	400.752	274	0.814	0.556	1.136	1.045	0.144	1.280	0.431
2016	420.850	321	0.957	0.730	1.140	1.057	0.135	1.264	0.425

Notes: L_t, N_t, d_t, f, c and D are the length, number, density, frequency, curvature and fractal dimension of tidal channels, respectively; α, β and γ stands for network connectivity of tidal channels

Tidal channel curvature (c) in the YRD changed little with small variance, 0.000118, during 1989–2016, which meant relatively stable small varied tidal channel development. Fractal characteristics (D) can mirror development degrees of tidal channels (Cui et al., 2001). During 1989–2016, D values always exceeded 1 in the YRD, with maximum and the minimum D value of 1.079 in 2003 and 1.037 in 1998, respectively. Tidal channels in 2003 were characterized by the most complex evolution and abnormally increasing branches, which was attributed to the first water and sand regulation project in 2002. It is generally believed that fractal dimensions of drainage systems are higher in the mountainous region than those in the lowland plain (Angeles et al., 2004). Low D values in the YRD might largely relate to the broad and gentle topography here.

The average α value was 0.099 in the YRD, which was relatively small. It indicated that the tidal channel network was mostly unidirectional water flow with a simple structure characterized by loop numbers, high linear connections and few ring connections (Wang, 2009). The average β value was 1.191 in the YRD. Low β implies low connectivity between nodes, and the connection path may be relatively weak with poor network connection ability (Wang, 2009). The γ of the YRD was 0.351 in 2003, close to 1/3, and showed an approximately tree-like structure. This meant well developed tidal channel network in 2003, which was also consistent with results extracted from the remote sensing image in 2003.

3.2 Morphological change of roads

Three indices were employed to describe morphological change of roads (Table 4). The length (L_r), number (N_r) and density (d_r) of roads had been increasing during 1989–2016, which implied increasing human impacts here in recent years. In the YRD, L_r increased to 186.284 km in 2016 from 48.536 km in 1989 with an increasing rate of 5.102 km/a, and d_r increased to 0.422 km/km^2 in 2016 from 0.132 km/km^2 in 1989.

Table 4 Results of different indices of roads in the Yellow River Delta during 1989–2016

Year	L_r (km)	N_r (per)	d_r (km/km^2)
1989	48.536	17	0.132
1992	57.404	15	0.137
1998	111.989	24	0.227
2003	159.052	36	0.337
2009	171.622	42	0.363
2012	161.015	39	0.321
2016	186.294	51	0.422

Notes: L_r, N_r and d_r are the length, number and density of roads, respectively

3.3 Changes of main landscape types

Three wetland types in the YRD were extracted by visual interpretation based on Landsat remote sensing images during 1989–2016 (Table 5). In terms of areas, MD

Table 5 Area and number of main landscape types in the Yellow River Delta during 1989–2016

Year	FM		SM		MD	
	P_A (%)	N_P	P_A (%)	N_P	P_A (%)	N_P
1989	24.03	85	13.38	62	52.00	103
1992	17.51	53	8.92	59	62.37	132
1998	9.83	46	7.64	86	73.36	103
2003	10.81	74	2.23	44	66.14	203
2009	9.75	81	2.37	26	61.18	117
2012	12.89	100	4.34	46	56.99	133
2016	16.09	176	5.94	79	44.03	133

Notes: FM, SM and MD are freshwater marsh covered by *Phragmites australis*, salt marsh covered by *Suaeda salsa,* and mudflats, respectively; the P_A (%) and N_P is area proportion and patch numbers of different landscape types, respectively was the largest followed by FM and SM in the YRD during 1989−2016. MD areas increased first and then decreased during 1989–2016, and FM and SM showed opposite change tendencies. Patch numbers mirrored and positively related to landscape fragmentation degrees. Patch numbers of MD changed little during 1989–2016 except in 2003 when an outlier was observed. Patch numbers of FM were decreasing during 1989–1998 and increasing during 1998–2016.

3.4 Impacts of tidal channels and roads on landscape types

In this study, 12 indices were applied to shape characteristics of tidal channels and road constructions. Principle component analysis (PCA) was employed to decipher predominant driving forces controlling landscape types shift in the YRD. Two factors, F1 and F2, were extracted and represented 91.31% of total variance. Most indices related to tidal channels were introduced into F1, and most parameters related to road constructions fall into F2 (Table 6). F1 mainly reflected contributions derived from tidal channel development, and F2 largely represented contributions from road construction.

Tidal channel development and road construction had different effects on P_A and N_P of FM, SM and MD in the YRD during 1989–2016 (Table 7). High R^2 values represent good match degrees of models and only three models were relatively credible with R^2 of 0.416, 0.599 and 0.808. Both tidal channels and road construction had negative effects on P_A of FM and MD, but had smaller R^2. Roads had a larger positive contribution, mirrored by the standard beta value of 0.551, to N_P of FM than tidal channels with a standard beta value of 0.335. FM species prefers to grow near fresh water though they can endure slight salinity conditions (Li et al., 2017). Road construction usually extended from inland to the coast and fragmented wetlands. Therefore, these roads, at least partly, destroyed the integrity of FM and increased patch numbers.

Both tidal channels and roads negatively relate to P_A of SM. Road construction was the main driver causing P_A decrease, which was confirmed by the standard beta value, −0.772, higher than that of tidal channel, −0.280. SM as a typical halophyte plant, usually occurs in areas with high salinity in ecotones between land and ocean and is affected largely by ocean dynamics (Li et al., 2017). Well developed tidal channels lead to good hydrological connectivity between rivers and oceans, which could keep soil salinity competent for SM growth. Road construction could split tidal flats and tidal channels, cut off hydrological connection between SM wetland and the ocean, obstructed SM extension inland, and finally introduce area decrease of SM wet-

Table 6 Component matrix of principle component analysis of tidal channels, roads and landscape types in the Yellow River Delta

Index	F1	F2
L_t	–0.967	0.164
N_t	–0.528	0.848
d_t	–0.961	–0.138
f	–0.735	0.586
α	0.994	0.023
β	0.993	0.032
γ	0.994	0.017
c	–0.034	–0.582
D	–0.540	0.841
L_r	0.515	0.835
N_r	0.526	0.819
d_r	0.473	0.858

Notes: L_t, N_t, d_t, f, c and D is the length, number, density, frequency, curvature and fractal dimension of tidal channels, respectively; α, β and γ stands for network connectivity of tidal channels; L_r, N_r and d_r is the length, number and density of roads, respectively

Table 7 Effects of tidal channels and roads on the landscape types in the Yellow River Delta

		F1	F2	R^2
FM	P_A	−	−	0.340
		(−0.397)	(−0.427)	
	N_P	+	+	0.416
		(0.335)	(0.551)	
SM	P_A	−	−	0.599
		(−0.280)	(−0.772)	
	N_P	+	−	0.058
		(0.057)	(−0.234)	
mudflats	P_A	−	−	0.067
		(−0.143)	(−0.215)	
	N_P	−	+	0.808
		(−0.546)	(0.714)	

Notes: FM, SM and MD are freshwater marsh covered by *Phragmites australis*, salt marsh covered by *Suaeda salsa,* and mudflats, respectively; the P_A (%) and N_P is area proportion and patch numbers of different landscape types, respectively; R^2 represented the decision coefficient of the models; values in brackets were standard beta coefficients in the linear regression models, and higher absolute values mean high contributions of factors, and the +/− meant positive or negative effects land. It is perplexing that tidal channels had negative effects on P_A of SM. Sand input by tidal channels and concomitant sedimentation from the Yellow River might hasten accretion and consequently hinders salt washing by tides, this keeps salinity change within a small range and thus induces SM community disappearance. This phenomenon is widespread observed in coastal wetlands of Panjin (Li et al., 2006). However, there are few studies on this phenomenon in the YRD and more attention should be paid to this.

Tidal channel development and road construction had a better explanation on N_P of MD (R^2 = 0.808). Tidal channels negatively related to N_P of MD with a standard beta value of –0.546. Roads positively related to N_P of MD with a standard beta value of 0.714. Roads extension blocked tidal channels and accelerated mudflat fragmentation. Tidal channel development could restrict MD, which mirrored by negative correlation between tidal channel development and N_P of MD.

4 Discussion

Impacts of tidal channels and roads on landscape features were site-depended different across in the YRD, which was divided into three regions to discuss various impacts of tidal channels and roads.

Besides region Ⅲ, tidal channel length was decreasing in other regions. Region Ⅲ is the changing region of the Yellow River estuary. It is greatly affected by the Yellow River water from the upper reaches and tidal waves from the sea. Road length had been increasing in all regions, indicating that increasing human activities occurs. FM area in region I and Ⅲ both increased fluctuant. In region II, FM area declined sharply from 1992 to 1998 and then increased gradually. This is perhaps because the Qing 8 project, which caused in a sudden decrease of the brackish water in 1996 and restricted FM growth. SM area change in region I was similar to that in region II. SM surrounded by tidal channels in regions I and II usually could not be washed by tide, which reduces soil salinity that did not meet growth requirements for SM. Mudflat area change in the three regions was essentially similar. SA, characterized by salt and water-logging resistance, was first introduced to the YRD around 1990. It did not grow in region Ⅱ. In the other two regions, it had been gradually spreading along the coastline in recent years.

Pearson correlation coefficient showed that only SA area was closely related to road length (r = −0.833, P <0 .05), while there was a greater correlation between SM area and road length (r = −0.954, P < 0.01). Multiple linear regression analysis yield standard coefficients, 0.632 and 0.873, for FM area vs. road length and SM vs. road length. This indicated that road construction was an important factor causing FM and SM degradation in region Ⅱ. In recent years, economic development like oil exploitation and breeding ponds encouraged many roads, thus indirectly destroyed the ecological integrity of the wetland and resulting in landscape types degradation.

It can be seen from the above that road construction had a great influence on the evolution of wetlands. Besides, tidal channel development will also be affected by road construction. For example, when road construction cut off some tidal channels, they can hinder the hydrological connectivity between wetlands and sea areas, reduce the transport of matter, energy and organic matter, and undermine the integrity of the wetland ecosystem. Road construction plays a more important role in the evolution of wetlands and the development of tidal channels.

Therefore, it is necessary to control the scope and intensity of human activities in the YRD regions. For example, in order to maintain the integrity and hydrological connectivity of tidal channels, road planning should be carried out according to local conditions, and tidal channel areas should be avoided as much as possible; existing shrimp ponds, fish ponds and aquaculture areas should be renovated, and the construction and expansion of breeding areas strictly controlled; the oil fields in the core area of the nature reserve and the buffer zone will be withdrawn to limit their exploration activities, and measures will be taken to repair the original wetland ecological environment.

5 Conclusions

From 1989 to 2016, tidal channel development and road construction had different effects on FM, SM, and MD in the YRD. Road construction had larger contributions on landscape area and patch changes than tidal channel development. It implied that anthropogenic activities like road construction has played a greater role in the evolution of landscape succession in the YRD. However, there are still some deficiencies in this study. It was difficult to get remote sensing images at the same time each day so as to avoid impacts of tides on interpretation accuracies. In the future, more attention should be paid to ecological effects of tidal channel changes facing external disturbance like human activities and sea level rise.

References

Angeles G R, Perillo G M E, Piccolo M C et al., 2004. Fractal analysis of tidal channels in the Bahía Blanca Estuary (Argentina). *Geomorphology*, 57(3–4): 263–274. doi: 10.1016/S0169-555X(03)00106-5

Chen Xiuzhi, Guo Shuiliang, Zhu Lili et al., 2011. Distribution pattern of main plant populations around tidal creeks in different grades in the Jiuduansha shoals in the mouth of Yangtze River. *Wetland Science*, 9(1): 52–60. (in Chinese)

Chen Yanguang, 2011. *Mathematical Methods for Geography*. Beijing: Science Press. (in Chinese)

Chrzanowski T H, Spurrier J D, 1987. Exchange of microbial biomass between a *Spartina alterniflora* marsh and the adjacent tidal creek. *Estuaries*, 10(2): 118–125. doi: 10.2307/1352175

Cook E A, 2002. Landscape structure indices for assessing urban ecological networks. *Landscape and Urban Planning*, 58(2–4): 269–280. doi: 10.1016/s0169-2046(01)00226-2

Cui B S, Wang C F, Tao W D et al., 2009. River channel network design for drought and flood control: a case study of Xiaoqinghe River basin, Jinan City, China. *Journal of Environmental Management*, 90(11): 3675–3686. doi: 10.1016/j.jenvman.2009.07.010

Cui Chengqi, Li Shitang, Sun Xiaoxia et al., 2001. Research on the development of the Huanghe River Delta coastline and the tidal creek system as well as fractional dimension–Research on the space–time lineage of the tidal bank coast of the Huanghe River Delta Ⅲ. *Marine Science Bulletin*, 20(6): 60–70. (in Chinese)

Gu Yuanze, Jiang Mingxing, Xu Congliang et al., 2000. The impact on the project of the Yellow River estuary Qing 8 and its influence on estuary evolution. *Journal of Sediment Research*, (5): 57–61. (in Chinese)

Horton R E, 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *GSA Bulletin*, 56(3): 275–370. doi: 10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Hou Minghang, Liu Hongyu, Zhang Huabing, 2014. Effection of tidal creek system on the expansion of the invasive Spartina in the coastal wetland of Yancheng. *Acta Ecologica Sinica*, 34(2): 400–409. (in Chinese)

Huang Haijun, Fan Hui, 2004. Change detection of tidal flats and tidal creeks in the Yellow River Delta using Landsat TM/ETM+ images. *Acta Geographica Sinica*, 59(5): 723–730. (in Chinese)

Ichoku C, Chorowicz J, 1994. A numerical approach to the analysis and classification of channel network patterns. *Water Resources Research*, 30(2): 161–174. doi: 10.1029/93wr02279

Isbell F, Craven D, Connolly J et al., 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, 526(7574): 574–577. doi: 10.1038/nature15374

Jiang Dongsheng, Yan Yongxin, Wang Jing, 2015. Influence of water and sediment regulation on hydrological characteristics in Shandong reach of the Yellow River. *Yellow River*, 37(12): 6–8. (in Chinese)

Kearney W S, Fagherazzi S, 2016. Salt marsh vegetation promotes efficient tidal channel networks. *Nature Communications*, 7(1): 12287. doi: 10.1038/ncomms12287

Lerberg S B, Holland A F, Sanger D M, 2000. Responses of tidal creek macrobenthic communities to the effects of watershed development. *Estuaries*, 23(6): 838–853. doi: 10.2307/1353001

Li G X, Wei H L, Han Y S et al., 1998. Sedimentation in the Yellow River delta, part I: flow and suspended sediment structure in the upper distributary and the estuary. *Marine Geology*, 149(1–4): 93–111. doi: 10.1016/s0025-3227(98)00031-0

Li Jianguo, Yang Deming, Hu Ke et al., 2006. Study on hetroptera kitag spatial characteristics in Honghai Beach of Panjin City. *Journal of Jilin University* (*Earth Science Edition*), 36(S1): 108-112. (in Chinese)

Li Min, Liu Shuaishuai, Xu Fei, 2017. Response of structure and functions of Comm. *Phragmites australis* + *Suaeda salsa* in Yellow River Delta to 3 kinds of human-caused disturbances. *Wetland Science*, 15(1): 92–98. (in Chinese)

Li Pulin, Chen Jing, Sun Bingxiang et al., 2018. Research on urban water system planning based on connectivity. *Yellow River*, 40(1): 31–35, 49. (in Chinese)

Lu Tao, Ma Keming, Fu Bojie et al., 2008. Effects of ditch network structure on landscape pattern in the Sanjiang plain, Northeast China. *Acta Ecologica Sinica*, 28(6): 2746–2752. (in Chinese)

Luo Meng, Wang Qing, Qiu Dongdong et al., 2018. Hydrological connectivity characteristics and ecological effects of a typical tidal channel system in the Yellow River Delta. *Journal of Beijing Normal University* (*Natural Science*), 54(1): 17–24. (in Chinese)

Mallin M A, Lewitus A J, 2004. The importance of tidal creek ecosystems. *Journal of Experimental Marine Biology and Ecology*, 298(2): 145–149. doi: 10.1016/s0022-0981(03)00356-3

Marani M, Belluco E, D'Alpaos A et al., 2003. On the drainage density of tidal networks. *Water Resources Research*, 39(2): 1040. doi: 10.1029/2001WR001051

Naiman R J, Decamps H, Pollock M, 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, 3(2): 209–212. doi: 10.2307/1941822

Obolewski K, 2011. Macrozoobenthos patterns along environmental gradients and hydrological connectivity of oxbow lakes. *Ecological Engineering*, 37(5): 796–805. doi:

10.1016/j.ecoleng.2010.06.037

Paillex A, Dolédec S, Castella E et al., 2009. Large river floodplain restoration: predicting species richness and trait responses to the restoration of hydrological connectivity. *Journal of Applied Ecology*, 46(1): 250–258. doi: 10.1111/j.1365-2664.2008.01593.x

Shi Haidong, Shen Yongming, Kang Min, 2016. Rapid response of tidal creek network patterns to the reclamation on the central Jiangsu coast. *Haiyang Xuebao*, 38(1): 106–115. (in Chinese)

Spurrier J D, Kjerfve B, 1988. Estimating the net flux of nutrients between a salt marsh and a tidal creek. *Estuaries*, 11(1): 10–14. doi: 10.2307/1351713

Sun Xiaogong, Zhao Haihong, Cui Chengqi, 2001. The fractal characteristics of tidal flat and tidal creek system in the Huanghe River Delta. *Oceanologia et Limnologia Sinica*, 32(1): 74–80. (in Chinese)

Teal J M, 1962. Energy flow in the salt marsh ecosystem of Georgia. *Ecology*, 43(4): 614–624. doi: 10.2307/1933451

Wang Jining, Meng Yonghui, Zhang Lixia, 2016. Remote sensing monitoring and change analysis of Yellow River Estuary coastline in the past 42 years. *Remote Sensing for Land & Resources*, 28(3): 188–193. (in Chinese)

Wang Kuifeng, 2019, Evolution of Yellow River Delta coastline based on remote sensing from 1976 to 2014, China. *Chinese Geographical Science*, 29(2): 181–191. doi: 10.1007/s11769-019-1023-5

Wang Yuncai, 2009. The connectivity evaluation of Shanghai urban landscape eco-network. *Geographical Research*, 28(2): 284–292. (in Chinese)

Wolaver T, Whiting G, Kjerfve B et al., 1985. The flume design —a methodology for evaluating material fluxes between a vegetated salt marsh and the adjacent tidal creek. *Journal of Experimental Marine Biology and Ecology*, 91(3): 281–291. doi: 10.1016/0022-0981(85)90182-0

Wu Deli, Shen Yongming, Fang Renjian, 2013. A morphological analysis of tidal creek network patterns on the central Jiangsu coast. *Acta Geographica Sinica*, 68(7): 955–965. (in Chinese)

Xia Min, Zhou Zhen, Zhao Haixia, 2017. Evaluation of water system connectivity of the district around Chaohu Lake based on comprehensive indexes. *Geography and Geo-information Science*, 33(1): 73–77. (in Chinese)

Xu Guobin, Zhang Jinliang, Lian Jijian, 2005. Effect of water–sediment regulation of the Yellow River on the lower reach. *Advances in Water Science*, 16(4): 518–523. (in Chinese)

Xu Jianhua, 2014. *Quantitative Geography*. 2nd ed. Beijing: Higher Education Press. (in Chinese)

Yin Yanhong, 1997. Status quo and progress in tidal channel. *Marine Geology Letters*, 13(7): 1–4. (in Chinese)

Yu Xiaojuan, Zhang Zhongsheng, Xue Zhenshan et al., 2018. Morphological characteristics and connectivity of tidal channels in the Yellow River Delta for 7 periods since 1989. *Wetland Science*, 16(4): 517–523. (in Chinese)

Zhao Xinsheng, Cui Baoshan, Sun Tao et al., 2010. The relationship between the spatial distribution of vegetation and soil environmental factors in the tidal creek areas of the Yellow River Delta. *Ecology and Environmental Sciences*, 19(8): 1855–1861. (in Chinese)

Zhao Yingshi, 2003. *Principles and Methods of Remote Sensing Application Analysis*. Beijing: Science Press. (in Chinese)

Zhu C M, Zhang X P, Huang Q H, 2018. Four decades of estuarine wetland changes in the Yellow River delta based on Landsat observations between 1973 and 2013. *Water*, 10(7): 933. doi: 10.3390/w10070933