Vulnerability assessment of the Yellow River Delta to predicted climate change and sea level rise

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Executive summary

The Asia-Pacific Network for Global Change Research (APN) funded a study assessing the vulnerability of the Yellow River Delta (YRD), in China, to predicted climate change and sea level rise. The study was coordinated by the Environmental Research Institute of the Supervising Scientist (***eriss***), in Australia, and Wetlands International–China Program, with the major local collaborator being the State Oceanic Administration of China.

The study's major objectives were to raise awareness of the issue of climate change and sea level rise in the Asia-Pacific region, to provide advice and training to national and local agencies on procedures for Vulnerability Assessment, and specifically, to obtain a preliminary understanding of the potential impacts of climate change and sea level rise on the biological, physical and socio-economic attributes of the YRD.

The YRD was chosen as a study site primarily because it has been nominated for the East Asian–Australasian Shorebird Reserve Network. Due to its importance as a habitat for migratory and resident shorebirds, a 1500 km^2 Nature Reserve has been established along the eastern coast of the delta.

The assessment included the following steps:

- Description of the YRD, including its physical, biological and socio-economic attributes;
- Identification of natural and anthropogenic 'forcing factors', including predicted climate change and sea level rise, and their impacts;
- Assessment of the vulnerability to existing forcing factors;
- Assessment of the vulnerability to climate change and sea level rise;
- Documentation of current responses to coastal hazards;
- Recommendations for future monitoring and management strategies;
- Identification of information gaps and research priorities.

Information was obtained from existing literature, including a number of quantitative estimates of impacts of climate change on specific attributes of the YRD.

The YRD represents the meeting point of the Yellow River with the Bohai Sea, in eastern China. The delta covers approximately 6000 km^2, although historically it has been in a

dynamic state due to the high sediment load and frequently changing course of the Yellow River. More recently, the river course has been stabilised, allowing substantial development to occur. The YRD is now a highly urbanised and industrialised region, with a population of 1.64 million and major industries including oil extraction and crop and cattle farming. Subsequent demands on water resources, both from within and upstream of the YRD have greatly reduced the flow of the Yellow River in the last decade. The Nature Reserve was established in recognition of the YRD's importance as a site for migratory and non-migratory shorebirds, however, it is under great pressure from urbanisation, farming, and oil and natural gas extraction.

The major physical attributes of the YRD include the river and underground water, the low topographical relief of the delta, the geomorphic units of the terrestrial delta, the subaqueous delta and the tidal flats, the sediment load of the Yellow River and subsequent sedimentation, and the natural resources of oil, gas and water. The major biological attributes include terrestrial and aquatic plants and animals, particularly the birdlife, which includes 152 species of protected birds. Over 500 000 shorebirds are estimated to utilise the wetlands of the YRD during their northward migration. The major socio-economic attributes include the population of over 1.64 million, and the primary industries of oil and natural gas extraction and crop and cattle farming.

The predicted climate change scenario for the YRD was based on regional climate change scenarios for temperate Asia or China specifically, by the IPCC and other investigators. The scenario used for this study included the following estimates:

- A rise in relative sea level of 48 cm by 2050 (specific for the recent YRD);
- A rise in mean air temperature of 1.4°C by 2050 and 3°C by 2100 (for China/East Asia);
- A rise in annual precipitation of 2–4.5% by 2050 (for East China).

The major natural forcing factors acting on the YRD (excluding climate change) are sedimentation, the Asian monsoon, El Niño, and flooding and storm surge. Major impacts associated with these include erosion and expansion of the coastal wetlands, damage to infrastructure, crops and livestock, and loss of human life. Major anthropogenic forcing factors include the large population and associated types of land use, oil and natural gas development, and water and air pollution. The major impacts include a reduction in freshwater supply, a reduction in surface and ground water quality, degradation of the Nature Reserve and the subsequent loss of wetland habitat and biodiversity.

The YRD is already extremely vulnerable to existing forcing factors. Although river flows have decreased in the last decade, the YRD is still highly vulnerable to flooding from both upstream sources and from storm surges. The high utilisation of water resources, while aiding in the development of industry and agriculture and enhancing the standard of living, will eventually result in major ecological consequences, such as salinisation, loss of wetland habitat and desertification. Without proper management, urban, industrial and agricultural activities will further pollute the already poor quality waters within the YRD.

The YRD is also vulnerable to predicted climate change and sea level rise. Increased moisture stress, insect pests and plant diseases resulting from climate warming are expected to have unfavourable effects on agricultural production. Salt marshes and other coastal wetlands are thought to be particularly vulnerable to permanent inundation and erosion as a result of sea level rise and increased storm surge. This would have flow-on effects to tourism, freshwater supplies, fisheries and biodiversity. Sea level rise will result in a number of other impacts including a reduction in the protective capacity of the dyke systems. Assuming a 1 m sea level rise and 2–3 m storm surge, approximately 40% of the YRD could be inundated. Saltwater intrusion will also be a major issue, further reducing already limited freshwater resources. The above impacts will have major consequences for both the socio-economic and biological attributes of the YRD.

A series of dyke systems have been in place in the YRD for many years to protect against floods both from upstream and from storm surges. Some of these have been upgraded whilst others require attention. Many of these flood control dykes will serve as protective barriers to sea level rise and increased storm surge, although the extent to which they can protect the adjacent land is uncertain. Other control measures are in place to prevent or minimise floods resulting from ice jam in the river. Freshwater shortages are being addressed by increasing the capacity of existing reservoirs or proposing the construction of new reservoirs.

The study identified a number of management strategies or countermeasures for protecting the YRD from both existing forcing factors and predicted climate change and sea level rise including:

- Integration of information from programs monitoring sea level rise, coastal zone ecology and sensitivity, and socio-economic and cultural indicators;
- Stabilisation of the course and mouth of the Yellow River;
- Consideration of flood risk in urban and industrial planning;
- Protection and management of coastal wetlands and the Nature Reserve;
- Control of urban and industrial pollution;
- Establishment of reservoirs for water storage and conservation;
- Increasing community awareness about environmental protection.

In addition, recommendations regarding the management of the Nature Reserve include:

- Development of an appropriate administrative and management system;
- Drafting and implementation of appropriate environmental protection laws;
- Increasing scientific research to provide a basis for management;
- Enhancing community awareness of ecology and environmental protection.

The YRD currently faces a range of serious ecological and socio-economic problems, most of which are related to water supply, be it in shortage, excess (flooding) or of poor quality. These issues highlight the need to consider both economic development and environmental protection when planning the future sustainable development of the YRD. In addition, it is now imperative that the issue of climate change and sea level rise are incorporated in any such plans. This study highlights the vulnerability of the YRD to predicted climate change and sea level rise, particularly in terms of exacerbating the region's current water supply and quality problems. The proposed management strategies provide the first step in effectively addressing the issue of climate change and sea level rise.

1 Introduction

The major wetlands of the Asia-Pacific region provide many economical and ecological values and benefits to humans. Foremost amongst these are the supply of water, the production of food and the amelioration of floods. In addition, the wetlands are major conservation zones for plants, fish and migrating birds. In recent decades the pressure on these habitats has increased as human populations have expanded and sought more land for urban and agricultural usage. These pressures have brought production activities into conflict with conservation, and in places have even resulted in the loss of the habitats concerned (IPCC 1991,Watson et al 1996).

Coastal and delta wetlands are expected to be highly susceptible to changes in climate and sea level (Watson et al 1996). Climatic changes, sea level rise and storm surges could result in the erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, changes in sediment and nutrient transport, a change in the pattern of chemical and microbiological contamination in coastal areas, and increased coastal flooding. Some coastal ecosystems are particularly at risk, including saltwater marshes, mangroves, coastal lagoons and river deltas (Watson et al 1996). Consequently, many of the essential features of the coastal wetlands that provide values and benefits to society could be lost. The Yellow River Delta (YRD) in China is an example of a vulnerable coastal wetland.

1.1 Project background

This report documents a component of an Asia-Pacific Network for Global Change Research (APN) project coordinated by the Environmental Research Institute of the Supervising Scientist (***eriss***), an Australian government research institute based in Jabiru, northern Australia, and Wetlands International (Oceania and China Offices). The project aimed to assess the vulnerability of two major wetlands in the Asia-Pacific region to climate change and sea level rise. The YRD was chosen as one of the wetland sites to be studied, for reasons outlined below, with the major aspects of the assessment and report writing being jointly undertaken by the Oceanic Management Department (in Beijing) and First Institute of Oceanography (in Qingdao), State Oceanic Administration of China and the Wetlands International–China Office (in Beijing).

The project supports the East Asian-Australasian Flyway initiative by developing standard habitat assessment and data handling procedures that provide the basis for further assessments and training of local personnel to undertake these tasks. It emphasises global change issues, especially those associated with climate change and sea level rise, and provides information that can contribute to global and national research programs and scientific policies.

1.2 The study area

The Yellow River flows across the arid inland regions of China into the Bohai Sea through the Yellow River Delta (YRD). As the Yellow River has changed its course frequently, there are several definitions of the YRD boundary, and the delta continues to expand due to extremely high loads of silt carried by the river. The ancient YRD comprised a large plain formed over the period 1128–1855, during which the river changed its course four times. Since 1855, with ten further changes of its course, the river shifted northward, leading to the formation of the present YRD (Cheng 1987, Cheng & Xue 1997). Dongying, today the principal municipality of the YRD, did not exist until 50 years ago. Geographically speaking, the YRD covers an area larger than the Dongying Municipality. The study area for the project includes the coastal wetlands in the delta plain, the tidal flats and the subaqueous delta system.

The key economic resource of the YRD is an oil field, administered by the Shengli Oil Administrative Bureau. Because of the frequent changes of the river's course, the YRD remained an underdeveloped rural area before the discovery of the Shengli Oil Field in the

1960s. Even today, the government is hesitant to locate projects, except for oil production, in this region. River ‘harnessing’ is the precondition for further development of the YRD. The government has approved an engineering project for strengthening the embankment along the Qingshuigou channel, and the first stage of that project is underway. At present, the wetland of the YRD is still in a natural state. Thus, it is important that further development and conservation of the wetland region be strictly managed and monitored.

1.3 Approach of the assessment

This report assesses the vulnerability of the natural and social systems of the YRD to climate change and sea level rise. Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change and sea level rise (Watson et al 1996). Vulnerability is a function of the sensitivity of a system to changes in climate and the ability of the system to adapt to changes in climate. Under this framework, a highly vulnerable system would be one that is highly sensitive to modest changes in climate, where the sensitivity includes the potential for substantial harmful effects, and one for which the ability to adapt is severely constrained.

Because available vulnerability studies have not employed a common set of climate scenarios and methods, and because of uncertainties regarding the sensitivities and adaptability of natural and social systems, the assessment of regional vulnerabilities is necessarily qualitative. However, this report provides substantial information on what is currently known about the vulnerability of the YRD to climate change.

The IPCC developed a Common Methodology (IPCC 1991) for vulnerability assessment which was tested in China (Wang & Zhao 1995) and by a wide range of other nations, including Australia (IPCC 1994). The approach being developed in China seeks to accommodate regional and local differences in coastal regimes by way of physical, biological and geographic conditions, as well as social and cultural variations, within and across the governmental jurisdictions. The present approach seeks to build upon policy frameworks and the strength of coastal management processes and procedures in terms of the institutional and administrative arrangements of Dongying Municipality and Shandong Province.

The approach developed will be used to address the vulnerability of coastal areas to both natural and human (anthropogenic) induced changes. Consideration of both natural and anthropogenic changes is essential if the impacts of long term, climate induced change are to be identified, planned for, and managed. By addressing both natural and anthropogenic changes, the vulnerability assessment has immediate utility, as it will assist in putting the natural variability of coastal systems (climatic, oceanographic, geomorphic, hydrologic, ecological) and the resilience of the system into planning and management frameworks. Thus, this will allow responses to be developed and implemented in ways that are endorsed politically and understood by the broader community. This will be achieved by utilising available information, initiating studies to fill the information deficiencies, and using appropriate tools for spatial information management and decision support systems. Additionally, it will build on and develop innovative approaches for governmental and community involvement in the coastal zone of China and nature reserve management of the YRD.

In a number of instances, quantitative estimates of impacts of climate change are cited in the report. Such estimates are dependent upon the specific assumptions employed regarding future changes in climate, as well as upon the particular methods applied in the analyses. To interpret these estimates, it is important to bear in mind that uncertainties regarding the character, magnitude and rates of future climate change remain.

A technical workshop was also undertaken as an integral part of the assessment. The workshop was conducted in Beijing, in January 1999, with participants representing a range of organisations, including relevant national and local government agencies, the Yellow River Delta Nature Reserve, and the collaborating organisations. The primary objectives of the workshop were to increase awareness of local and national decision-makers of the potential impact of climate change and sea level rise, disseminate information on the vulnerability assessment process and the overall findings of the YRD study, and to obtain constructive feedback and advice on the study and its findings (Vulnerability assessment of major wetlands in the Asia-Pacific region 1999).

1.4 Aims and objectives

The aim of the project was to develop an approach to link the research, planning and environmental management requirements for the coastal areas of the YRD that could be affected by climatic change and sea level rise. The approach is intended to facilitate ongoing assessment of the vulnerability of the YRD to the effects of short-term changes in climate and other environmental factors that occur within planning horizons of approximately 100 years.

The project objectives were:

- To establish common standards to enable governments (national, province, local, community council) to respond to the impacts of natural and anthropogenic changes in the YRD and the coastal zone of China;
- To develop a scenario for climate change, including assessments of sea level rise, variation in tides, wind storm surges and flooding, based on published research;
- To assess the current vulnerability of the natural and social resources of the YRD to existing coastal hazards;
- To assess the future vulnerability of the natural and social resources of the YRD to climate change and sea level rise;
- To recommend future management responses to the predicted environmental changes.

2 Description of the YRD

2.1 Introduction to the Yellow River and the YRD

2.1.1 The Yellow River

The Yellow River is considered to have the highest sediment content in the world (Milliman & Meade 1983). In recent years the Yellow River has carried about 1 billion tons of sediment annually to its delta and to the coast.

The Yellow River rises in Qinghai Province and flows across the arid inland regions of China (Qinghai and Gansu Provinces, Ningxia Hui Autonomous Region and Shaanxi, Shanxi, Henan and Shandong Provinces) through the YRD and into the Bohai Sea. The total length is about 5460 km (figure 1; Cheng & Xue 1997). The lower reaches of the river have often shifted over the last 6000 years. In the North China plain, flood waters from the river have caused heavy losses for people (Xue 1993).

Presently, the Chinese government is managing to harness the Yellow River and to use its water and sediments. Generally, three hazardous areas occur in the Yellow River basin (Cheng & Xue 1997). The first is the Loess Plateau, where large volumes of sediment are eroded and carried into the river.

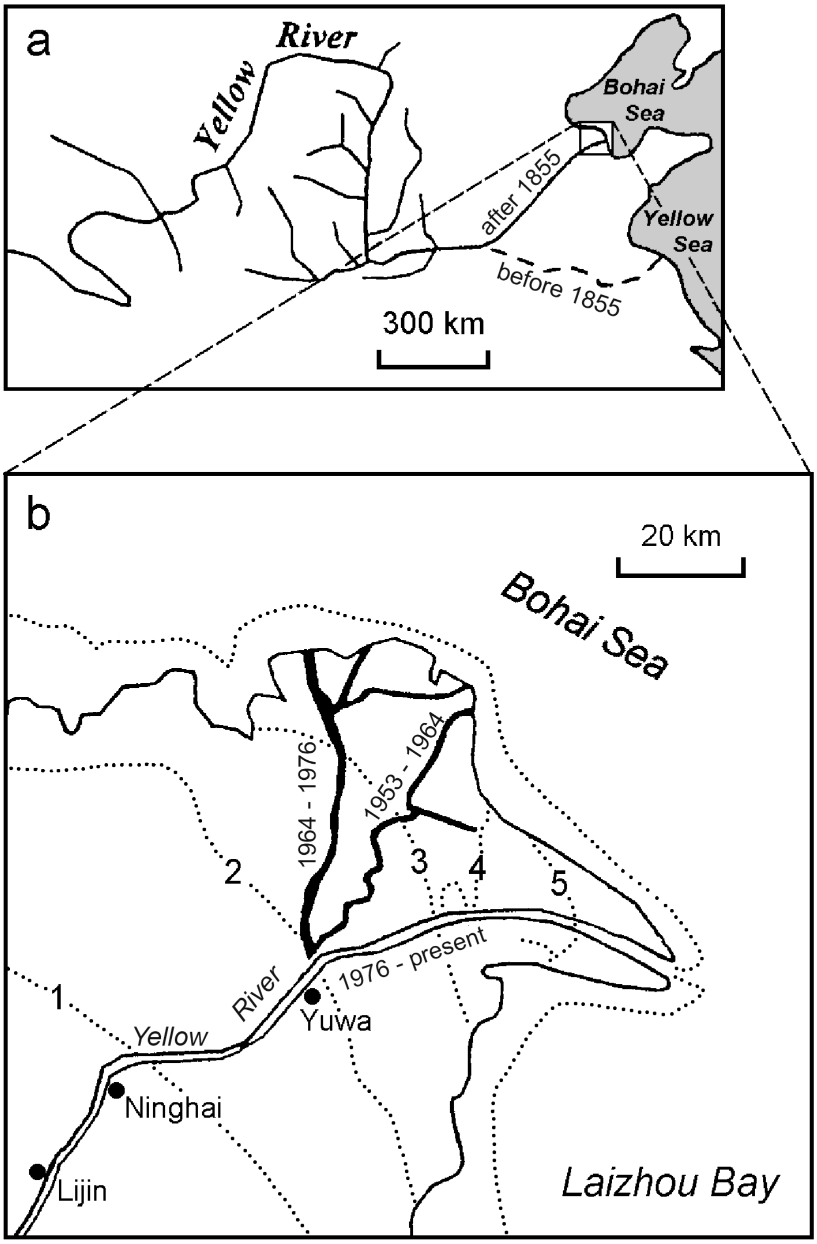

Figure 1 Map of the Yellow River: (a) the Yellow River basin; (b) the modern Yellow River delta and the historical changes of the coastal line; 1. Coastline of 6000 years BP; 2. Coastline of 1855; 3. Coastline of 1934; 4. Coastline of 1976; 5. Coastline of 1980.

The second is represented by the unstable lower reaches of the river where the channel bed is higher than the flood plain because of sediment deposition. The third is the delta plain where shifting of the distributary courses and the reduced water resources results in a range of environmental problems.

2.1.2 The Yellow River Delta (YRD)

The Yellow River Delta (YRD) is located in the north-east of Shandong Province (118°03′E to 119°20′ E and 37°20′N to 38°20′N), facing the Bohai Sea in the north and bordering Laizhou Bay in the east. Much of the YRD area is under the jurisidiction of the Dongying Municipality, Shangdong Province. Although the YRD covers an area larger than Dongying Municipality in terms of geography, the study area for the project is the modern YRD, within

Dongying Municipality, comprising an area of about 6000 km^2 and a population of 1.64 million (at the end of 1995). In the present report, the term YRD and Dongying Municipality are used interchangeably.

2.1.3 YRD evolution since 1976

The embankments of the Yellow River were broken at Tongwaxiang, Henan Province, in 1855. At that time, the Yellow River abandoned its former river course to the Yellow Sea through the north Jiangsu Plain. The flood water from the Yellow River entered the channel of the Daqing River to the Bohai Bay through north-east Lijin County, Shandong Province, where it created a new delta. During the period 1855–1995, the silt carried by the river flow created 5400 km^2 of new land (Chen et al 1997). The rate of sedimentation has caused the lower discharge channel to shift every 8–10 y (Cheng 1987, Cheng & Xue 1997, Yang & Wang 1993). The most recent major shift occurred in 1976 (figure 2). The evolution of the Qingshuigou channel (ie the current Yellow River channel), the new river course that resulted from this shift, is illustrated by a series of Landsat images (Remote Sensing TM Images: 1 Dec 1976, 21 Nov 1981, 3 Dec 1988, 26 Jan 1991, 2 April 1992, 15 Sept 1994, 4 Oct 1995, 20 Sept 1996 – 1/200 000 or 1/500 000; Liu et al 1987, Fan & Guo 1992).

Since 1976, the northern Diaokou River channel no longer received any sediment and the sub-delta of this river channel became unstable. This resulted in net erosion, and in a regression of the coastline (figure 3). Between 1976 and 1989, the coastline at the mouth of the Diaokou River channel moved about 4 km landwards due to erosion with an average scouring thickness of over 10 cm y^{-1} (Li et al 1992).

Just before the flood season in 1996, a new channel was artificially constructed in the downstream section of the Qingshuigou channel. This new channel diverts the river runoff from the former east-protruding river mouth to a new river mouth extending north-eastwards. This work was carried out mainly for economical reasons. The new river channel will create a new sub-delta in the position of the offshore oil field of the Shengli Oil Field, which is situated presently in shallow sea. This new sub-delta will play a very important role in the development of the offshore oil field, because it will make it possible to avoid expensive offshore infrastructure for its exploitation.

2.2 Physical attributes

2.2.1 Geology

The YRD lies in a fault-depression basin of Cenozoic Era on the North China Platform of Sino-Korea ancient land. It lies to the west of the Tancheng-Lujian fault zone, to the east of the Jiyang depression, and to the south of the Bohai Depression (Gao & Li 1989).

The YRD was formed on a metamorphic basement with a complete, deposit stratigraphic sequence and a total depth of over 10 km.

The surface of the YRD is formed from sediments deposited during the Holocene Epoch. There are two primary types: the Yellow River alluvium and marine deposits. Yellow River alluvium is the main alluvium in the YRD, and can be divided into four sub-types: river bed-back swamp alluvium, inter-river depression-flood alluvium, natural levee alluvium, and alluvial fan sediment. Most of the marine hydrodynamic factors are acting on the sand and mud from the river. Based on its characteristics and position, the marine alluvium may be divided into two types: the tidal flat sediment and the nearshore sediment.

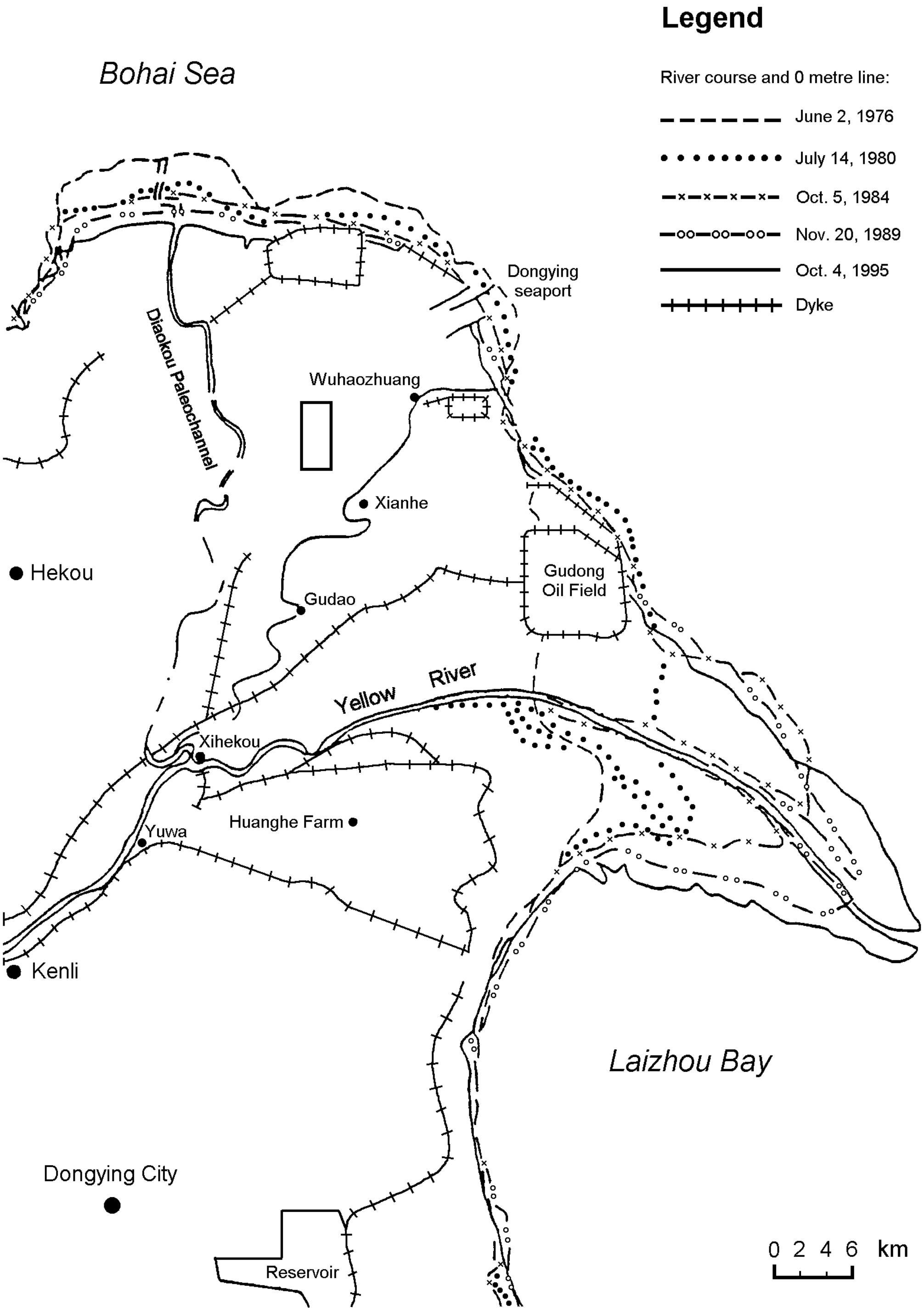

Figure 2 Map of the dynamic evolution of the Yellow River mouth (the river courses and 0-m lines from 1976 to 1989 are drawn according to the *Atlas of Remote Sensing Dynamical Analyses on the tidal flats along the Yellow River Delta*)

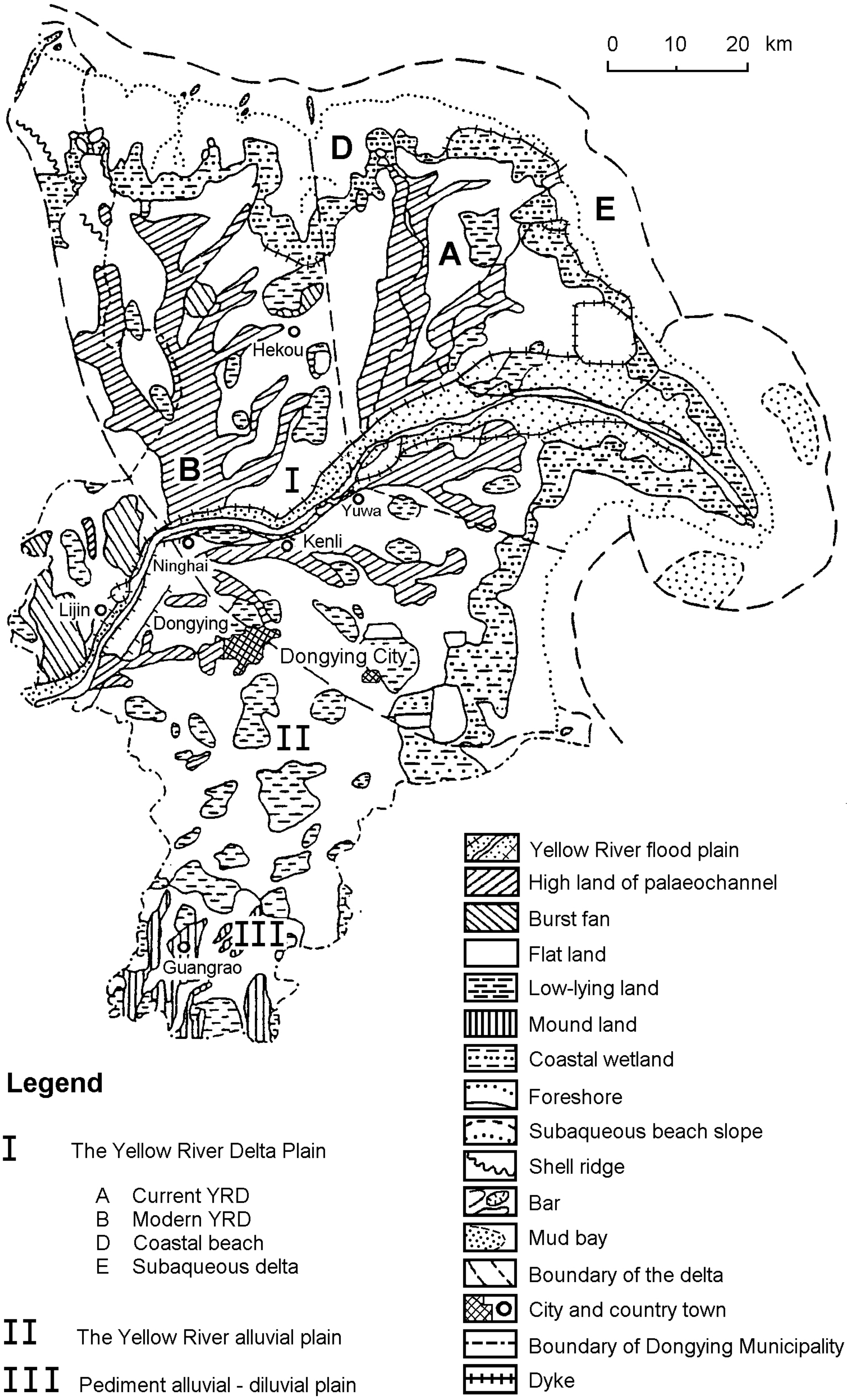

Figure 3 Terrestrial geomorphic map of the YRD region

2.2.2 Climate

Monsoon climate

The YRD has a monsoon climate of the warm-temperature zone with four distinct seasons. It is dry and windy in the spring, hot and rainy in the summer, cool and clear in the autumn, and cold, dry with some snow in the winter. In addition, there are distinct inland climate characteristics.

The average annual temperature across the region is 12.2–12.6°C. The highest average temperature is 25.9–26.2°C in July and the lowest -3.3–3.9°C in January. The highest temperature recorded is over 36.2°C and the lowest is -10.3°C. The frost-free period lasts 210 days per year. Average annual precipitation is about 600 mm, with 68%, 18%, 3% and 11% of this falling in summer, autumn, winter and spring, respectively. Average annual evaporation is 1900–2400 mm. The average annual relative humidity is 68%, the mean aridity is 1.6, and the continental index is 62.3, which indicate a semi-humid climate. The average wind velocity is 3.7 m s^{-1}. Prevailing wind directions are northwest by northward in winter and spring, and southeast by southward in summer and autumn (Science and Technical Committee of Shandong Province 1991, Yang & Wang 1993, Zhao & Song 1995).

The distinct economic advantage of the climate in the YRD is that precipitation is mostly concentrated in the growing season. The major disadvantage of the climate is its instability with variable precipitation, strong winds in winter and spring and abrupt change of annual temperature.

Major meteorological disasters

The major extreme meteorological events that occur in the YRD are as follows.

Drought and flood

Drought and flood are the main meteorological disasters for agriculture. There have been five severe droughts and three destructive floods since 1959.

Strong windstorm

The annual mean duration of strong wind (wind scale 8–17 m s^{-1}) is 15.4 days. The maximum is 30 days. The maximum wind velocity is 30.7 m s^{-1}. Strong wind is very destructive to agriculture, fishery, transportation and communications. The prevailing wind is from the north-east.

Hail

Hail occurs approximately once a year. The maximum is 5 times in one year. It mainly occurs from April to September and lasts 5–10 minutes in each occurrence. Hail diameter is 15–25 mm.

Rainstorm

Rainstorm is an extreme rain event with precipitation exceeding 50 mm. It is a main cause of flood disaster in the YRD.

Storm surge

Storm surge in the YRD mainly results from strong north-east winds, resulting in the collision between the surge tide of Bohai Bay and the high tide of Laizhou Bay. Spring and autumn are the windy seasons. High surge occurs if strong southeast winds are succeeded by strong northwest winds. Storm surges often occur during the flood season of the Yellow River. As a result of the flat topography at the mouth area, a 3 m storm surge can intrude inland up to 10 km. Storm surges often bring disasters to the delta (Yang & Wang 1993).

2.2.3 Hydrology

River hydrology and groundwater

The Yellow River exhibits four periods in its flow regime. The first, from the end of March to June, has a low discharge and constant water flow. However, due to increasing water consumption along the Yellow River, especially from the rapid development of water diversion works for irrigation, the flow is now frequently disrupted. This has occurred in 18 of the years between 1972–1992, and in the 1990s it has happened earlier and lasted longer. This is the key period for irrigation, so the disruption often has serious consequences. The second period, from July to October, is the main flood season, during which there is much more precipitation in the middle and lower reaches of the river, and a large discharge with a high flood peak. The third period is from October to the middle of December, during which the lower reaches of the river are controlled by atmospheric high pressure systems. Thus, the weather is clear, and the river discharge is steady. The fourth period is from the end of December to March, known as the ice-bound season. Although discharge at this time is not great, the water level rises rapidly due to poor drainage caused by ice blocking the river channel and forming an ice dam. Consequently, 'ice floods' happen regularly in the lower reaches, causing danger to life and properties.

Based on observations from 1950–95 at Lijin hydrological station near the mouth of the Yellow River, the mean annual discharge of the river is 41.9×10^9 m^3. The annual water discharge fluctuates greatly, with a maximum of 79.31×10^9 m^3 and a minimum of 9.15×10^9 m^3, representing almost a factor of nine difference. The average rate of discharge in this region is 1330 m^3 s^{-1}. The maximum at flood peak is 10 400 m^3 s^{-1} and the minimum is zero (Science and Technical Committee of Shandong Province 1991, Yang & Wang 1993). The Yellow River is the second largest river in China, and has the highest sediment-content of all rivers in the world. The average annual sediment load is 1.049×10^9 t with a maximum of 2.1×10^9 t (1958) and a minimum of 0.242×10^9 t (1960). The average sediment concentration is 25.53 kg m^3, with a maximum sediment concentration of 222 kg m^3. In recent years, with the increase in water diversion structures the river discharge and sediment load have decreased abruptly. The average discharge and sediment load from 1986–92 were 17.6×10^9 m^3 and 0.411×10^9 tons, accounting for 42% and 39% of the long-term average, respectively.

The Yellow River has a pH of 8.0–8.3, general hardness of 2.16–5.56 mg L^{-1} and a salinity of 0.2–0.6g L^{-1}. It is the major source of water consumption for people, animal and production (Wang et al 1997b).

Located near the sea beach areas, the groundwater of YRD is categorised as loose rock pore water, and includes both saline water and slightly saline water. Because of its high salinity, it is not particularly suitable for primary production. The saline water is comprised predominantly of NaCl and $NaSO_4$, while the slightly saline water is predominantly NaCl based.

Marine hydrology

The tide of the subaqueous YRD is controlled by an amphidromic point of M_2 tide (38 09ºN, 119 04ºE). The mean high water interval is 10–11 hours in the Yellow River mouth. The average spring tidal range is 1.3–1.78 m near the river mouth where the tide type is irregular semi-diurnal. The neap tidal range is 0.46–0.78 m (Zang et al 1996, Yang & Wang 1993).

A stationary tidal wave system dominates the tidal current field with the greatest current at the mid-tidal level in the subaqueous delta. Many observations have indicated that the ellipticity of the tidal current is less than 0.1, the principle axis has parabathic and diabathic components, and the tidal current flows generally along the isobaths on the delta front. The flood current moves to the south and the ebb current to the mouth. The tidal current curves were measured inside the river mouth with no river discharge; ebb current in excess of 1.75 m s^{-1} causes erosion.

Since 1976, the subaqueous delta of the Yellow River has rapidly expanded into Laizhou Bay, with the 2-m isobath prograding seawards at a mean rate of 1.29 km y^{-1}. During this expansion, a protruding mouth spit formed. The tidal current at the front of the delta has been strengthened by the effect of topography from the advancing delta front (Li et al 1992). The maximum spring tidal current velocity increased from 0.9 m s^{-1} in 1976 to 1.58 m s^{-1} in 1991. A strong tidal current can widen the distance of river-driven suspended silt dispersal and erode the subaqueous delta of the Yellow River in the dry season.

2.2.4 Topography and geomorphology

Topography

The topography of the YRD is low and smooth. The elevation of the southwestern part of the YRD reaches 11 m above sea level and the north-eastern part less than 1 m. The slope is about 1/7000. Table 1 shows the relationship between surface area and elevation (Liu & Drost 1997).

Table 1 Relationship between surface area and elevation in the YRD (from Liu & Drost 1997)

Elevation (m)	Surface (ha.)	% of total area	Elevation (m)	Surface (ha.)	% of total area
0~1.0	73 355	9.5	6.0–7.0	73 000	9.5
1.0–2.0	126 801	16.4	7.0–8.0	64 682	8.4
2.0–3.0	101 140	13.1	8.0–10.0	57 355	7.4
3.0–4.0	90 383	11.7	10.0–12.0	15 266	1.9
0–4.0	391 679	50.8	12.0–17.0	16 733	2.1
4.0–5.0	77 494	10.0			
5.0–6.0	75 390	9.8	**Total area**	**771 599**	**100**

The elevation of the YRD reflects a sedimentation history of shifting river channels. Each of the river channels has created its own individual alluvial fan, forcing the water into a new channel through nearby low-lying back swamps. This process results in a pattern of partly overlying, partly adjacent fans. Each fan is highest in its central and upstream parts, and is marked along its central axis by the remnants of the river channel; usually a narrow, meandering creek. Back swamps between existing fans were filled with sediments from newer fans. Some back swamps, however, have not been completely covered by new fans.

While the sedimentation process proceeded in a seaward direction, such back-swamps became isolated depressions, surrounded by higher territory. The summer rains tend to cause inundation in such depressions, as these depressions have no natural outlet for water. Examples of such isolated depressions are present between the 1926–29 and 1934–76 fans, and between the 1953–64 and 1964–76 fans.

Geomorphology

The modern YRD refers to the fan formed since the Yellow River breached at Tongwaxiang of Henan Province in 1855, and flowed into the Bohai Sea through the Daqing River mouth in the south, covering an area about 9000 km^2. It can be divided into a terrestrial delta (about 6000 km^2) and a subaqueous delta (about 3000 km^2), with intervening tidal flats (Gao & Li 1989, Zang et al 1996, Li et al 1992, Xu et al 1997, Yang & Wang 1993).

Terrestrial delta

The terrestrial delta is shown in figure 3. The annual average amount of sediment discharge of the Yellow River is about 1.05×10^9 t, of which 64% is deposited in the river bank and river bed of the Yellow River mouth. This deposition made the divided channel of the YRD become a frequently fluctuating 'hanging river', forming the fan terrain of gentle tilted land and inter-river depressions on the framework of river-built 'highland'. Under the action of the river and marine vessel power, various morphological patterns were established. The terrestrial part of the YRD can be divided into four types: river-built highland, gentle tilted land, depressions and river mouth sand spit. These are briefly described below.

River-built highland: Owing to accretion of the river channel, the riverbed and the accumulative bodies of both sides of the river are higher than the ground around them. Since June 1855, there have been 11 river diversions, forming many bifurcated river channels (old courses) radiating from the apex of the delta. The densely distributed river channels overlapped and formed finger-shaped mounds, termed river-built highland, which is 2–3 m higher than the ground around them.

Gently tilted land: This is a transitional morphological form, inclining from the river-built highland to inter-river depressions, with a slope of 1/3000 to 1/7000.

Depressions: These are relatively low lands on the delta plain, including inter-river depressions, humid land and so on.

River mouth sand spit: This is the bifurcated river channel and the natural levee banks either side of the channel extending toward the sea. It includes a small river mouth sand spit group, fan-shaped sand spit group, round stack sand spit group and ox-horned sand spit.

Subaqueous delta

The subaqueous delta is shown in figure 4. The subaqueous delta, consisting of many layered subaqueous subdeltas, is the expanding part of the terrestrial delta, surrounding the terrestrial delta with a half wide *clitellum,* covering an area of about 3000 km^2. The subaqueous delta lobe to the west of the Tiaohe River mouth is in a stage of dynamic equilibrium, with weak erosion and weak siltation. The subaqueous delta lobe from the Tiaohe River mouth to Shenxiangou River mouth is mainly being eroded. Not only is the front of the terrestrial delta falling into the sea, but the subaqueous delta is eroded flat under the actions of waves and tidal currents, and the coastline retreats and becomes straight. From Shenxiangou River to the Xiaoqing River mouth in the south, the present river mouth of the YRD is in the stage of strong progression, where subtidal muddy flats have developed at both sides of the river mouth.

According to the morphogenesis and its characteristics, the subaqueous delta may be divided into two large geomorphic units: subaqueous delta plain in the current river mouth area, being in a strong progression stage, and subaqueous delta bank-slope along the abandoned river bank, being in an eroding stage. It is composed of many geomorphic forms again such as tidal ditch-shaped bar, tidal ditch-shaped pool, estuary sand bar, estuary pool, mud and underwater drift and so on.

Tidal flats

The tidal flats are displayed in figure 4. Similarly to the subaqueous delta, the development of tidal flat is controlled by the dynamic processes of tidal current at the river mouth. Along the coast of the present Yellow River Mouth (YRM), deposition is the dominant process. Along the coast of the abandoned channels, dynamic geomorphologic conditions have reversed since the Yellow River mouth migrated to the south in 1976. Wave-scouring and erosion have become the main dynamic process, which has rebuilt the tidal flats into a series of particular dynamic geomorphic types and an ecological system that have been changing with time (Li et al 1992).

The tidal flats may be divided into two types: the super-tidal flat and the intertidal flat. The former is the area between the average spring high tide level and the average high tide level, with a width of 1–3 km. The latter is that between average high tide level and the lowest tidal level, and can be divided into three zones: high tidal flat, middle tidal flat and low tidal flat.

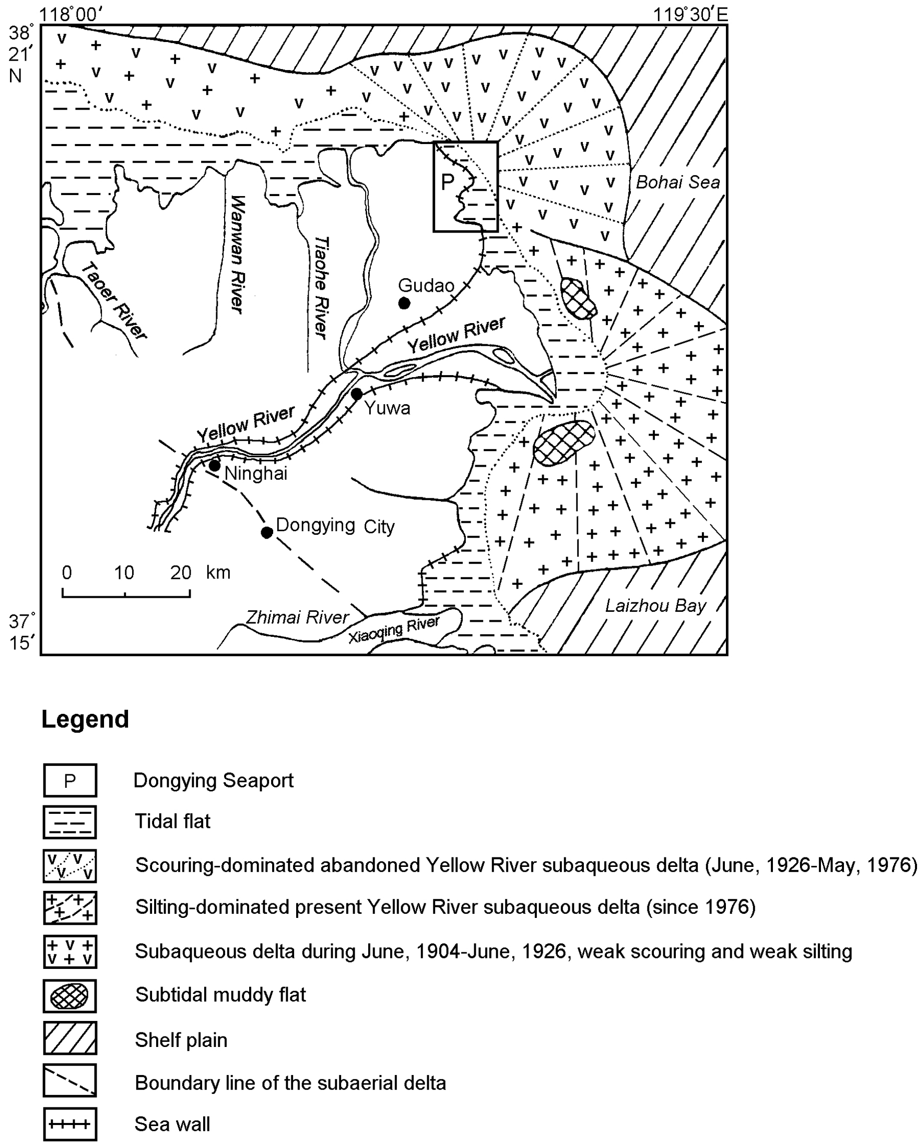

Figure 4 Geomorphic map of the subaqueous delta of the Yellow River

1. Dongying Seaport; 2. Tidal flat; 3. Scouring-dominated abandoned Yellow River subaqueous delta (June 1926 – May 1976); 4. Silting-dominated present Yellow River subaqueous delta (since 1976); 5. Subaqueous delta during June 1904 – June 1926, weak scouring and weak silting; 6. Subtidal muddy flat; 7. Shelf plain; 8. Boundary line of the subaerial delta and 9. Sea wall.

2.2.5 Sedimentation

Sedimentation in the upper distributaries and the estuary of the Yellow River

Many scientists have been studying and measuring the Yellow River for almost a century. Recently, Li et al (1998a) conducted a systematic study of the sedimentation of the Yellow River and its mouth.

As stated in section 2.2.4 (Geomorphology – terrestrial delta), the average annual sediment discharge of the Yellow river exceeds 1×10^9 t, of which 64% is deposited in the Yellow River mouth. The suspended sediments of the Yellow River are derived from the Loess Plateau where the sediment is loose and easily eroded by storms. High sediment concentrations of several hundred kg m^{-3}, at times exceeding 1000 kg m^{-3}, are often measured in the lower reaches of the Yellow River during floods. Although the concentration of suspended sediments falls significantly following large river flows in the delta areas, the sediment concentration remains more than 100 kg m^{-3} in the lower layer of the river. The grain size of suspended sediment is finer in the delta than in the Loess Plateau due to sorting along the lower reach of the river. The sediment transportation and fluid characteristics of the YRD have been observed and studied for the last 20 years (Li et al 1998a, Qian et al 1981, Van Den Berg & Van Gelder 1993, Wei & Li 1995). Major results are as follows.

1. The physical nature of water with a high sediment concentration was influenced by suspended sediments more than by temperature. The sedimentation on the distributary of the YRD is influenced by the tide, especially the sediment concentration during the flood period.
2. River and suspended sediment discharge into the modern YRD is affected by two factors, natural and anthropogenic. The 4–6 year periodicity reflects the natural changes in the upper part of the Yellow River basin because no rivers have entered the lower reach of the Yellow River since the bed became higher than the surrounding plain. As a result of the pumping of water from the river, the discharge has decreased and the sediment concentration increased since the 1970s. The mean river and suspended sediment discharge into the delta between 1970 and 1993 were 2.81×10^{10} m^3 and 7.1×10^8 t y^{-1}, respectively, which are different to earlier data from Milliman and Meade (1983). Up to now, the capacity of reservoirs that have been built along the Yellow River has exceeded the mean annual river discharge, forcing the government of China to pay attention to the shortage of water resources on the YRD.
3. According to the discharge distribution, each year can be divided into two periods: a flood season from July to October, with mean discharge of 1669 m^3 s^{-1} since the 1970s, and a dry season. During the dry season, the tidal water penetration is more than 20 km and the tidal current extends several kilometres in the lower distributary channel. During the flood season, the tidal wave penetration is commonly less than 15 km and no tidal current or tide elevation intrudes into the river. There is a so-called tidal sensitive zone inside the river mouth. The length of the zone is related to the discharge, amounting to 6–7 km with a river discharge rate of 1100 m^3 s^{-1}. This zone is very active in terms of sedimentation, and functions as a high velocity zone where the river bed is being eroded and the suspended sediment is dispersed into the delta front during the ebb periods, and as a low velocity zone where the suspended sediment carried by the Yellow River is trapped and deposited rapidly as the 'plastic' bed during the flood periods. The rapid deposition of the low velocity zone can be enhanced by the effect of salt permeation during the flood period. One dimensional current simulation and river-induced current computation show that the tidal sensitive zone is a major area where the kinetic energy of the river has been largely dissipated, and the so-called high velocity zone of the ebb is relative to the low velocity of the flood.

Sedimentation on the present subaqueous delta of the Yellow River

A large amount of observational data indicate that hyperpycnal underflows can be formed and move along the front of the delta when sediment concentration in the river effluent exceeds 18 kg/m^3 (Wright et al 1986, Wright et al 1988, Wright et al 1990). Because the mean sediment concentration is 25.3 kg m^{-3} in the distributary of the Yellow River, the frequency of hyperpycnal plumes is very high at the delta front (Li et al 1998b). The large amount of sediment transported by hyperpycnal plumes has been deposited on the delta front slope, especially at its base. A shear front, which obstructs the river inflows and small-scale circulations, has resulted in rapid deposition in the river mouth area (Li et al 1994). Since the mouth bar is accumulating rapidly and expanding seawards, the delta slope becomes steep and unstable. Submarine landslides have occurred due to instability (Yang et al 1990). Although the YRD and the Mississippi delta are both derived from large river systems, the YRD is typical of hyperpycnal underflows and thus different from the Mississippi delta in processes of formation and in environments of deposition (Coleman & Wright 1975, Li & Xue 1993). Conclusions about sedimentation on the present subaqueous delta of the Yellow River are as follows.

1. The Yellow River has transported a very large amount of sediment that accumulated on the modern delta resulting in rapid shoreline movement. The modern delta is composed of 12 individual delta lobes within 2 sub-deltas; one that was formed from 1855 to 1934, and another from 1934 to present. The distributary has often migrated on the delta and one lobe is formed from each migration. The last lobe has formed since 1976, growing at a mean speed of 1.29 km y^{-1}. The delta lobe is composed of many coalescing river mouth bars. When each new body of sediment is formed, three sedimentary environments are distributed in the subaqueous delta. The lower delta plain is composed of tidal flats influenced by high river discharge and distributaries influenced by tide. The delta front is composed of river mouth bar, delta slope and down-drift mud. The prodelta occurs off the 10-m isobath.

2. Two forms of river mouth bars occur in the Yellow River estuary. One is composed of a double-intertidal-lobe and a single-channel, which develops during high river discharge. The other form is composed of a double-channel and single-lobe, which develops during the dry season. The deposition rate on the river mouth bar is the highest among all environments in the delta. The quantitative distribution of the Yellow River sediments shows that about 30–40% of the sediment transported into the sea is deposited on the bar at the mouth. The sedimentary thickness can be in excess of 2 m in one mouth. The long axis of the bar, which is parallel to the general tidal current direction, indicates that the tidal current field dominates suspended sediment dispersal and deposition.

3. As mentioned above, the sedimentation rate of the mouth bar is the highest in the modern YRD because most of the kinetic energy of the river is dissipated there. The dissipation appears specifically in three ways. The first is the mechanism of a shear front that pushes the river plume landward (Li et al 1994) and forces convergence of the suspended sediments. The second is the small-scale circulation formed within the shear front, which returns water to the landward side of the river inflow. The last is the so-called ‘bulldozer’ effect in the tidal sensitive region inside the river mouth (see section 2.2.5 Sedimentation in the upper distributaries and the estuary of the Yellow River).

The low-concentration hyperpycnal plumes, which have a small density difference from the ambient water, have dissipated and accumulated approximately 20% of total sediment on the front of the delta.

There are two processes that disperse suspended sediment from the front of the delta. One is the hyperpycnal plume, which transports fine sediment into the down-drift mud adjacent to the river mouth, prodelta, and the centre of the Bohai Sea and north of the Yellow Sea under the action of residual currents. The second is the high hyperpycnal underflows, which drive the turbid body into the upper part of the prodelta to form the subaqueous delta rise. The subaqueous rise zone should be recognised as an independent geomorphologic unit, which occurs between the slope and prodelta (approximately 10–12 m depth).

2.2.6 Natural resources

Rich resources of oil, natural gas, water, brine and geothermic energy are located in the YRD, among which the reserves of oil, natural gas and brine rank first in the coastal area of China (Chen et al 1997, Environmental Monitoring Station of Dongying Municipality 1994).

Oil and natural gas resources

The oil and gas fields proven and extracted in the Shengli Oil Field – the second largest oil field in China – are mostly located in the area of the YRD. The proven reserves of geological oil and natural gas are 3.2×10^9 tons and 25.7×10^9 cubic metres, respectively. Presently, 64 oil and gas fields have been detected. Of these, 49 have been explored, including nine large oil fields with 61% of the proven geological reserve, ten intermediate oil fields with 18% of the geological reserve and 30 small oil fields representing the remaining 12%. The prospected oil reserve of Jiyang depression, in which the YRD is located, is 8×10^9 t.

Water resources

The Yellow River dominates the system for fresh water management in YRD. During 1950–87, the Yellow River at Lijin County had an average annual discharge of 40.4×10^9 m^3 of water and 1×10^9 t of sediment. However, the average annual discharges for the period 1987–1995 were significantly lower: 17.3×10^9 m^3 of water and 0.42×10^9 t of sediment. The Xiaoqing and Zhimaigou Rivers, originating in Jinan, are two regional rivers in the YRD, 34 km of which are within Dongying Municipality's boundary. They have a drainage area of 594 km^2 (within Dongying Municipality) and an average annual discharge of 580×10^6 m^3. Zhimai River, 48 km of which is within Dongying Municipality, originates in Gaoqing County in Zibo municipality. Its river basin covers 1129 km^2 (within Dongying Municipality).

The mean annual discharge through local rivers, due to the local precipitation surplus, is 448×10^6 m^3 (related to 5500 km^2 of land surface). This water discharge is variable. In the past ten years a maximum of 746×10^6 m^3 was recorded in 1990 and a minimum of 258×10^6 m^3 in 1986. The discharge through the Yellow River is more than 60 times greater than the local run-off: an average of 27.5×10^9 m^3 per year (5000 mm) in the period 1973–1993. This discharge has shown a tendency to decrease in recent years, especially in spring. Zero-discharge in spring occurred at Lijin County from 1972–91 for 0–35 days per year, but since 1992 this has occurred 79–130 days per year.

The water resources of the YRD are subjected to a substantial amount of urban and industrial pollution. This is further discussed in section 3.2.4.

Underground brine

Underground brine is mainly found in alluvion and marine alluvium. The alluvion is located primarily in the river and its bank areas, in the form of a band with a depth of 1–7 (12) m. The marine alluvium is distributed mainly in the coastal areas with a depth of 3–10 (31) m. The total brine storage is about 7.4×10^9 m^3. There are many elements in the brine, such as K, Br, Mg, etc, indicating that the exploitation prospect is good.

Salt and halogens

The region is also rich in reserves of salt and halogens. The reserves of salt are located at a depth of 2900–4400 m, with an estimated geological reserve of around 600 × 10^9 tons. The reserve of underground halogens lie within a mineral bed of around 800 km^2, at a depth of approximately 2500–3000 m, and with an *in situ* reserve of about 3.5 × 10^9 m^3. To date, these resources have not been exploited.

2.2.7 Land types and use

Land types

Environmental differentiation in the YRD is great. Many geomorphologic units or land types have been formed by the interaction of the Yellow River and the nearby sea. The land types have been divided into units within three main geomorphologic types (table 2).

Table 2 Land types and their surface area in the YRD

Land type	Area (ha)	% of total
TERRACES		
Terrace uplands	16 295	2.4
FLOOD PLAIN		
Present flood plain	73 032	10.7
Abandoned river courses	128 815	18.8
Embanked former back-swamps	344 624	50.3
Isolated depressions	67 038	9.8
COASTAL ZONE		
Salt marshes and tidal flats	22 492	3.3
OTHERS		
Cities/towns	5 907	0.8
Water	22 492	3.7
Area for reed production	4 677	0.7

Terrace uplands are present in the YRD as small patches in the south, around Guangrao County. The general elevation of these terraces is high, over 10 m above sea level. The present flood plain is located along the present river channel. Abandoned river courses are composed of levees and crevasse-splays. Often, the sediment is sandy, and most of the land is used as farmland. The embanked back swamps are the most typical and widespread land type in the YRD. Most of the land is irrigated and used as farmland or for cattle breeding. At various places isolated depressions occur in the flood plain landscape. Depending on the impact of flooding by river water or by seawater, the land is used as farmland, as reed beds for cellulose production, as a site for fresh water reservoirs, or simply remains unused. The coastal zone is subdivided according to the varying influence of the sea. Thus, one form of salt marsh occurs above the mean high water level, with three types occurring between the high tide and low tide water levels (Land Management Bureau of Dongying Municipality 1993, Xu et al 1997).

Land use

The land resources of the YRD are abundant (~ 790 000 ha), with the surface area of the YRD being nearly 5.33 times the surface area of the Yangtze River Delta. Moreover, the process of accretion from sediment carried by the river continued to increase the amount of land (21 km^2 y^{-1}) for the period 1989–1995 (Chen et al 1997).

The population density in the YRD is approximately 210 persons km^{-2}. This is low in comparison with its surroundings – an average of 557.6 persons km^2 in Shandong Province. This low population density is mainly due to the previous unfavourable physical conditions in the new, low-lying land, with frequently shifting river courses. The revenues from oil and gas exploitation increased the potential for investments to improve these physical conditions, with infrastructure for agricultural and urban-industrial development. Consequently, the YRD is considered as a regional immigration area.

The various land uses of the YRD are shown in figure 5. Forestry and cattle breeding are concentrated in Hekou District and in Kenli County. About 90% of the total forest area and 90% of the total grassland are concentrated here. Irrigated agriculture is concentrated in the region to the south of the Yellow River. Paddy fields are concentrated around the cities of Dongying, Kenli, Hekou and Lijin, and in the neighbourhood of the Shengli Oil Field, in order to provide locally produced food to the local inhabitants. Industries are also concentrated in these regions. Aquaculture and salt pans are limited to the coastal zone. However, most of the coastal zone is unused land due to the high salinity.

Table 3 presents the area occupied by the various land uses. As much as one third of the land in the YRD is unused for agricultural or industrial production. Considering the rural land use, table 3 reveals the ratio between agriculture/forestry and cattle breeding is 4:1. The results of a land suitability assessment showed that this ratio should be 5.2:3. Thus, the present land use is not in balance with the land suitability, showing a relative over-development of agriculture, an under-development of cattle breeding and a serious under-development of forestry. Table 3 does not present the Nature Reserve as a specific land use unit, but as a mosaic of the various land use activities that are practised within its borders.

Agriculture in the YRD is predominantly classed as being 'small-scale peasant economy', or the so-called 'grain-cotton model'. However, it is considered difficult to maintain sustainability with the grain-cotton model. Because of various unfavourable physical conditions (drought, infertility, impeded drainage and salinity), the agricultural productivity is low. At present, the surface areas of the irrigated and non-irrigated farmlands are similar, each occupying about 140 000 hectares. The existing water resources in the Yellow River are not fully utilised, so it is considered possible to make more land suitable for irrigation (Land Management Bureau of Dongying Municipality 1993, Xu et al 1997, Soil and Fertilizer Working Station 1988).

The coastal zone is incompletely used. However, the development of marine or freshwater aquaculture industries is considered to offer possibilities for intensification of the land use in this zone.

2.3 Biological attributes

2.3.1 Plant resources

The flora of the Yellow River Delta Nature Reserve (YRDNR) represents the natural flora in the YRD. The YRDNR is a newly formed wetland ecosystem, which has three features. First, due to the young age of the terrestrial land, various plant resources are still in the initial stage of succession and development. Second, because the terrestrial area of the reserve continues to increase with accretion at the river mouth, the plant communities are continuously extending toward the coast. Third, the formation, development and succession of various plant resources in the YRDNR are largely undisturbed by human impacts.

Flora

Flora composition: In the reserve, there are 393 species of plants, among which there are: 4 divisions and 116 species of phytoplankton; 3 families, 3 genera and 4 species of fern; 2 genera and 2 species of gymnosperm; 54 families, 179 genera and 271 species of angiosperm (11 families, 58 genera and 87 species of monocotyledons and 43 families, 121 genera and 184 species of dicotyledons).

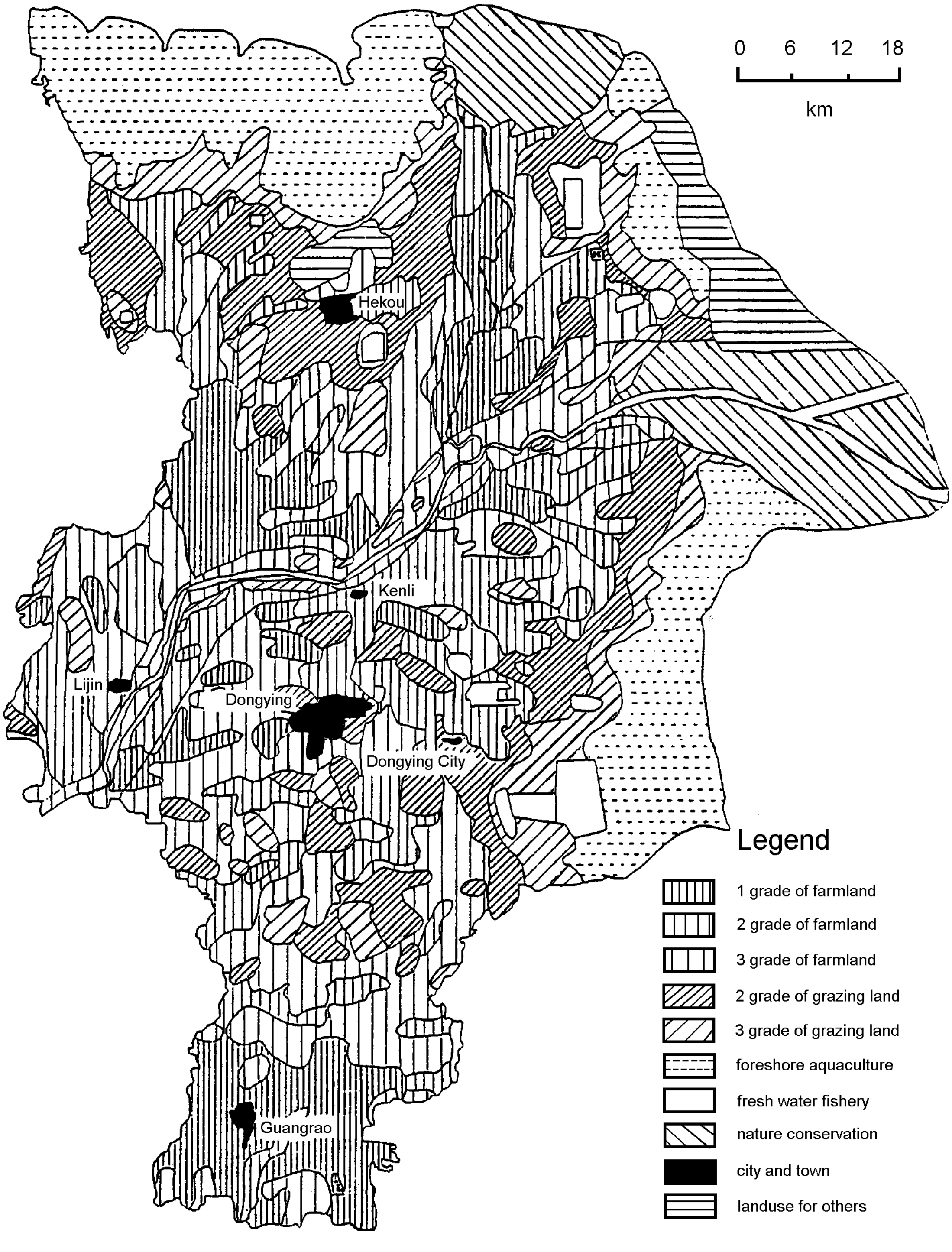

Figure 5 The evolution map of land suitability for agriculture in the YRD

Table 3 Distribution of land use in the YRD

Land use*	Area (ha)	% of total
URBAN INDUSTRIAL		
Residential area	31 886	4.1
Industry	7 653	1.0
Airport	335	0.1
AGRICULTURE		
Non-irrigated farmland	139 752	18.1
Irrigated farmland	148 611	19.3
Paddy field	28 135	3.7
Orchard	2 456	0.3
CATTLE BREEDING	83 417	10.8
FOREST	13 749	1.8
UNUSED	261 379	33.9
OTHERS		
Aquaculture	14 869	1.9
Reed land	24 216	3.1
Fresh water reservoirs	12 868	1.7
Salt pan	1 281	0.2

* The Nature Reserve is not classed as a land use type, instead being considered as a mosaic of the various land use activities practised within its borders.

Geographical components of flora: According to the classification in '*China Vegetation*', the YRD reserve occurs in the warm temperate broad-leaf forest zone, northern deciduous *Quercus* spp. subzone, Yellow River plain cultivation area. The flora in the reserve mainly comprises temperate components.

Vegetation forms

Based on the classification system in '*China Vegetation*', the vegetation in the reserve has been divided into five vegetation type groups, with 9 vegetation types, 26 plant formations and plant association, as outlined in table 4 (Zhao & Song 1995, Xu et al 1997).

Most of the vegetation in the YRDNR is natural vegetation. The main artificial vegetation in the reserve is *Robinia pseudoacacia* (English name: Black Loquat) plantation, which joins the *Robinia pseudoacacia* plantation around the reserve, forming the largest *Robinia pseudoacacia* plantation in coastal China.

Phytoplankton

The annual phytoplankton variation in the mouth of Yellow River old course is different from that in the current Yellow River mouth to the sea. There are two peaks of biomass, which occur in June (4.5 mg m^{-3}) and the end of August (3.2 mg m^{-3}). The nadir appears in July (2.8mg m^{-3}).

As mentioned above, there are 4 divisions and 116 species of phytoplankton. This includes 102 species of bacillariophyla, which account for 88% of the total phytoplankton.

The average total number of net phytoplankton is 2.26×10^6 m^{-3} from April to December, and 3.27×10^6 m^{-3} from December to February. The variation is different among different shallow seas.

Table 4 Classification of vegetation within YRDNR

A_1 Broad-leaf forest

- B_1 deciduous broad-leaf forest
  - C_1 Form. *Robinia pseudoacacia*
  - C_2 Natural Form. *Salix* spp.

A_2 Bush

- B_2 salt thicket
  - C_3 Form. *Tamarix chinensis*

A_3 Meadow

- B_3 typical meadow
  - C_4 Form. *Imperata cylindrica*
  - C_5 Form. *Artemisia capillaris*
  - C_6 Form. *Calamagrostis epigejos*
  - C_7 Form. *Cynodon dactylon*
  - C_8 Form. *Digitaria sanguinatis, Eragrostis pilosa*
- B_4 salt-meadow
  - C_9 Form. *Suaeda heteroptera*
  - C_{10} Form. *Aeluropuslittoralis* var. *Sinensis*
  - C_{11} Form. *Phragmites australis*
  - C_{12} Form. *Trachomitium lancifilium*
- B_5 salt-hygrocole meadow
  - C_{13} Form. *Phragmites australis*

A_4 Paludous vegetation

- B_6 herbaceous swamp
  - C_{14} Form. *Phragmites australis*
  - C_{15} Form. *Typha* spp.
  - C_{16} Form. *Triqueter* spp.
  - C_{17} Form. *Polygonum lapathifolium*

A_5 Aquatic vegetation

- B_7 submerged aquatic vegetation
  - C_{18} Form. *Ceratophyllum demersum, Hydrilla verticillata, Myriophyllum picatum*
  - C_{19} Form. *Potamogeton malainus*
  - C_{20} Form. *Potamogeton crispus, Vallisneria gigantea, Najas* spp.
  - C_{21} Form. *Ruppia rostellata*
- B_8 *Hydrophyta natantia* vegetation
  - C_{22} Form. *Lemna minor, L. Trisulca*
  - C_{23} Form. *Spirodela polyrhira, Lemna minor*
  - C_{24} Form. *Potamogeton distinctus, P. Natans*
- B_9 *Hydrophyta adnata*
  - C_{25} Form. *Nelumbo nucifera*
  - C_{26} Form. *Sagittaria sagittifolia* var. *Sinensis*

The phytoplankton can be divided into three ecological formations:

C1: Higher-halophilic formation: *Rhizosolenia alata findica, Chaetocero densus, Nitzschia pungens*, etc, are 29–30% halophilics.

C2: Lower-halophilic formation: *Chaetoceros abnormis, Skeletonema coata tum*, etc.

C3: Freshwater formation: *Scenedesmus quadricauda, Pediastrum* spp., *Cyclotella, Menghiana*, etc.

2.3.2 Animal resources

Fauna types

The animals in the YRD can be divided into two ecological communities: the terrestrial eco-community and the marine eco-community. There are 1466 species of wild animals recorded, among which there are 300 species of terrestrial vertebrates (20 species of mammals, 265 species of birds, 9 species of reptiles, 6 species of amphibians) and 664 species of terrestrial invertebrates (477 species of insects, 19 species protozoan, 18 species of protochors, 68 species of arachnids, 13 species of molluscs and 40 species of crustacean) (Zhao & Song 1995, Xu et al 1997).

There are 67 species of freshwater fish, among which 39 species are cyprinidal. Among the marine animals recorded, there are 5 species of mammals, 1 species of reptile, 85 species of marine fish, 99 species of molluscs, 82 species of polychaeta, and 25 species of medusa.

According to the geographic classification of the terrestrial animals of China, the terrestrial animals in the YRD belong to the Nearctic pattern, north-east sub-pattern, north China region, and Yellow River–Huaihe River Plain sub-region. It is a transitional zone from the Oriental pattern to the Nearctic pattern. In the geographic classification of marine animals for China, the marine animals in the YRD belong to the Yellow Sea–Bohai Sea fauna. It is also a transitional zone for the cold-warm water aquatic species and warm water species. The influx of fresh water brings a large quantity of nourishment and there are abundant mollusc and crustacean resources. Thus, the marine environment is exceptionally suitable for fish, resulting in the area being a major spawning ground.

With its large areas of shallow sea and bog, abundance of wetland vegetation and aquatic biological resources, YRD provides birdlife with exceptional habitat for breeding, migrating, and wintering, making the region an important ‘transfer-station’ for inland north-east Asia and around the western Pacific ocean for bird migration.

The Nature Reserve and importance for bird migration

Wetlands are considered valued components of the natural environment. Wetland habitats are recognised as being important for their biological diversity, as sanctuaries for migratory and resident bird populations, and for their contribution to estuarine and marine productivity. These values have been nationally and internationally acclaimed for the YRD.

In the YRD, wetlands occupy an area of 4500 km^2, of which 2000 km^2 is supratidal wetland, 1000 km^2 intertidal wetland and 1500 km^2 subtidal wetland. The ecological environment is vulnerable in the YRD, especially the river mouth, sub-delta tidal flats and coastal wetlands.

The Nature Reserve of the YRD is a newly-formed wetland ecosystem and is a conservation area mainly for the protection of rare and endangered birds. It is located at the Yellow River Mouth area and near the abandoned channel of the Yellow River before 1976. The total area is 1530 km^2, of which 65% is river, waterlogged and foreshore, 15% is grassland, 12% is forest, and 8% is farmland.

Due to deposition of large quantities of sand and silt carried by the Yellow River, areas of new mud flats are continually being formed (ie 21 km^2 y^{-1} for the period 1989–1995; Chen et al 1997). Thus, the reserve area increases continuously, making it one of the most rapidly expanding land reserves in the world. With its large areas of shallow sea and bog, abundance of wetland vegetation and aquatic biological resources, this reserve provides the birds with exceptional habitat for breeding, migrating and wintering. Therefore, the reserve is an important 'transfer station' for inland north-east Asia and the western Pacific Ocean for bird migration (Zhao & Song 1995).

The Yellow River Delta Nature Reserve (YRDNR) comprises the largest newborn wetland in China (figure 6). The Sino-Japanese Agreement for Bird Protection, lists 227 species of birds protected in China, of which 152 species (67%) occur in the YRDNR. In addition, 51 species in the reserve, accounting for 63% of the total species, were listed as protected birds in the Sino-Australian Agreement for Bird Protection (Zhao & Song 1995, Xu et al 1997).

The rare and endangered species of birds of YRDNR include the following:

***Grus japonensis* (Red-crowned Crane)**: About 800 arrive in the reserve each year, of which 200 winter here. This is the most northerly wintering site for this bird (in mainland Asia). Its flocks often occur together with *Grus grus liffiordi.*

***Ciconia boyciana* (Oriental White Stork)**: In the middle of October each year, this bird comes from the north and stays for a short time before continuing to migrate southward. In middle and late March of the following year, it returns from the south and stays several days before migrating northward. The maximum population recorded is 40 birds (of a global population estimated at 2500–3500 individuals; Rose & Scott 1997).

***Otis tarda dybowskii* (Great Bustard)**: 700–800 Great Bustard winter here with a maximum population of up to 400. They migrate to the reserve in early November each year and leave for breeding grounds in late March of the following year.

***Grus grus liffiordi* (Common Crane)**: This species migrates to the reserve for wintering in the middle of October each year with maximum numbers up to 6000 and a minimum population of about 300.

***Cygnus cygnus* (Whooper Swan)**: About 2000 Whooper Swans winter at YRDNR. They remain in the reserve from the middle of November each year to the middle of the following April.

In recognition of the importance of the Reserve to Eurasian Cranes and Red-crowned Cranes, the Forestry Administration has nominated the area to be part of the East Asian Crane Site Network. This is an international cooperative program to promote the appropriate management of international important sites for migratory cranes.

The YRD is also an important area for passage and wintering of waterfowl, particularly herons and egrets (Ardeidae), swans, geese and ducks (Anatidae), shorebirds, and gulls and terns (Laridae) (Scott 1989). The area is considered to support over 500 000 shorebirds during their northward migration (Barter et al 1998). Recently it has been shown to meet the Ramsar Convention criteria for 15 species of shorebirds (Barter et al 1998). The key habitat used by shorebirds is tidal flat. In recognition of the area's importance for migratory shorebirds, the site has been nominated for the East Asian-Australasian Shorebird Site Network.

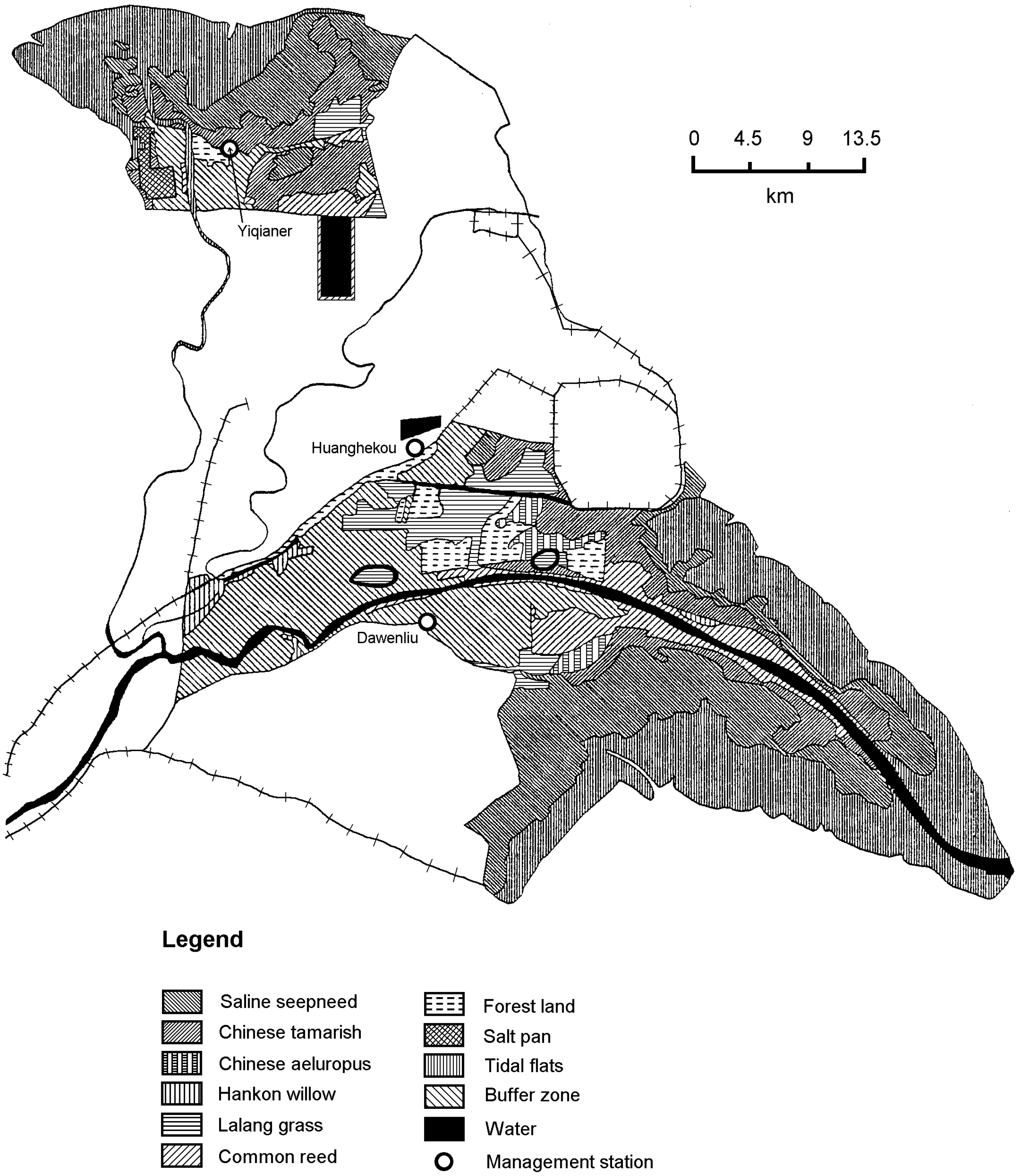

Figure 6 Vegetation and birds in the YRD Nature Reserve

2.4 Social, economic and cultural attributes

2.4.1 Administration and governmental structure

Dongying Municipality, Shandong Province, is located in the YRD. The population consists of 1.64 million people. Seventy percent of these (1.15 million) take part in agriculture, both directly and indirectly. The remaining 30% (490 000) take part in non-agricultural industries. Dongying Municipality is subdivided into five administrative units: Guangrao County, Lijin County, Kenli County, Dongying District and Hekou District (table 5; Wang et al 1997a, Wang et al 1997b, Statistical Bureau of Dongying Municipality 1994a,b).

Table 5 Area and population of the administrative units of Dongying Municipality

County	Area (ha)	Population	Persons/km^2
Guangrao County	115 100	461 600	401
Lijin County	106 800	288 900	271
Kenli County	211 800	208 700	98
Dongying District	116 100	489 800	422
Hekou District	233 600	172 100	74

The Yellow River Delta Nature Reserve (YRDNR) is located in the YRD, with a geographical position from 118º33´E to 119º20´E and from 37º35´N to 38º10´N. The Nature Reserve consists of two separate parts: the floodplains and abandoned river mouth in the north (approx. 40 000 ha) and the flood plains and active river mouth in the east (approx. 105 000 ha). The total area is 145 000 ha. The preserve was established in December 1990, approved by the Dongying government, and became a provincial Nature Reserve in November 1991. In October 1992, it was approved as a State Nature Reserve by the State Council of China.

2.4.2 Social infrastructure and social development

Based upon the current Official Statistical Issue of Economic and Social Development of Dongying Municipality, major aspects of the social infrastructure and social development are as follows (Wang et al 1997a,b, Statistical Bureau of Dongying Municipality 1994a,b):

- The total population in 1995 was 1 641 145 persons, of whom the non-agriculture population was 493 436, or about 30%.
- Urban income is 5666 Yuan/capita, with a nominal growth rate of 27.6%, and a real growth rate of 12%. Rural income is 1636 Yuan per capita, with a nominal growth rate 29.3% and a real growth rate 6.8%.
- Education: There are two universities and colleges with 7810 students enrolled and several middle level vocational schools with 7279 students enrolled in 1995. Nine-year compulsory education has progressed dramatically, now reaching 59 towns and villages of Dongying. In 1995, there were 157 ordinary middle schools and 584 primary schools, with total enrolments of 108 220 and 151 119 students, respectively. The data show that the total number of students presently in school is around 18% of the region's total population.

2.4.3 Present economic development

Gross regional product (GRP) and its components

The gross regional product (GRP) in 1995 was 21.74 billion Yuan, with a growth rate of 9.7%. The structure of production as measured by the shares of primary, secondary and tertiary sectors, and also their rate of growth is shown in figure 7a, while the change of GRP is shown in figure 7b (Wang et al 1997a,b). It can be seen that the economic structure of Dongying Municipality is dominated by the secondary sector, which is proportionately far greater than either the national or the provincial averages.

The agriculture sector

The total value added (VA) of the agricultural sector is 2.37 billion Yuan. The shares of its structural components (crop farming, forestry, animal husbandry and fishing) and their growth rates are shown in figure 8.

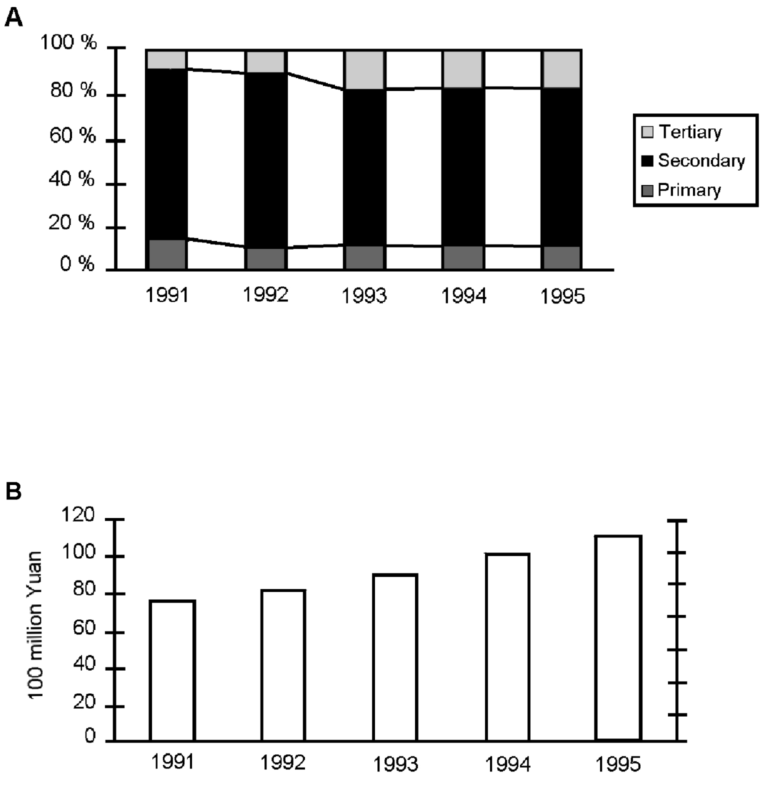

Figure 7 (a) Change in structure and (b) growth of Gross Regional Product (GRP) of Dongying Municipality from 1991–1995

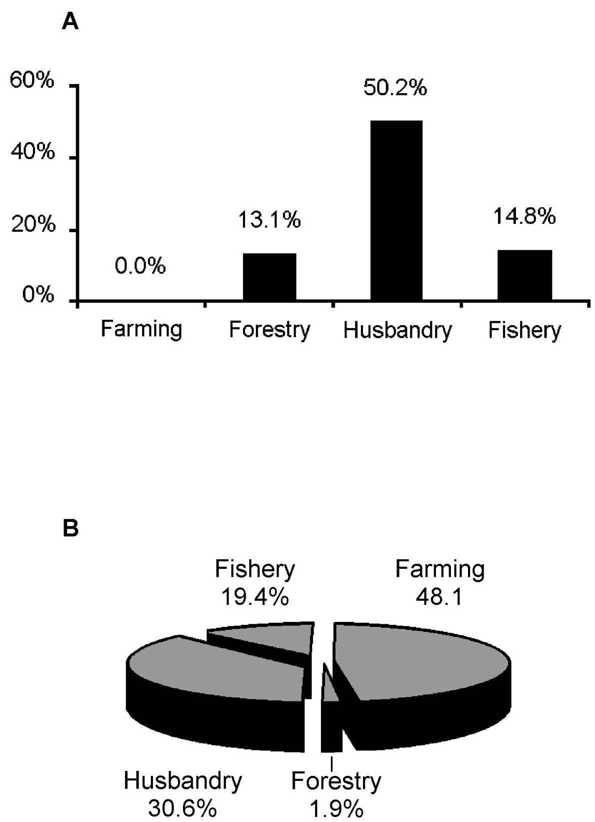

Figure 8 (a) Growth rate and (b) structure of primary sector output for Dongying Municipality in 1995

Industrial sector

The dominant products of the industrial sector and their growth rates are shown in table 6. As noted above, the principal activities are oil-related, although food processing, textiles, chemicals, and paper products make a sizeable, and rapidly expanding contribution (Wang et al 1997a).

Table 6 Features of the dominant industrial products of Dongying Municipality, 1995

Product type	Production	Compared with 1994 (±%)
Crude oil	3.00027×10^7 t	-2.9*
Natural gas	1.28524×10^9 m^3	-1.7*
Edible	2.3875×10^8 t	+112.4
Grain wine	6.5×10^3 t	+170.8
Beer	5.2×10^3 t	+205.9
Clothing	1.2216×10^6 t	+36.6
Machine-made, paper & paperboards	8.0301×10^4 t	+62.8
Chemical fertilisers	1.6×10^4 t	+110.5
Cement	6.9×10^4 t	+372.6

Note: The products with '*' had negative growth rate in 1995; they are listed due to their importance in Dongying Municipality

Investment

The value of fixed asset investment in 1995 was 9.778 billion Yuan, with a growth rate of 11.6% over 1994.

The retail sector

The total value of retail sales in 1995 was 3.588 billion Yuan, with a nominal growth rate of 23.4% and real growth rate of 11.2%. These were dominated by sales from state owned enterprises (SOE) and collectives, although rural and informal production both make a significant contribution to overall output.

Foreign trade

In 1995 the value of merchandise exported from Dongying Municipality was 2.207 billion Yuan, a decrease of 12.8% compared with 1994. Within this total, the export value of industrial products was 2.02 billion Yuan, and the export value of agricultural products was 0.187 billion Yuan.

Integrative development of the YRD

In China's Ninth Five-Year Plan, the government has promoted a coordinated economic development strategy, and seven cross provincial economic regions are outlined. One of these economic regions is the Bohai Rim Economic Region that includes Eastern Liaodong Peninsula Shandong Peninsula, Peking, Tianjin and Hebei Province. Dongying Municipality is an important component of this region and it should abide by the regional development strategy set up by the central government, of which one key aspect is the coordinated development and opening of new markets in order to promote common prosperity.

Acceleration of the comprehensive development of YRD and stabilisation of the river course to the sea is one of the strategic aspects of the development of the industrial belt of the Bohai Rim.

It is emphasised in the Ninth Five-Year Plan and Outline of the 2010 Long Term Target of Shandong Province that 'The Development of the YRD' should realise fully the comparative advantage of its concentration of oil and gas resources, the vast area of coastal beach and foreshore land, and other rich land resources. It should develop modern agriculture, chemical engineering with salt as one raw material, petro-chemicals, and industries for petroleum. It is necessary to enhance the comprehensive development of agriculture, effectively manage the downstream establishment of northern grass land, develop foreshore land, and accelerate the establishment of household farms and pastures with an appropriate scale. It is necessary to further improve the industrial structure, change the current state of mono-structure, create a petroleum substitute industry to be the leading industrial sector, and gradually establish nationally important bases for plantation, husbandry and fishery, petro-chemical industry, light and textile industries (figure 9).

3 Identification of forcing factors

The major current forcing factors affecting environmental, socio-economic and cultural attributes of the YRD include climate change, sea level rise, sedimentation in the YRD plain and the Yellow River mouth, the Asian monsoon, El-Niño and typhoons.

3.1 Natural forcing factors

3.1.1 Climate change

Climate change is divided into two components: natural change and anthropogenic change (human-induced change). The atmosphere is subject to natural variations on all time scales, ranging from minutes to millions of years (Bayliss et al 1997). However, vulnerability assessment is currently considered in the context of variation in climate that is expected to result, or has resulted, from human interference with atmospheric processes (Warwick et al 1993, IPCC 1994). The average rate of present climate warming probably would be greater than at any time in the past 10 000 years. As presented by IPCC working group I and group II (Watson et al 1996, Wang & Zhao 1995, Houghton et al 1992), global warming of about 0.3–0.6 ºC for the last 100 years has been detected. Warming of about 0.6–0.8 ºC in East Asia (China) for the last 100 years has been shown by Hulme et al (1992). Scenarios for global climate change due to human activity have indicated that global temperature and precipitation might increase further (Houghton et al 1990, 1992). Human activities are increasing the atmospheric concentrations of greenhouse gases, which alter radiative balances and tend to warm the atmosphere.

The changes in greenhouse gases and aerosols, taken together, are projected to lead to regional and global changes in temperature, precipitation and other climate variables. This may result in global changes in soil moisture, increase in global mean sea level, and prospects for more severe extreme high-temperature events, floods and droughts in some places. Based on the range of sensitivities of climate to changes in the atmospheric concentrations of greenhouse gases and plausible changes in emissions of greenhouse gases and aerosols, climate models project that by 2100, the mean annual global surface temperature will increase by 1.0–3.5 ºC, that mean sea level will rise by 15–95 cm, and that changes in the spatial and temporal patterns of precipitation would occur (Watson et al 1996).

Indirect effects of climate change would include predicted increases in the potential transmissions of vector-born infectious diseases resulting from extensions of the geographical range and season for vector organisms. Projections by models (that entail necessary simplifying assumptions) indicate that the geographical zone of potential malaria transmission in response to world temperature increases at the upper part of the IPCC-projected range (3.5ºC by 2100) would increase from approximately 45% of the inhabited area of the world to approximately 60% by the latter half of the next century. This could lead to potential increase in malaria incidence, primarily in the less well-protected temperate zone (eg China), subtropical and tropical populations (Watson et al 1996).

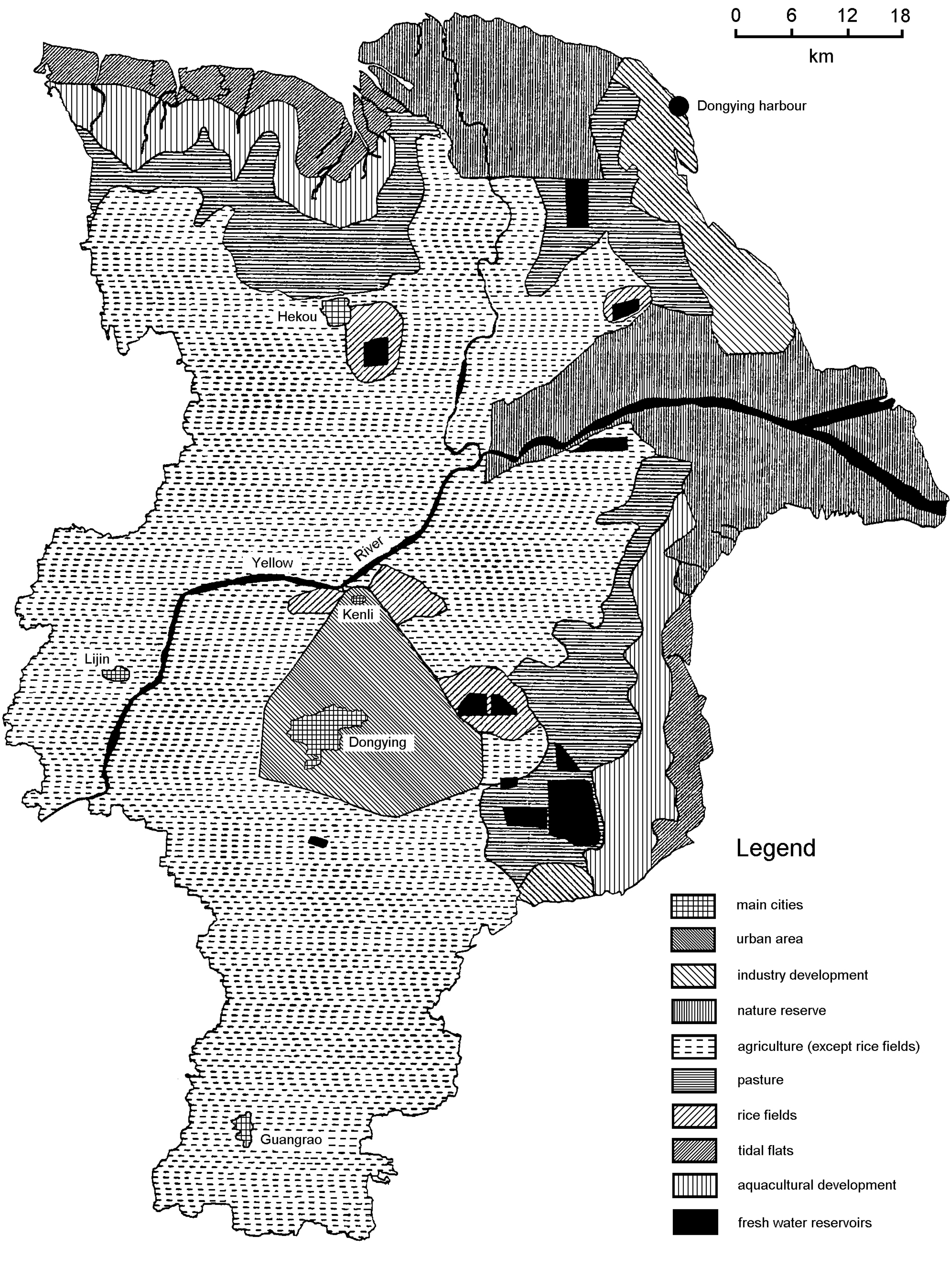

Figure 9 Integrative development of the YRD

Considering the global warming projection as simulated by the global social-economic-climate-impact model (GSECIM) combined with seven GCMs, the regional future climate change for China and East Asia has been calculated (Wang & Zhao 1995). Table 7 shows the future climate change scenario as simulated by the GSECIM model combined with the composite GCM (Hulme et al 1992).

Table 7 Climate change scenario for China and East Asia in the future (1991–2100) compared with the present climate (1951–1980) (DT: change of temperature, and DP: change of precipitation)

	Year										
	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
DT(ºC)	0.20	0.35	0.65	0.88	1.06	1.40	1.64	2.01	2.30	2.66	2.95
DP(%)	0.6	1.1	1.9	2.6	3.2	4.2	4.5	5.5	6.3	7.2	8.9

These data suggest that the change of temperature due to human activity in the future might be much more obvious than that of the precipitation in China and East Asia. For a more detailed investigation, the year 2050 has been chosen as a reference point for the present report. Distribution of the annual and seasonal temperature and precipitation in China for 2050 and the present climate have been calculated. The temperature might increase clearly from the present time to the year 2050. It is predicted that the effect of temperature induced by human activity might be much larger than that of precipitation in China. The more warming, the more evaporation is caused. The combined effects of both precipitation and evaporation might induce a drier climate in China, especially in the winter, spring and autumn seasons, and in north-east China (YRD is in east China).

Seasonal and annual changes of temperature and precipitation induced by human activity in broad regions of China were also estimated, and are shown in tables 8 and 9. Here, the regions chosen are North-east China (32.5–52.5ºN, 122.5–132.5ºE); East China (22.5–42.5ºN, 92.5–117.5ºE) and West China (32.5–47.5ºN, 77.5–87.5ºE), respectively. Overall, temperature and precipitation might increase in China, especially in winter (Wang & Zhao 1995).

Table 8 Change of annual and seasonal temperature (ºC) in East China , North-east China, West China and all of China from the present to the year 2050

	Months				
	Annual	**Dec-Jan-Feb**	**Mar-Apr-May**	**Jun-Jul-Aug**	**Sep-Oct-Nov**
East China	1.42	1.43	1.37	1.42	1.45
North-east China	1.47	1.53	1.47	1.37	1.52
West China	1.57	1.48	1.44	1.49	1.53
All China	1.49	1.48	1.44	1.49	1.53

Table 9 Change of annual and seasonal precipitation (%) in East China , North-east China, West China and all of China from the present to the year 2050

	Months				
	Annual	**Dec-Jan-Feb**	**Mar-Apr-May**	**Jun-Jul-Aug**	**Sep-Oct-Nov**
East China	3.3	4.2	4.5	2.9	2.2
North-east China	3.7	5.0	4.1	3.0	4.3
West China	4.9	8.0	5.8	2.4	3.4
All China	4.0	5.7	4.8	2.8	3.3

3.1.2 Sea level rise

The long-term geological record of sea level change

During recent years, studies on the Quaternary geology and geomorphology along the coast of eastern China and on the adjacent shelf have made considerable headway. In the coastal area, a few marine layers and relics of ancient shorelines have been found. On the shelf, non-marine layers and relics of submerged ancient shorelines have also been found.

In the process of a rapid descent of sea level of the late Wurm, beginning from 25 000 BP, the sea level took several intermittent stops, forming four buried terraces at 112, 136, 141, 155 m below present sea level. Based on the depths of these terraces and ^{14}C dating data, it is estimated that the sea level descended to -115 m at 23 700 BP, -137 m at 20 550 BP, -143 m at 17 600 BP, and from -150 to -160 in 16 000–15 000 BP (figure 10; Li & Zhou 1993, Zhao 1982, 1993).

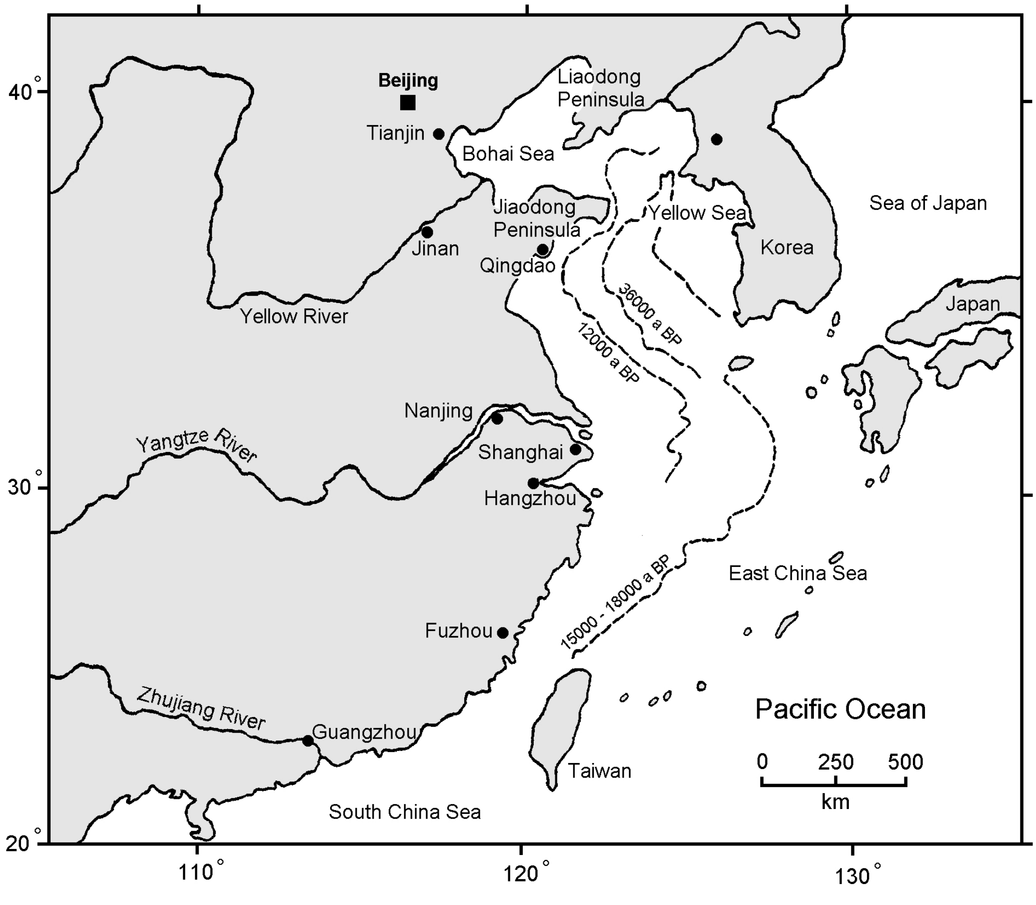

Figure 10 Late Pleistocene coastline changes in the Bohai Sea, the Yellow Sea and the East China Sea (based on Wang & Wang 1980; Liu et al 1987; First Institute of Oceanography, SOA 1989)

Along with the warming of the climate during the end of the late glacial period to the early postglacial period, the sea level also rose rapidly. If the change in sea level from -160 m at 15 000 BP to slightly higher than 0 m at 6000 BP is considered, the average rate of sea level rise reached 16.7 mm/yr. In the process of the rising of sea level, several stops or oscillations occurred, thus forming several obvious submarine terraces in the East China Sea: ie the -120–100 m and -75–60 m terraces (Li et al 1987).

Debate about the issue of whether or not the postglacial high sea levels have occurred has been ongoing. Some consider that the rising of sea level reached up to 3 m higher than that of the present by the end of the Atlantic stage, and since that time, the fluctuation of sea levels had an amplitude of 6 m (Zhao et al 1982, 1993). This is the theory of sea level fluctuation over the past 6000 years.

Predicted future sea level rise

In terms of global changes, sea level rise is one of the main possible consequences of warming of the global climate. Due to the gradual concentration of greenhouse gas in the last several decades, the greenhouse effect on the atmosphere is intensified day by day, with more and more solar heat held in the earth, and the temperature in the earth (atmosphere) has been raised. It is generally estimated that global sea level rise over the past 100 years has been 1–2 mm y^{-1} (Scor Working Group 1989, 1991); that is a total rise of 10–25 cm estimated by 1995 (Watson et al 1996). In addition, some studies show that the global sea level rise rate was close to 2 mm y^{-1} in the last several decades (Douglas 1991, 1995, IGBP 1992, Gornitz 1994). For the next century, global sea level will rise at a much faster rate, perhaps 2–4 times than at present, because of global warming (Warwick et al 1990, 1993). For example, additional sea level changes of 18 cm by 2030, 35 cm by 2050 (Woodworth 1990, Douglas 1992) and 44 cm by 2070 (Church et al 1991) have been estimated. The best estimate of global sea level rise over the next century is from the Intergovernmental Panel on Climate Change (IPCC 1992, Watson et al 1996): 18 cm (4.5 mm y^{-1}) by 2030 and 31–110 cm by 2100 (mean value of 66 cm, rate of 6.0mm y^{-1}).

The State Oceanic Administration of China (1996) summarised tide-gauge data from 44 stations along the China coast from 1959–1989. The mean rate of sea level rise was 1.4 mm y^{-1}. According to the geodetic survey data from nine stations along the China coast by the Station Survey Bureau of China in 1992, sea level rise during the last hundred years was 19 cm in the East China Sea, and 20 cm in the South China Sea. Thus, the rate of sea level rise has been 2–3 mm y^{-1}, which is predicted to continue in the future (Chen 1997).

The real net impact on a coastal area is the result of sea level rise combined with the crustal vertical movement in the area. After correcting for neotectonic vertical movements, the annual average rate of mean sea level rise along the typical coasts of China was calculated by Chen (1997). The YRD is located in the Bohai Sea neotectonic subsidence area for which the subsidence rate in the Quaternary is 5 mm y^{-1}. The estimated relative sea level rise rate in the YRD is 8 mm y^{-1} and the sea level rise will be 48 cm by the year 2050 (table 10).

Table 10 The predicted values of relative sea level rise of the main coastal areas of China (Yang & Xie 1985, Chen 1997)

Area	Sea level rise rate (mm y^{-1})	Subsidence rate of land (mm y^{-1})	Relative sea level rise (mm y^{-1})	Sea level rise by 2050 (cm)
Recent Yellow River Delta	3	5	8	48
Old Yellow River Delta	3	10	13	72
Coastal Plain of North Jiangsu	3	2	5	28
Yangtze River Delta	6	3	9	50
Pearl River Delta	6	2	8	44

3.1.3 Sedimentation

Sedimentation is one of the natural forcing factors controlling vulnerability of the YRD and it directly affects coastline changes, coastal wetland loss and expansion, land use and social and economic development of Dongying Municipality.

The modern YRD covers the fan areas north to the Taoer River mouth and south to the Zhimaigou River mouth, with an area over 6000 km^2 and a coast line of 350 km. The delta fan has been expanding at a rate of about 21 km^2 per year over the period 1989–1995 (Chen et al 1997). The Qingshuigou channel, ie present channel of the Yellow River into the Bohai Sea, can be divided into four sections, namely the delta channel section, the fluvial-maritime section, the current section and the offshore section (figure 11; Song et al 1997).

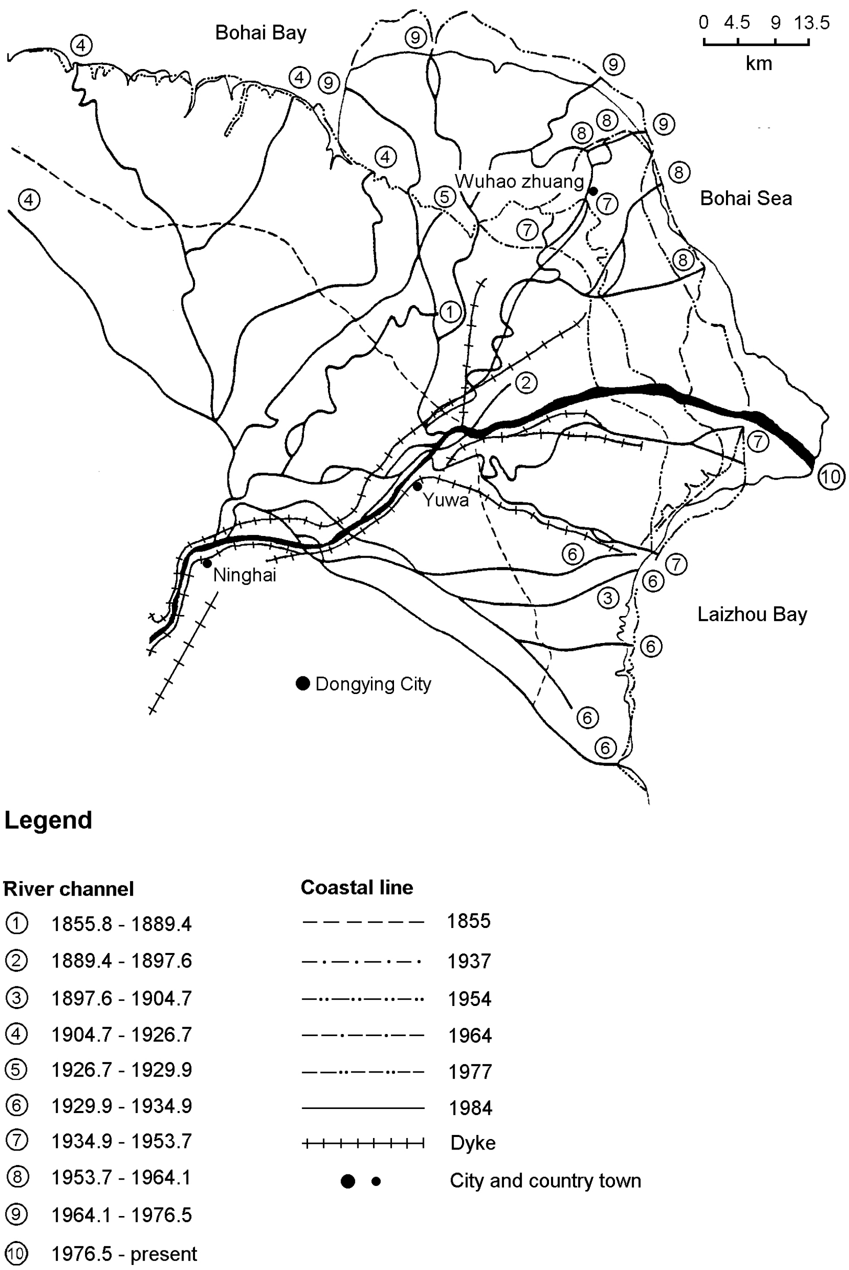

Figure 11 The modern Yellow River Delta and shifts of the river channel

In the delta channel section, upstream from Qing-8 (Q-8), the river is not affected by the tide. The fluvial-maritime section is between the upper boundaries of the tidal estuary and tidal current. The river bed in this section has a positive slope, but is affected by incoming water and sediment load, size and shape of the mouth bar, and height of tidal surges. Retrogressive erosion or siltation occurs in this section depending on the growth and reduction of the bar in the mouth of the river. This section is between Q-8 and Q-11 and is also called the mouth section (figure 10). The tidal current section extends from the river section to the shallow sea of depth 10 m. Both discharge flow and tidal current occur in this section and the river mouth bar develops in it. The section can be further divided into a negative bed slope, the mouth bar crest, steep front slope and gentle slope sub-sections. The length of the section is now about 10–15 km. In the offshore section, the sea water depth is over 10 m and the flow and sediment transport are controlled by sea currents.

Conventionally, the delta channel section and the fluvial-maritime section are called inner-mouth sections because the flow is confined between dykes. Correspondingly, the tidal current and offshore sections are called outer-mouth sections. The location of the mouth bar varies with tidal current over shore time periods. If the tidal current is strong and discharge weak, the mouth bar moves into the inner-mouth section. If the tidal current is weak and discharge strong, the mouth bar moves to the outer-mouth section. As the Yellow River Mouth is a weak tidal river mouth, the latter process usually dominates.

The sediment transporting capacity of the sea current affects the development of the river mouth. Sediment deposition at the river mouth results in the extension of the channel, but the extruding channel mouth is scoured back quickly if the sediment-laden flow is switched to a new channel. In addition, the sea currents may scour the river mouth in the non-flood season because the sediment transported by the river flow is less than the sediment carrying capacity of the sea currents. In 1988–1989, the river mouth was eroded by 4 km. The total eroded sediment in the 8 month period was estimated at 50×10^6 t. In 1995 and 1996, the river discharge was cut off for 122 and 133 days, resulting in considerable erosion of the mouth. If the annual sediment load:water ratio is less than 0.01 t m^3, the river mouth does not extend and the entire sediment load can be carried away by the sea currents. By comparing satellite images of the YRD in 1976 and 1988, the Diaokou channel mouth area was eroded by 5 m in depth while the Qingshuigou channel mouth area was silted up by 14 m in the same period. This demonstrates that the coast-scouring capacity of the sea currents is considerable in the development of the delta territory. Measurements proved that the sediment carried away by sea currents consists mainly of fine particles of diameter < 0.025 mm. According to long-term records, such fine sediment is about 40–60% of the total amount at the Lijin Station (Song et al 1997).

3.1.4 Asian monsoon

To date, the most critical uncertainties for climate change and sea level rise predictions in China are the lack of credible international projections of the effects of global change on the Asian monsoon or the ENSO phenomenon, which have great influence on river discharge and the Bohai Sea tidal currents.

The modern climate of China's mainland is principally controlled in winter by direct or modified polar continental air masses. The northerly winter monsoon, carrying cold and dry air from middle high latitudes, is prevalent in the lower layer of the troposphere. In summer, most of the mainland comes under the influence of tropical to subtropical marine air masses and tropical continental air masses. The southerly summer monsoon with its warm and humid air from the lower latitudes is prevalent in the lower layer of troposphere. The changes in prevalent wind from winter to summer are distinctive. As the monsoon advances and retreats, precipitation and surface air temperature show a distinctive seasonal variation. Hot summers have plentiful rainfall, while cold winters are dry.

There are two types of summer monsoon in China: the southeast monsoon originating from the Pacific, and the southwest monsoon from the Indian Ocean. Variations in the summer monsoon are often reflected by changes in summer precipitation and its starting time. Historical data suggest that the start of the rainy season from the south to the north in East China is a clear response to the northward progression of the rain belt, ie the northward movement of the summer monsoon. In Shangdong Province, such changes in rainy season precipitation are approximately the same as those in the lower Yangtze River basin (Zhang 1983). Rainy and dry spells have occurred in the Yangtze River basin during the last 800 years, with the major dry spells concentrated in periods – 1200–1264, 1523–1590 and around 1920 to the present – an indication of the so-called 'phenomenon of clustered occurrence'. The yearly variation in precipitation in the rainy season shows quasi-cyclic changes over periods of about 2–3 years, 5 years and 20 years (Wu 1981), obviously a result of quasi-periodic variations in the monsoon circulation.

The reconstructed climatic sequence of plum-rain for the 18th century has provided certain details about the advance and retreat of the southeast monsoon (Zhang & Wang 1990). The plum-rains in the 18th century on average started on June 15th and ended on July 6th, with a mean length of about 20 days, while showing a 2–3, 5–6 and 34-year quasi-periodic change, also reflecting the oscillations of the summer monsoon circulation.

The winter monsoon of China is mainly characterised by the incidence and strength of cold waves or cold air masses. For example, in the past 500 years the periods 1440–1520, 1620–1720 and 1810–1900 AD experienced high incidence and strength (Zhang & Zhu 1978).

The configuration of land and sea is a critical factor in the generation of a monsoon-type climate. Sea level has fluctuated many times in response to global glacial-interglacial changes over the past 130 000 years. As a result, transgressions and regressions have taken place on the eastern coastal area of China and the extensive continental shelf area. The resultant changes of land-sea interaction have thus had a notable effect on variations in the East Asian monsoon.

According to much Chinese research, it can be concluded that, during the past 130 000 years, three major large-scale marine transgressions (125 000–70 000, 40 000–25 000 and 11 000–6000 BP) and two major regressions (50 000–45 000 and 18 000–15 000 years BP) took place in the coastal areas of East and South China, as well as on the adjacent continental shelf (Chen et al 1977, Yang & Xie 1985, Qin et al 1987). The temperature and rainfall patterns in present China and the eastern part of North-west China show isolines running approximately parallel to the general trend of the mainland coast, indicating that the air temperatures and precipitation values in these areas are closely related to their distance to the sea. For instance, at 18 000 years BP, the eastern coast of China shifted eastwards about 1000 km. At the same time, the heat source of the summer monsoon was concentrated in the west Pacific alone.

Geological records indicate that the East Asian summer monsoon was weak 18 000 years BP and that since about 12 000 years BP it has gradually strengthened. After about 9000 years BP the Holocene Climate Optimum began, lasting until 5000 years BP, and with the summer monsoon being strong. In the Holocene Optimum, the annual average temperatures in the southeast monsoon region were 2–3ºC higher than those of today, with annual precipitation values at least 100 mm higher.

The changing influence on temperature of proximity to the ocean is important for the origin and development of monsoon. During the late glacial monsoon, the exposure of the continental shelf as a result of sea level fall decreased by about two-thirds the area of the Yellow Sea and the Bohai Sea north of the Taiwan Strait, and about one-fifth the area of the South China Sea (Wang & Wang 1990), whereas the area reduction of the West Pacific was very small, with an indetermiate fall in water temperature. The marine heat source of the present East Asian monsoon is located in two areas, ie the west Pacific and the South China Sea. During the glacial period, however, the heat source was mainly concentrated in the West Pacific alone.

3.1.5 El Niño

El Niño is a periodic phenomenon of sea-atmosphere interaction. Opinions vary on its formation mechanism, physical process, warm-water source and dynamic exchanges between marine currents from the east and the west. El Niño phenomena not only coincide with years with higher atmospheric temperatures, but also can often bring about serious marine calamities.

The relationship between El Niño and China's regional precipitation has been studied recently (Mo et al 1995), and results showed that:

1. The variations of China's precipitation and the East Pacific equatorial surface temperatures occur over a 3.5 year cycle. The unusual equatorial Pacific surface temperature is positively correlated with precipitation in the Yellow River basin, the Yangtze River lower reaches and the southern areas, and consistent with the development of a typical El Niño. However, this typical El Niño process is very different from the influence on the precipitation in the flood season in the middle reaches of the Yellow River.
2. The longitudinal location where El Niño begins has a very important relation with the precipitation in the middle areas of the Yellow River basin and to the south of the lower reaches of the Yangtze River in the year following the El Niño year. For example, if El Niño begins at the central part of the equatorial East Pacific Ocean, it will greatly affect the precipitation in the flood season in the lower reaches of the Yangtze River and the southern areas.

Thus it can be said that El Niño can indirectly influence regional precipitation in China and in the important river areas in the flood season.

Across the world, the most serious recent natural hazards caused by El Niño were: the 1993 rainstorm from Japan to Mississippi, USA; drought in the south of Africa; forest fires in New South Wales of Australia; drought in Indonesia; storms along the Peru and Ecuador coasts; Brazil's most serious drought this century; and the floods from December 1993 to January 1994 in the south of England. In China, the most serious natural calamity caused by El Niño was large scale flooding in the drainage area of the Yangtze River from June to September 1998, resulting in a loss of more than 100 billion Yuan RMB, as well as many lives.

3.1.6 Flooding and storm surge

Whilst flooding and storm surge are often the direct or indirect result of several of the forcing factors described above, they are considered sufficiently important to be discussed separately.

Flood disasters

Flood disasters in the YRD include: floods in the Yellow River in summer; storm surge and typhoon induced sea surges; ice jam floods in spring; and local rainstorms and waterlogging (Lu et al 1997).

The Yellow River floods

The biggest flood disaster occurred in 1846 with peak discharge at Sanmenxia of 36 000 $m^3 s^{-1}$ and a total (12 days) discharge of 12×10^9 m^3. The second largest flood occurred in 1933 with peak discharge 22 000 $m^3 s^{-1}$. Because the capacity of the Yellow River channel downstream of Aishan is only 10 000 $m^3 s^{-1}$ much damage and loss is created by the floods. According to local historical records, the dykes of the Yellow River in the delta were broken at more than 70 places in 23 years within the period 1883–1938.

The Yellow River flood occurs in late July and August with high peak discharge but a short duration. The maximum discharge varies from year to year and the sediment concentration is high. If the dyke in the delta is broken, the possible inundated area varies with the position of the break. The closer the break to the river mouth, the smaller the inundated area. It takes more than 5 days for a flood to travel from HuaYuankou to Lijin, usually giving residents in the delta sufficient time to implement flood control measures.

Storm surges

When strong north-east winds occur, a large amount of water flows into Bohai Bay and Laizhou Bay through the Bohai Strait which results in surges at the YRD. If a surge occurs in conjunction with an astronomic spring tide, a resultant storm surge of 2–3 m can occur. Heavy disaster zones of storm surges are Zhanhua County, Wudi County and Yangjiaogou Town. Yangjiaogou lies to the south of the YRD. There are only poor and broken dykes along the coastal line of the YRD where high storm surges occur.

According to local records 96 storm surges of 2–3 m occurred in the Laizhou Bay from BC 48 to AD 1949, 21 of which were serious. In the last 100 years, storm surge occurred 15 times in the coastal area of the reserve, with a height of greater than or equal to 3.5 m. On 31 August 1938 the storm surge reached 3.6–4.1 m, subsequently inundating an area of up to 300 000 km^2. Since the foundation of the People's Republic of China in 1949, the total area inundated by storm surge has reached 112 000 km^2, resulting in 529.6 million Yuan (RMB) of economic loss (Science and Technical Committee of Shandong Province 1991, Yang & Wang 1993, Zhao & Song 1995). Storm surges with a wave height over 3 m (Yellow Sea System) will often cause serious disasters due to the low slope of the delta.

Ice-jam flood

The lower reaches of the Yellow River stretch from south-west to north-east. The ice covers in Henan Province begin to melt in early spring when the ice cover in the delta is still solid. Flow into the delta is blocked by the ice cover, resulting in an ice-jam. Prior to 1949, 26 ice jam floods occurred, resulting in major impacts.

Rain storm and waterlogging

Rainfall from June to September is about 70% of the total annual precipitation. The ground water table in the delta is about 2 m. A strong rain storm often causes waterlogging because the drainage system is not capable of discharging such high volumes of water in summer. Recorded data show that waterlogging disasters occurred in 27% of the years between 1500 and 1949. An additional impact of such waterlogging is a rise in the water table and subsequent salinisation of the soil.

3.2 Anthropogenic forcing factors

Although the YRD has a relatively low population it is of high economic importance at both the provincial and national scale. Arable fields cover 40% of the area, and are the dominant land use. About 30% of the area is not yet used by man; the tidal flats are included in this area. The remaining 30% of the YRD is used for pasture, residential and industrial purposes, oil production, forestry and various other purposes.

Neighbouring the Beijing-Tianjin-Tangshan economic zone in the north, and situated between the inland of north-east Asia and the Yangtze River Plain, Dongying Municipality is considered to be one of China's areas that will be opened economically to the outside world. The abundant oil and gas resources in the Shengli Oil Field provide a basis for the present economic development, and will further enforce the industrial capacity of the coastal area. In addition, Shengli Oil Field will be connected in the future with the coal mining areas in central and northern China, after the construction of Dezhou-Longkou Railway. The proximity of Dongying Harbour to the Korean Peninsula and Japan may facilitate the establishment of economical connections from within Dongying Municipality to the outside world.

3.2.1 Population increase

At present, the population density of Dongying Municipality or the YRD is 8053 persons per km^2. Prior to 1997, the annual population birth and death rates were 1.04% and 0.54%, respectively, resulting in an annual population growth rate of about 0.5%. This growth rate is currently lower than that of the entire country (0.8% per year) (Wang et al 1997b). However, with the high-speed development of oil and gas resources and interrelated industries and agriculture, a great number of people will migrate into the area to work and live, and the YRD will most likely have a higher than average population growth rate. The increasing population of the YRD will place greater pressure on a number of the region's resources including the supply and quality of the water resources (section 3.2.4).

3.2.2 Land tenure and use

Land tenure and use of the YRD has been described in section 2.2.7. However, one of the major consequences of land use for urban and rural development, both in the YRD and in the middle and upper reaches of the Yellow River, has been an increase in the occasions when the flow in the stream ceases and the channel dried. This phenomenon began in 1972. In the 1980s, the stream stopped flowing and the channel bed dried 1–2 times, lasting from several days to more than 10 days. In the 1990s, the frequency increased, the duration of no-flow conditions was prolonged, the first period of no-flow conditions was earlier, and the upstream distance increased. The annual average rate of discharge at the Lijin hydrological station since 1990 is 178 $m^3 s^{-1}$, 38% less than that in the 1980s (286 $m^3 s^{-1}$). The annual frequency of flow cessation and drying increased to 3–6 times and it lasted up to 2–4 months. In 1995, dry conditions reached to Jiahetan, a distance of 628 km. Table 11 lists the general information of stream cessation and drying in the Lijin hydrological station and the Xihekou hydrological station (Cheng & Xue 1997, Division of Policy & Shengli Oil Management Bureau 1994, Lu et al 1997).

Table 11 Stream flow cessation and drying in Lijin and Xihekou

Year	Lijin		Xihekou	
	No. of days	First day	No. of days	First day
1987	17	Oct 3	51	April 2
1988	13	June 27	59	June 18
1989	20	April 4	47	April 3
1991	14	May 16	54	May 15
1992	82	March 16	152	Feb 14
1993	61	Feb 13	82	Feb 11
1994	74	April 4	81	April 2
1995	119	March 4	154	Feb 20
1996	136	Feb 14	161	Feb 8

Another major consequence of the urban and industrial and rural land uses of the YRD is that of pollution. The water quality of the YRD is described in detail in section 3.2.4.

3.2.3 Oil and natural gas development

In the YRD, a dense network of oil and gas pipelines and distributing stations exists. The pipelines connect the oil fields with the big cities and industry. Some smaller oil fields are not yet exploited. At this moment, only two offshore oil fields, in the Bohai Sea, are exploited.

By exploration during the Eighth Five-Year Plan (1991–1995), the proven geological oil reserve of Shengli Oil Field increased by 0.5×10^9 t, and the proven natural gas reserve increased by 5.4×10^9 m^3. Approximately 160×10^6 t of crude oil was produced during this period, and the annual oil production was stabilised at approximately 30×10^6 t y^{-1} (Wang et al 1997b). The produced crude oil is mainly exported to oil processing factories in eastern China.

In the Ninth Five-Year Plan period (1996–2000), the annual increase of the proven oil reserve due to continued exploration is expected to be 0.1×10^9 t, and the annual increase of the proven reserves of natural gas is expected to be 1×10^9 m^3.

The exploitation strategies will include the following: stabilising the production of old oil fields, starting with production in less attractive oil fields (eg fields with a high water content, small fault fields, offshore oil fields), starting with production in new fields.

According to national planning, the total investment for the expansion of oil production will be 12 billion RMB (or 1.4 billion US dollars) during the Ninth Five-Year Plan period. The production of crude oil in 1996–2000 is expected to exceed the production during 1991–1995 by 23×10^6 t. The annual natural gas output has to be stabilised at a level over 1.1×10^9 m^3. The annual offshore oil production will amount to 2×10^6 t.

Dongying Municipality has grown from the establishment of Shengli Oil Field, and Shengli Oil Field is a resource based industry. In the previous central planning system, Shengli Oil Field produced mainly crude oil and sent the oil to other regions for processing into high value-added downstream products. In the future, the development of an oil refinery and downstream production activities must be supported at Shengli Oil Field, by expanding its 1.5×10^6 t heavy crude oil refinery to a 5×10^6 t capacity refinery, as well as producing downstream chemical products.

However, oil and natural gas resource development and use already result in significant pollution of the environment, as detailed in section 3.2.4 below.

3.2.4 Pollution

Although pollution is a direct consequence of the above three anthropogenic forcing factors, it is a sufficiently important issue to discuss separately. Pollution of the YRD can be divided into air quality, industrial solid waste, and water quality.

Air quality

The total annual amount of industrial atmospheric emissions in the YRD is approximately 27×10^6 m^3, of which 43.2% is emitted from crude oil production and processing, 36.7% from the generation of electricity via coal combustion or thermal utilisation, and 2.4% from the chemical industry (Mu et al 1997). The chief pollutants are sulphur dioxide (SO_2), reaching around 47 686 t y^{-1}, of which 9731 t originates from the petroleum industry. The other major air pollutants are smoke and dust, NO_x and CO, with annual emissions of approximately 18464, 7414 and 8760 t, respectively. The annual emission of hydrocarbons from the petroleum industry is approximately 2462 t.

Industrial solid waste

With poor treatment and a low utilisation rate, the amounts of industrial solid waste and urban waste have increased sharply. In 1994, the amount of industrial solid waste reached 71 × 10^6 t, of which only 20% was fully utilised. In the city outskirts solid wastes dumps contain approximately 120 × 10^6 t of waste. Occupying a total area of 11 000 ha. Oil residue, oil sludge, and other oily pollutants are the main sources of solid waste. Their untreated quantity reaches 65% of the total amount. Coal slag and power coal slag is mainly from industrial thermal and electrical power plants. Their untreated amount accounts for only 27% of the total (Mu et al 1997).

Water quality

In addition to the Yellow River there are many smaller rivers in the YRD. These rivers are fed by local rainwater and constitute a south-north water system to the Bohai Sea in the northern part of the YRD, and a west-east water system to Laizhou Bay in the southern part of the YRD. The south-north water system includes the local rivers – the Chaohe, Caoqiao, Tiaohe and Shenxiangou Rivers, and the regional rivers, the Zhimaigou and Xiaoqing. These rivers drain the rainfall surplus in the rain season and also urban and industrial waste water.

The various industries in the YRD produce over 40 × 10^6 m^3 of urban and industrial waste water annually (table 12), the majority of which is discharged into the sea through the local rivers. Waste water from outside the YRD, mainly from the cities of Jinan and Zibo, flows through the YRD to Laizhou Bay via the regional Xiaoqing River and Zhimaigou River, polluting the flood plain and the aquatic environment in the river, in their estuaries, in the adjacent tidal flats and the shallow sea.

Table 12 Industrial wastewater and its pollutants in the YRD

Industry	Discharge amount (10^4 T)	Rate of treatment (%)	Specific pollutants			
			COD (t)	Oils (t)	TSS (t)	Phenol (g)
Petroleum production	830	23.8	3266	197	718	11 115
Petroleum processing	168	81.9	248	65	134	1 415
Chemical	57	100.0	4	0	20	0
Paper	146	25.0	382	0	342	0
Thermal, electric power	385	99.7	173	1	88	43
Machinery electronics	87	88.3	36	2	15	2
Other	394	99.8	68	1	49	157
Total	2067		4123	266	1368	12 732

Surface water quality

Organic pollution is the main source of surface water pollution, and originates from those rivers whose complex index exceeds the 5th grade of the national water quality standard by over a factor of three. The detection frequency of organic pollutants such as BOD_5, COD and oil matter reaches 100%, while that of the volatile organic, phenol, is 90%.

Surface water near the city is heavily polluted. Water quality in Dongying town, through which the upper section of the Guangli River flows, has been slightly polluted, while the lower section is highly polluted due to urban and industrial sewage. In this region, four types of organic compounds exceed the national water quality standards. Consequently, it is urgent that the methods to control urban sewage water are tightened.

Surface water near industrial pollution sources has been polluted heavily. Water quality in the upper section of the Dongchun village of Tiaohe River is good, with only slight pollution. However, sewage from Shouzhan enters the river near the mouth, resulting in an increase in BOD_5 from 4.7 to 5.4 mg L^{-1}, COD from 143 to 442 mg L^{-1}, and oil matter from 0.303 to 0.721 mg L^{-1}. The water of the upper section of Shenxiangou River is supplied by the Yellow River through the west river mouth, so the water quality is good, and can reach the standard for recreational water. But the downstream reaches are polluted by effluent originating from paper product plants, with a resultant decline in water quality.

Water quality of the Yellow River and reservoirs

According to the 1990–1996 monitoring analysis on the Kenli profile, conducted by the Environment Protection Station of Dongying Municipality, overall water quality of the Yellow River is good (Division of Policy, Shengli Oil Management Bureau 1994, Geography Institute Academia Sinica et al 1991, Mu et al 1997). Concentrations of most chemical elements are within the 3rd grade of the national water quality standards (GB3838-88), except COD and oil matter, whose concentrations exceed the 5th grade of the national water quality standards. Thus, it can be concluded that although the water quality of Yellow River is good in general, it has already been polluted to some extent by such pollutants as oil. Table 13 details the surface water quality of local rivers in the YRD.

The concentrations of particular heavy metals in water of the reservoirs is as follows: the range of Pb is 0.002–0.003 mg L^{-1}; Cr(VI) 0.0075–0.015 mg L^{-1}; Cd 0.0017–0033 mg L^{-1}; and As 0.0017–0.0035 mg L^{-1}. These ranges are within the national drinking water standards.

Organic pollutants are detected in all the reservoirs of YRD. As far as the volatile organics such as phenol and cyanide are concerned, their rate is above 80%, a little below the 1st grade of the national water quality standards.

Dissolved oxygen (DO) in the reservoirs meets the 3rd grade of the national standards of surface water quality. DO in the reservoirs of Gudong, Guangnan exceeds 7 mg L^{-1}, thereby meeting the 2nd grade of the water quality standards. However, DO in the reservoir of Gubei is very low.

Ground water quality

The main feature of the groundwater of the modern YRD is a high mineralisation due to effects of high soil salinity and seawater. The salinity of the upper-layer water ranges from 7.7–67.5 g L^{-1}, with an average value of 24.6 g L^{-1}. The contents of different chemical components including positive and negative ions such as SO_4, Na, Cl and so on are 80% (Mu et al 1997, Division of Policy, Shengli Oil Management Bureau 1994, Geography Institute Academia Sinica et al 1991).

The concentrations of particular elements in the upper layer ground water, especially in some areas of the YRD, are higher than national standards for drinking water. These concentrations are mostly attributed to direct input from polluted surface waters. Due to the high salinity of the groundwater located to the north of Xiaoqing River in the YRD, it cannot be appropriated for use as a drinking water source.

4 Vulnerability assessment

This section assesses the current vulnerability of the YRD to existing forcing factors, and the future vulnerability of the YRD to predicted climate change and sea level rise. It is important that existing vulnerability is assessed in order to evaluate the significance of vulnerability due to predicted climate change and sea level rise. Essentially, it recognises that climate change and sea level rise represents just one of a number of forcing factors potentially impacting on a system.

Table 13 Surface water quality in the Yellow River Delta

Rivers	Section	Organic Pollutants (×)[1]	% over standard[2]	Water quality	Heavy metals (×)[1]	% over standard[2]	Water quality[3]
Xiaoqing River	Xiaoqiao	2.58	55.6	Serious pollution	0.462	0	20
	Shicun	3.71	66.7	Serious pollution	0.647	0	20
	Sancha	3.18	55.6	Light pollution	0.429	11.1	30
Guangli River	Dongyingcun	1.20	11.1	Heavy pollution	0.238	0	20
	Guangliqiao	2.20	44.4	Middle pollution	0.374	0	20
	Haigang	1.95	33.3	Middle pollution	0.197	0	20
Yihong River	Daoxiangcun	11.25	22.2	Middle pollution	0.502	20	40
	Kenlinan	1.59	33.3	Middle pollution	0.362	20	40
	Yangjichang	1.31	22.2	Middle pollution	0.587	20	40
Tiaohe River	Laoyemiao	2.08	22.2	Middle pollution	0.495	20	40
	Dongcuizha	1.11	13.3	Middle pollution	0.478	0	20
	Diaokouqiao	2.35	22.2	Middle pollution	0.232	0	20
Shenxiangou River	Gudaoxi	0.69	11.1	5th class water	0.228	0	20
	Wuhaozhuang	1.59	55.6	Heavy pollution	0.491	20	40
Zhimaigou River	Wangying	1.03	33.3	Middle pollution	0.386	10	30
Guangpugou River	Dongwanglu	1.35	11.1	Light pollution	0.450	20	40
Chaoqiaogou River	Sikouqiao	0.42	11.1	5th class water	0.219	0	20
Liupaigan River	Zhuanjinyicun	1.76	44.4	Middle pollution	0.476	20	40
Zi River	Dongzhou	23.60	44.4	Serious pollution	0.625	0	20

1 Average exceedence of the pollutant over the National Standard Class 5.

2 Percentage of samples whose pollution index surpasses the National Standard Class 5

3 Where 10: High-quality third class water; 20: High-quality fifth class water; 30: Fifth class water; 40: Low-quality fifth class water.

4.1 Vulnerability to current forcing factors

The YRD is very dynamic and depends highly on the fluvial process of the river. Historically, the river has shifted its channel regularly and frustrated long term development planning. The area is short of local water resources with the main water resource being the Yellow River. The Yellow River water is turbid and the annual discharge has decreased dramatically in the past decade due to water diversion from upstream reaches. Nevertheless, because the Yellow

River bed is several metres higher than the surrounding ground of the delta, floods including ice jam floods still pose a real threat to the local people. In addition, storm surges may induce seawater to flow inland for several tens of kilometres, inundating the coastal areas. Sea level rise could further exacerbate this (section 4.2). With the increase in economic development, water and air pollution have become more serious issues. Accordingly, sustainable ecological development of the delta requires stabilisation of the Yellow River channel, long-term strategies of water resources development, flood risk analysis and control measures, air and water pollution control and management and development of the wetland Nature Reserve (see sections 5 and 6).

According to the Ninth Five-Year Plan (1996–2000) and outline of the 2010 Long Term Target of Shandong Province for the period 2001–2010, the YRD will be developed at a large scale. Therefore, population pressure will increase within the YRD region irrespective of environmental change. This will be significant for the natural resources of the region through the demand for increased access to the resource base of the coastal wetlands. Strategic planning is required to address this problem at the biophysical regional level, and ensure that population growth and development can proceed in an orderly fashion and not degrade the significant environment values that underpin economic growth in the YRD. Major factors affecting the ecology and agricultural, industrial and economic development in the YRD and the life of the local people are the water resource, pollution, and storm surge and flooding, with the former possibly being the most significant. These are elaborated upon below.

4.1.1 Water resources

Impact of water resource utilisation on environment

The utilisation of water from the Yellow River affects the environment both positively and negatively.

The negative effects include: salinisation induced by irrigation percolation and by seepage from canals and reservoirs; occupation of land by water diversion works and reservoirs; displacement of inhabitants from submerged areas of reservoirs; impacts on coastal marine and wetland species due to a reduction of water and sediment flowing into these regions, and; desertification induced by the deposition of sediment from the diversion of heavily silt-laden flood water. Nevertheless, such effects on the environment can be reduced to the minimum by employing proper strategies.

The positive effects include: the development of industry and agriculture, improving water supply and enhancing the living standard of the local people; the development of forests and other environmental improvements; desalinisation of groundwater and prevention of salt-water intrusion due to the seepage of surface and irrigation water; localised climate changes such as increased humidity due to an increase in the water surface area; recreational use of surface water; improvement of soil quality due to the utilisation of highly silt-laden water from the Yellow River for landfill and ground level raising. In addition, to the south of the Xiaoqing River, water diverted from the Yellow River promotes the recharge of local ground water preventing groundwater depression.

Assessment of the water resources in the YRD

The YRD is poor in local water resources, with 314 m^3 per capita, much lower than the average values of Shandong Province (464 m^3 per capita) and all of China (2710 m^3 per capita). Nevertheless, the delta is rich in water resources derived from upstream. The water resources from the Yellow River are sufficient for long-term development of the area. The estimated discharge from the Yellow River for the years 2000 and 2010 is 4 and 3.6×10^9 m^3, respectively; both values are higher than the estimated demand for the corresponding years.

Nevertheless, most of this water flows to the delta between July and October. It is estimated that for a normal year the water available from March to June in the years 2000 and 2010 will be only 1.27 and 0.89 × 10^9 m^3, respectively. For a dry year, the corresponding estimates are 0.64 and 0.58 × 10^9 m^3. The highest water demand and water shortage occurs from March to June. According to the estimations of water demand by Dongying Water Resource Bureau, the water shortage in the dry season in the years 2000 and 2010 will equal 395 and 651 × 10^6 m^3, respectively. Measures to counteract this are discussed in sections 5 and 6. However, the present water shortage is not due to a lack of water resources but instead, from inadequate diversion and storage capacity. The shortage could be eased or solved by the construction of new hydraulic works, although significant investment would be required (sections 5 and 6).

Associated with the diversion of water for irrigation along the middle and lower reaches of the Yellow River has been a reduction in sediment discharge. In the Yellow River, the annual sediment discharge of the Yellow River has decreased from 11 × 10^8 t to be 9.5 × 10^8 t. It is estimated that more than 1.5 × 10^{10} m^3 of water per year has been taken from the Yellow River for irrigation over the last decade, representing about 1.74 × 10^8 t of sediment per year. The increasing diversion of water for irrigation and other purposes over the next decade will withdraw further sediment from the Yellow River.

The water demand in the YRD will reach a maximum value of 3.5 × 10^9 m^3 in 2010, assuming that water conservation measures will work and water demand per capita and per area farmland will reduce. The implication of this is that 91% of the estimated river flow will need to be extracted in 2010. The population of the delta is predicted to be 2.1 × 10^6 by 2030. If the water demand remains at 3.5 × 10^9 m^3 from 2010 to 2030, the water demand per capita will equal 1670 m^3, substantially higher than that of developed countries (about 1000 m^3 per person). At present, the water consumption per capita in the delta area is 979 m^3. This is much higher than the average value for China of 450 m^3 per capita, but lower than the average values for USA (2316 m^3 per capita), Canada (1507 m^3 per capita), Russia (1307 m^3 per capita) and Italy (986 m^3 per capita). As the increasing cost of land will most likely prevent the construction of more reservoirs, water conservation measures will become increasingly important.

During 1995 and 1996, the stream was dry for almost half a year, which coincided with the maximum season of water use (table 11). As a result, the crop production in Dongying decreased by about 5 × 10^6 kg; and about 117 000 ha of irrigation area and 1 million people were affected. It also caused the loss of a billion Yuan in industry and 10 million Yuan in agriculture. Moreover, the shortage of water resources most probably induced over-exploitation of the ground water, possibly leading to problems such as salinisation and alkalisation in soil. About 153 000 hectares of national conservation area are also affected by stream dessication. The shortage of available water resources has become an important restriction towards sustainable development, and the conservation of the coastal wetlands and Natural Reserve in the YRD.

The water quality of the Yellow River is sufficient for irrigation and urban use, being qualified as second class water. However, river water in other areas of the delta is qualified as fourth class and fifth class, while the groundwater resource is polluted by salt water and polluted surface water. Thus, the Yellow River, is now also threatened by increasing pollution. The pollution index of the Yellow River is 12.4 and that of other rivers is also higher than 10. Serious attention needs to be paid to the control of pollution of the region’s water resources. Pollution of the YRD is further discussed below.

4.1.2 Pollution

As the YRD is located on the coast of the Bohai Sea, the air capacity is enlarged by the effects of sea-land breeze and air exchange. Thus, air pollution generated from Dongying City does not remain in the region for long periods. As a result, the general air quality in Dongying is good, not exceeding the standard air quality limits. However, with economic development and an increase in population, air pollution may become a significant factor.

As detailed in section 3.2.4, the water quality of the Yellow River is generally good, but not so for the YRD as a whole. According to the monitoring results from Kenli section from 1990–1994, the contents of most chemical elements are within the state standards of 3rd class water quality (GB3838-88), except the excessive contents of COD and oil matters whose values exceed the state standards of 5th class water quality (Environmental Monitoring Station of Dongying Municipality 1994). Thus, it can be concluded that although the water quality near the river month is generally good, it has been lightly polluted by such organic pollutants as oil in some way.

The concentrations of heavy metals in sediments of the rivers such as Xiaoqing River and Zhimaigou River are higher than that of heavy metals in sediments of other rivers in China, especially for Cr and Pb, which range from 1.5 to 5 times higher than the average high values of national and foreign rivers. While, the concentrations of Cu, As, Zn and Ni are within the average range, they are mostly in the upper limits of the range. Given this, it is essential that more attention be paid to the problems of heavy metal pollution in the YRD.

Due to the influences of saline soil and seawater, the main feature of the groundwater is high salinity. The salinity of upper layer water is 7.7–167.5 g L^{-1} with an average value of 24.6 g L^{-1}. The concentrations of pollutants in the groundwater upper layer are higher than the state drinking water standards. The groundwater in most place of the north side of Xiaoqing River is not suitable for exploitation as drinking water. Groundwater quality in the south side of Xiaoqing River, where salinity is less than 1 mg l^{-1}, is good and can be used for well irrigation. From 1975 to 1993, the groundwater level decreased rapidly from 7.6 to 11 m, due mostly to uncoordinated water usage.

Problems of water pollution have become more and more complex. Many industries are allowed to discharge sewage without any form of treatment. However, the development and construction of sewage treatment facilities requires large investment. With further urban development, the domestic sewage output will increase rapidly. According to the plans for city development and growth of industrial production, sewage discharge will increase 8.2% by 2000. Therefore, by the end of this century, if untreated, its discharge will reach 6.1×10^6 t, and then 6.56×10^6 t in 2010.

4.1.3 Storm surge and flooding

Hazard and risk are viewed as key issues as they relate to physical impacts on the natural and built environment. These terms are often applied to assessments of the effects of extreme events, be they natural or human-induced. For example, there are hazards arising from storm surge events which may place property and people under varying degrees of risk depending on the nature of the event and the location or circumstances of the property or person. In turn, hazardous conditions place property, people and plant and animal communities at risk. That is, life and location at risk in a hazardous situation have a probability of being lost, destroyed or damaged.

Storm surge often occurs in the coastal area of the YRD in spring. In the past 100 years, storm surges with heights over 3.5 m (Yellow River system) occurred six times, in 1845, 1890, 1938, 1964, 1969, and 1992. The storm surge induced seawater to flow inland for several tens of kilometres. The stage in the river is often much higher than the ground level because the ground elevation along the coast is only 1–2 m (Yellow River System). According to recorded data, the 1 in 100 years, 1 in 50 years and 1 in 10 years storm surge heights are 3.93 m, 3.70 m and 3.10 m, respectively. They threaten the delta seriously. Embankments along the coast line protect the coastal wetlands, except to the south of the river. The elevation of the embankments is 4.9 m. To the south of the river the coastal dykes are unable to protect the land against storm and tidal surges. The system is vulnerable, especially if a storm surge coincides with a typhoon. Therefore, it is important to strengthen the embankments.

Several other factors make the YRD more susceptible, and therefore vulnerable to flooding. The gradual increase in sedimentation at the river mouth, and the closed dykes built to protect the oil fields and the Nature Reserve, both reduce the flood discharge capacity of the river, increasing flood risk. In addition, the delta flood control system as a whole may not be strong enough to control a 1 in 100 year flood; the newly constructed dykes have yet to experience high floods, while many of the dykes to the south of the Yellow River are weak and require reinforcing. Finally, continued urban and industrial development within the YRD will simply serve to increase the amount of infrastructure and people at risk.

4.2 Vulnerability to climate change and sea level rise

Based on the range of sensitivities of climate to changes in the atmospheric concentration of greenhouse gases (Watson et al 1996) and plausible changes in emissions of greenhouse gases and aerosols, climate models project that the mean annual global surface temperature will increase by 1–3.5°C by 2100, and that changes in the spatial and temporal patterns of precipitation would occur. The average rate of warming probably would be greater than any seen in the past 10 000 years, although the actual annual to decade rate would include considerable natural variability, and regional changes could differ substantially from the global mean value. These long-term, large-scale human-induced changes will interact with natural variability on a time scale of days to decades (eg El-Niño phenomenon) and thus influence social, cultural and economic well-being. This is discussed below.

4.2.1 Climate change

As stated in section 3.1.1, climate warming might induce a drier climate in China, particularly in winter, spring and autumn. As a result of this, the mean agricultural yield in the YRD would probably decrease due to reduced water availability. This means that by 2050, the net balance between precipitation and evaporation would be negative and moisture stress would be more severe than today, although precipitation by 2050 would increase somewhat. Therefore, the probable impact of climate warming on agricultural production in the YRD region would be unfavourable.

Climate warming may cause an increase in the frequency of the occurrence of typhoons and storm surge. Scientific research indicates that the frequency of occurrence of typhoons along the Chinese coast may increase by a factor of 1.76 each time the air temperature rises by 1.5ºC (Wang & Tong 1992). According to IPCC (1995), there could be an increase of 3–5 ºC in air temperature in the next 100 years. If so, the frequency of occurrence of typhoons along the Chinese coast could increase by a factor of 3.5.

The coastal system is economically and ecologically important and is expected to vary widely in its response to changes in climate and sea level. Climate change and sea level rise or changes in wind and storm surges could result in the erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in the mouth of the Yellow

River and the Laizhou Bay, changes in sediment and nutrient transport, a change in the pattern of chemical and microbiological contamination in the mouth and the coastal areas, and increased coastal flooding. Some coastal ecosystems are particularly at risk, including saltwater marshes and coastal wetlands. Changes to these ecosystems would have major negative effects on tourism, freshwater supplies, fisheries, and biodiversity. Such impacts would add to modifications in the functioning of coastal oceans and inland waters that already have resulted directly from pollution, physical modification, and material inputs due to human activities.

The warming of the climate or the 'greenhouse effect' will have a significant influence on agriculture in the YRD region. The direct results of climate warming are the increases in evaporation, saturation deficit of the air, wind velocity and the variation in high-wind days, which, in turn, will lead to a decrease in the retention of rainfall in soil, thus extending drought periods. In addition, as these natural hazards intensify, the growth of crop plants will be seriously influenced, leading to a decrease in production and quality of the farm products.

Furthermore, climate warming may lead to an increased incidence of plant diseases and insect pests, as follows. Firstly, as the temperature in winter becomes higher, insect pests and viruses could better survive the winter season, hence leading to an increase of the initial number of insect pests and viruses. Secondly, the high temperature in winter may also lead to a decrease of the hibernation stage of pest species. As a result of the increased initial number of pest species, and their extended plague period, the probability of harm to farmland increases.

In summary, an increase in mean surface temperature will cause the following problems to agriculture in the YRD region: (1) instability of agricultural production, an increase in the occurrence of meteorological hazards to farming and an increase in plant diseases and insect pests leading to a decrease in crop production and the quality of the products; (2) patterns and structures of agricultural production systems will have to be changed, and some practical adjustments made; (3) farming conditions will be changed, which will lead to a great increase in the cost of farming.

4.2.2 Sea level rise

Climate warming is predicted to cause a rise in sea level in the recent YRD region. The estimated relative sea level rise rate in the YRD is 8 mm y^{-1} and the sea level rise could be 48 cm by the year 2050 (table 10). This will lead to critical impacts such as the frequency/intensity of storm surges and El-Niño events, beach erosion and landward retreat, wetland loss, salt water intrusion and land salinisation.

Sea level rise will result in a higher base from which storm surge forms. The sea level rise will probably increase the impacts resulting from wind and storm surge. If a sea level rise of 48 cm occurs along the coast of the YRD by the year 2050, one in a hundred year wind and storm surges would become one in fifty year events, and in some cases, one in ten year events. Therefore, coastal erosion and the loss of existing beach areas will increase. The coastline will retreat many tens of kilometres, and the coastal wetlands and Nature Reserve area will be damaged or possibly disappear. In the vicinity of the Yellow River estuary, coastal retreat in the past years was around 36 m y^{-1}. Along the abandoned coast of the Diaokou River coastal retreat was 2–5 km from 1954 to 1980 and the total eroded area was 65 km^2. While such coastal erosion has generally been a result of natural evolution, more recently, sea level rise has facilitated the retreat in some coastal sections.

Relative sea level rise also leads to a higher lowest water level in coastal areas. As a result, it could partly or even completely paralyse the existing drainage system designed for the present discharge of water from the region. If the future relative sea level rises 48 cm, the drainage systems of the YRD will be shortened for 5–10 hours. Consequently, large amounts of water and sediment will be retained in the hinterland. Sea level rise also lowers the level of capacity of the existing disaster prevention facilities (eg dykes). If sea level rises 0.5–1 m, the actual flood control functionality of the flood prevention walls along the Yellow River and the coast of the YRD will be degraded from the protection level of 'one in a hundred years' to 'one in ten years' or even 'one in five years'.

Sea level rise also implies the raising of the level of mean erosion plain of the river and the alteration of the hydrodynamic conditions in the Yellow River mouth. Thus, sediment siltation in the lower reaches of the river and estuaries will be accelerated. Hence, drainage will not be effective during flood seasons in the areas with a number of river outlets, while the siltation rate will be faster if tidal gates are constructed at the outlets.

Sea level rise will increase the water depth of the submarine coastal slope, and gradually decrease the winnowing action of waves on submerged coastal sediments, but erosion on upper beaches by breaking waves is likely to be enhanced. At the same time, the slopes of riverbeds will be reduced, decreasing fluvial sediment discharges. However, human impacts involving diversion of river discharge for urban water supply, and the construction of dams for irrigation, have also decreased sediment discharges enormously (section 4.1.1). As a result of both natural and human influences, a reduction in sediment supply to the coastal zone is a world-wide phenomenon, and one that will be further enhanced when combined with increased frequency of storm surges and El Niño events accompanying climate change and sea level rise.

The coastal region of the YRD with a mean present elevation lower than 2 m covers an area of more than 4000 km^2, more than 60% of which is waterlogged or partially waterlogged lowland. So, in the coastal region, particularly low-lying land, impacts from typhoons and storm surge will be greatly intensified by a rise in sea level. The frequency of flooding, inundation of low-lying land and level of destruction will increase. Thus, sea level rise and associated factors will cause some part of the coastal zone and low-lying land to be submerged or turned into wetland. Estimates indicate that as a consequence of a 1 m sea level rise and storm surge of 2–3 m, about 40% of the YRD area (301 300 ha) will be inundated. Whether the coast will really be submerged in the future depends not only on the relative sea level rise but also on the protection facilities such as coastal dykes in the area (sections 5 and 6). However, it is certain that sea level rise will increase the risk of submergence of coastal wetlands.

An increase in sea level will exacerbate the current severe problems of tectonically and anthropogenically induced land subsidence in the YRD. Saltwater intrusion into aquifers and surface waters in coastal areas also would become more serious. The destruction of precious fresh water resources in coastal areas resulting from relative sea level rise will exert an adverse impact both on the lives of coastal inhabitants and on industrial and agricultural production. This kind of phenomenon has occurred in the YRD coastal zone and the coastal cities along the Yellow Sea and Bohai Sea. In the Laizhou Bay Plain, to the south-east of the YRD, the rate of salt water intrusion has increased from 90 m y^{-1} in early 1980s to 400 m y^{-1} at present (Mo et al 1995, Li & Xue 1993). According to an investigation conducted in the Laizhou Bay, a total of cultivated land of 333 km^2 has lost its irrigation capability and 40 km^2 has turned into salinised land in the past several decades, dropping the local agricultural production by 20–40%. Sea level rise will increase the intrusion of salt water upstream along the Yellow River, resulting in the expansion of estuarine areas in the upper reaches. It will not only increase the salinisation of water in estuarine areas, but also degrade the aquifer and ground water quality on both banks of the river.

By using the Bruun rule, the response of major tourist coastline in the Yellow River Delta Natural Reserve has been estimated. It is predicted that it will lose more than 80% of its present area if sea level rises to 48 cm by the year 2050. Protection and nourishment of the Nature Reserve beaches provide the principal management solutions to these problems.

The continuing rise of sea level at the rate of a few millimetres per year, although not threatening spectacular damages of the sort described earlier, is still important. The situation will be aggravated if sea level rise increases by the amounts predicted to accompany global warming in the future. The YRD, a developing region with about 2 million people living in the low-lying land of the coastal areas, is especially vulnerable to future sea level rise. Many people will be affected, and direct and indirect economic losses and mitigation activities will pose serious financial burdens. Of course, whether disasters caused by sea level rise will occur in the YRD depends on several factors, ie not only the sea level rise, but also the adequacy of the local protection facilities, local vertical crustal movement and so on. Hence it is very important for the relevant authorities to conduct a disaster/hazard evaluation for the area now, in order to formulate a specific policy and corresponding measures for the reduction of prevention or possible disasters from the sea level rise in the area.

5 Current responses to existing forcing factors

5.1 Storm surge and extreme wave

5.1.1 Analysis of the consequences of storm surges

Figure 12 shows the calculated inundated areas by storm surges. The estimated inundated areas for several storm surge intensities are shown in table 14. The inundated areas are large because the landscape is flat with minimal changes in altitude.

Table 14 Storm surge influence in the YRD

Position	5 years WSS		10 years WSS		50 years WSS		100 years WSS	
	ESS (m)	NDH (m)	ESS (m)	NDH (m)	ESS (m)	NDH (m)	ESS (m)	NDH (m)
Yangjiaogou	2.81	4.0	3.04	4.3	3.54	4.8	3.75	5.0
Shenxiangou	2.22	3.4	2.39	3.6	2.92	4.1	3.29	4.1
Chaohe	2.60	3.8	2.81	4.0	3.46	4.7	3.46	4.7
Flooded area (km^2)	1355		1442		2672		2952	

WSS: Wave storm surge

ESS: Elevation of storm surge

NDH: Necessary dyke height

5.1.2 Control of storm surges

The tidal dyke in the north of the YRD can withstand assaults of one in 20 years storm surges. However, in the east of YRD there are only low and broken tidal dykes. There are no tidal dykes in Guangrao County. Therefore, the east part of the YRD is under the threat of storm surge. To safeguard the delta against sea surges, the tidal dykes in the east part must be completed and enhanced. Table 15 presents designed crest elevations of tidal dykes against sea surges of different frequencies.

Table 15 Designed crest elevations of tidal dykes against storm surges of different frequencies

	Sea surge frequency					
	0.002	**0.01**	**0.02**	**0.05**	**0.10**	**0.20**
Yangjiaogou	5.5 m	5.0 m	4.8 m	4.5 m	4.3 m	4.0 m
Shenxiangou mouth	4.5 m	4.1 m	4.0 m	3.8 m	3.6 m	3.4 m
Chaohe mouth	5.1 m	4.7 m	4.5 m	4.2 m	4.2 m	3.8 m

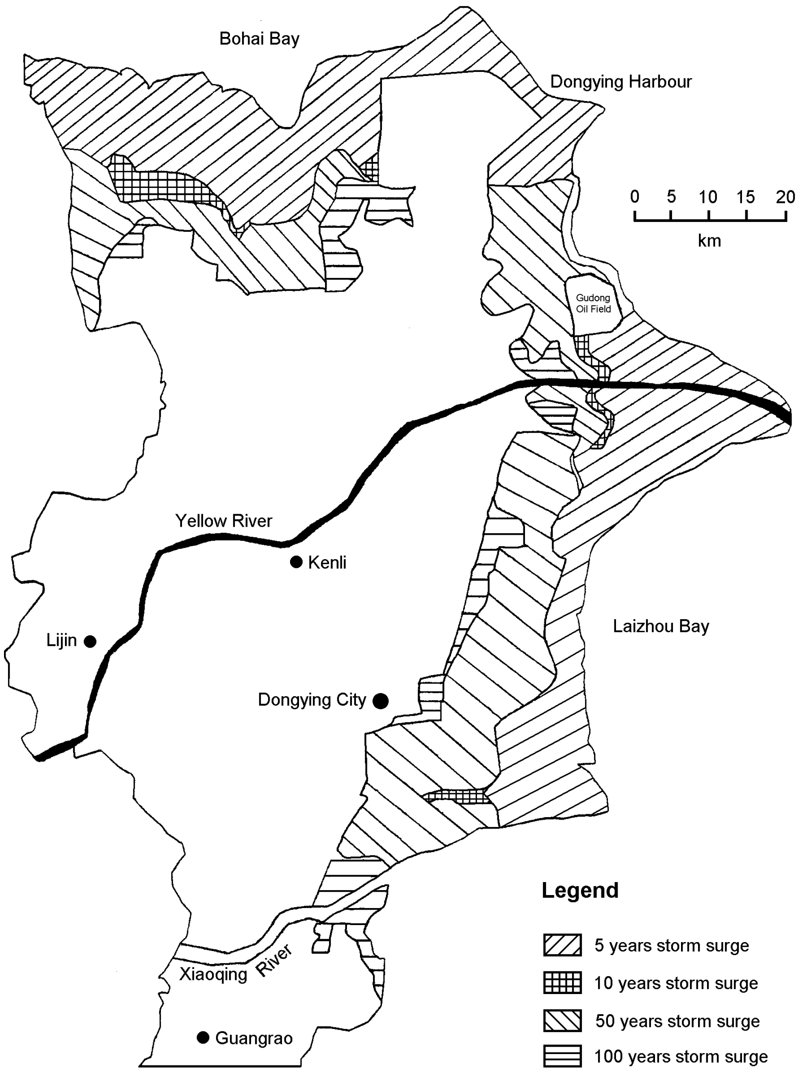

Figure 12 Areas inundated by storm surge in the YRD

5.2 Stream dessication and water resource shortages

The YRD area experiences seasonal shortages in water supply for agricultural purposes. Major strategies to overcome this include optimisation of river flow, enhancing water utilisation efficiency, taking water conservation measures, constructing more reservoirs and diversion engineerings, and greater utilisation of silt-laden water during the flood season. Strategies for different districts should be selected according to local situations.

From the long-term development perspective, the utilisation of highly sediment charged flood water from the Yellow River is the main strategy and should be studied further. Irrigation quotas for the Dongying Municipality are considerably higher than those of Shandong Province (table 16). Therefore, there is a great capacity for the farmers in the delta to save water in irrigation practice and enhance water use efficiency.

Table 16 Comparison of irrigation quotas at the Provincial and Municipal level (m^3 ha^{-1})

Water source	Dongying Municipality		Shandong Province (Agric. Dept)	
	2000	2010	2000	2010
Canal	5 670	5 670	3200–3880	2660–3200
Paddy field	16 200	15 150	11 250	9750
Pumped well	3 255	3 210	2340–3045	2790

The present capacity of reservoirs in Dongying Municipality is 485×10^6 m^3. This is planned to increase to 769×10^6 m^3 by 2005 and to 1125×10^6 m^3 by 2010 (Ninth Five-Year Plan and the development plan for the period 2001–2010). Thus, water shortage is not anticipated to be a major obstacle to economic development.

5.3 Flooding

Since 1949, the government has paid particular attention to flood control in the Yellow River basin and to marine hazard control along the coast of the YRD. Flood control for the delta had been listed in the Comprehensive Plan of Flood Control in the Lower Reaches of the Yellow River. Following development of the local economy, especially the Shengli Oil Fields, the flood and marine hazard control system was reinforced on an ongoing basis. This system comprises the following (Zhang et al 1997, Lu et al 1997):

Flood control system

The dykes upstream of Siduan are natural dykes and have been enhanced three times since 1949. The third dyke enhancement was completed in 1985 and is capable of controlling a 22 000 m^3 s^{-1} flood at HuaYuankou, and a 10 000 m^3 s^{-1} flood downstream of Dongping Lake. The dykes between Aishan and Siduan were designed according to 11 000 m^3 s^{-1} flood stage with a freeboard of 2.1 m. Downstream of Siduan the South Dyke, flood control dyke, North Dyke and East Dyke were constructed one by one. The dykes were designed to control a 8000–11 000 m^3 s^{-1} flood with a freeboard of 0.8–2 m. In addition, the Nanshan dyke on the south bank of the river at Lijin, and the Xiaojie flood retention basin strengthen the flood control system and safeguard the oil fields. In addition,the government has proposed a plan to stabilise the current channel of the Yellow River for 100 years.

Wind storm surge control system

In the period 1982–1997 the Shengli Oil operators built long dykes at several places to protect the oil field against wind storm surges. The dykes have since been linked to form a continuous structure capable of protecting against a one in one hundred year flood event. The dyke crest was enhanced several times and it is now 3.5–4 m (the Yellow Sea system).

Ice-jam flood control system

The major measures for controlling ice-jam floods are (1) to break the ice cover by explosion, bombing by air and ice breaker vessels; (2) to operate the Sanmenxia Reservoir, also the Xiaolangdi Reservoir in the future, to release 800 m^3 s^{-1} discharge at the beginning of the ice/frozen season. In this way the onset of freezing can be delayed and the thickness of the ice cover is decreased, maintaining a larger wetted area beneath the ice cover. In spring when the ice cover begins to melt, the released discharge from the Sanmenxia Reservoir is controlled below 200 $m^3\ s^{-1}$; (3) ice flood diversion projects, such as Xiaojie and Nanshan flood diversion projects. The Nanshan flood retention basin can be used for flood control and ice-jam flood control.

Drainage system

The drainage system consists of 11 rivers, including the Chaohe River, the Zhanli River, the Shenxiangou to the north of the present Yellow River, and the Guangli River, the Zhimaigou River, and the Xiaoqing River to the south of the Yellow River. The discharge capacity of the Xiaoqing River and the Zhimaigou River is 360 $m^3\ s^{-1}$ and 491 $m^3\ s^{-1}$, respectively. The Dasun and Qinghu gates in the Nanshan dykes share a total drainage capacity of 87 $m^3\ s^{-1}$.

Moreover, the First Phase Engineering Project, when it is completed, will greatly enhance the flood control capacity for the delta. As a result of living with flood risks, the local people of the YRD have accumulated experience through their flood control practices. They understand the laws of flood propagation and can take emergency measures to reduce flood damage if necessary. In addition, as the local economy grows, it will be more capable of funding flood control measures, such as river dredging and dyke reinforcement.

6 Future responses to climate change and sea level rise

6.1 Environmental monitoring

Environmental monitoring is required in the YRD to provide data and information for: i) further understanding of the processes and extent of environmental change; ii) development of management strategies and action plans; iii) implementing management prescriptions; iv) auditing the effectiveness of management actions; and v) assessing the performance of the overall management processes.

Management of the coastal wetland and Nature Reserve of the YRD requires that effective monitoring programs are implemented and that the results are effectively utilised. Monitoring of ecological change in wetlands can be undertaken at several levels and with vastly different techniques. Satellite imagery, often linked to a GIS, aerial photography, flora and fauna surveys at the species and community levels, physico-chemical analyses and biomonitoring of the coastal wetlands of the YRD and the Yellow River all have particular advantages and disadvantages.

Monitoring also encompasses social, economic and cultural dimensions of change in the coastal zone of the YRD. Social science survey techniques are needed to monitor levels of awareness and community attitudes to the effects of environmental change. Such work should be undertaken in a manner to ensure that the biases do not overwhelm all community interests, as well as to ensure that there is a high level of community involvement in ongoing assessment of environmental change.

Apart from monitoring to assist with maintenance of the intrinsic values of the region, there is a need to provide national and international benchmarks from which to measure changes in the East Asian Monsoon environment in Chinese coasts. The east China coasts, and especially the YRD, provide an excellent opportunity for the establishment of a Coastal Wetland Environmental Reference Center for the coastal regions with the East Asian Monsoon. The circumstances that make this region special are that it has a sound history of research, and that there is a considerable body of material that could be collated and synthesised to provide baseline descriptions of the essential characteristics and attributes of change in this type of environment. The State Administration of Oceanography, China (SAOC) and Yellow River Delta Conservation and Development Research Center (YRDCDRC) have a considerable infrastructure already in place to facilitate continuous measurement of climatological and hydrological parameters, and a number of permanent sampling stations have already been established.

6.2 Counter measures and strategies

The strategies for environmental protection and sustainable development of the YRD are listed as one of the two main national development strategies in the Ninth Five-year National Economic and Social Development Plan and 2010 Long Term Target. However, there is still much work to be done in order to implement the strategies. It is recommended to integrate sound environmental planning in the governmental planning documents and there is also a need to improve the environmental monitoring system, particularly for the nature preservation zone in the YRD. Learning from international experience is useful, and Japanese experience on monitoring the natural environment is quoted below, for reference.

In Japan, environmental monitoring of various parameters of the environment is conducted with systematic networks consisting of a number of monitoring stations, which cover the whole country. Although China's National Bureau of Environmental Protection has also established such monitoring stations, the monitoring of the natural environment in China needs further strengthening and improvement. The Japanese experience of 'Green Census' is extremely useful for reference in providing basic data on management of natural environment.

Specific recommendations for future responses and strategies towards recognising, understanding and managing for the potential impacts of climate change and sea level rise are presented below.

1. Implement a system of monitoring sea level rise, environment and management

The environmental protection mechanisms of Dongying Municipality and Shengli Oil Field include quite good monitoring systems for environmental pollution. However, their capability is still weak in monitoring of changes in the ecological and physical environments. Therefore, it is necessary to develop and implement the following monitoring stations and information systems:

- A system of monitoring sea level changes and coastline evolution, ie an integrated survey system between sea and land on the same datum plane (mean sea level of the Yellow Sea) by using standard methods for remote sensing, geographical positioning systems and GIS.
- Fixed tide-gauging stations in the Yellow River mouth region and along the coast of the Nature Reserves.
- A number of fixed monitoring stations for the ecological environment in the coastal zone that is most sensitive to environment changes.
- A dynamic monitoring system equipped with advanced technology and methods such as remote sensing GIS, which can provide information and early warning of environmental effects in time.
- Earth digital information system that includes data about natural, social, economical and cultural attributes at every important site of the YRD and the coast of the YRD.

2. Harnessing the mouth and tail course of the Yellow River

Continued efforts to stabilise the mouth and tail course of the Yellow River are needed to enable ongoing regional development. Although the quantity of water and sediment flowing from the Yellow River's upper and middle reaches has decreased markedly in recent years, resulting in longer dry periods in the lower reaches, the Yellow River's flood peaks during the flood season still place the YRD under relatively high flood risk.

3. Consideration of flood risk in urban and industrial planning

The layout of local economic development should be based on flood risk analysis. Industries should be arranged in the zones with less flood hazard. If a zone of high flood hazard is needed to develop industry or important economy, a flood control dyke system capable of controlling floods and wind and storm surges needs to be constructed. Although the flood control system of the YRD has been greatly reinforced, the sustainable development of the YRD and protection of the coastal wetlands require higher standard flood control systems and more studies on risk analysis and flood control strategies.

4. Protection and management of coastal wetlands and the Nature Reserve

The YRD, most of which is in relatively primary condition, boasts the youngest estuary wetland ecosystem in the world. The conservation status of this area aims to protect the newly formed wetland ecosystem and rare birds in imminent danger. It plays an important role in protecting and maintaining the ecology of the region, and is also a valuable site for carrying out scientific research. A major aspect of this recommendation is the need to monitor the waterbird (both migratory and non-migratory) populations.

The Nature Reserve of the YRD is located in a high risk zone of storm surges. The construction of dykes should not disturb the environment of the Nature Reserve. It is suggested that a flood diversion channel through the Nature Reserve may favour the fresh water ecological environment.

5. Vegetation belts and eco-forestry

Development of vegetation belts should be continued. These include the Chinese Tamarisk forests close to the shore and coastal protection forest belts, shelterbelt forests along the great dykes of the Yellow River and the branches of other river systems, forest belts in farmland, and greenery patches and parks in cities and towns.

6. Effective urban and industrial pollution control

The Shengli Oil Field, local industries, villages and township enterprises all have the responsibility to control pollution. All waste water must meet the relevant standards before being discharged. Particular attention should be given to the Shenxiangou River, Yihong River, Guangli River, Xiaoqing River and other rivers, which have been seriously polluted.

7. Water conservancy project system of irrigation-drainage-storage-prevention

The establishment of reservoirs on the plains of the YRD should be a priority. In addition, the irrigation and drainage network should be sufficient to make full use of the water and sand resources, to drain salt water to prevent salinisation, and to lower the underground water level. At the same time, tidal barrages along the sea beach need to be built and existing ones repaired. Such measures will help alleviate the problems of soil salinisation and impacts of natural disasters.

8. Increase community awareness of environmental protection

The nation's awareness of, and concern over the ecology and environmental protection of the YRD must be increased. We propose that activities for eco-environmental protection should be sponsored jointly by the Propaganda Departments of Dongying City and Oilfield, the Education Bureau, the Environmental Protection Bureau, the YRD National Nature Reserve Management Bureau, and the Broadcasting and Television Station. Geography and biology teachers should be at the forefront of development of a popular science network. There is a need to increase community awareness of the environmental issues associated with the development of the YRD, including those related to climate change and sea level rise.

6.3 Management of the YRD Nature Reserve

It is an extremely difficult task to effectively administer the Nature Reserve of the YRD. Firstly, the ecological environment is very vulnerable; secondly, the YRD has just started to be comprehensively developed on a large scale. The local people have a strong desire to develop the economy. Petroleum recovery is what the country needs urgently and is the potential pillar of economic development. So there is a striking contradiction between environmental protection and economic development. In addition, random cultivation and herding, burning grass on wasteland and hunting make it even harder to manage the Nature Reserve.

In order to administer the Nature Reserve scientifically and effectively, the following recommendations are proposed:

1. Develop an administrative system and effective management patterns

In addition to the development of an administrative system within the Administrative Bureau of the Nature Reserves, a United Protection Committee of the Nature Reserve should be established. The municipal government, together with Shengli Oil Field, Agricultural Bureau, Husbandry Bureau, Fishery Bureau, Land Bureau, Environmental Protection Bureau and the Bureau of Public Security should take important problems concerning nature protection into consideration before decisions are made. In addition, they should address and manage as best as possible the contradiction between protection and development and the relationship between each aspect and the Nature Reserve.

2. Draft and implement laws and regulations and administer legally

Lay down concrete laws and regulations for the protection of the Nature Reserve in accordance with the laws for nature protection made by the state.

3. Separate time and space – multi-use administration

Wetlands can be used in many ways as resources. With protection as the main task, the Nature Reserve should develop a more diversified economy to become powerful economically, and hence to promote development of nature protection. The key to the relationship of a diversified economy and nature protection is the separation of time and space. At present, the Nature Reserve is divided into a core zone, buffer zone and experimental zone. Landscape management measures, such as fixed tourist routes, cutting of reed separately and seasonal closure of the Nature Reserve during nesting need to be implemented. Given the presence of oil in the Nature Reserve, strict environmental guidelines need to be developed. If oil recovery is to be continued and further developed in the reserve, industry should control oil pollution strictly, limit the amount and land use for oil wells and improve technology and working practices as far as possible. Funds could be established for nature conservation, to be fed into environmental management of the region and the further conservation and development of the Nature Reserve. Some ecological compensating measures also can be implemented. For example, the establishment of another ecological environment of the same type and same area elsewhere, for balance of resources.

4. Strengthen scientific research to provide a basis for management

It is necessary to set up fixed observation stations and an ecological monitoring system. As well as the study of natural science, effective nature protection is the combination of applied ecology and social science.

5. Enhancement of people's consciousness of ecology and environmental protection

The Nature Reserve, or more specifically the Nature Reserve Management Bureau, should make contributions to the enhancement of community awareness of ecology by means of publicising popular science, undertaking or promoting teaching practice at colleges and high schools, and ecological tourism. It should set a good example through self-development and encourage local community involvement in protection and management, such as working as bird protectors.

6.4 Proposals for future research

1. **Monitoring of the Yellow River mouth evolution and sea level changes and their effect on the YRD environment**
   - a To analyse, evaluate and forecast the transformation of the Yellow River mouth flow path and effect on the environment of sea and land areas made by the Yellow River's water and sand changes.
   - b To analyse, evaluate and forecast the impacts of future sea level changes (on the environment and economic development of the YRD) and to put forward further countermeasures.
2. **Study of land management, environmental improvement and disaster prevention and alleviation**
   - a Countermeasures for alleviation of disasters resulting from flooding and storm surge and the effect of sea level rise on low land.
   - b Engineering and biological protection of the YRD's eroded sections.
   - c Ecological restoration of degraded land.
   - d Cleaning and production technology of serious industrial pollutants.
3. **Study of biodiversity and natural conservation and management of coastal wetland**
   - a Ecological study of endangered and migratory rare birds.
   - b Protection and rational development and use of coastal wetland resources.
   - c Effect on the natural reserve made by harnessing the river mouth and developing oilfields.
   - d Coordinated development of the natural reserves and the YRD.
   - e Study of laws and regulations for management of natural reserves.

4. **Study of ecological agriculture patterns and sustainable development of large agriculture in the YRD**
   a. To study various kinds of ecological agriculture patterns suitable to the YRD through typical demonstration stations.
   b. Develop a scheme for land utilisation and optimisation on the basis of a sound cycle of ecology and high efficiency output.
   c. Transformation of salinised soil and efficient use of water and sand resources.
   d. Selection, introduction and breeding of salt-resistant tree species and suitable crops.
   e. Breeding and intensive processing of *Spirulina*.

7 Major conclusions

The study area of the project was the modern YRD where Dongying Municipality is located. The main scope included the coastal wetlands, the tidal flats and the submersed parts in the delta. The vulnerability assessment was based on an assessment of present, past and geomorphic changes in the coastal zone and predictions of likely further change. An ecological assessment was then superimposed. Information specific to the region was supplemented from studies carried out in adjacent coasts and bays. The assessment provided views of change at a biophysical regional scale for the coastal wetland of China, and for the Nature Reserve within the YRD as an example of a local scale assessment.

This vulnerability assessment was undertaken using a cause and effect framework. The approach used recognised that climate and sea level rise need to be examined in the context of the natural variability of the processes affecting the coastal wetlands of the YRD. Two sets of forcing factors have been identified – natural and anthropogenic (human). These affect natural, social, economic and cultural systems and result in a range of governmental responses.

The Yellow River is the river with the highest sediment contents of all rivers in the world. The YRD and the YRD Nature Reserve is the most rapidly expanding delta system and wetland region in the world. With its large areas of shallow sea and bog, abundance of wetland vegetation and aquatic biological resources, the Nature Reserve provides the birds with exceptional habitat for breeding, migrating and wintering. Therefore, the reserve has become an important ‘transfer station’ for north-east Asia and the western Pacific Ocean for bird migration.

The greatest asset of the YRD is its rich land resource, averaging 0.48 ha per capita, which is 5.33 times that of the Yangtze River Delta. In addition, there are land resources that are yet to be developed and utilised. There are also rich fisheries resources, while salt and halogen resources are also considerable. Major oil and natural gas reserves are the most important source of production of the YRD. The water resource comes mainly from the Yellow River. In recent years, river flows have decreased dramatically, and there are now serious seasonal shortages of water.

Understanding of biodiversity and nature preservation must be considered as one of the issues for the development of the YRD. Wetlands and other marshes, once considered as useless obstacles to economic development, are now recognised as an environmental resource for their great values in recycling chemical substances and their biological diversity. The wetlands of the YRD provide habitat for hundreds of species of animals and plants.

Petroleum exploration and production is a dominant factor for economic development of the YRD. However, this will continue to have adverse impacts on the Nature Reserve unless management practices are improved. The geological survey will affect the breeding of birds, fishes and shrimps. Spillage of petroleum, high voltage transmission lines, and highways and dykes, all have some negative impacts on the Nature Reserve. If oil recovery must be undertaken in the reserve, there should be strict guidelines regarding pollution control, minimisation of habitat loss, and ongoing technological improvements. Additionally, industry could be required to contribute funds that go towards the effective conservation and environmental management of the Nature Reserve.

Forcing factors impacting on the YRD include natural and anthropogenic factors. Major natural factors include climate warming and sea level rise, the East Asian monsoon, El-Niño events, sedimentation and erosion in the river and along the coast. Flooding and storm surge, phenomena caused by several of the above factors were also considered forcing factors for the purposes of this study. Major anthropogenic forcing factors include population increase, oil and natural gas development, land use, economic development and environmental pollution. These factors together will cause a series of hazards and risks such as disasters of wind and storm surges, coastal erosion and retreat, coastal wetland loss, floods and drought, salt-water intrusion and land salinisation, and a loss of biodiversity.

Climate change and sea level rise, as well as being natural processes, are also being significantly influenced by anthropogenic factors. The temperature in China could increase by about 0.88 ºC in 2030, 1.40 ºC in 2050 and 2.95 ºC in 2100, due to anthropogenically-induced climate change. Precipitation also could increase by about 2.6% in 2030, 4.2% in 2050 and 8.9% in 2100. These figures indicate that the change of temperature due to human activity might be much more obvious than that of the precipitation in China. The more warming, the more evaporation caused, potentially resulting in a drier climate in China, including the YRD, especially in winter, spring and autumn seasons. Predicted climate change and sea level rise could increase the frequency of occurrence of storm surges, typhoons, high-speed winds and El Niño events, which, in turn, could cause serious damage to the natural and non-natural resources of the YRD. Effects might also include drought and changes to the seasonality of precipitation in the upper and middle reach region of the Yellow River, leading to longer durations of stream dry out in the lower-reach of the Yellow River. However, given the potential increase in extreme events, flood hazards will still exist during storm periods.

A direct effect of an increase in mean global surface temperature is sea level rise. Although this effect will occur slowly and with a delay in time scale, it could result in major impacts. The predicted relative sea level rise rate in the YRD is 8 mm y^{-1} with a predicted overall sea level rise scenario of 48 cm by the year 2050 (table 4). Combined with storm surge and more extreme storm events, sea level rise will result in adverse impacts including beach erosion and landward retreat, wetland loss, saltwater intrusion and land salinisation, loss of infrastructure and agricultural damage. If the sea level rises along the coast of the YRD by 48 cm by 2050, a one in one hundred years recurrence of wind and storm surge would change into one in fifty years, and possibly even one in ten years. Sea level rise will also obstruct the drainage of water on land and urban and industrial runoff water of cities and towns, thereby increasing the incidence and magnitude of flooding and pollution. This would exacerbate the shortage of water both for industry and domestic use.

The Yellow River is the major source of water supply in the YRD region. With the economic development in the upper and middle-reach areas, the volume of water dammed and used has increased consistently, while the volumes of water and sediment discharged to the lower reach of the river has consequently decreased, and the duration of drying of the river has increased. Since the 1980s, the precipitation in the watershed area of the Yellow River has decreased by 30–50%, and the drought, which is potentially related to climatic warming, has greatly intensified. If the climate continues to warm and precipitation continues to decrease in the future, the Yellow River will very likely become a seasonal river, which will also greatly intensify the shortage of water resources in the YRD region. It has been predicted that by 2010, 91% of the estimated river flow will be extracted for domestic, industrial and agricultural purposes.

The quality of freshwater resources is deteriorating. The major rivers are considerably polluted. The groundwater resources are under stress from both industrial and urban pollutants, and saltwater intrusion. The ongoing development of the YRD and sea level rise in the future will further degrade the environmental condition of water resources. If the process of environmental deterioration is not efficiently controlled, and the quality of water of the Yellow River, which is the major source of water supply in the YRD region, cannot be improved, water shortages will cause major impacts to the ecological and socio-economic development of the YRD region.

The YRD is a precious land. It has great potential for development because of its rich resources and favourable location. However, attention should be paid to the disadvantages of this region. There are a lot of restrictive factors since this region is the border where the river and the sea meet and the land and the sea connect. With continuing development, the environment will be under great pressure and the region will be in urgent need of land restoration and environmental protection. Special attention should be paid to the main conflicting factors affecting YRD's sustainable development: those between large scale development and a vulnerable environment; the region's future development plans and the restrictions imposed on them by the Yellow River (eg the Yellow River's flowing water is restricted by how much water is used in the upper reaches); future development and the potential impacts of predicted climate change and sea level rise; and present industrial structure and the non-reproducibility of mineral resources. In land renovation and restoration, priority should be given to the key problems such as realignment of the Yellow River mouth and the flow path lowering underground water level, protecting the ecological environment and restoring salinised soils.

In dealing with the relationship between environmental protection and economic development, we need to acknowledge that for the sustainable development of the YRD, both issues need to be considered in unison. The sustainable development strategy put forward in Our Common Future and the 21st Century Agenda aims at promoting the harmony between human beings and nature, and person to person. Therefore, importance should be attached to the protection of fragile ecological systems, minimising industrial polluting sources and the building of rural ecological environments. Large and important projects should not be planned in areas where the ecology is fragile. Dynamic environmental monitoring and management systems should be set up and improved for efficient management and control. The public's awareness of the environment, ecology and sustainable development should be strengthened, thus assisting in further development being undertaken on the basis of scientific knowledge and understanding.

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References

An ZS, Wu XH & Wang PX 1991. Changes in the monsoon and associated environmental changes in China since the last interglacial. In *Loess, environment and global change*, ed Liu Tungsheng, Science Press, Beijing, China.

Barter M, Tonkinson D, Lu Juan Zhang, Zhu Shu Yu, Kong Yi, Wang Tian Hou, Li Zuo Wei & Meng Xian Min. 1998. Shorebird numbers in the Huang He (Yellow River) Delta during the 1997 northward migration. In *Shorebirds Survey in China (1997)*, eds Chen Kelin, Li Zuowei, Barter M, Watkins D, and Yuan Jun, Wetlands International – China Program and Wetlands International – Oceania. Beijing, China.

Bayliss B, Brennan K, Eliot I, Finlayson CM, Hall R, House T, Pidgeon R, Walden D & Waterman P 1997. *Vulnerability assessment of predicted climate change and sea level rise in the Alligator Rivers Region, Northern Territory Australia*. Supervising Scientist Report 123, Supervising Scientist, Canberra.

Chen JY 1997. The impact of the sea level rise on China's coastal areas and its disaster hazard evolution. *Journal of Coastal Research* 13(3), 925–930.

Chen CH, Lu YC, & Shen CD 1977. The evolution of natural environment in the southern Liaoning Province over the last 10 000 years. *Scientia sinica* 6, 603–614.

Chen SP, Liu GH, Xu XG, Mu CR, Drost HJ, Chen XL, Fang HL, Zhang P & Yan J 1997. Environmental assessment and information system of the Yellow River Delta. Sub-report 3, *Support for Sustainable Development of the Yellow River Delta,* UNDP Project No. CPR/91/144.

Cheng GD 1987. Evolution and framework of the modern Yellow River Delta. *Marine Geology and Quaternary Geology* 7 (Suppl), 7–18.

Cheng GD & Xue CT 1997. *Sedimentological geology of the Yellow River Delta*. Geology Press, Beijing, China.

Coleman JM & Wright LD 1975. Modern river deltas: Variability of process and sand bodies. In *Deltas: models for exploration*, ed ML Brunssard, Houston Geosociety.

Church JA, Godfrey JS & Jacket DR 1991. A model of sea level rise caused by ocean thermal expansion. *Journal of Climate* 4 (4), 438–456.

Division of Policy, Shengli Oil Management Bureau 1994. Annuals of Shengli Oil Fields, Internal data.

Douglas BC 1991. Global sea level rise. *Journal of Geophysical Research* 96 (C4), 6981–6992.

Douglas BC 1992. Global sea level acceleration. *Journal of Geophysical Research* 97 (C8), 698–706.

Douglas BC 1995. Global sea level change: determination and interpretation. *Reviews of Geophysics* Supplement, 1425–1432.

Environmental Monitoring Station of Dongying Municipality 1994. *Annuals of environmental monitoring of Dongying Municipality in 1994*. (Internal data).

Fan ZM & Guo YS 1992. *Atlas of remote sensing dynamic analysis to the coast beach of the Yellow River Delta*. China Ocean Press, Beijing, China.

First Institute of Oceanography, State Oceanic Administration 1989. *Landform atlas of China* (Lüshun-Dalian Area). Science Press, Beijing, China.

Gao SM & Li YF 1989. *Environment of landform formation and sedimentation of the Yellow River Delta*. Science Press, Beijing, China.

Geography Institute, Academia Sinica & Environmental Protection Institute, Shengli Oil Management Bureau 1991. *Survey of pollution fountainhead of Shengli Oil Fields and environmental assessment of oil pollution materials into sea*. (Internal data).

Gornitz V 1994. Sea level rise: a review of recent past and near-future trends. *Earth Surface Processes and Trends* 4, 316–318.

Houghton JT, Callander BA & Vamey SK (eds) 1992. *Climate change 1992: the supplementary report to the IPCC scientific assessment*. Cambridge University Press, Cambridge.

Houghton JT, Jenkins GJ & Ephraums JJ (eds) 1990. *Climate change: the IPCC scientific assessment*. Cambridge University Press, Cambridge.

Hulme M, Leemans R, Zhao Zongci, Wang Futang, Markham A, Wigley T, Ding Yihui & Jiang Tao 1992. *Climate change due to the greenhouse effect and its implications for China, CRU/WWF/SMA*. Banson Productions. London.

IGBP 1992. *Global change and terrestrial ecosystems: the operational plan*. International Geosphere-Biosphere Program, Royal Swedish Academy of Sciences, no 21, Stockholm.

IPCC 1991. *Common methodology for assessment vulnerability to sea-level rise*. Ministry of Transport and Public Works, The Hague, The Netherlands.

IPCC 1992. Update the consensus. *Tiempo* 21, 200.

IPCC 1994. *Preparing to meet the challenges of the 21st Century.* Conference Report. World Coast Conference, 1993, Noordwijk, The Netherlands, 1–5 November 1993.

Land Management Bureau of Dongying Municipality 1993. *Land resource of Dongying Municipality. Land use map of Dongying Municipality (1/100,000)*. (Internal data).

Li GX & Xue CT 1993. Sediment thickness, sedimentation rate and silt body shape of the Yellow River subaqueous delta lobe. *Marine Geology and Quaternary Geology* 13 (4), 35–44.

Li GX, Cheng GD, Wei HL, Pan WG, Ren YC, Ding D, Zhou YQ & Zhao JR 1994. Shearing zone of the current field off the modern Yellow River mouth. *Chinese Science Bulletin* 39 (10), 928–932.

Li GX, Chen G & Xu GQ 1987. Sea level changes in coastal zones of China since late Pleistocene. In *Late Quaternary sea level changes*, eds Qin Yunshan & Zhao Songling, China Ocean Press, Beijing, China.

Li GX, Wei HL, Han YS & Chen YJ 1998a. Sedimentation in the Yellow River Delta, part I: flow and suspended sediment structure in the upper distributary and the estuary. *Marine Geology* 149, 93–111.

Li GX, Wei HL, Yue SY, Cheng XJ & Han YS 1998b. Sedimentation in the Yellow River Delta, part II: suspended sediment dispersal and deposition on the subaqueous delta. *Marine Geology* 149, 113–131.

Li PY & Zhou LP 1993. Occurrence and palaeoenvironmental implications of the late Pleistocene loess along the eastern coasts of the Bohai Sea, China. In *The dynamics and environmental context of Aeolian sedimentary systems*, ed K Pye, Geological Society Special Publication 72, 293–309.

Li PY, Wu SY, Liu BZ, Zhang QN & Xu XS 1992. Tidal flat landforms and their scouring-silting changes in the central part of the modern Yellow River Delta. *Acta Oceanologica Sinica* 14 (6), 74–84.

Liu GH & Drost HJ 1997. *Atlas of the Yellow River*. The Publishing House of Surveying and Mapping, Beijing, China.

Liu MH, Wang YJ & Wu SY 1987. *Late Quaternary sedimentation of the Yellow Sea*. China Ocean Press, Beijing, China.

Liu TS, An ZS, Lu YC, Yuan BY, Wu ZY, Chen MY & Zheng HH 1985. *Loess and environment*. Science Press, Beijing, China.

Lu JK, Li XP, Li DM, Chang W & Cui ZG 1997. Risk analysis of water disaster in the Yellow River Delta. Sub-report 12, *Support for Sustainable Development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Milliman JD & Meade RH 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology* 91 (1), 1–21.

Mo J, Liu SQ, Wang XG, Lu HY & Wang YJ 1995. El-Niño and marine hazards. In: *Geological hazards and environmental studies of China offshore areas*, Qingdao Ocean University Press, Qingdao, China.

Mu CR, Zhu WY, Wang JH, Wang WY, Chen RG, Lan CG & Zhang RP 1997. Environmental sanitation and the developing trends and renovation methods in the Yellow River Delta. Sub-report 6, *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Qian N, Zhang R & Li JF 1981. Auto-adjustment effect of transportation silts in the low reach of the Yellow River. *Acta Geography Sinica* 36 (2), 143–155.

Qin YS, Zhao YY, Chen LR & Zhao SL 1987. *Geology of the East China Sea*. Science Press, Beijing, China.

Rose PM & Scott DA 1997. *Waterfowl population estimates*, 2nd edn, Wetlands International Publ. 44, Wageningen, The Netherlands.

Science and Technical Committee of Shandong Province 1991. Comprehensive survey report of coastal zone and foreshore resources in the Yellow River mouth region. *A collection of comprehensive investigation for resource of the coastal zones*, *Shandong Province*. China Science and Technical Press, Beijing, China.

Scor Working Group 1989 1991. The response of beaches to sea level changes, a review of predicative models. *Journal of Coastal Research* 7, 895–921.

Scott DA (compiler) 1989. *A directory of Asian wetlands*. IUCN, Gland, Switzerland and Cambridge, UK.

Soil and Fertilizer Working Station 1988. *Soil of Dongying Municipality. Soil Map of Dongying Municipality (1/200,000)*. (Internal data).

Song ZH, Cheng YJ, Li WX, Wang ZW, You BH, Wang CH, Xing H & Zhou D 1997. Study on harness of the Yellow River Mouth flow path Sub-report 9, *Support for sustainable development of the Yellow River delta*, UNDP Project No. CPR/91/144.

State Oceanic Administration 1996. *China Ocean Agenda 21*. China Ocean Press, Beijing, China.

Statistical Bureau of Dongying Municipality 1994a. *Statistical annuals of Dongying Municipality* (1992–1994). China Statistics Press, Beijing, China.

Statistical Bureau of Dongying Municipality 1994b. *Statistical data of national economy of Dongying District, Hekou District, Kenli County, Lijin County and Guangrao County*. (Internal data).

Van den Berg JH & Van Gelder A 1993. Prediction of suspended bed material transport in flows over silt and very fine sand. *Water Resources Research* 29 (5), 1393–1404.

Vulnerability assessment of major wetlands in the Asia-Pacific region. Internal Report 316, April 1999, Supervising Scientist, Canberra. Unpublished paper

Wang FT & Zhao ZC 1995. Impact of climate change on natural vegetation in China and its implication for agriculture. *Journal of Biogeography* 22, 657–664.

Wang HJ, Li BX, Li ST & Bian BY, 1997a. Economic sustainable development of the Yellow River Delta. Sub-report 2, *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Wang HJ, Zhang QS, Chen SP, Li BX, Wang ZY, He SL, Liu GH & Xu XG 1997b. *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Wang J 1990. The possible frequency changes of the N-W Pacific Typhoon in global warming. *Quaternary Science* 3, 277–281.

Wang JX & Tong JA 1992. *A collection of the oceanic data along the coasts of Shandong Province*. Land Plan Office of Shandong Province, Jinan, China.

Wang JT & Wang PX 1980. Relationship between sea level changes and climatic fluctuations in east China since late Pleistocene, *Acta Geographical Sinica* 35, 299–312.

Wang LJ & Wang PX 1990. Late Quaternary paleoceanography of the South China Sea: glacial-interglacial contrasts in the enclosed basin. *Paleoceanography* 5 (1), 77–90.

Wang YM, Wu ZZ, Wu Y & Chen Q 1997c. Land use and regional programming of the Yellow River Delta. Sub-report 4, *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Warwick RA, Barrow EM & Wigley TML 1990. Sea level rise. In *Climate change: the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 257–281.

Warwick RA, Barrow EM & Wigley TML (eds) 1993. *Climate and sea level changes: observations, projections and implications*. Cambridge University Press, Cambridge.

Watson RT, Zinyowera MC & Moss RH (eds) 1996. *Climate change 1995 – impacts, adaptations and mitigation of climate change: scientific-technical analysis*. Cambridge University Press, Cambridge.

Wei HL & Li GX 1995. Prediction of sediment transport rate in the low reaches of the Yellow River. *Marine Geology and Quaternary Geology* 15 (4), 69–79.

Woodworth PL 1990. Asearch for acceleration in records of European mean sea level. *International Journal Climatology* 10, 129–143.

Wright LD, Wiseman WJ & Bornhold BD 1988. Marine dispersal and deposition of the Yellow River silts by gravity-driven underflows. *Nature* 332, 629–632.

Wright LD, Wiseman WJ & Yang ZS 1990. Processes of marine dispersal and deposition of suspended silts off the modern mouth of the Yellow River. *Continental Shelf Research* 10 (1), 1–40.

Wright LD, Yang ZS & Bornhold BD 1986. Hyperpycnal plumes and plume fronts over the Yellow River Delta front. *Geo-Marine Letters* 6, 97–105.

Wu DM 1981. An analysis of abnormal precipitation during plume rains season in the lower reaches of the Yangtze region in 815 years (1163–1977). *Scientia Atmospherica Sinica* 5 (4), 376–387.

Xue CT 1993. Historical changes in the Yellow River Delta, China. *Marine Geology* 113, 321–329.

Xu XG, Cai YL, He XY, Zhang HY, Zhang YM, Fu ZY & Drost HJ 1997. Environmental system of the Yellow River Delta. Sub-report 5, *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Yang HR & Xie ZR 1985. Sea level changes and climatic fluctuations over the last 20 000 years in China. In *Contribution to the Quaternary Glaciology and Quaternary Geology*, vol 2, ed HR Yang, Geological Publishing House, Beijing.

Yang ZS & Wang T 1993. *Ocean environment for exploitation and development of Chengdao Oil Field.* Qingdao Ocean University Press, Qingdao, China.

Yang ZS, Keller GH & Lu NZ 1990. Bottom morphology and instability of the modern Yellow River subaqueous delta. *Journal of Ocean University of Qingdao* 20 (1), 7–21.

Zang QY, Li PY, Wu SY, Zhang QN & Shen XZ 1996. *Nearshore sediments of the Yellow River*. China Ocean Press, Beijing, China.

Zhang DE 1983. The regional dry-humid changes and their relation with winter temperature in China over the last 500 years. *Bulletin of Meteorological Science* 4, 40–46.

Zhang DE & Wang BG 1990. The reconstructional study of Meiyu activity over the lower Yangtze River basin in the 18th century. *Scientia Sinica* B (12), 1333–1339.

Zhang DE & Zhu SL 1978. A preliminary analysis of winter temperature pattern in the southern China during the last 500 years. In *Proceedings of Symposium on Climatic Changes*, Science Press, Beijing, China.

Zhang QS, Wang ZY, He SL & Hu CH, 1997. Harness of the Yellow River Mouth and water resource. Sub-report 1, *Support for sustainable development of the Yellow River Delta*, UNDP Project No. CPR/91/144.

Zhao XT 1982. Sea level changes in eastern China during the past 20 000 years. *Acta Oceanologica Sinica* 1 (2), 248–258.

Zhao XT 1993. *Holocene coastal evolution and sea level changes in China*. China Ocean Press, Beijing, China.

Zhao YM & Song CS 1995. *Scientific survey of the Yellow River Delta Nature Reserve*, China Forestry Publishing House, Beijing, China.