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LONG-TERM ECOSYSTEM CHANGE IN JIAOZHOU BAY AND ITS CATCHMENT: THE DPSIR APPROACH

ABSTRACT. Jiaozhou Bay is a semi-closed embayment, affected by anthropogenic factors around Qingdao, China. This article illustrates the long-term change in the Bay and its catchment using the driver-pressure-state-impact-response (DPSIR) approach. Under the Chinese national macro-socioeconomic policy, rapid development and massive urbanization occurred in Qingdao that has resulted in the serious reduction and quality deterioration of its arable land and the variation in water resources. The production and consumption pattern changed with population growth and an increasing demand for water and food as well as pollutants emissions. The pressure alteration in the Bay and its catchment has created far-reaching impacts on the ecosystem. These changes include: significant deterioration in water quality of the catchment; decreased river runoff into the bay; shift in the nutrient regime of the Bay; decreased tidal prism in the Bay; increased eutrophication in the Bay; fragmentation of natural habitats and loss of biodiversity. Relevant policies aimed to formulate the promotion of the water quality have been done in the system. However, the deterioration trend has not yet been halted or reversed. Hence new management mechanisms are under discussion to improve the ecosystem in this area.

KEY WORDS: catchment; ecosystem; DPSIR; Jiaozhou Bay; long-term change

INTRODUCTION

In an ever-changing world, the global coastal zone stands out as an area undertaking extraordinary changes. These changes are formed by natural processes and phenomena, while human society is a greater driver for them in the coastal zone [Crossland et al., 2005]. Long-term ecosystem changes have occurred around the world in many coastal systems such as the Black Sea [Oguz, 2005], the Chesapeake Bay [Hagy et al., 2004], the North Sea [Clark and Frid, 2001], the Bohai Sea [Ning et al., 2010], and Daya Bay [Wang et al., 2008]. Human development of coastal regions has modified coastlines around the world, by deforestation, cultivation, changes in habitat, urbanization, agricultural impoundment and upstream changes to river flow [Crossland et al., 2005]. Coastal bays are interfaces of strong land–ocean interaction. Their ecological functions are more complicated and vulnerable to human activity and land-source pollution are much important than those of the open ocean [Wang et al., 2008].

The driver-pressure-state-impact-response (DPSIR) framework is adopted by Land-Ocean Interactions in the Coastal Zone (LOICZ) program as the approach to organize insights and research approaches on the dominant forcings and effects on the global coastal zone [Newton and Icely, 2008, Crossland et al., 2005]. DPSIR uses a core set of indicators for environmental performance and considers human activities as an integral part of the ecosystem [Kitsiou and Karydis, 2011]. It is used in this article to link natural, social and economic sciences with policy responses to analyze ecosystem change in the catchment-coast continuum of Jiaozhou Bay and its catchment. In the following sections, the bay is described and its catchment is delineated. DPSIR is used as the analytical tool to present the ecosystem change in the long term. Integrated coastal area and river basin management (ICARM) is suggested as a management path choice for Jiaozhou Bay and its catchment in order to manage and conserve the bay.

DESCRIPTION OF THE SYSTEM

Jiaozhou Bay is a typical semi-enclosed water body that is connected with the Yellow Sea through a narrow channel (~2.5 km), with a surface area of 390 km^2 and an average depth of 6–7 m. The maximum depth is up to 60~70 m in the eastern part of the Bay [Zhang, 2007a]. The system is located in the warm temperate zone with a clear monsoon climate. The annual precipitation is 340–1243 mm with an average of 635 mm [Liu et al., 2005]. This bay is characterized by semi-diurnal tides with a mean tidal range of 2.7~3.0 m and a maximum of 5.1 m [Zhang, 2007a]. The tidal current at the spring tide can be 2–3 $m \cdot s^{-1}$ at the bay mouth and the residual current is <20 $m \cdot s^{-1}$. The water residence time varies from <5-10 days in the mouth to ~100 days at the head of the Bay [Liu, 2004]. Waves are typically wind-induced and low in energy, with mean wave height 0.1–0.4 m and maximum less than 1.9 m [Yang et al., 2004]. So the water mass movement in the Bay is dominated by tides, especially the semi-diurnal M2 tide, which contributes to around 80~90% of the kinetic and potential energy [Liu et al., 2007b]. The peak flood currents are much stronger but of shorter duration than those of the ebb tide as a result of tidal asymmetry [Yuan et al., 2008]. The different residence time of the water above-mentioned leads to strong spatial gradient in nutrient concentration in the Bay with high and low in the head and mouth, respectively. However, stratification of water column is generally weak due to a strong tidal current [Zhang, 2007a]. More than ten small seasonal streams, the Yanghe, Daguhe, Moshuihe, Baishahe and Licunhe, empty into the bay with various amounts of water and sediment loads. With the economic development and population growth in the catchment area, most of these streams, however, have become channels of industrial and domestic waste discharge.

The watershed delineation is done in the interface of ArcSWAT[1] The DEM for the delineation is downloaded from the CGIAR-CSI website [Jarvis et al., 2008]. According to the attribute table of the delineation result, the whole catchment of Jiaozhou Bay is around 7734.9 km^2. The DG basin accounts for 81.6% of the catchment while the second largest, the MS basin, only 5.9%; most of the catchment is within the boundary of Qingdao and it is 81.8% of the whole catchment (Table 1 and Fig. 1).

Based on historical monitoring data, the main contaminants in Jiaozhou Bay are identified as N, P, organic matter, and oil [Gao et al., 2008]. The main issue in the Bay is the increase of harmful algal blooms (HABs). Both the frequency and scale of HABs events have increased since the 1990s [Xiao et al., 2007]. The main HAB species include *Biddulphia aurita, Eucampia zoodiacus, Mesodinium rubrum, Noctiluca scintillans,* and *Skeletonema ccostatum* [Wang, 2006]. Since the summer of 2007, green algal bloom has begun a new issue concerned in the Bay.

According to the Qingdao Urban Master Plan (2006-2020), the population in Qingdao is set to reach 12 million with the urbanization rate as 77.8% in 2020, which will increase the pressures on the Bay and its catchment and lead to ecosystem change in the long-term perspective.

[1] ArcSWAT can be downloaded at http://swatmodel.tamu.edu/software/arcswat.

Table 1. Catchment of Jiaozhou Bay and its distribution

Basin	Area (km^2)	Region	Area (km^2)
LS	18.5	Jiaonan	331.8
HP	18.8	Jiaozhou	1272.1
LC	138.5	Jimo	1149.6
CD	249.2	Laixi	1548.9
BS	253.3	Pingdu	1381.3
YH	294.9	Districts	643.7
MS	459.7	Qingdao	**6327.4**
DG	**6301.9**	other	1407.5
Total	7734.9	Total	7734.9

Note: DG – the Daguhe Basin, YH – the Yanghe Basin, CD – the Caowenhe—Daoerhe Basin, HP – the Haipohe Basin, LC – the Licunhe Basin, LS – the Loushanhe Basin, BS – the Baishahe Basin, MS – the Moshuihe Basin.

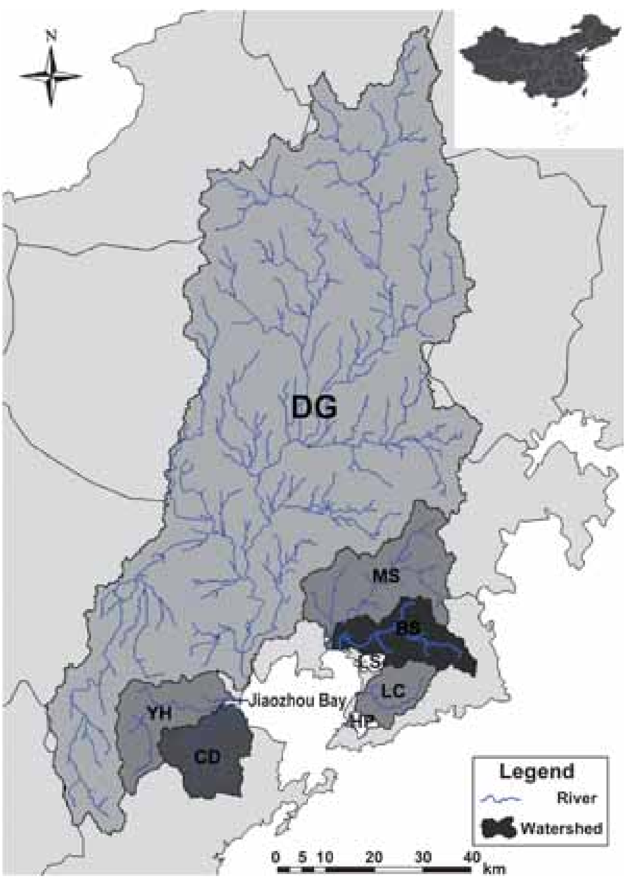

Fig. 1. Jiaozhou Bay and its catchment

DPSIR FOR THE BAY AND ITS CATCHMENT

Since the adoption of reform and openness policy in 1979, economic development has been set as the center of all affairs. However, China has paid its costs for environmental deterioration [Liu and Diamond, 2005].

Generally speaking, statistics is conducted based on the administrative system in China. It is difficult to figure out the specific detail of the socioeconomic values such as the local demography and economy for the DPSIR framework. As 81.8% of the catchment is included in the Qingdao Prefecture, in the following sections, the analysis for the trend under the framework of DPSIR will be mainly based on Qingdao.

Socio-economic drivers

Population

There are several major urban centers within the catchment, especially the downtowns of Laixi, Jimo, Jiaozhou and the six districts of Qingdao. It is newly issued that the total population in Qingdao is 8.7 million in 2010. The registered population in Qingdao Prefecture has been on the rise. However, the rising trend slowed down since the 1990s. The urban population density in Qingdao increases faster and is larger than the overall population density. In 1949, the urban population density was 2.47 times of overall population density. It increased to 2.84 times in 1980, and 2.98 times in 1990 as well as 3.34 times in 2007 (Fig. 2).

Urbanisation

Urbanization relies on a stable supply of natural resources including fresh water, fuel, land, food and all the raw materials

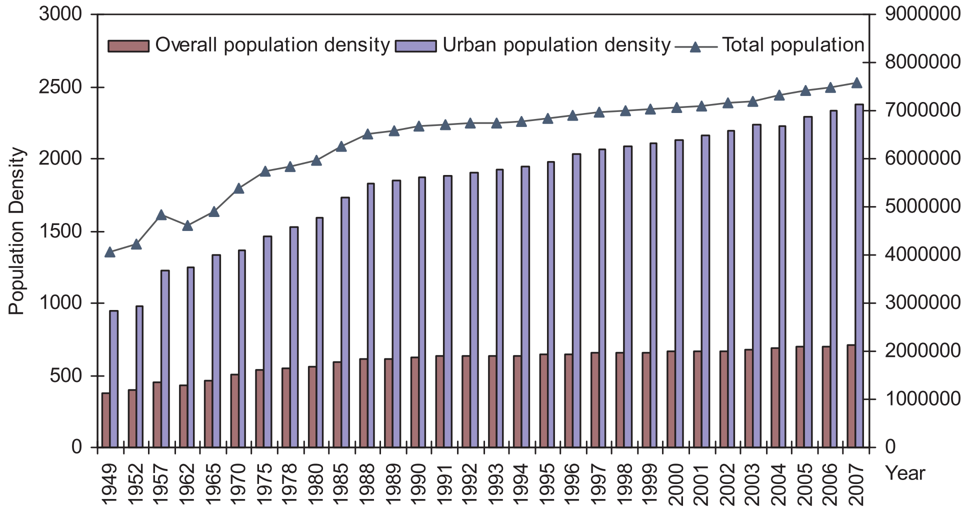

Fig. 2. Total population and population density in Qingdao

[WRI, 1998, UNFPA, 1999, Hardoy et al., 2001]. Along with rapid urbanization and city sprawl, there are definitely drastic increases both in natural resource demands and in the area from which these resources are drawn [O'Meara, 1999]. Urbanization also leads to significant alterations of physical environment far beyond city limits, resulting in habitat loss and accumulation and spread of wastes in the planet.

It is well known that China has been undergoing a rapid and unprecedented process of urbanisation since 1978. It is newly released that the urbanisation rate of China is 49.7% in 2010, increased by 13.6% since 2000. One of the remarkable features for urbanisation in China is migration from the rural to the urban, and migration from the inland to the coastal regions

Qingdao is a coastal city with a more rapid process of urbanisation. On the other hand, its administrative boundary changed for several times since 1949. The current boundary and administrative structure was formed in 1994 with seven districts and five county-level cities. In addition, the definitions of "urban" population in statistic yearbooks are not consistent. It is noted that the Yearbook of Qingdao included the items

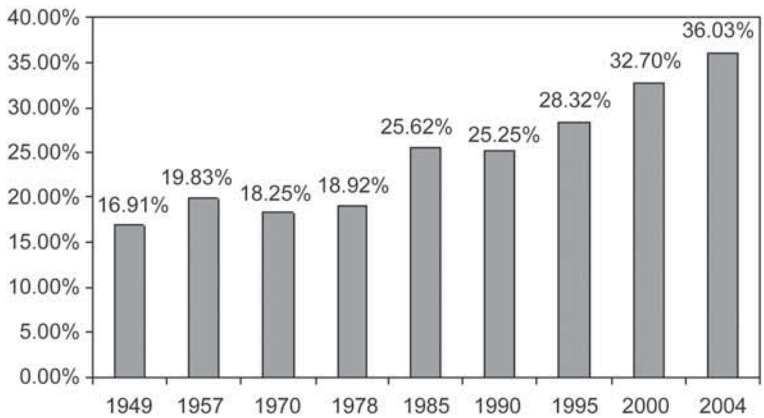

Fig. 3. Urbanization rate of Qingdao in particular years

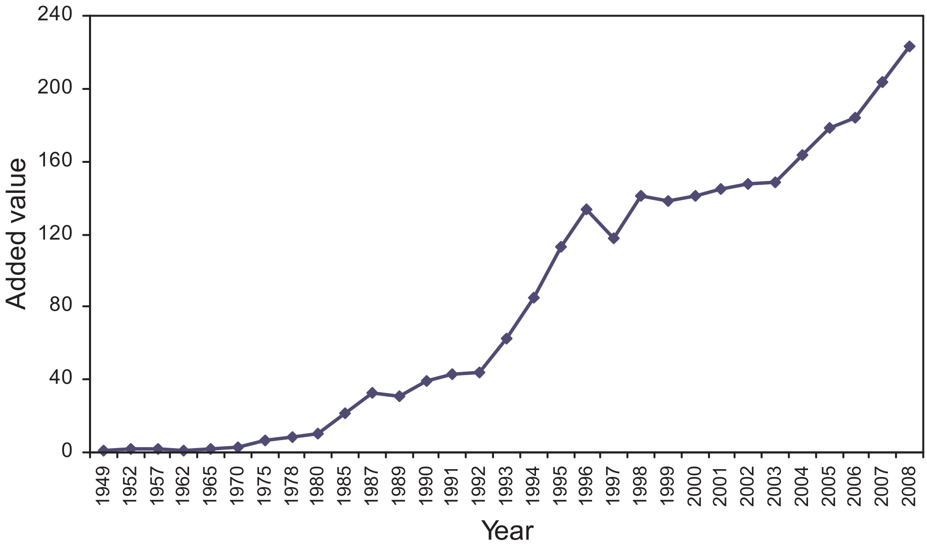

Fig. 4. The added value of primary industry in Qingdao (Unit: 10^4 Yuan)

of urban and rural population before 2005 but they are not listed since 2006. This may be explained that the existing household registration system is under review currently and people's migration is too extensive. All these factors influence the demography.

For the sake of simplicity, the data from the Yearbook of Qingdao before 2006 are used to illustrate the urbanisation trend in the catchment. According to the yearbook, rural population decreased from 1959 to 1961, and it is on the rise in all other years. On the other hand, the urban population increases in all the past years. Several examples of urbanisation rate are illustrated in Fig. 3.

Agriculture

China initiated agricultural reforms in the late 1970s as part of its economic transition program by decentralizing farm production decision to family units. These reforms resulted in remarkable progress in the agricultural sector, which in China is characterized by scarce land, abundant labor and small-scale production with limited but rising mechanization. The overwhelming majority of crop production originates from tiny farms. While a large part of livestock production also comes from small, part-time "backyard" operations, full-time "specialized" household operations and commercial operations have grown rapidly [OECD, 2005]. Since the reforms, Chinese agricultural production has grown, such that today China ranks as the leading global producer of many agricultural commodities. This growth has been achieved largely through substantial increases in productivity, a result of both market-based policy reforms and the adoption of modern agricultural technology and farming practices [U.S. International Trade Commission, 2011].

In the recent years, the proportion of the agricultural sector in the economy of Qingdao is decreasing, although the added value of this sector is increasing except in the 1960s and in 1997. In addition, the added value increased slowly before 1980 and sharply after that year. The added value of this sector in 2008 is 22.34 billion Yuan, which is 21.9 times of that in 1980, 5.7 times in 1990, and 1.6 times in 2000 (Fig. 4).

The total area of arable land for grain is on the trend of decreasing which that for cash crop is increasing. The total production of grain is also on the trend of increasing with the growth of population. The total production of grain increased from 7.23×10^5 t in 1949 to 3.34×10^6 t in 2008. Meanwhile, the

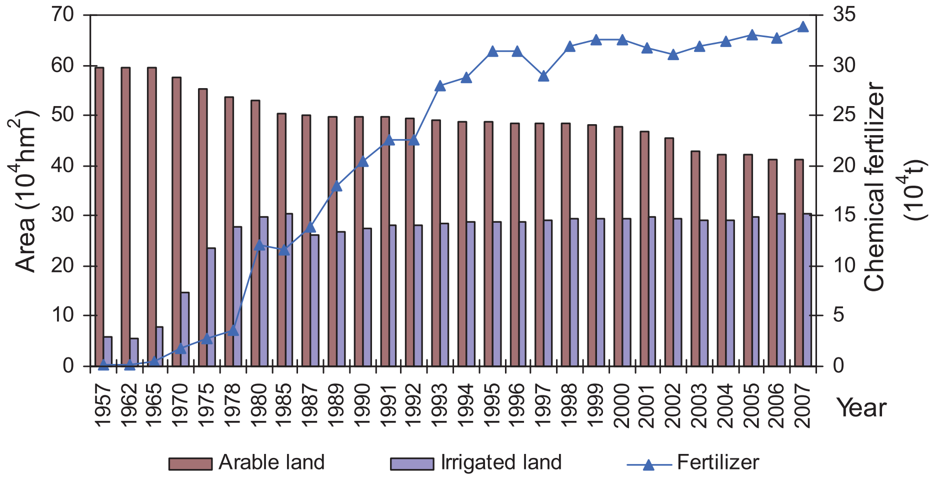

Fig. 5. Arable land, irrigated land and fertilizer application in Qingdao

output per hectare increased from 855 kg in 1949 to 6540 kg in 2008 (Fig. 5).

To increase the input of fertilizer is one of the important ways to increase output of the arable land while it is reducing. The use of fertilizer is on the trend of increasing except 1997 and 2002 when the weather impacted agricultural production to cause the decrease of fertilizer input. The fertilizer use intensity has the similar trend. The use of net fertilizer in 2007 is 3.39×10^5 t, which is 19.26 times of that in 1970, 2.81 times in 1980, and 1.66 times in 1990 (See Fig. 5). On the other hand, the fertilizer use intensity in 2007 is 820.4 kg/ha, which is 26.79 times of that in 1970, 3.61 times in 1980, and two times in 1990. The extensive and heavy use of fertilizer makes great contribution to harvest but it also poses heavy pressure on the environment.

In addition, in order to prevent flooding and provide service of irrigation for the agricultural sector, a lot of reservoirs were built in the catchment. This changed the runoff regimes of the rivers and water cycle in the catchment.

Industry

China has entered the later half of the intermediate industrialization phase[2]. This country has experienced the most intense industrialization of any nation in history, and the consequences, both positive and negative, have been profound. As a 'world factory', it exports products but consumes natural resources and leaves pollutants behind [Liu and Diamond, 2005].

As a coastal city, Qingdao is one of the economic reforming forefronts in China. This region has gone through a zigzagging road of industrialization. In the early 1950s, its industry was mainly textile with a small scale. In 1949, the total industrial output was only 2.16×10^8 yuan with the fixed assets of 4.3×10^8 yuan; while its total industrial output was 8.12×10^{11} yuan with the fixed assets of 4.73×10^{11} yuan and the revenue of 5.34×10^{10} yuan in 2008 (Fig. 6 and Fig. 7). During this period, the ratio between light and heavy industries evolved from 84.61 : 15.39 in 1949 to 42.91 : 57.09 in 2008, which indicates that heavy industry has increasingly grown in the past decades and the industrial structure has significantly changed.

Rapid industrial development and urbanization transfer more and more land away from agricultural production, threatening China's capability to feed itself. During the course of industrialization, the environment has been getting worse by the

[2] From China Daily, http://www.chinadaily.com.cn/business/2007-08/10/content_6021874.htm, accessed on Oct. 7, 2008.

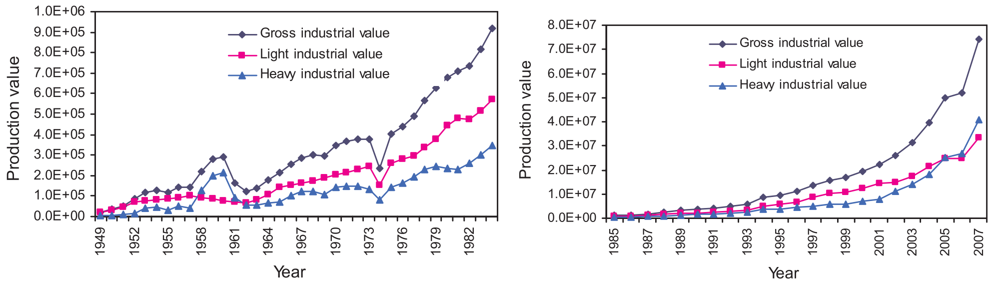

Fig. 6. Production value of industry in Qingdao (10^4 Yuan)

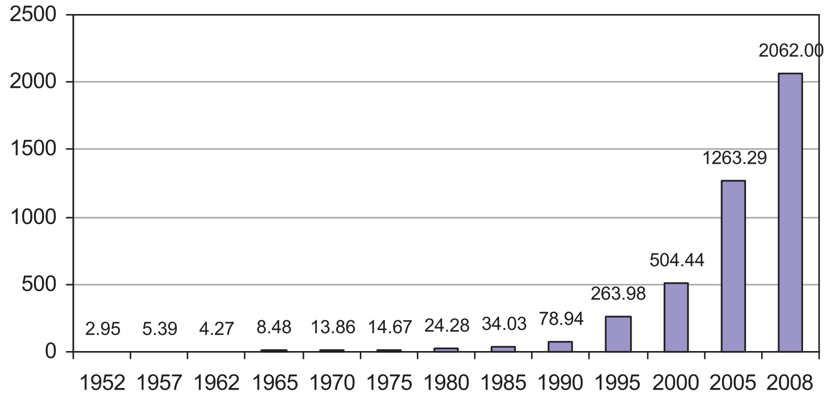

Fig. 7. Gross industrial value of Qingdao

day [Diamond, 2006]. On the other hand, heavy industry relies on consumption of energy and raw material such as oil, raw coal, and iron ore. The negative impacts will be the increase of air and water pollution, to some extent, as well as soil pollution.

Pressures

Land

Industrialization and urbanisation as well as population growth posed pressures on arable land availability. Resources such as land and freshwater are non-tradable goods that are difficult to obtain through international trade. On the other hand, more and more intensive agriculture formed a challenge to land quality.

According to the newly issued census, population in Qingdao accounts for 9.1% of that in Shandong Province, which is 7.15% of the total population in China mainland. On the contrary, the proportion of the arable land is 5.91% for the Province in the country, and 5.37% for the City in this province. This asymmetry poses a big challenge on the grain production in Qingdao and the Province. According to the Yearbook of Qingdao, the urban area in 2007 is 250.7 km^2, which is 9.28, 3.48, 2.66, and 2.10 times of that in 1949, 1980, 1990, and 2000, respectively. The Urban Master Plan of Qingdao (2006-2020) issued in 2009 set the target of urban area in 2020 as 540 km^2, which is increased by 85.2% compared to that in 2002. The urban sprawl also extended to the coast by coastal reclamation, which makes the Bay reduces from c.560 km^2 in 1928 to c. 360 km^2 in 2003.

China's arable land roughly accounts for 7% of the world total, while its usage of chemical fertilizer accounts for around 30% of the world total usage. The ratios of arable land for Shandong in the country, and of Qingdao in the Province are shown in the above, while the ratios of fertilizer usage for the province in the country, and the city in the province are 9.79% and 6.77%. Taking nitrogen fertilizer as an example, the world average usage per hectare is 60 kg, while this for China as a whole is 205 kg, and 393 kg for Qingdao.

The above percentages indicate that the pressures from land in Qingdao are potentially larger than that of Shandong province and of the country as a whole which is also potentially larger than the world on the average.

Water resources

The natural water endowment in the catchment is relatively worse. Water shortage is relatively serious in Qingdao with a per capita share of 312m^3 per annum, which is only 12% of the national annual average share and 3% of the world share per capita. Meanwhile, the seasonal and annual variation in water resources is remarkable with uneven geo-distribution.

The water consumption in the seven districts of Qingdao from 1995 to 2005 increased from 8.32×10^7 t to 1.37×10^8 t with the increase of water use per capita from 104 L to 142 L, while the population in the districts grew from 2.18 million to 2.65 million (Fig. 8). It is clear that the increase rate of water use is larger than that of population growth.

Water sources for domestic use have been developed with the growth of Qingdao. Groundwater from the Haipo Aquifer was first extracted for municipal water use in Qingdao around 1900 with the daily supply of 400 m^3. Other groundwater supply sites were established in 1908, 1919, and 1958 in the coastal aquifers. But these sites have all been abandoned due to groundwater pollution and sand over-extraction from the river beds. The water from the Daguhe was supplied as municipal water use since 1968. However, rigid water demand growth challenged the water supply network. Hence water transport project from the Yellow River to Qingdao was proposed in 1982 and the first supply from this project occurred in 1989. In the 21st century, the reclaimed water from wastewater treatment plants was supplied for industrial use. Meanwhile, the desalination plant located in the west coast of the Bay will be completed at the end of 2010.

Generally speaking, the increase of water consumption implies the increase of sewage. The domestic sewage rose from 3.49×10^7 t to 2.35×10^8 t with an average of 1.08×10^8 t from 1990 to 2008. During the same period, the industrial sewage emission didn't vary too much with an average of 9.38×10^7 t and the largest volume of 1.07×10^8 t in 1991. Hence, the total sewage volume

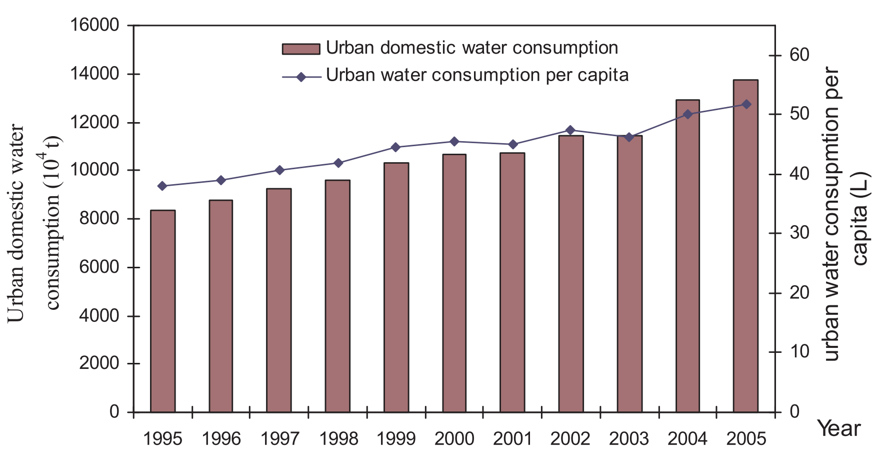

Fig. 8. Urban domestic water consumption and water consumption per capita

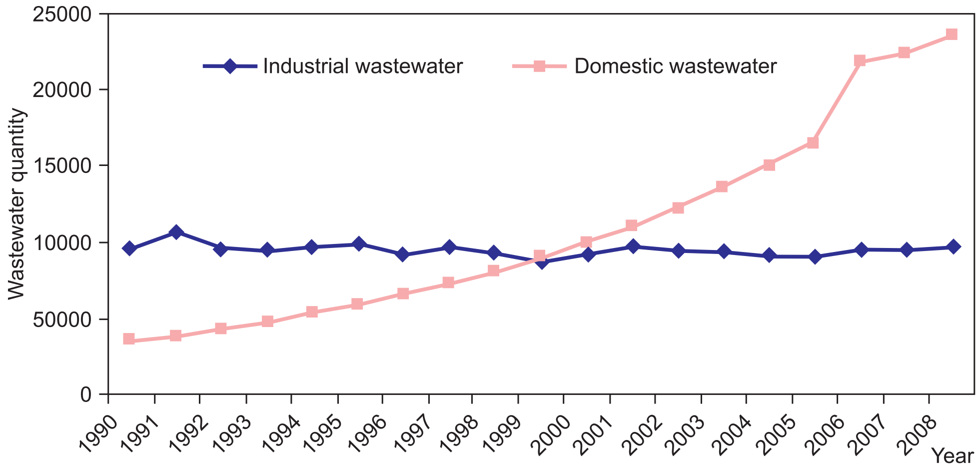

Fig. 9. Domestic wastewater and industrial wastewater in Qingdao since 1990 (10^4 t)

correlates with that of the domestic sewage ($R^2 = 0.996$) (Fig. 9).

As shown in the above, the fertilizer usage in Qingdao is on the rise either in terms of the total quantity or usage per hectare, although the available arable land is on the decrease. However, not all the fertilizer is taken up by the crops. Only 30%~40% will be used by crops in the land, and the rest will be remained in the earth, water and air. Most of the fertilizers will dissolve in the surface water through precipitation, runoff, eluviation and permeation, which ultimately causes water pollution. Non-point source discharges, especially agricultural runoff, are the main causes of water pollution. Agricultural wastewater in Qingdao, including agricultural runoff, animal wastewater, agricultural product processing wastewater and so on, begun to increase from 1990 and reach its peak as 6.30×10^8 t in 1996, and then the discharge of agricultural wastewater started on the track of decreasing. The average discharge of this wastewater from 1990 to 2007 is 5.91×10^8 t, which is 5.9 and 6.3 times as much as municipal wastewater and industrial wastewater discharges, respectively (Fig. 10).

Most direct discharge companies are located in the west coast of the Bay and some in

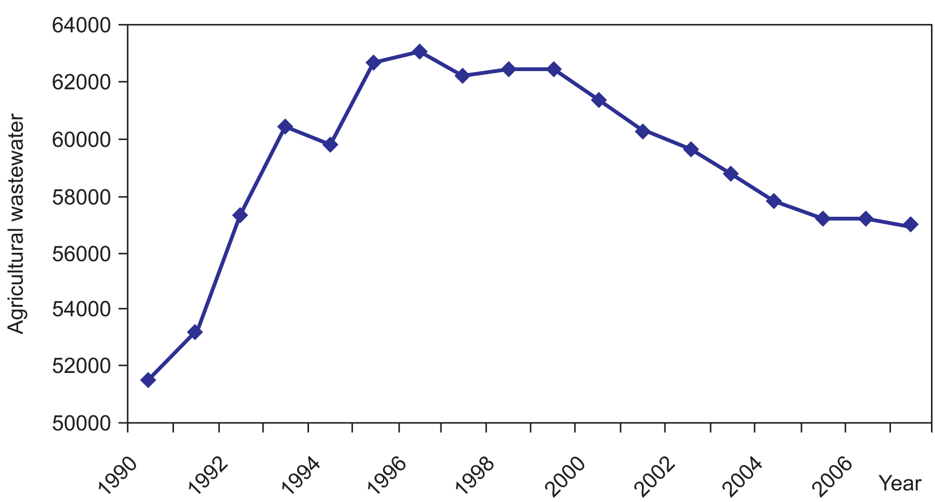

Fig. 10. Agricultural wastewater in Qingdao since 1990 (10^4 t)

the east. These companies discharge about 1.8×10^7 t wastewater into the Bay with 2590 t COD and 95 t ammonia nitrogen [Zhang, 2007b]. 71.51% of pollutants are transported into Jiaozhou Bay by rivers draining into the Bay [Zhang, 2007b]. The Daguhe, Moshuihe, and Licunhe are the three largest sources according the statistics in the year of 2007 [Li et al., 2009].

States and impacts

LULC changes

According to land-use-land-cover (LULC) studies for Qingdao, LULC changes in this area are distinctive. For instance, the arable land reduced by 63787 hm^2, the grassland, water body by 35146 hm^2 and 5641 hm^2, from 1995 to 2005. On the contrary, urban area increased by 65636 hm^2, and forest by 31229 hm^2.

Variation in water resources

Due to damming and increased water use in the catchment, river runoff into the Bay is in the trend of decreasing. Take Nancun Hydrological Station (NHS) in the Dagu watershed as an example, river flow is plotted as shown in Fig 11. This figure indicates that the runoff at NHS represented the decreasing trend since the late 1960s and further reduced in the early 1980s. There was even no runoff in several years after 1981. The trend of runoff variation is in accordance with that of precipitation variation before the 1960s, and the annual peaks of runoff and rainfall were all in the same years. The runoff and rainfall data at NHS from 1951 to 2000 are both divided by every decade into five groups and one-way ANOVA is used to compare the means of each decade for the two types (Fig. 12). It shows that there are no significant differences between the groups of rainfall data ($p > 0.05$), however, the runoff means are on the contrary ($p < 0.05$). The means since the 1980s are one order of magnitude less than those before that decade; the mean in the 1950s is 23.5 $m^3 \cdot s^{-1}$ and that in the 1980s 2.6 $m^3 \cdot s^{-1}$. According to the same statistical method, there are significant differences among the decadal means of runoff from 1973 to 1998 at Zhangjiayuan Hydrological Station in the upstream of the Dagu watershed; and so are there at the Lanxitou Hydrological Station in the Wugu, a tributary river of the Daguhe.

Liu et al [2007] describes the groundwater variations and submarine groundwater discharge in the coastal aquifers of the Bay due to human extraction [Liu et al., 2007a]. Due to groundwater abstraction in Dagu Aquifer and Baisha Aquifer, seawater intrusion happened from 1981 to 1996, and 1976 to 1990, respectively. From 1981 to 1999,

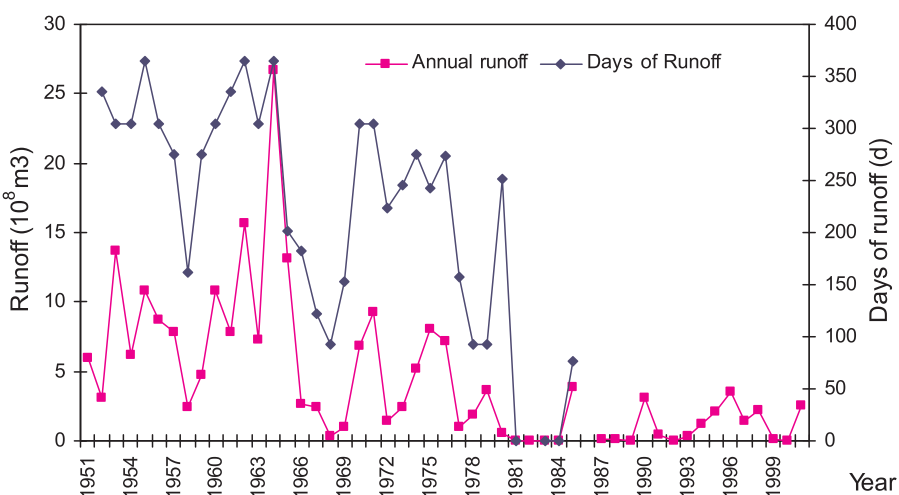

Fig. 11. Annual runoff and days of runoff at Nancun Hydrostation

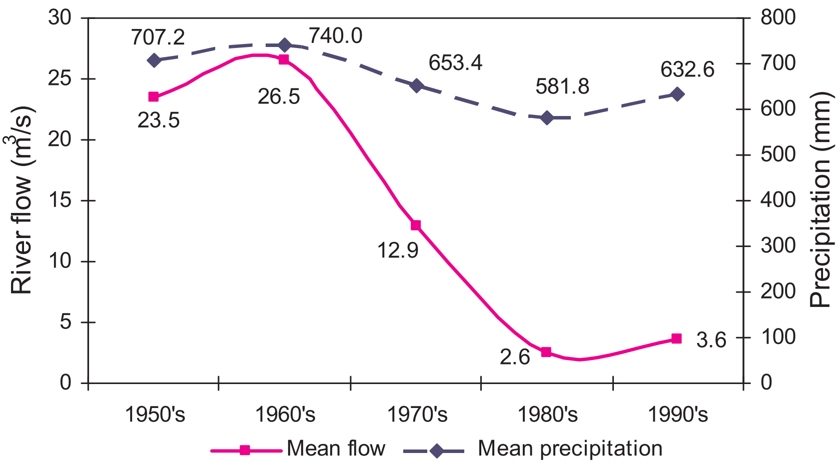

Fig. 12. Inter-decadal variation of river flow and precipitation at Nancun Hydrostation

a depression was formed near the coast of the Dagu Aquifer due to excessive groundwater abstraction, and seawater intrusion occurred. Therefore, no groundwater could be discharged into the Bay in 1981–1999. The construction of a low permeability subsurface dam in 1998 greatly constrained the groundwater discharge from the aquifer to the sea, although the groundwater level has been rising since 1999. Groundwater regimes of the catchment have experienced great changes over the last several decades and therefore it changed the groundwater discharge conditions.

Water quality of the catchment

In the 1960s and 1970s, water quality in the Daguhe was high with [Cl^-] as 18 ~ 40 mg/L, [HCO_3^-] as 94 ~ 211 mg/L, and total dissolved solids as 0.1 ~ 0.4 mg/L; In the late 1980s this river was polluted by industrial wastewater, municipal wastewater, pesticides, chemical fertilizers, and animal and human waste [Ye, 2006]. The average concentration of NO_3^-, NO_2^-, and NH_4^+ in the section ~30 km to the Estuary (referred to as Section I), the lower stream of this river, was 1.98 mg/L, 0.12 mg/L, and 1.02 mg/L, respectively, from 1982 to 1988; while the water quality was much worse with [NO_3^-] as 1.63 mg/L, [NO_2^-] as 0.85 mg/L, and [NH_4^+] as 5.36 mg/L in the section ~18 km to the Estuary (referred to as Section II) (Environmental Protection Bureau of Qingdao, 1990). In the late 1990s, there was no improvement in both sections, and even worse in Section II, with [NO_3^-] as 4.11 mg/L, [NO_2^-] as 0.14 mg/L, and [NH_4^+] as 0.46 mg/L in Section I and [NO_3^-] as 3.32 mg/L, [NO_2^-] as 0.94 mg/L, and [NH_4^+] as 7.16 mg/L in Section II which might be impacted by seawater incursion (Ye, 2006). The main contaminants in all the sections of the Daguhe within Qingdao were COD, NH_4^+, and SS (suspended sediments) from 2000 to 2005. The water quality in the upstream was stable and high while that in the midstream and lower stream was in the trend of worsening, and the quality in Section II was the worst [Meng et al., 2008].

The Moshui River is one of the heavily polluted surface waters in Qingdao [Wang et al., 2009]. Part of this river from its midstream changed into a wastewater drain since 1997 and [NO_3^-] was as high as 9.47 mg/L, [NO_2^-] as 0.69 mg/L, and [NH_4^+] as 15.66 mg/L in the section ~7.5 km to the estuary [Ye, 2006]. The pollution was even worse in the last 10 years as industrialization developed in its catchment and wastewater was drained into the river without any treatment [Wang et al., 2009].

After the 1980s, water quality of the Baisha River was threatened by pesticides, chemical fertilizers, industrial and municipal wastewater, and animal and human waste. From 1997 to 2001, the average [NO_3^-] was as high as 41.40 mg/L, [NO_2^-] as 0.61 mg/L, and [NH_4^+] as 0.32 mg/L in the section ~3km to the estuary. There is still lack of wastewater treatment facilities in the catchment [Ye, 2006].

There are no industrial and municipal wastewater source points in the Yanghe catchment. The main threats to water quality are from agricultural runoff, animal and human waste in the rural areas [Wang et al., 2009].

From 2001 to 2007, water quality in all seven estuaries including the Daguhe Yanghe, Licunhe, Moshuihe, Haipohe, Loushanhe, Banqiaofanghe were polluted, and other five except the Daguhe and Yanghe were heavily contaminated [Wang, 2009].

Nutrient regime in the Bay

Nutrient survey in Jiaozhou Bay began in the 1960s. From the 1960s to the 1990s, it is reported that nutrient concentrations have increased 4.3 times for NO_3–N, 4.1 times for NH_4–N, 3.9 times for DIN and 1.4 times for PO_4–P [Shen, 2001]. DIN concentration was less than 0.20 mg/L from the 1960s to the 1990s although it was on the rise. At the beginning of the 21st century, DIN concentration continued to increase, with the average as 0.42 mg/L which is 13.7 times as much as that in the 1960s; and DIP concentration increased, too, with the average as 0.019 and 4.4 times as much as that in the 1960s [Shen, 2001].

The atomic ratio of DIN : PO_4–P increased rapidly from 15.9 ± 6.3 for the 1960s, to 37.8 ± 22.9 for the 1990s. SiO_3–Si concentration has remained at a low level from the 1980s to the 1990s. The high ratio of DIN : PO_4–P and low ratios of SiO_3–Si : PO_4–P (7.6 ± 8.9) and SiO_3–Si : DIN (0.19 ± 0.15) showed the nutrient structure of Jiaozhou Bay has changed from more balanced to unbalanced during the last several decades. The possibility that DIN and/or PO_4–P as limiting factors of Jiaozhou Bay phytoplankton has been lessened or eliminated, and that of SiO_3–Si limiting has been increased.

Tidal prism and surface area of the Bay

The overwhelming influence of human activities, especially land reclamation, is the main cause of the significant changes in hydrodynamic conditions and water exchange in Jiaozhou Bay [Shi et al., 2011]. The surface area of the Bay has reduced about 200 km^2 with a direct effect of tidal prism deceasing (Table 2).

The human-induced changes of the coastline position-configuration and nearshore bathymetry have resulted in substantial changes in the residual current patterns, especially in Qianwan Bay, Haixi Bay, and northeastern Jiaozhou Bay.

The overall tidal prim of Jiaozhou Bay has been reduced by 26% as compared to that in 1928. This is considerably less than the 35% reduction obtained by other studies (Shi et al., 2011). The decreasing water-exchange

Table 2. Changes of surface area and tidal prism in Jiaozhou Bay

Year	Surface Area (km^2)	Tidal Prism (10^8 m^3)
1915–1932	560 [a]	n.a.
1935	559 [a]	12.667 [c]
1963	423 [a]	10.065 [c]
1980	n.a.	9.626 [c]
1985	374.4 [a]	n.a.
1988	393.9 [b]	9.48 [c]
1992	n.a.	9.593 [c]
1997	371.4 [b]	9.22 [b]
2002	363.4 [b]	9.08 [b]
2004	362.4 [b]	n.a.
2005	358.9 [b]	9.02 [b]

Note: the letters a, b, and c in the table indicate the references: Jia [2006], Ma [2006], and Zhang [2007b].

ability corresponds to an increasing average residence time (ART) over the past several decades, particularly after the 1980s. In addition, the influences of the return flow of the bay water from the open sea back into the estuary were quantified by determining the return flow factor for each year. An existing tidal prism model was revised by introducing a mixing factor κ, and a simplified formula was developed for Jiaozhou Bay. The revised tidal prism model suggests continued deterioration in water quality and exchange ability of Jiaozhou Bay in the near future.

Dredging is carried out continuously within the Bay to build new port and industrial installations and maintain shipping channels.

Habitats deterioration and biodiversity loss

Due to human activities, large areas of natural wetlands around Jiaozhou Bay have been transformed into sea salt fields and shrimp ponds. This makes the wetland landscape pattern changed significantly, and coastal landscape pattern becomes simple. Due to wetland loss and increased pollution, biodiversity deterioration in the intertidal mudflat is remarkable.

In the 1960s, eastern coastal intertidal zone was typical with healthy environment and rich biodiversity. The number of species was then over 170, while this number began to reduce in the 1970s and it was about 17 in the 1980s. There was even no species collected in some sections of this zone [Zhao, 2002]. In Cangkou intertidal zone, the number of species was about 34~141 in the 1930s to the 1960s; this number reduced to 17~30 in the 1970s to the 1980s; while this habitat was totally lost due to land reclamation in the 1990s [Zhang, 2009]. The composition and number of species has changed in the intertidal zone of the Dagu Estuary in the last several decades: the number of species was over 20 in the 1980s, reduced to about 10 in the 1990s, and several in the 2000s (Fig. 13). The 1980s' dominant species *Mactra quadrangularis* has been replaced by

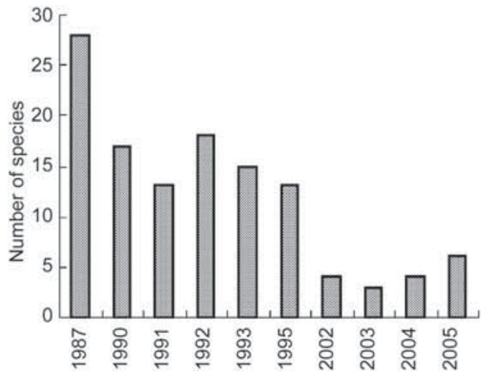

Fig. 13. Change of species numbers in the intertidal zone of the Daguhe estuary (revised from [Wang et al., 2007])

Sinonovacula Constricta [Wang et al., 2007]. Fish stock of the Bay was about 7400 t and that of crustaceans and cephalopods around 1000 t in the 1980s with the maximum sustainable yield as 2300 t. While the fishery survey in 2003 indicates that fish stock is 490 t and that of crustaceans and cephalopods around 374 t with significant biodiversity loss [Zhang, 2009].

Eutrophication in the Bay

At present, Jiaozhou Bay is mainly polluted by nitrogen and phosphorus from the land-based sources, which leads to eutrophication, frequent occurrence of harmful algal blooms and thus ecosystem deterioration. There were 12 HABs occurred in the Bay from 1990 to 2007, which brought heavy ecological, social and economic losses [Zhang, 2009]. The HABs areas are mainly distributed in the east and north of the Bay [Ge, 2003].

Qian et al [2009] assess eutrophication development in the Bat since the 1980s[3] [Qian et al., 2009]. It shows that the eutrophic degree and extent gradually increase in the Bay (Fig. 14). From the 1980s to the 1990s, E was less than 1 while it increased gradually, reached to 1 in the middle 1990s, and became

[3] The assessment equation is the same as Equation 2 (P. 903) in Xiao et al (2007) but they uses E to replace N. If E I 1, the system is regarded as eutrophic. The larger the E value, the more eutrophic.

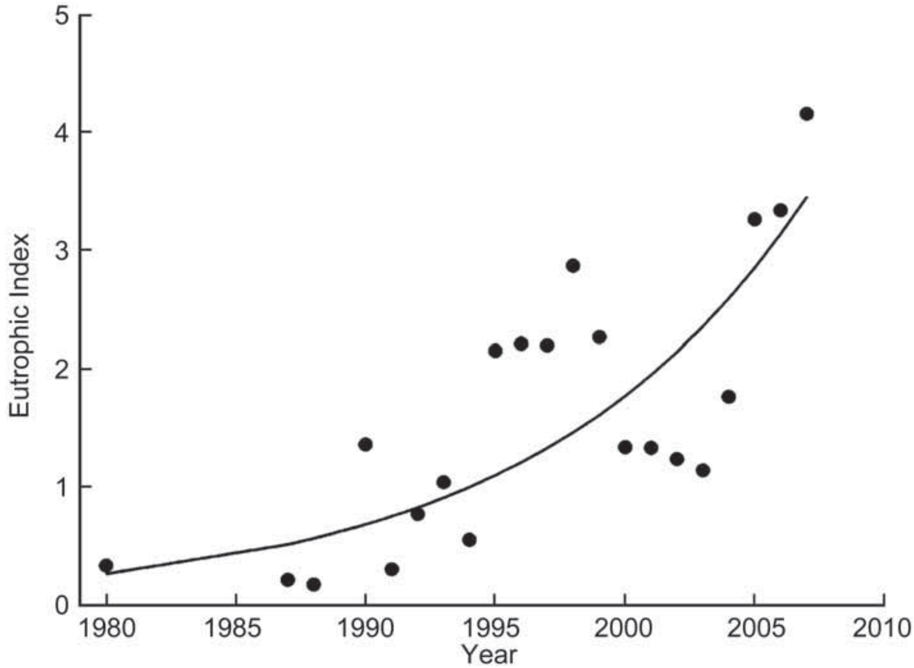

Fig. 14. Change of eutrophic index of Jiaozhou Bay since 1980 (adopted from Qian et al, 2009)

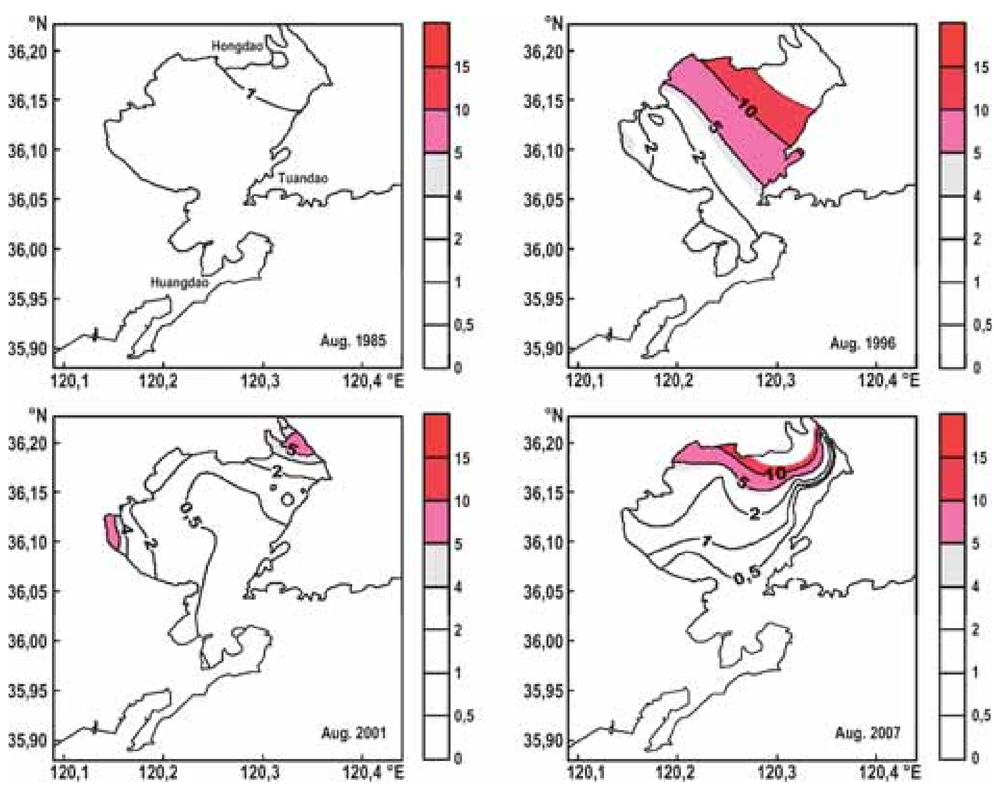

Fig. 15. Distribution of eutrophic waters of Jiaozhou Bay in different years (adopted from Qian et al, 2009)

larger than 2 in the late 1990s and 3 in 2005, and it even surpassed 4 in 2007.

Qian et al [2009] produce graphic to describe the distribution of eutrophic waters in the Bay (Fig. 15) [Qian et al., 2009]. It is clear that the northeast part of the Bay kept eutrophic in the last several decades. The Moshui River runoff is the main contributor to this effect. In the 21st century, the northwest part became eutrophic, too. This can be attributed to increased pollution from the Daguhe runoff.

Other changes and impacts

Other ecological factors in Jiaozhou Bay also changed in the last several decades. The COD in the Bay has gradually increased since the 1990s. Especially, the surface COD in 1998 is larger by 44.7% than that in 1991. Dissolved oxygen in the Bay was in the trend of decreasing [Zhao, 2002]. Surface temperature of the Bay also increased by 0.75 from the 1960s to the 1990s.

Phytoplankton is the producer in the food web of the ocean. The phytoplankton community of Jiaozhou Bay is composed mainly of diatoms and secondly of dinoflagellates[4]. The changes in nutrient structure of the Bay may have led to the decrease of large diatoms and a shift of phytoplankton species composition. It is likely that there is a trend from large diatoms to smaller cells in Jiaozhou Bay. The number of dominant species has also reduced, which indicates the biodiversity loss.

Policy responses

Environmental protection as a national policy

The first national conference of environmental protection was held in 1973 and since then there have been six national conferences of environmental protection held in China. The legislation and national policy for environmental protection has come into being. The law of marine environmental protection, laws of water pollution, air pollution, and law of environmental impact assessment as well as other laws of natural resources have been implemented during these decades.

Measures to protect Jiaozhou Bay

The local people's congress of Qingdao passed a proposal to protect Jiaozhou Bay in 2005 and a new development strategy, "Protecting the Bay, Developing around the Bay", was issued in November 2007. It is top priority to prevent the Bay and its catchment from pollution and reduce contaminants from the land-based sources. The local legislature has taken measures to release two pieces of new regulations, i.e. *Marine Environmental Protection Regulation of Qingdao and River Channel Management Regulation of Qingdao* in 2009. Marine Functional Zoning for Jiaozhou Bay and its adjacent waters and Planning for Wetland of Jiaozhou Bay have been issued. Wastewater treatment facilities are being improved in the catchment. Since July 2007, the waste discharge permit scheme came into force in Qingdao. All the major basins around the Bay have been under regulation. In 2009, wastewater pipeline was up to 265 km and the total investment is more than that in the last ten years. So the point sources are under effective control.

POLICY ANALYSIS AND FUTURE OUTLOOK

Tidal rivers have a strong influence on their adjacent estuary and the surrounding coastal area. During the last 15 years it became more and more obvious that coastal zones in the vicinity of large rivers cannot be managed independently from the rivers and their catchments. The concept of an ICARM is reflected in the UNEP-ICARM approach, in the European Water Framework Directive and partly in LOICZ. All these are focused on water-related topics. The spatial integration of river basin and coastal waters does not always reflect the interaction between terrestrial and aquatic systems well. Therefore, it is not a replacement, but a

[4] According to Wang et al. [2006], 313 species including 224 diatoms and 69 dinoflagellates have been identified in Jiaozhou Bay since the 1930s.

supplement to traditional Integrated Coastal Zone Management (ICZM). Objectives are to raise awareness as well as to promote and to ensure sustainable integrated coastal water – river management.

Neither integrated coastal zone management nor integrated river basin management has been established for Jiaozhou Bay and its catchment. The policies and measures taken to alleviate, prevent and control pollution in the Bay and its catchment are thus not integrated and coordinated among different departments. Rivers in the catchment are divided into sections managed by different local governments, which is difficult to solve the problems between the upstream and the downstream. Coastal management is also conducted by local marine authority, fisheries department, authority of environmental protection and so on. It is difficult to share data and information and conduct joint enforcement among different departments. This sector management mechanism cannot solve the pollution and ecosystem deterioration effectively and efficiently.

As human activities around the Bay and in its catchment are increasing and intensifying, the pressure on the bay and its catchment will continue and even become larger. It is necessary to consider managing the bay and its catchment in an integrated approach. Hence ICARM should be a proper path choice for managing and conserving the bay and its catchment.

CONCLUSIONS

An analytical tool, DPSIR, is used in this article to present the causes and effects in the ecosystem change of Jiaozhou Bay and its catchment. Drivers include national and local policies, population growth, economic development, and urbanization. Pressures represent by two aspects, i.e., land and water resources, given by the drivers. State and impacts show the state change of Jiaozhou Bay and its catchment and their impacts on the ecosystem. Response examines the policy reactions and measures taken to alleviate the trend of ecosystem changes and their impacts.

Under the Chinese national macro-socioeconomic policy, rapid development and massive urbanization occurred in Qingdao that has resulted in the serious reduction and quality deterioration of its arable land and the variation in water resources. The production and consumption pattern changed with population growth with an increasing rigid demand for water and food as well as pollutants emissions. The pressure alteration in the Bay and its catchment has created far-reaching changes and had impacts on the ecosystem. These changes include: significant deterioration in water quality of the catchment; decreased river runoff into the bay; shift in the nutrient regime of the Bay; decreased surface area and tidal prism of the Bay; increased eutrophication in the Bay; fragmentation of natural habitats and loss of biodiversity. Relevant policies aimed at the promotion of the water quality in the system have been formulated. However, the deterioration trend has not yet been halted or reversed. This is because the policies and measures, if not all, are based on sector management approach and ignore the interactions between the bay and its catchment. It is suggested the catchment-coast continuum concept should be used as the basic principle for policy design and ICARM can be one of the path choices. ■

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