CHAPTER

SEA LEVEL CHANGE, SEA WATER INTRUSION, AND COASTAL LAND SUBSIDENCE

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CHAPTER OUTLINE

Marine Geo-Hazards in China. http://dx.doi.org/10.1016/B978-0-12-812726-1.00014-0

In the global changes, climate warming and sea level rise have the most serious impacts on human society. At present, more than half of the world's population live in the coastal areas less than 50 km from the sea; the average population density in coastal areas is about 10 times higher than inland. Dutch scholars estimated that if in the next century the sea level rises 1 m, land of 500×10^4 km^2, population of 10×10^8, and about one-third arable land in the world will be under its direct impact. Therefore, in recent years, governments of all countries in the world, society in general, and the scientific community have paid great attention to the research on sea level rise and its influence on the coastal zone. In 1989, the president of the American Academy of Sciences pointed out that "the coastal zone management should consider the future sea level rise."

The coastal line length of the mainland of China is about 18,000 km; the coastal area is the forefront of China's reform and opening up and the focus of economic development. The coastal areas have Yellow River, Yangtze River, and Pearl River as three big deltas and low and flat coastal plain, which are vulnerable to the risks of future sea level rise. The Chinese coastal structures' raised areas and subsidence areas receive different amounts of river sediment, which causes the basic differences between hill coast and plain coast, while the hill and plain coasts have completely different reflection on the global sea level rise. In the big river delta areas with developed economies and dense populations, human activities exacerbate the sea level rise. Therefore, since the 1990s, the research on sea level rise on the human living environments in coastal areas has focused on the global sea level rise to the regional relative sea level rise, because in the seriously affected areas, the rise rate of the latter can be several times or even a hundred times that of the former, which has more serious risks for the economic development of coastal areas.

Though the sea level rise is a slow process, the considerable degree of rise caused by long-term accumulation is enough to multiply impact on the economic construction, city municipal construction, people's production and life, in these coastal areas, and this kind of influence is more extensive and in-depth than any natural hazards.

The risk of sea level rise can be shown only when there are big tide, storm surge, hard rain, and flood, but its "invisible" risk, which can't be easily recognized by people, is more regional and for long term, and its hazards are often not easily cured. The gradual rise of sea level reduces the river gradient and reduces the sediment amount into the sea. The beaches in the world have a universal lack of amount of sand amount. The sea level rise happens with the increase of El Niño phenomenon and storm surge frequency, and water power increases, which have great power to scour the beaches and erode the coast. According to estimates of the IPCC (Intergovernmental Panel on Climate Change), until 2100, when the sea level rises 50 cm, the main tourism beaches in China will lose 13%−66% of the current areas.

The delta and coastal lowland with relative high sea level rise rate will have large areas (mainly the altitude less than 2 m) under the threat of being flooded by seawater. With the rise of relative sea level, the inland river navigation and port shipping will be influenced, the river water quality in cities will be seriously polluted, and the more frequent and stronger storm surges will make the seawater intrude into the underground freshwater layer, resulting in the salinization of farmland and influencing the agriculture biological balance to worsen the water resources and water environments.

With many factors influencing the relative sea level rise, land subsidence will be the important, and even the main part, of concern for the Tianjin area, which is located in North China and already has a water shortage. The excessive exploration of underground water causes the land subsidence and further causes the rise of relative sea level, which inevitably produces the aforementioned risks. With regard to the land subsidence itself, it will also bring big risks to the people living there.

This chapter, through the wide collection of the previous research results, summarizes and discusses the research status of sea level rise in China, the existing problems, the risks caused by the sea level rise in coastal areas, and the prevention countermeasures, focusing on the prediction of the past, now present, and future change trends of relative sea level rise in Chinese big river deltas (the Yellow River delta, the Yangtze River delta, and the Pearl River delta). This chapter emphasizes the risks of sea level rise and the corresponding prevention countermeasures.

The sea level rise is both global and regional; it can directly produce many marine geological hazards. The land subsidence increases the degree of sea level rise in regions, and at the same time the relative sea level rise also threatens the survival of coastal cities. The authors here want to emphasize the following: the relative sea level rise, seawater intrusion, and land subsidence have interactions and they become the reason and result of each other, so comprehensive analysis is very necessary; with regard to the factors influencing the relative sea level rise, seawater intrusion, and land subsidence, although the natural factors should not be ignored, the damage on the natural environment from human activities is, to some extent, much more than the damage from natural forces. Therefore, improving public awareness and preventing damage as early as possible are very crucial to reducing the risks of sea level rise.

1. SEA LEVEL CHANGE

The global climate warming will result in sea level rise. Perhaps in the past, you had no idea about the sea level, when you stop to think about the aspects of human life influenced by climate change, you will be surprised—our city plans, industry's technological developments, environment protection strategy selections, all of these are based on the hypothesis of stable sea level.

Global sea level is the eustatic sea level, it means the global mean sea level, and it is not the sea level of a certain place (such as Tanggu, Wusong).

If we start from the first tide station in the world in 1682, the tide station in Amsterdam, the Netherlands, there have been more than 300 years of history of observation on the modern sea level plain. The systematic regional contrast and research started in 1940s. The summary of nearly 60 years of research results concluded that in the recent 100 years, the global sea level continues rising. Currently there is international prediction with different degrees on the future global sea level change; its whole change trend is to increase the rising. But because the sea level change is relative to the land, the land itself will have different scales of changes due to different reasons. Therefore, globally speaking, the whole trend is that the global sea level has a rising trend, but in the specific individual regions, the rise and fall changes of land ground must be added in. So the relative value of the relative sea level rise changes in the region have a greater difference, and even show different sea level changes.

The actual sea level change at one certain place in the world is the sum of the global sea level rise value plus the land rise or fall value; this is the relative sea level. Some big deltas in the world, including Yangtze River and Yellow River deltas' land subsidence rate are all above 6−100 mm/a; they are all 5−100 times the current eustatic sea level rise rate (Fig. 14.1) (Milliman et al., 1989). In the American Mississippi River delta, the current relative sea level rise has 85%−90% caused by land subsidence (Day and Templet, 1989). Therefore, the sea level change research report of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1990 correctly pointed out that "the research on sea level must include the change of sea level and land level." Recently the international scientists have paid much attention to the research on the relative sea level, because it has more practical meaning on the evaluation of sea level rise's influence on human society than the eustatic sea level change (Titus et al., 1991). In 1991, Gornitz in the United States researched the risk class of coast in the United States; its sea level index used the relative sea level (Gornitz, 1991). The sea level research report published by UNESCO in 1990 had used the phrase "relative sea level

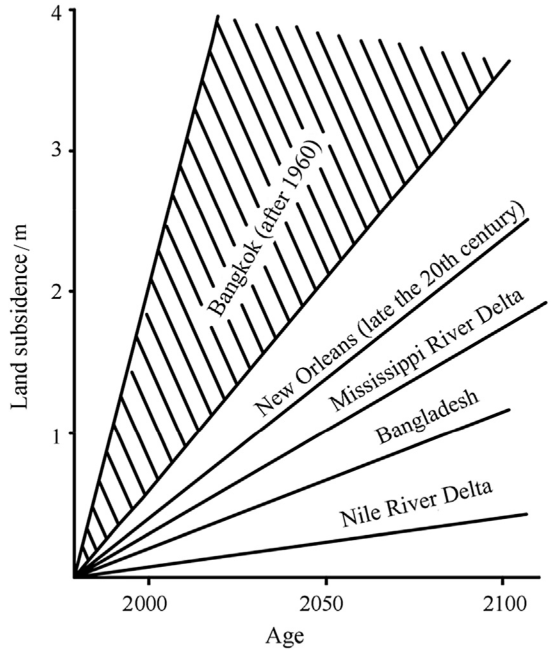

FIGURE 14.1

Land subsidence amount estimation of main delta areas in the world (Milliman et al., 1989). Currently the land subsidence rate of many river deltas in the world has the maximum of 100 times of the eustatic sea level rise rate, if without control, by 2100, the land subsidence will still be the main part of relative sea level rise.

change"; the report clearly pointed out that "we don't research the absolute sea level (namely the eustatic sea level), we research the relative sea level" (Titus et al., 1991).

There are many papers about sea level published recently in China, and they gradually differentiate the eustatic sea level and the relative sea level with emphasis of using the relative sea level rise value to evaluate the risk and loss of Chinese coastal areas during the sea level rise; this is now a trend.

1.1 RESEARCH PROGRESS OF GLOBAL SEA LEVEL CHANGE

In the last 10 years, some international organizations, such as UNESCO's IPCC and IOC (Intergovernmental Ocean Commission) all published research reports about the global sea level change. The United States and the Netherlands and other governments also published research reports about the global sea level change. In 1994, the Department of Earth of Chinese Academy of Sciences also published *Influence and Countermeasures of Sea Level Rise on Chinese Delta Areas*.

The sea level research is connected with the global change at the beginning, namely the global climate warming causes the sea level rise. The famous Swedish geophysicist Morner reported the global sea level change problem in the sea level group at the annual meeting of ASAS (American Society for the Advancement of Science) in 1990. Fig. 14.2 is from the original figure of Morner; we

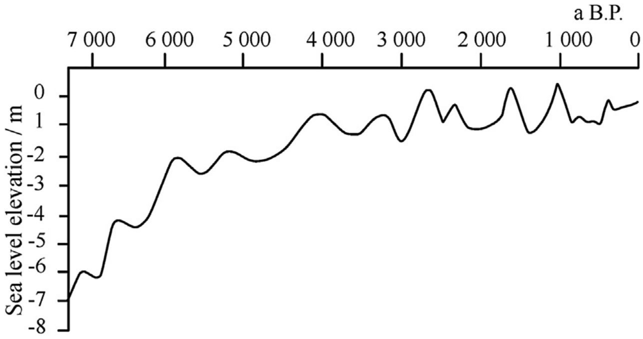

FIGURE 14.2

Global sea level change in the recent 7000 years.

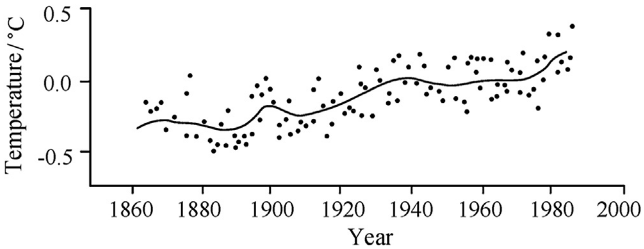

FIGURE 14.3

Global average temperature (Rising waters, 1991).

can see the global sea level change in the recent 7000 years—in the recent 4000 years, though the sea level has had small rises and falls, the whole trend has been rising. Fig. 14.3 shows the average temperature in the world since 1860, we can see from this figure that since 1900, the global average temperature has risen 0.5°C.

On December 7, 2009, the United Nations Climate Change Conference opened in Copenhagen, Denmark. This was a meeting called "the last chance to save mankind." The climate change is one of the most serious and deepest challenges we and our future generations face. Scientists predict that with the continuous aggravation of greenhouse effects, by the end of this century, the global temperature rise will be between 1.1°C and 6.4°C. What is more surprising is as seen from the latest greenhouse gas emission increase rate, the earth climate has begun to develop to rise to the harsh 6°C–7°C, which is much more greater than the 2°C as the earth ecological warning line. There is no doubt that the global climate warming will produce a big influence on the future global sea level rise! The bottom line for human beings is to control the global temperature rising at 2°C or even lower; once it is over 2°C, the global warming will be out of control, and then even if humans want to take remedial measures, there will be no chance to fix the problems. Therefore, the Copenhagen Accord agreed upon at the United Nations Climate Change Conference held in Copenhagen published the statement: "We underline that climate change is one of the greatest challenges of our time. To achieve the ultimate objective of the

Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2°C, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change. We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2°C, and take action to meet this objective consistent with science and on the basis of equity."

1.1.1 Sea Level Change Research in Past 100 Years

For the global sea level change in the past 100 years, in recent years many scholars worldwide did research and calculations, and published different values. The global sea level rise values in the past 100 years are mostly according to GLOSS and the actually measured records of the tide stations in the world of PSMSL were used to analyze and calculate values. But the recorded data themselves have two problems. Firstly, PSMSL's tide stations' geographical distributions are not even; in the 1980s, Europe accounted for 32%, North America accounted for 18%, and Japan accounted for 16%, which accounted for 66% of the total tide stations in the world, so the sea level rise value calculated on this cannot represent the real global sea level rise value. After 1985, the sea level observation stations of GLOOS had been increased to 300, and with the geographical distributions greater than in the past, it is predicted that in this century, the recorded data will be more representative. Secondly, the MSL records are strongly influenced by the vertical motion on land (Woodworth, 1991).

B C Douglas of American Oceanic and Atmospheric Administration made a strict screening of the tide station records in the world; he eliminated the stations that are easily influenced by the structural motion (such as Japan), stations with short record years (there are less than 100 stations in the worldwide tide stations with records of more than 50 years), and stations with no records for a long time; he only selected the records from 21 representative stations (the average recorded years was 76 years) for the calculation, and obtained the global sea level average rise rate in the past 100 years—1.8 mm/a (Douglas Bruce, 1991). This may represent the relatively correct value of the global sea level rise in the last century. At the same time, in the reports and papers of some authoritative scientific organizations and others from around the world put forward that the world sea level rise average value in the past 100 years is also similar with the Douglas calculation, such as UNESCO is 1.0−1.5 mm/a (Stewart et al., 1990), International Geosphere-Biosphere Program is 1.0−2.0 mm/a (IGBP, 1992), and Woodworth of mean sea level service is 1.0−2.0 mm/a. Ren (1993) took its mid-value to estimate that the global sea level rise rate in the past 100 years is 1.5 mm/a.

What should be further noted here is that because of the uneven tide station distribution and the different structural rise and fall motion and the different tide position record times and the different research methods, the results from different researchers have big differences, the annual rise rate is between 0.5 and 3.0 mm/a, and most of them are between 1.0 and 2.0 mm/a (Table 14.1).

1.1.2 Estimation of Global Sea Level Rise in the Future 100 Years

The global sea level rise rate in the past 100 years is generally estimated as 1−2 mm/a, and there are big differences in the estimation values between each party. In order to estimate the global sea level rise value in the future 100 years, the value differences will be huge with bigger uncertainties. Recently

Table 14.1 Estimation Value of Global Sea Level Rise in the Past 100 Years

Rate/(mm/a)	Resource Data	Reference
1.2 ± 0.3	Station 130, 1880–1982	Gornitz and Lebedeff (1987)
1.15	Station 155, 1880–1986	Barnett (1988)
2.4 ± 0.9	Station 40, 1920–1970	Peltier and Tushingham (1989)
1.7 ± 0.13	Station 84, 1900–1980	Trupin and Wahe (1990)
1.8 ± 0.1	Station 21, 1880–1980	Douglas Bruce (1991)

the international organizations generally use low values, namely 50 cm (IGBP) or 60 cm (UNESCO). The reasons for using the low value for the global sea level rise in the future 100 years are as follows.

① The revised report of IPCC in 1992 about the global climate warming pointed out: the sulfur emitted by the burning of fossil fuels has cooling effect for the atmosphere, so the estimation value of global warming will be revised to be low.
② The methane emitted from the rice fields may have been estimated too high in the past (IPCC, 1992b).
③ The production of chlorofluorocarbons in the world in 1991 is reduced by 46% since 1988 (annual report of World Watch Institute in 1991).

The reasons that estimation value still has big uncertainty are as follows.

① There is still a lack of accurate measurement data for the annual erosion balance about the ice cover and ice amount in Antarctica. The uncertainty of the estimation value for annual snow accumulation in Antarctica is ±20%, which is corresponding to the global sea level change value 10 cm/100 a (IGBP, 1992).
② Currently the CO_2 produced by humans has one-third absorbed by the ocean, and the CO_2 amount in the ocean is about 50 times than in the atmosphere; some minor changes in the ocean carbon cycle can have big influences on the atmosphere. However, we don't have accurate knowledge about the process and amount of the carbon exchange between ocean and atmosphere.
③ The global sea level rise value in the future 100 years is estimated mainly according to the global climate warming value, while the global climate warming has about 60% caused by CO_2 emission. But the global CO_2 emission amount in the future is more or less based on the human factors, such as the population and economy growth, industrial structure adjustment, energy price, technology progress, fossil fuel supply, nuclear energy, and renewable energy utilization. These factors are currently difficult to be estimated.

IPCC's estimation for the sea level rise value in the future 100 years is established on the hypothesis that the greenhouse gas emission amount still increases based on the current rate. If the emission amount has decreased or increased in mass, then the sea level rise's estimation value in the future 100 years will also be reduced or increased. In the future decades, with the industrial development and population growth in some developing countries, the coal-burning amount will inevitably increase, so it is difficult to reduce the global CO_2 emission amount in the near future. Therefore, the global sea level rise trend in the near future is difficult to change.

In view of the uncertainty of the estimation of global sea level rise value in the future 100 years, in 1990, the first working group of IPCC put forward four plans for the greenhouse gas emissions, such as CO_2, and based on this, further predicted the change of global temperature and sea level in the future. These four plans include:

A. Normal emission plan without restriction.
B. Energy supply is converted into low carbon fuel, especially the natural gas and forest damages are controlled, and the Montreal Protocol internationally restricting the production of CFCS is fully implemented.
C. Renewable energy and nuclear energy replace the mineral fuel in the latter half of the 21st century, and CO_2 and other gas emission amount are accordingly largely reduced.
D. In the early half of the 21st century plan C is achieved; in about 2050, the CO_2 emission amount is reduced to 50% of that in 1985.

The corresponding CO_2 concentration and relative temperature change in the atmosphere in the 21st century these four plans are shown in Fig. 14.4.

Warrick and Oerlemans in the report of IPCC in 1990, according to the above plan A, estimated the global sea level rise degree in the 21st century; its best estimated sea level average rise rate is about three to five times that of the average rate in the past 100 years (Fig. 14.5).

In addition, they also, according to the plans B, C, and D about the greenhouse gas emission restriction, estimated the respective sea level rise degree, the best estimation values of the four plans are shown in Fig. 14.6. We can see from the figure that the best estimation value for the global sea level rise in 2050 under each plan is between 20 and 31 cm (Douglas Bruce, 1991).

In 1992, some European and Chinese scholars cooperated and published *Climate Change Caused by Greenhouse Effect and Its Response in China*; this report according to the greenhouse gas emission plan of IPCC in 1992, estimated that the global temperature rise in 2050 is 1.2°C and in 2100 is 2.5°C. Based on this, the best estimation value of the sea level rise in 2050 is 22 and 48 cm in 2100, as shown in Fig. 14.7 (Hulme et al., 1992).

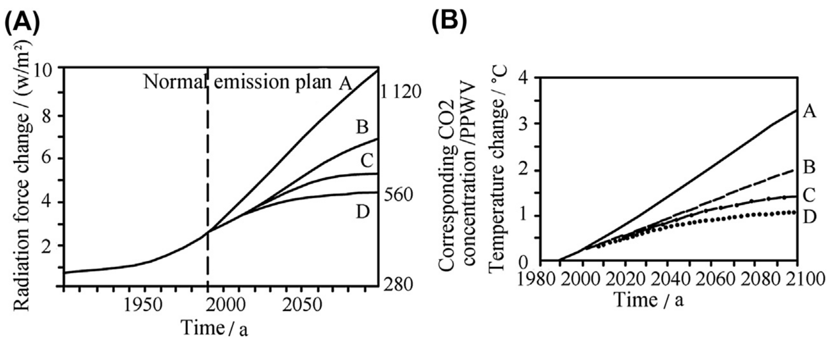

FIGURE 14.4

Four plans' corresponding atmosphere CO_2 concentration and corresponding temperature change map in the 21st century. (A) The atmospheric CO_2 concentration and radiation force increment prediction. (B) The prediction of corresponding temperature rise degree (the first working group of IPCC, 1990).

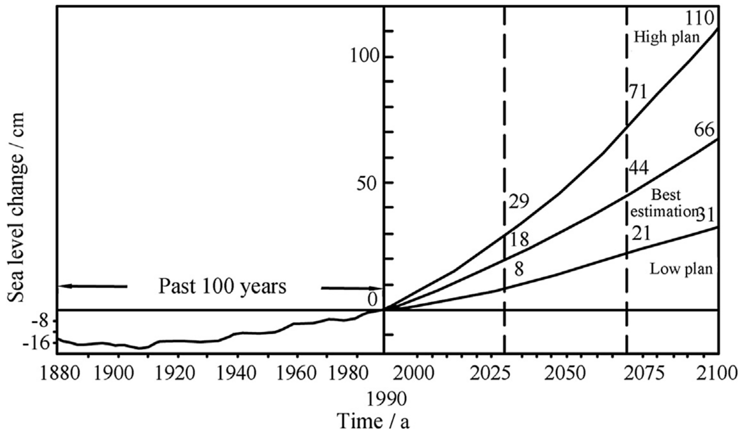

FIGURE 14.5

Sea level rise estimation in the 21st century under plan A of IPCC in 1990 (Warrick and Oerlemans, 1990; the historical parts from 1880 to 1990 in the figure are taken from Barnett, 1988).

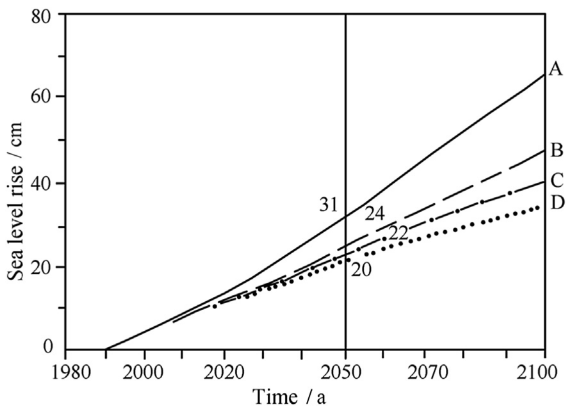

FIGURE 14.6

Respective best estimation of four plans of IPCC for sea level rise in 1990 (Warrick and Oerlemans, 1990).

We can know from the previous discussion that the estimation of greenhouse gas emission change, the global temperature rise caused by greenhouse gases, and the further caused sea level rise in the 21st century, were based on the current knowledge, so, there is much uncertainty between each link, and, the longer the time, the bigger the uncertainty. As shown in Figs. 14.6 and 14.7B, the best estimation value in 2050 of each prediction plan has small disperse, which are all between 20 and 31 cm. Therefore, we have reason to think that the most likely degree of rise degree of the global mean sea level in 2050 is 20—30 cm (Shi and Yang, 1994). But there is big disperse from 2050 to 2100.

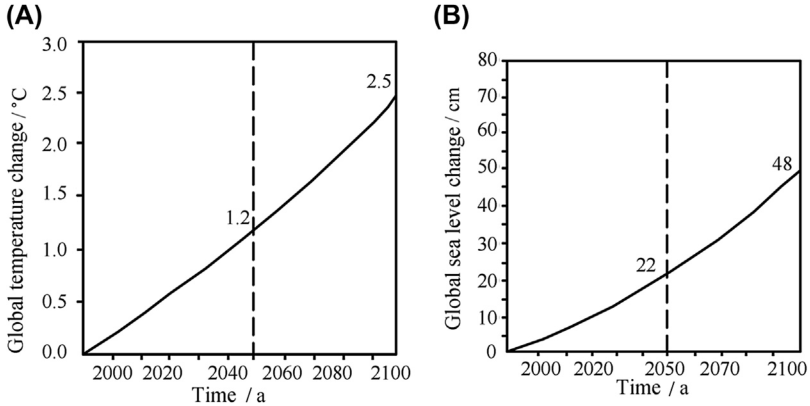

FIGURE 14.7

Global temperature and sea level change estimated by IS92a plan of IPCC in 1992. (A) The best estimation for global temperature rise in the 21st century. (B) The best estimation for global sea level rise in the 21st century.

Currently the best estimation for the global sea level rise rate in the future 100 years is the value provided by IPCC. If the greenhouse gas continues the emission as in the current situation, the best estimation in the proposed plan (proposed in 1990) provided by CZMS of IPCC is 18 cm in 2030, 44 cm in 2070, and 66 cm in 2100, namely the global sea level average rise rate is 4.5 mm/a from 1990 to 2030, 6.5 mm/a from 2031 to 2070, and 7.3 mm/a from 2071 to 2100 (IPCC Coastal Zone Management, Subgroup, 1992a) (Fig. 14.8). This group proposed that the global sea level rise value in 2100 has the biggest estimation of 110 cm, the smallest estimation of 31 cm, and best estimation of 66 cm.

According to IPCC Third Assessment Report (TRA) (2001), from tide stations data, the average global sea level rise rate was 1.0–2.0 mm/a in 20th century, with the best estimate value of

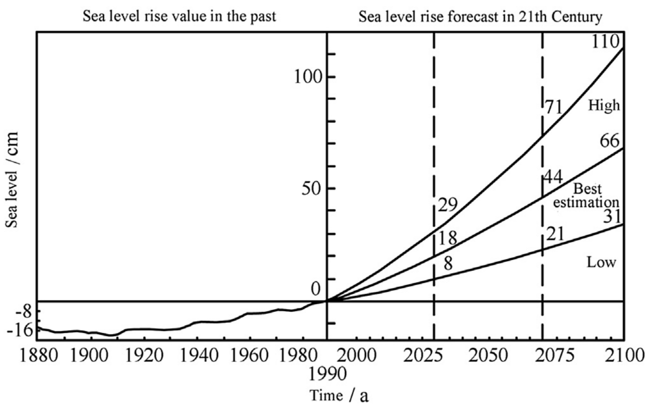

FIGURE 14.8

Global sea level rise value estimation in the future 100 years (IPCC, 1992a).

1.5 ± 0.5 mm/a. The report also pointed out that the sea level will rise 20−70 cm during 1900−2100, or rise 9−88 mm if adding in the contribution of the uncertain land glaciers. In IPCC Forth Assessment Report (AR4) (2007), the sea level rise rate was 1.8 ± 0.5 mm/a in 1996−2003, and that of 20th century was 1.7 ± 0.5 mm/a. Even so, whether the sea level rise is accelerating in these years or the rise is only a change of time, we don't know. IPCC Forth Assessment report forecasted that until the end of 21st century, if without considering land ice melting, the steric sea level will rise 18−59 cm. If adding land ice melting, the rise data need to add 10−20 cm, and the most will reach 79 cm. After that, some scholars pointed out that at present the polar ice cap is decreasing quickly and the sea level will rise 1 m or more until 2011, so they thought that the IPCC Report maybe underestimate the risk of sea level change.

However, based on data from tide stations and satellite observation, Rhamstorf (2007) believed that the sea level rise rate in 1990−2006 was far greater than the data from IPCC. According to statistical model that was established by surface temperature and sea level change of the 20th century, Rhamstorf thought that the sea level will rise 1.4 m in that 21st century, which is larger than IPCC estimation.

Gregory and Lowe (2000) thought that 60% of the sea level rise comes from thermal expansion. Through simulation of the coupled ocean atmosphere general circulation model and assuming the atmospheric greenhouse gas concentration during 2100−2199 keeps the value of 2100, Landerer (2007) estimated that the sea level will rise 26 cm until 2011, while until 2199 under the action of thermal expansion it will rise 56 cm.

1.2 RESEARCH PROGRESS OF CHINESE SEA LEVEL CHANGE

In the middle of the 1980s, IPCC established GLOSS to improve the sea level observation methods, and recently it put forward some new observation technologies, such as satellite radar altimetry, GPS, and others. In recent years, applying GPS and other advanced ground measurement technology to monitor the land vertical motion rate has made great progress. Recently the international scientific field has established "GPS service center of geodynamics" to monitor the instantaneous land vertical motion. If the GPS is installed on the satellite, the observation efficiency of GPS can be 500 times higher than on the ground.

The application of GEOSAT satellite altimetry technology can accurately measure the ocean surface change repeating many times in the global range and in all weather, namely the sea surface terrain and the mean sea level, which compensates for the disadvantages of the routine observation methods such as few observation data and long repeating period. Recently, Wang Haiying, Xu Houze, and Wang Guangyuan from Wuhan Institute of Geodesy and Geophysics of Chinese Academy of Sciences used the satellite altimetry data to research the sea level and sea surface terrain in Chinese offshore waters and obtained new understanding of the data.

Han et al. (1994) according to the quantitative estimation of sea level rise influence technology route recommended by the third work group of IPCC, used high and new technology, including TM remote sense data handle and geographic information system to carry out the quantitative research and analysis for the risk of sea level rise on Tianjin plain at west coast of Bohai Sea on the social economy; its results were appraised and recommended by the Eastern Hemisphere sea level rise and coast management international seminar of IPCC. After processing of the TM image data of Tianjin plain on May 9, 1991, they picked up the latest land utilization type and superposed it with the 0−6 m isobath plus coast erosion and accumulation data to draw the environment terrain map. This map can display and accurately calculate the total land area that will be flooded and overflew under the condition of no dam protection when the future sea level rises to a certain height, and the respective area of every land utilization type. In addition, according to the TM image data and the environment terrain map, we can quantitatively display and evaluate the degree of influence of every sea level rise height on the industry and agriculture and population in Tianjin city. The environment terrain map is also good to analyze every possible environment deterioration behind the dam, such as seawater intrusion, swamping or wetland, soil salinization, and foundation softening, thus good for the preconsidering of the corresponding countermeasures to work out the comprehensive environment and coast zone management plan.

Liu et al. (1998b) used the remote sense and geological information system to predict the land flooding loss caused by different sea level rises in Liaohe River delta. The new understanding they obtained was that if there is no protection, when the relative sea level rises 50 cm, the land of about 4,000 km^2 will be flooded, including the whole Yingkou downtown and half of the Panjin downtown; and when it rises 100 cm, the land of 5,000 km^2 will be flooded.

Zhang et al. (1999) divided the Guangdong coastal areas into 20 evaluation units (zones) and established the influence evaluation system of sea level rise and evaluation factor system to evaluate the comprehensive grade and zoning for the risks of sea level rise on each coastal section (prehazard evaluation). They designed the comprehensive evaluation model for the influence of sea level rise on the economic development of Guangdong coastal areas. The results showed that the hazard prevention ability index in the model turned the negative evaluation into the positive evaluation, and made the evaluation results of coast hazard risk grade more practical, so the evaluation results could be used to guide the macro hazard prevention, hazard relief, and hazard reduction.

Owing to the annual average tide data in 1912−1993 of Wusong tide station, using multivariate stepwise regression and maximum entropy spectrum analysis and other methods, Qin and Li (1997), Li et al. (1998b) analyzed the absolute sea level long-term change trend and periodical change rule of Shanghai with Wusong as representative, and based on this rule, established the superposition model for the long-term prediction of the absolute sea level long-term prediction, and predicted the sea level change trend of Shanghai area in the future 50 years; they also made detailed evaluation for the reasonability and reliability of the prediction value, and gave out the absolute and relative sea level rise prediction values of Shanghai area in 2010, 2030, and 2050. The absolute sea level rise prediction value was a little smaller than the prediction value of IPCC in 1992 and 1995, and it was closer to the prediction result of IPCC in 1995. This shows that using multivariate stepwise regression method according to the actual tide data to determine the sea level change trend may be more practical for the actual sea level change characteristics than using the fixed functions to determine its trend. Nevertheless, the long-term prediction of sea level is a complex problem, and with the continuous accumulation of actual data in the future, we should further improve the prediction model to reduce the prediction uncertainty as much as possible.

1.2.1 Chinese Sea Level Change in the Past Decades

The rise rate of global sea level (namely the eustatic sea level) in the past 100 years is generally estimated as 1−2 mm/a. In China, according to the estimation of State Survey and Drawing Bureau, in the past decades, the Chinese sea level average rise rate is about 1.4 mm/a. But for the specific sea level at each place, namely the relative sea level, it will differ greatly. According to the analysis of Ren (1995) for the tide records at 32 tide stations, in the recent 30−80 years, 20 stations documented relative sea level rise, 12 stations documented relative sea level fall, and the rise and fall speed at each station was not the same. Therefore, the relative sea level is much more important for the Chinese life, society, and economy.

The tide stations with longest records in China are Wusong and Tanggu; they all have tide records of nearly 90 years. These two stations are located in the river delta areas with the biggest relative sea level rise rate in the past. Tanggu's and Wusong's relative sea level rise rates were, respectively, 24.5 mm/a and 11 mm/a, and were mainly caused by the local land subsidence. The factors causing land subsidence are natural factors and human factors; the latter is the main reason for the relative sea level rise.

The land subsidence degree in the river delta areas has had big changes in space and time. Take Shanghai (area of 400 km^2) for example. from 1921 to 1992; the average land subsidence rate was 24 mm/a from 1921 to 1948, and sharply increased to 110 mm/a from 1957 to 1961; after the control of underground water exploration and taking recharge and remedial measures, the average land subsidence rate was reduced to 59 mm/a from 1962 to 1972, and it was further reduced to 4.3 mm/a from 1972 to 1992 (Fig. 14.9) (Ren, 1995). But in the Shanghai downtown, the geological distribution of land subsidence is very uneven, and the coastal area of Huangpu River is obviously higher than other areas in the downtown.

Tianjin is the same as Shanghai. In Tianjin new port area, according to the monitor results for 50 benchmarks from November 1985 to October 1986, about 80% of the whole port area had land subsidence of about 20 mm; only the Tanggu tide station was 4 mm. The land subsidence of Tanggu,

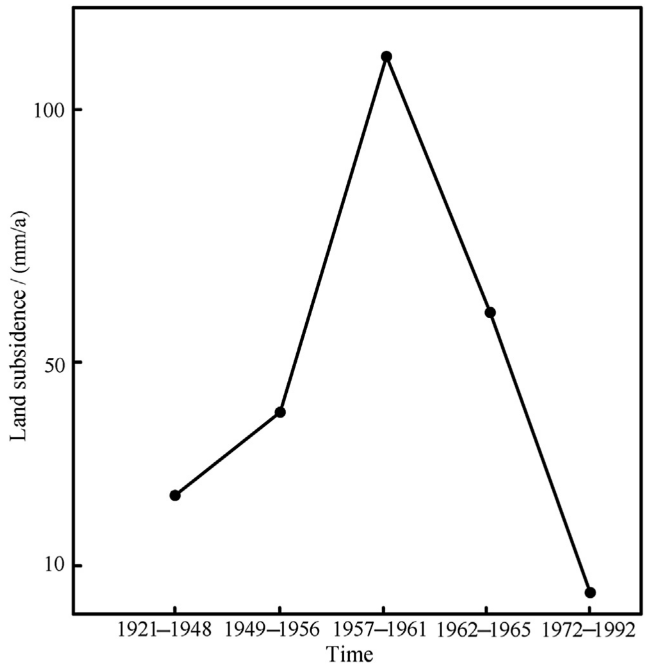

FIGURE 14.9

Land subsidence rate change of Shanghai from 1921 to 1992.

Hangu, and Dagang as the old Yellow River delta coasts in 1986 were all 40–50 mm (Ren, 1993). Therefore, using the records for one tide station to evaluate the influence of sea level rise for the whole delta is not complete and accurate.

Hong Kong and Macau tide stations are the stations with the longest tide sequence in South China. They all have histories of more than 70 years from 1925, but the records at these two stations are still lacking. Hong Kong station doesn't have records from 1930 to 1949; while Macau station was moved three times, and the tide records from 1963 to 1981 have phase error. Huang et al. (2000a,b) took 1959 as the interface, used the monthly average sequence at Macau station as the basis for the former section (1925–1958), converted them into the Hong Kong sea map as the base level, used the monthly average sequence at Hong Kong station as the main for the latter section (1959–1996), and these two stations constitute the universal sequence in 72 years. Then used the positive and inverse Fourier change method to delete the periodical fluctuation of less than 4a to obtain the low filter series, and then performed the linear regression calculation; they obtained the sea level rise rate in the recent 72 years as 1.8 ± 0.1 mma; 1.8 mm/a can be treated as the rise rate of the eustatic sea level in Pearl River area, and this value has good consistence with the value in global background.

Huang et al. (2000a,b) took 24 representative measurement points from the total 71 measurement points in the Pearl River delta area for analysis, the phase 3–phase 5 leveling from 1951 to 1989 showed that there are 10 measurement points having land subsidence rate less than 2.0 mm/a, five having 1.5–1.7 mm/a, four having 1.1–1.3 mm/a, and five of less than 1.0 mm/a. Therefore it is thought that the land subsidence rate on the Pearl River delta plain is generally 1.5–2.0 mm/a. We can know from the aforementioned that the relative sea level rise rate in the Pearl River delta area is about 3.3–3.8 mm/a.

The estimated relative sea level rise rates of Chinese coasts by the representative researchers are listed in Table 14.2 (Yang and Shi, 1995a,b).

1.2.2 Estimation of Sea Level Rise in Future Decades in China

As mentioned previously, in the next century (2100), the eustatic sea level rise estimation has big uncertainty. For the relative sea level, its uncertainty varies widely, because the relative sea level

Table 14.2 Relative Sea Level Rise Trend Estimation of Chinese Coast in Recent Decades

Researchers and Publication Year	Average Rise Rate/(mm/a)	Data Reference
Emory and You (1981)	2.5 (−1.9–11.5)	8 tide stations, 1950–1980
Yu (1986)	2.1 (3.0–10.8)	16 tide stations, 1960–1980
Wang (1986)	3.5 (9.5–10.5)	20 tide stations, 1950–1980
Zhou et al. (1992)	0.7 (2.9–2.6)	7 representative stations, 1950–1989
Huang et al. (1992)	0.3 (3.3–2.2)	12 tide stations, 1953–1983
Zheng et al. (1993)	1.4–2.0	50 tide stations
Ren (1993)	1.0–4.0 (3.4–27.8)	32 tide stations, 1960–1989

The values in the brackets in the rise rate column in the table are the change range calculated based on the data of each tide station, of which "−"means the relative sea level fall; the data years in the data reference column are different at each station, those listed in the table are the representative years.

contains a large part of land subsidence, while the Chinese land subsidence is mainly cause by human factors. The future land subsidence trend is mainly determined by a series of social and economic factors and local governments and are not easily predicted and are more difficult to calculate using the mathematical methods.

Because the estimation value of sea level rise in the future 100 years has big uncertainty, so for the Chinese river delta and coastal plain, we must carefully and completely work out the relative sea level rise value in the future decades. Listing several values for selection is scientific, but it inevitably adds difficulty for management to make decisions. Ren's (1993) research determined the relative sea level rise values in the past 30 years and the most possible relative sea level rise values in the future 40 years of the old Yellow River delta (Tianjin area), the Yangtze River delta (Shanghai area), the Pearl River delta, and the modern Yellow River delta (Dongying), as shown in Table 14.3. The eustatic sea level rise value in 2030 in the table uses the best estimation of IPCC.

In the Table 14.3, the land subsidence rate of the modern Yellow River delta and the Pearl River delta are mainly the structural subsidence value, so now is the same with 2030. The land subsidence rate of old Yellow River delta and Yangtze River delta include structural subsidence, sediment compaction, and the land subsidence caused by the excessive exploration of underground water; the latter is the main (for example, about 90% of the land subsidence values of Tianjin new port area in the past were caused by the excessive exploration of underground water).

Chen et al. (1993) analyzed every tide station data in detail on the Chinese coast, and through the repeated benchmark measurement's balance standard, carried out the unified check, and in the end they obtained a good representative average sea level rise rate of 2.1 mm/a at six stations, including

Table 14.3 Relative Sea Level Rise Rate of Old Yellow River Delta, Modern Yellow River Delta, Yangtze River Delta, and Pearl River Delta (mm/a)

Time	Area	Eustatic Sea Level Rise Rate	Land Subsidence (mm/a)	Relative Sea Level Rise Rate	Sea Level Rise Estimation
1956–1985	Old Yellow River delta	1.5	23[a]	24.5	
	Modern Yellow River delta	1.5	3–4[b]	4.5–5.5	
	Yangtze River delta	1.5	5–10	6.5–11.5	
	Pearl River delta	1.5	1–1.5[b]	2.5–3.0	
	Old Yellow River delta	4.5	10	14.5	60
2030	Modern Yellow River delta	4.5	3–4	7.5–8.5	30–35
	Yangtze River delta	4.5	3–5	7.5–9.5	30–40
	Pearl River delta	4.5	1–1.5	5.5–6.0	20–25

[a]*According to the cooperative measurement results with Tianjin Baodi base rock benchmark in every year from 1966 to 1985, Tanggu tide station benchmark elevation has total fall of 0.489 m, namely the average annual fall is 24.45 mm. The annual rise rate minus Baodi base rock benchmark elevation is 1.3 mm, the actual annual fall of Tanggu tide station benchmark is about 23 mm.*

[b]*The modern Yellow River delta land subsidence rate is based on* Modern Crust Vertical Motion and Ground Deformation of Yellow River Delta and Its Adjacent Area *by Hu Huimin, Huang Liren, and Wang Ruobai. The land subsidence rate of the Pearl River delta is based on the oral report of Zhang Hunan from Guangdong Seismological Bureau on February 13, 1993, and* Geotectonic and Geological Environment of Coast in South China *by Zhang Hunan, Chen Weiguang, and Huang Kunrong.*

Qinhuangdao, Qingdao, Wusong, Kanmen, Xiamen, and Zhapo (Chen et al., 1993). Other related research results are similar to these results. This shows that it is practical to directly use the future global sea level rise estimation for the Chinese coast. Therefore, the investigation group of Department of Earth of Chinese Academy of Sciences during the estimation of the relative sea level rise degree in some focus areas for 2050 took the global sea level rise of 20−30 cm as the basic composition, and respectively, obtained the Pearl River delta of 40−60 cm, Shanghai area of 50−70 cm, and Tianjin area of 70−100 cm.

Based on tide station data in recent 40 years, Chen et al. (2008) thought that the sea level rising rate in Chinese coast area is 2.3 mm/a. Through data of T/P satellite altimeter, Yan Mei and other scholars estimated that the average sea level rising rate of China is 4.93 mm/a.

According to 2010 China Sea Level Communique, during 2001−2010, the average sea level in Chinese coast was at historic highs; it was 25 mm higher than 1991−2000 and 55 mm higher than 1981−1990. Because of climate warming and other factors, there was obvious spatial difference among Chinese coastal sea level change as follows: the sea level rose 11 and 10 mm, respectively, in the Bohai Sea and the Yellow Sea; a little rise in the East China Sea coast; but down 24 mm in the South China Sea.

According to 2014 China Sea Level Communique, the Chinese sea level wavelike rises in these years. The rising rate is 3.0 mm/a in 1980−2014, which is higher than the average global sea level rise. In 2014, the Chinese sea level is 111 mm higher than normal years (the average sea level in 1975−1993), 16 mm higher than that of 2013, and is the second highest year from 1980. The Chinese sea level changed obviously in different regions in 2014. Compare with the normal years, the sea level rise in the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea is 120, 110,115, and 104 mm, respectively. When compared with 2013, the greatest rising rate is 38 mm, which occurs in the East China Sea. Then the sea level of the Yellow Sea and the Bohai Sea rise 22 and 13 mm, respectively. The sea level rise is the minimal in the South China Sea with the value of 10 mm.

1.3 INFLUENCE FACTORS OF SEA LEVEL CHANGE

In the global environmental problems, the climate warming and sea level rise have the biggest influence, of which the sea level rise is much more important, because the coastal zone is the area with the dense population, developed economies, and many metropolises. The sea level is the unity of seawater volume and ocean basin volume; it is the comprehensive reflection of sea and land motion. In the current stage, the sea surface rise and fall that we recorded through the tide stations are actually a kind of relative sea level change; it not only includes the seawater surface fall caused by the amount of seawater increase and decrease but also includes the superposition and reduction of the rise and fall activities of land on the sea surface height. The factors influencing these two activities are very complex. According to the difference of actions influencing the relative sea level change, it can be divided into two categories of natural factors and human factors.

1.3.1 Natural Factors

The natural factors influencing sea level change mainly include the coast rise and fall caused by modern structural motion, ocean basin water volume increase, glacier variation, and other factors.

1.3.1.1 Coast Rise and Fall Caused by Modern Structural Motion

In the world, especially the Pacific Rim area, the coastal vertical structural motion extent and rate are very big in some subduction zones, collision zones, or strong extensional zones. For example, in the North America Mendocino triple point area, the Izu Peninsula and the Ryukyu Islands in Japan, Taiwan Island in China, and the North Island in New Zealand, the Holocene structural lift can be up to 20–50 m, the average vertical deformation rate is up to 5 mm/a or higher (Lu and Ding, 1994). At the same time, in these areas, much evidence has been found to divide the structural motion component of coast lift and the component of climate sea level rise and fall.

What needs special attention is that the strong seismic activities in the coastal zones will cause sudden land subsidence and can cause sharp change in large scale of sea level in some local sections to produce earthquake genetic coast terrace, depression, and other special landforms. For the coast lift or depression with the scale of dozens of centimeters and even several meters caused by this kind of instantaneous earthquake, there are many reports and research from New Zealand, Japan, Alaska, and other sections in the Pacific Rim seismic belt (Lu and Ding, 1994).

The Chinese coastal zone, such as Bohai Sea and its coast, Quanzhou in Fujian, Nanao in Guangdong, and Qiongzhou in Hainan Island, all had strong seismic activities, causing the sharp rise and fall change of ground. Therefore, when we discuss the influence of sea level rise and fall on environment, in-depth research on the dynamic process of the modern structural motion in coastal zone is a very necessary research topic.

The Chinese eastern coast is located at the west margin of the West Pacific structural belt; the neotectonics motion since Quaternary and the current structural motion in the last hundred years are very strong. With regard to the vertical rise and fall motion, the difference in different areas is very obvious. Eastern Liaoning peninsular, Shandong peninsular, and the southeastern coastal areas including Taiwan Island are the crust continuous lift areas, and their lift velocity is very close to the rise velocity of the global sea level, the relative sea level rise trend is nearly 0 and even negative value; the North China plain, northern Jiangsu plain, and Yangtze River delta areas are the crust continuous fall areas, the structural fall is superposed with the global sea level rise, adding rise to the degree of relative sea level.

According to the relative altitude of the Tang County profile in end of Tertiary and the Guangci surface and Tangshan surface in the same period, also the sediment burial depth, namely the overlying sediment thickness of the Tang County surface at the same period, Lu and Ding (1994) estimated the rise and fall degree and average rate of land at each coastal section; the preliminary results are as follows

① The Yellow Sea and Bohai Sea coast on eastern Liaoning peninsula is the arched uplift with the uplift extent of 50–100 m, and the average lift rate is 0.02–0.03 mm/a.
② The lower Liaohe River estuary coast is the fault depression with the subsidence extent of 300–500 m, and the average subsidence rate is 0.12–0.25 mm/a.
③ The Bohai Sea coast in western Liaoning and northern Hebei is the block uplift with the uplift extent of 100–200 m, and the average rate is 0.03–0.06 mm/a.
④ The local west bank of Bohai Bay and northwest bank of Laizhou Bay are the fault depression and gravity balance depression with the subsidence extent of 500–700 m, and the average rate is 0.18–0.25 mm/a.
⑤ The Jiaodong peninsula coast is the arched uplift with the lift extent of 50–200 m, and the average rate is 0.02–0.06 mm/a.

⑥ The local northern Jiangsu coast is the fault and balance depression with the subsidence extent of 100—300 m, and the average rate is 0.03—0.1 mm/a.
⑦ The Yangtze River delta tilts and subsides to the northeast with subsidence extent of 20—500 m, and the average rate is 0—0.2 mm/a.
⑧ The Zhejiang, Fujian, and Guangdong coast lies in the structural lift area. The uplift extent of eastern Zhejiang and northern Fujian sections is estimated as 300—500 m, and the average lift rate is 0.1—0.2 mm/a. The lift extent from Hanjiang River estuary to Pearl River estuary in eastern Guangdong is 150—250 m with the average lift rate of 0.05—0.1 mm/a.
⑨ The eastern coast of Taiwan Island has strong lift in the recent 2—3 million years, its lift extent is at least above 1500 m. The modern tableland on eastern coast of Taiwan has lift rate of 5—7 mm/a, and the average is 3—5 mm/a.

The Pearl River, Yangtze River, and Yellow River as three big deltas and Tianjin area are the structural subsidence areas; the structural subsidence is the important composition for the relative sea level rise in these areas. According to the repeated land benchmark measurement and Holocene sediment layer thickness and absolute year estimation, the subsidence velocity is generally 1—3 mm/a; it increases toward the sea and decreases to the land (Li, 1993a). What should be pointed out is that the measurement and estimation of crust structural subsidence is very difficult. Take the repeated benchmark measurement as the example, in addition to the measurement error due to technical problems, the obtained subsidence rate also includes the local ground surface subsidence.

The long-term (about 3 Ma) structural rise and fall estimation on each coastal zone in China reflects that though most of the Chinese coastal zones have small crust vertical deformation rate, this slow structural motion is still a determining factor for the shaping and forming of a series of characteristics of the Chinese coastal zones, and it becomes an important component for the regional relative sea level change.

1.3.1.2 Ocean Basin Water Volume Increase and Glacier Variation

The crust motion with large scale such as the change of ocean basin water depth, the change of glacier and polar ice volume, or the mantle motion change can all cause the geoid change, and further cause the rise and fall of sea level. The sea surface form change such as the expansion of seawater volume with heat and contraction with cold, input of freshwater, weather system processes, and ocean current changes can also cause changes of sea level.

The land glacier variation with the cold and warm climate is the leading factor controlling the seawater volume and seawater surface rise and fall. In the time scale of less than dozens of hundreds of thousands of years, the water amount at the earth surface is basically stable. Generally, the amount of water consumed by ocean is basically balanced with the amount of water received. But when the climate has sharp change, this balance will be seriously disturbed; in the cold glacial period, lots of ice and snow accumulated on the land, the seawater volume shrank, and the sea level fell; in contrast, in the warm interglacial period, the accumulated ice and snow largely melted, the seawater volume increased, and the sea level rose.

Since the Cambrian period, there have been three big glacial periods and interglacial periods in the world; the time cycle of each change is 10—100 Ma. The Quaternary is the last glacial period in the earth's history, starting from the obvious coldness in late Neogene, it has the history of about 3 Ma until now, but compared with the last two big glacial periods, it is just unfolding, its cold glacial climate will still last for a very long time. In the Quaternary glacial period, there is the secondary change of glacial period and interglacial period with the cycle of 0.1—1 Ma. According to the duration of each glacial period, the Dali (Yumu) glacial period at the latest stage will still last for several tens of thousands of years or longer; the post glacial period in the recent 10,000 years is not the end of this glacial period and the start of another interglacial period but is the relative warm stage with a short period in this glacial period—the third interglacial staircase.

According to the late Quaternary stratum and Paleontological data analysis revealed by the drillings in the Chinese eastern coast and continental shelf area, in about 70,000 years since the Dali (Yumu) glacial period, there were three obvious climate cold and warm and sea level rise and fall changes, its cold low sea surface and warm high sea surface periods, respectively, lasted for 12,000—17,000 years (Zhang, 1991b). According to this rule, the postglacial period since Holocene—the Dali (Yumu) glacial period, the third interglacial will still last for more than 2000 years. However, according to the climate and sea surface change process since the late Holocene, this interglacial warm and peal period of sea surface have passed, and since the middle of middle Holocene, the climate and sea surface height slowly falls during the fluctuation, showing that it is in the transitional period into the next relatively cold low sea surface glacial period.

In summary, in the periodic climate change with scale of more than 1000 years, the interglacial in the Quaternary glacial period is in the transitional stage to the glacial period. According to the existing alternating cold and warm rule, for a long time in the future, the natural climate will continue to slowly get colder. In this process, changes of every kind of short period (10—100 year) will be very frequent. At the beginning of this century, the climate will basically keep the current status, later it will slightly rise, and then at the end of this century or the beginning of the next century, the temperature will fall again. In this alternating cold and warm process of natural climate, the annual average temperature change extent will remain at ±2°C.

The ice cover volume in Antarctica is 10 times bigger than that of Greenland. The whole melting will make the global eustatic sea level rise 65 m, so its response to the global climate warming will have determining influence on the global eustatic sea level change.

In recent years, after detailed research, scientists have generally thought that in the future 50—200 years, the ice cover in Antarctica will not be melted by the climate warming, and the western ice cover in Antarctica will also not be broken up. It is estimated that in the future 200 years, the ice cover in Antarctica will have a volume increase of 0.5% due to the global warming (Ren, 1990), which is equivalent to the 30 m fall of global eustatic sea level, so the ice cover in Antarctica will have possible negative effect on the future global eustatic sea level change.

1.3.2 Human Factors

The human factors influencing the sea level change are mainly greenhouse effect, land subsidence caused by the excessive exploitation of underground water, oil and gas resources, and the water level lift trend, of which the recent land subsidence has the biggest influence. The land subsidence in the coastal areas in the world is a universal phenomenon.

1.3.2.1 Greenhouse Effect

Domestic and foreign experts treat the greenhouse effect produced by CO_2 and other greenhouse gas emissions as the main reason for the sea level rise. In the recent hundreds of years, with the rapid increase of world population and intensification of industrialization, human beings are more and more merciless exploring nature, the surface forests have been seriously destroyed, and vast amounts of underground fossil fuels have been excessively exploited. According to the statistics, currently the annual consumed mineral energy in the world is up to 70×10^8 t oil equivalent, and the tropical forests are disappearing from the earth at the rate of 900–2450 hm^2 every year. With these activities, CO_2 and other greenhouse gases in the atmosphere sharply increase. Before the large scale of industrialization, namely the first half of the 19th century, the CO_2 concentration in the atmosphere was about 270×10^{-6}, by 1988 it had increased to 345×10^{-6}, an increase of nearly 30%. Other greenhouse gases also increased very fast. Currently the CO_2, C_2O, and CH_4 gases emitted into the atmosphere every year, respectively, amount to 50×10^8 t, 0.12×10^8–0.15×10^8 t and 4.25×10^8 t. The increase of CO_2 and other greenhouse gases make the radiation heat absorbed by atmosphere increase, thus resulting in the temperature rise, so that the land glaciers melt and the global sea level rises.

Though the idea that the greenhouse effect causes the obvious rising of global sea level has become the mainstream thought that is widely accepted both domestically and abroad, there are some experts who have taken objection or have a more careful attitude, and there are different ideas in every link of CO_2 increase–greenhouse effect–sea level rise. In the divergent public opinions about the sea level change, most domestic and foreign experts think that due to the action of greenhouse effect, in the recent hundreds of years, the global sea level has obviously risen; some experts think that the action of greenhouse effect is not so strong, and the local or regional sea level change with different trends and of different extents are very promising; few experts think that the current sea level has a falling trend.

Fig. 14.10 is the actual measured CO_2 concentration change curve from 1958 to 1988. Fig. 14.11 is the CO_2 concentration change trend in the recent hundreds of years, of which the curve section before 1958 is estimated according to the ice core analysis, and others are the estimated values after the 1980s to 2050 (Yu, 1995). The left upper corner in Fig. 14.11 is the change curve of CO_2 concentration in atmosphere from 2000 until now, it is estimated according to the content of C^{13} in the tree rings. We can know from Fig. 14.10 that the current CO_2 concentration in atmosphere has reached 350 ppmv (volume unit as millionth), and as shown by the curve in Fig. 14.11, the CO_2 concentration in atmosphere in the middle of last century was about 280 ppmv, so now we have just a 25% increase.

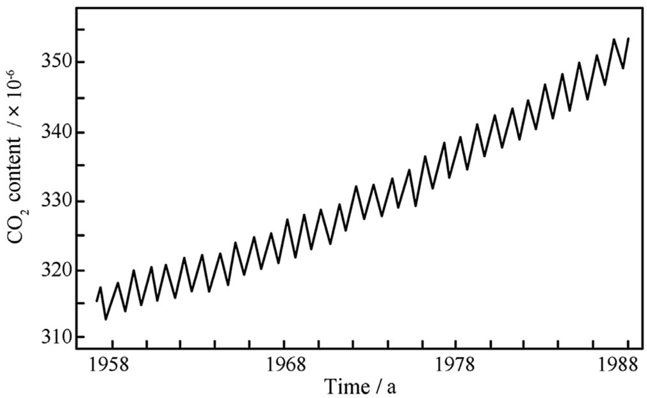

FIGURE 14.10

CO_2 concentration change in atmosphere (Keeling et al., 1989).

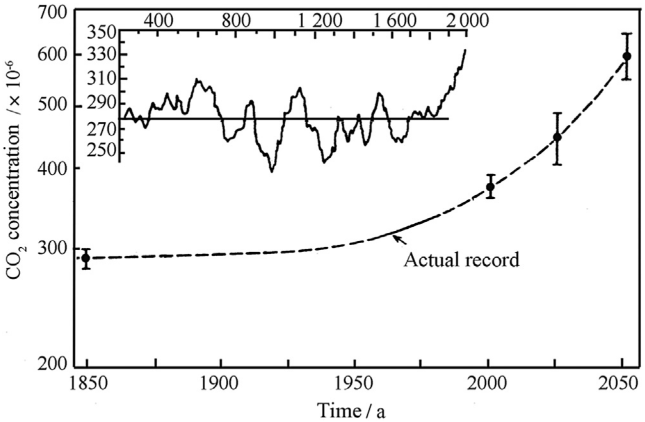

FIGURE 14.11

CO_2 concentration change trend in atmosphere (WCDP and WMO, 1986).

Fig. 14.12 is the average temperature anomaly of the Southern Hemisphere, the Northern Hemisphere, and the global. See from the figure, from 1850 until now, the temperature of the two hemispheres all rise slowly, and the global average rise is 0.5°C, its rise trend (1850–1990) is basically consistent with the change trend of CO_2 content concentration in atmosphere in Fig. 14.11. This shows that during the process of global climate warming, the CO_2 content increase in atmosphere is an important reason.

The report provided by the first working group of IPCC in May 1990 predicted that by 2030, if the greenhouse effect is equivalent to the CO_2 doubling, the global average temperature will rise 1–2°C, and the sea level will rise about 20 cm (Yu, 1995). But according to the analysis of some experts (Chao, 1993), in the recent hundreds of years, due to the influence of human activity, the CO_2 content in the nature has increased sharply; it can indeed make the global temperature rise, climate warm, and sea level rise, but this kind of climate warming under human activity is comprehensively mixed with the earth atmosphere's and ocean's natural force influences, therefore it increases the difficulty for the future prediction, so we must be very careful to prevent the enlarging of human influence while underestimating the climate warming itself in the analysis process.

Currently, the thoughts about temperature and sea level rise in large scale include the human exaggeration with different degree. The important reason for this deviation is firstly the data are mostly from some local areas or regions, and they may not have global meaning; secondly, in the short term, the observation data as the basis for temperature and sea level rise are difficult to show as a link in the normal alternating process or as a reflection of the abnormal trend.

1.3.2.2 Land Subsidence

There are areas with certain thickness and composition of fine particles in the Quaternary sediment layer in which the excessive exploitation of underground flow will cause the soil layer condensation and will further cause the land subsidence; this is more obvious in the big and medium cities in the river deltas and coastal lowlands. Its subsidence rate is much more than the global sea level rise rate, for example,

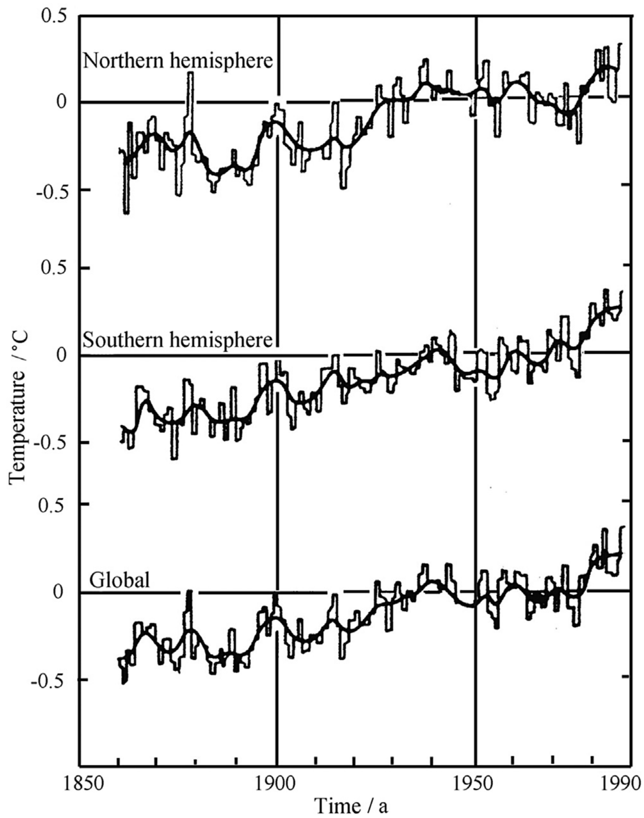

FIGURE 14.12

Average temperature anomaly of the Southern Hemisphere, the Northern Hemisphere, and global (for the average deviation from 1850 to 1979, the curve is low pass filtering) (Wigley et al., 1986).

the maximum subsidence in Shanghai from 1921 to 1965 reached 2.63 m, the maximum subsidence rate was 287 mm/a, and the maximum subsidence in Tianjin downtown was 2.7–2.9 m (Li, 1993a,b). The land subsidences in some cities are gradually connected, such as the Suzhou, Wuxi, and Changzhou area in Yangtze River delta and Tianjin, Cangzhou, and Huanghua on the coast of the North China with the area of several thousands of square meters, at 2×10^4–3×10^4 km^2. The land subsidence becomes a factor that can't be ignored when predicting the relative sea level rise on the Chinese coast.

The land subsidence has close relationship with the underground exploitation and the dynamic changes:

① The land subsidence center has obvious consistency with the underground exploitation funnel central area.

② The land subsidence area is basically consistent with the underground water centralized exploitation area.

③ The land subsidence isograms distribution direction is basically consistent with the underground water exploitation funnel distribution direction, and the rate of land subsidence has good corresponding relation with the exploitation amount and exploitation rate of underground liquid.
④ The land subsidence and compaction amount of every layer are closely related with the change of pressure-bearing water level.
⑤ The development of land subsidence in many areas has been controlled through the artificial recharge or restriction of the exploitation of underground water to resume and lift the underground water level, and some areas have made the ground rise again.

So, when we estimate the relative sea level rise, we must consider the land subsidence as an important influencing factor caused by the exploitation of underground flow.

1.3.2.3 Trend Water Level Uplift

The reclamation of river beach and tidal flat in the estuary delta areas, the river bed occupied by municipal construction, embankment, tidal sluice gate, and others, either reduce the river bed section area to make the drainage not smooth, or reduce the adjustment and reservoir ability of water network, resulting in the trend uplift of water level. After the embankment of the Pearl River delta in the 1950s, the water level had obviously uplifted, rising 9—38 cm from Xijiang Makou to Modaomen in the flood season from 1959 to 1979 with the average rise rate of 5.0—10.0 mm/a (Li, 1993a). The water level of the middle and downstream of Huangpu River in the flood season from 1954 to 1992 uplifted 10—20 cm with the average rise rate of 2.5—5.0 mm/a.

The trend of water level rising in the river delta area is mainly caused by human activity, which makes the ground have relative subsidence; its effect is similar with the land subsidence, so it can be seen as a component of relative sea level rise.

In summary, in a series of correlated factors such as human activity, climate change, and sea level rise and fall, there is a very complex interaction mechanism. Currently, it is not as strong for the greenhouse effect and its action on climate change and sea level change as many people believe. Therefore, with the sea level change, though the greenhouse effect is a warning influence factor, currently and in the future dozens of years, the extent of its influence is far less than the effect of crust and ground rise and fall activities on the relative sea level, and of course it will not cause a disastrous sharp rise in sea level.

In a word, it is generally thought that humans are the main force causing the global environmental changes. The global relative sea level rise is mostly caused by human activity, especially in the delta areas. Bangkok, located in the Menam River delta of Thailand, had the maximum land subsidence reaching 75—160 cm due to the excessive exploitation of underground water from 1978 to 1987, which was 50—100 times bigger than the global eustatic sea level rise rate. The America Mississippi River delta due to the construction of all kinds of irrigation works and other human activities, had annual land loss (flooded by sea) of 100 km^2. Tanggu in the Chinese old Yellow River delta due to the excessive exploitation of underground water had the total land subsidence of 285 cm from 1955 to 1985, which was nearly 100 times higher than the global eustatic sea level rise rate (Ren, 1990). Therefore, the research on the global relative sea level rise must be paid attention to when determining the influence of human activity.

1.4 RISK OF SEA LEVEL RISE AND ITS PREVENTION COUNTERMEASURES

Sea level rise will bring a series of adverse effects on the natural environmental evolution and social and economic development of the coastal areas, and it is an important environmental problem that can't be ignored for the coastal areas to achieve a sustainable development strategy; this has become one of the hot topics of global change research that has received international attention. If in the next century the sea level rises 1 m, it will directly influence about 500×10^4 km^2 of land, population of about one billion, and about one-third of the cultivated land in the world. Taking into account the special storm surge and seawater intrusion, the coastal zone below 5 m above sea level will be affected, these areas of population and food production account for about half of the world.

1.4.1 Risk of Sea Level Rise

The rising of sea level is a slow process, but the accumulation in long term is very considerable, which is enough to influence many aspects of coastal economic construction, municipal construction, and people's production and lives; this influence is much wider and deeper than any other natural hazard. The rise of the sea level is often associated with the tide, storm surge, storm floods, and other superposition when fully displayed, but the tide, storm surge, and storm floods are short time, sudden and "visible" events, almost attract people all the attention. The sea level rise is the background and foundation of these sudden natural disasters, hidden behind them, and is "invisible."

The sea level rise will not only cause the tidal beaches and wetlands and other lowlands to flood, and aggravate the coast hazards such as coast erosion, storm surge, low depression flood, and seawater intrusion, but also influence the ocean and coastal environmental evolution process and the development and utilization of every natural resource and water supply and drainage system in the city, port and wharf design, and seawall and culvert and other irrigation engineering to cause great social losses. The research on sea level rise influence on the Chinese coast is still in the early stage, so the research content is not wide and the research depth needs to be further deepened. The research areas are mostly centralized in the river delta plain areas such as the Yellow River delta, the Yangtze River delta, and the Pearl River delta, which are obviously impacted by the sea level rise.

1.4.1.1 Coast Erosion Caused by Sea Level Rise

The main response of sea level rise in the coastal zone is the coast erosion and displacement of coastal sandbank to the coast. The sea level rise makes the wave breaking point move upward on the coast beach, which may damage the coastal buildings. The upward moving of wave breaking point will cause the high tidal beach to become narrow; sediment becomes coarse and coastal wetlands are lost. The coastal wetland loss makes the beach surface wave elimination and causes the coastal erosion. Because of the continuous rise of the sea level, the increased water depth makes the disturbance action of wave on the old coastal zone gradually reduce and causes horizontal sand supply reduction at seabed, while on the other hand strengthens the scour of surf on the upper beach. At the same time, the gradually increased sea level reduces the river gradient and reduces the sediment amount of river into the sea. Before more than 30 years ago, in addition to individual abandoned estuaries, the delta was eroded backward in China, the vast majority of the coast was slowly silted or stabilized (Xia et al., 1993a,b). Since the late 1950s, the Chinese coastline's migration direction has changed inversely; most sandbanks, mud banks, or coral reef coasts turned from siltation or stability into erosion to cause the coastline to move backward. According to the statistics, about 70% of the sandy beach and most of the mud tidal beach in the open waters eroded, and the coastal beach erosion range became more and more enlarged, and the erosion velocity became stronger and stronger. On the Atlantic coast of the United States, houses built on the seashore 5 or 10 years ago are now threatened by coastal erosion and have to build seawalls to protect.

More and more coastal erosion has brought serious impact on the production and lives of coastal people, causing road interruptions, collapse of coastal villages and factories, deterioration of bathing beach environment, flooding of coastal protection forest by seawater, destruction of bank protection engineering, destruction of spawning fields and feeding grounds of marine fishes, flooding of salt pans and farmland by seawater, and other serious issues.

The systematic concept of the sea level rise causing coastal erosion was first put forward by Bruun in 1962. He researched the practical examples of coastal erosion in 40 countries and listed six coastal erosion factors, of which the sea level rise is the most common factor for the around the world. For 30 years, the theory of Bruun law applicable to partial sandy coast has been confirmed by laboratory and field observation; it is the current popular method to calculate coastline change. The retreat distance of the coast near Yangtze River delta calculated by Ji et al. (1993) according to Bruun law is shown in Table 14.4.

Among all coast erosion factors, the influence of sea level rise accounts for a big proportion. The coast retreat calculated according to Bruun formula is caused by the sea level rise factor, it belongs to the part of total erosion and total coastline retreat. According to the Bruun analysis, the seriously eroded coast has beach erosion caused by sea level rise accounting for 15%—20% of the total erosion. The future sea level rise rate continues to increase, which will make the sea level rise factor's proportion in the total coast erosion continue to increase. In the coastal erosion research on Ocean City in Maryland, United States, events estimated that the coastal erosion retreat caused by sea level rise accounts for 20%—25%, while the proportion of sea level rise factor in the coastal erosion in 2025 will be increased to 38% (Ji et al., 1993).

1.4.1.2 Aggravation of Storm Surge

The storm surge is the sea surface abnormal rise with heavy wind caused by typhoon or temperate zone storm surge such as cold wave and other disastrous weather, the increase value is more than 1 m; sometimes it is superposed with the astronomical tide, the tide level has sharp increase of 3—6 m, resulting in the seawater flooding; meanwhile heavy winds, huge waves, and heavy rains form the big hazards, flooding the land and swallowing the ports and wharfs, villages and farmlands, and bringing big hazards to people's lives and properties in the coastal zone.

Table 14.4 Retreat of Coast With Sea Level Rise Calculated According to Bruun Law

Coast Section	Beach Gradient/‰	Coast Retreat at Sea Level Rise of 1 m/m
Abandoned Yellow River delta coast	1.3—3.6	2.8—7.7
Middle coast in Jiangsu	0.3—0.9	11.2—33.4
Southern coast in Jiangsu	1.1—1.2	8.3—9.1
Nanhuizui coast	0.6—3.9	2.2—16.7
Northern coast of Hangzhou Bay	2.8—4.5	2.2—3.6

The storm surge is the biggest natural hazard causing people and property loss in the Chinese coastal zone. The sea level rise directly causes the initial sea surface of storm surge water increase and the increase of high tide level, which not only aggravates the storm surge hazard degree but also causes the increase of hazard frequency, causing more losses of life and property. In the Pearl River delta area, if the sea level rises 50 cm, the storm surge level of bank section near Guangzhou station will decrease from a 50-year reoccurrence to once in a decade. On the back sections in Yangtze River delta and its adjacent areas with relative big tide level (such as Ganpu and Xiaoyangkou), if the sea level rises 50 cm, it will make the storm surge level decrease from 100-year reoccurrence to 50-year reoccurrence; while on other bank sections with relative small tidal difference, the sea level rise of 20 cm will possibly make the storm surge level decrease from 100-year reoccurrence to 50-year reoccurrence (Zhu and Ji, 1993). In the west back of Bohai Bay, according to the estimation of Xia Dongxing and other researchers, if the sea level rises 90 cm, the storm surge level in 100-year reoccurrence will also possibly become a 20-year reoccurrence (Xia et al., 1993a,b).

The rise of seawater temperature with the sea level rise may cause the increase of tropical cyclone hazard, so then aggravating the storm surge hazard. Zhu and Ji (1993) comprehensively researched the historical storm surge hazard and temperature data in the nearly 500 years in Yangtze River delta area, and found that the years with storm surge hazard in the warm 16th and 18th centuries was 20%–30% more than the cold 15th, 17th, and 19th centuries. Wang and Liu (1991) analyzed the relationship between annual typhoons in the nearly 100 years of the northwestern Pacific, annual landing times of typhoons in China, and global temperature changes, finding that after the temperature lag of 26 years of typhoon, they had good correlation, and further estimated that when the temperature rises 0.5°C and 1°C in the next century, the frequency of typhoons at northwestern Pacific will, respectively, increase 63% and 134%; the typhoon landings in China will also increase 63% and 119%.

The strength and frequency change of typhoon and storm surge hazard have great influence on the coastal protection engineering design. For example, according to the estimation of the Dutch Ministry of Transport and Public Works, for all of the Netherlands it will cost as much as 0.159 billion euro to deal with the 10% increased storm surge strength, which is more than 40% of the cost for fighting the sea level rise of 60 cm (Netherlands Ministry of Transport and Public Works, 1991).

1.4.1.3 Seawater Intrusion

The sea level rise increases the strength of seawater intrusion; the aggravation of seawater intrusion hazard is also thought to be one of the important influences on sea level rise, and this phenomenon is more obvious in the estuary area. The sea level rise forms salt wedges at estuary back. The current research is mainly on Yangtze River and Pearl River with certain data basis. Using relative experience and numerical calculation and other methods for the seawater intrusion strength at Yangtze estuary caused by the sea level rise, the comprehensive research of Yang and Zhu (1993) showed that if the future sea level rises 50 cm, the intrusion distance of 1‰ southern branch slack water and 5‰ isohaline in the dry season will, respectively, increase 6.5 and 5.3 km than the current status, and the risks obviously increase. The calculation results of Li (1994), who used Ippen empirical formula for the Pearl River estuary, also showed that the sea level rise would increase the seawater intrusion hazard, and that if the future sea level rises from 40 to 100 cm, the 0.3 isohaline intrusion distance at each waters will generally increase about 3 km.

Except that the estuary salty water line is back due to the sea level rise, the coastline also has the same change. Because the seawater's contact with land underground water surface is increased, the salty water's seepage strength into the inland will be increased, so that the underground water quality has heavy salt, which also influences the human and livestock's drinking water, deteriorate soil, and make the fertile farmland become abandoned.

In several areas in northern China's Liaoning, Hebei, and Shandong provinces, due to the little rainfall and excessive exploitation of underground water, the freshwater level in the coastal underground water reservoir layer is decreasing, so that there is a man-made environment that is beneficial for seawater intrusion. The hazard of seawater intrusion into the underground water reservoir layer continues to become more and more serious; for example, in the Shandong peninsular with Laizhou Bay as the main, the seawater intrusion area of 731 km^2 has impacted cultivated land area of 4.5×10^4 ha and now a population of more than 445,000 lacks water (Zhao et al., 1991). The future sea level rise and coastal tide level rise will definitely aggravate this hazard.

1.4.1.4 Damaged Water Resource and Water Environment

Previously we discussed the aggravation of relative sea level rise on the seawater intrusion hazard. In addition, with the relative sea level rise, in some coastal rivers the tide will move further to the inland, and because of the flood tide uplift, the polluted water has back fluctuation, which will inevitably worsen the river pollution. These polluted rivers often lag at the interface of current and runoff in the river channel to impede the city sewage, causing the river water quality to be seriously polluted in the city, and further causing water supply source pollution. In the Chinese coastal areas, especially in the southern Yangtze estuary, the water supply always sources from the river's surface waters; many cities are located in the estuary areas into the sea, such as Shanghai at Yangtze River estuary, Hangzhou at Qiantang River estuary, Ningbo at Yongjiang River estuary, Wenzhou at Oujiang River estuary, Fuzhou at Minjiang River estuary, and Guangzhou, Foshan, and Zhuhai at Pearl River estuary. Among them, Shanghai downtown and the Pearl River delta have more serious problems.

In Shanghai, the water quality of Huangpu River and its branch Suzhou River are all seriously polluted, and currently the river pollution content of two-thirds of the river channels in Huangpu River are over the index. According to the water quality analysis and calculation for the main water supply source Wusongkou, the current seawater intrusion brings risk to the water quality of Wusongkou [refers to the chlorinity in water source (Cl) $> 200 \times 10^{-6}$], usually it is under the situation of the flow amount of Yangtze River into the sea less than 11×10^3 m^3/s, while during the 50 cm rise of the sea level, if the flow amount of Yangtze River into the sea is kept as 11×10^3 m^3/s, it will have obvious impact; see from the monthly flow amount data at Datong station of Yangtze River for many years that the chance of Yangtze River's monthly flow amount in the dry season of less than 11×10^3 m^3/s is only 40%, and the chance for less than 13×10^3 m^3/s is 60% (Yang and Zhu, 1993).

The northern coastal areas lack surface waters, so the city water supply depends on the underground water as the largest water source, such as Dalian, Qinhuangdao, Yantai, and Qingdao. Currently, the seawater intrusion into underground water reservoir layers in these areas due to the excessive exploitation of underground water has produced big risk for the city water supply.

Even if the future sea level rise can stop the underground water level from falling, the tide level rise will cause the enlargement of the negative value areas of underground water level in many Chinese coastal cities; this will definitely aggravate the underground water pollution and intensify the city water supply shortage.

1.4.1.5 Flooded Coastal Lowland

The most obvious influence of sea level rise on the coastal area is the flooding area enlargement at the high water level. The Chinese coastal zone altitude height is generally low, especially the Pearl River delta and Yangtze River delta alluvial plain. The sea level rise is the greatest threat to towns, farms, oil fields, port industrial facilities, and aquatic products breeding bases in these areas. According to expert estimation, if the future sea level rises 50 cm, the whole Yangtze River delta and northern bank of Hangzhou Bay and northern Jiangsu coastal plain will have losses of tidal beach and wetland areas, respectively, of 550 and 246 km^2, which, respectively, account for 11% and 20% of the current bottomland and wetland areas, of which the influence of sea level rise can account for 44%–65% (Zhu and Ji, 1993). Because the west bank of Bohai Bay and Tianjin are the large depression, the sea level rise and land subsidence will bring big losses for these areas. If the sea level rises 30 m without protection, the natural coastline will retreat 50 km, namely, reaching the Tianjin downtown, and Tianjin may become the Venice in China in this century and the flooded land will be about 10,000 km^2. If the sea level rises 100 cm, the coastline will retreat 70 km, and the total area under the possible influence of seawater will be about 16,000 km^2 (Xia et al., 1994). The tidal beach and wetland loss not only decreases precious land, tourism, and biological resources but also weakens the beach surface wave elimination and impact persistent ability, so when there is storm surge, even astronomical tide, these delta areas, Shanghai port, Tianjin port, Shengli oil field, and Dagang field will all be seriously threatened.

Generally, the scale of coastal tidal beach and lowland flooding losses mainly depends on the relative sea level rise extent, ground elevation, and gradient of costal lowland. During the foreign evaluation and prediction of influence of sea level rise on the coastal areas, usually the future sea level rise extent is compared with the ground elevation of coastal lowland to calculate the flooded land to estimate the losses, but there is no confirmation that this method is applicable for the Chinese delta and coastal lowland. Under the existing sand supply condition, the problem is to what extent the sea level rise will cause the seawater intrusion to flood the lowland, and this needs to be further studied.

1.4.1.6 Flood Prevention Ability Reduction

The relative sea level rise will definitely directly influence for the long term the important coastal engineering facilities; these engineering facilities are mainly the coast protection engineering, irrigation engineering, and port and wharf engineering. Meanwhile, the relative sea level rise will also strengthen the difficulties of city flood prevention and flood drainage.

1.4.1.6.1 Coast Protection Engineering. Almost all the Chinese coastal plain has seawalls and other coastal protection engineering, but the protection abilities of such seawall engineering is generally limited. Except for a few cities and industrial areas (Bund of Shanghai flood protection wall, Qinshan nuclear plant, and Jinshan oil and petroleum headquarter protection wall) having a high standard of seawalls for about a 1000 years, most of the other seawalls are only for the period from 20 years to 50 years. The rise of sea level and tide, and the strengthening of tide and wave action will not only cause the seawall attacked and eroded directly by winds and storms, at the same time, the rise in sea level leads to a significant reduction in the amount of water required for the same height of the storm, thus significantly reducing the return of the extreme tide level, increasing the chances of seawater overflowing the seawall, and reducing or even damaging the defenses. In the Yangtze River delta plain, in the comparison and analysis of historical highest tide level at each seawall design reference station superposed by the sea level rise value and the selected wave climbing value and the local seawall top elevation, if the future sea level rises 50 cm, there will be an historical highest tide level, and the seawall length that will flood and overflow by the tide will be about 32% of the total length in the area (see Table 14.5) (Yang and Shi, 1995a). This influence may be more serious in some other delta areas where the current seawall protection standard is much lower (such as the old Yellow River delta and modern Yellow River delta).

1.4.1.6.2 Water Conservancy Engineering. Most of the Chinese estuaries into the sea (except Yangtze River, Pearl River, and other big rivers) have lots of culvert and sluice engineering, these engineering projects usually have the comprehensive roles of tide block, flood drainage, and water reservoir for irrigation. The strengthening of sea level rise, tide level lift under sluice, and tidal uplift will shorten the culvert natural drainage duration and reduce drainage intensity. For example, the flood drainage at the coastal plain depression in northern Jiangsu has only a small part by Jiangdu water pumping station that drains southward into the river; it is mainly by the Sheyang, Huangsha, Xinyang, and Doulong as four big ports to drain into the sea. If the future sea level rises 50 cm, the four sluices and one tide drainage duration will on average be reduced 15%−19%, the one tide drainage total amount has average reduction of 20%−30% (Du and Shi, 1993), resulting in the big reduction of drainage ability of every culvert and sluice. The reduction of drainage ability of culvert and sluice will result in the nonsmooth drainage in depression, prolonging inner flood ware accumulation, thus aggravating the flood hazard losses. The Pearl River delta also has a similar problem because this area has very low terrain, and lots of ground that is even lower than the local average sea level; currently it is difficult for the depression water accumulation to have the self-drainage, and it is mostly by mechanical and electric drainage. According to the preliminary estimation, if the future sea level rises 50 cm, the mechanical and electric drainage capacity will have to increase at least 15%−20% to ensure that the current depression flood drainage standard is not reduced (Fan, 1994).

1.4.1.6.3 Port and Wharf Engineering. Many ports (including sea ports and river ports) on the Chinese coast bear the role of national major goods import and export and the transport mission of bulk cargo; they play a huge role in the national economic development. The future sea level rise will bring many adverse effects on the port and wharf facilities. Firstly, the sea level rise and strengthening of wave action will not only increase the chances of port building wave overflow, but also cause the strengthening of wave scour and uplift on every kind of marine construction, and they will directly threaten the safety and life of wharf and wave protection bank. Secondly, the sea level rise and tide level lift will cause great reduction of the original engineering design standard, which makes the flooding frequency of wharf, port roads, stack fields, and storage facilities increase, and enlarges the range. Take the old port area of Tianjin port as an example. Since 1970s, due to the fast land subsidence, the average water level at front of wharves has risen 0.5−0.7 m, and the lowest place of wharves has fallen nearly 1.0 m below the historical highest tide level. In 1992, due to the strong typhoon storm attack, the wharves, passenger station, storage facilities, and stack fields were all flooded, sustaining direct economic losses of 400 million RMB. The preliminary estimation shows that if the relative sea level rises 50 cm, which meets the local highest historical tide level (the repeat period in most areas is about 50 years), in the 16 major coastal ports in China, except the newly built Yingkou port, Qinhuangdao and Shijiusuo coal port, and Beilun port in Ningbo, other ports will all be flooded to different degrees, of which the most serious hazard will be on the old port areas in Shanghai port and Tianjin port (Table 14.6) (Yang and Shi, 1995a), and if there is also wave climbing, the flooding situation will be more serious. In addition, the current and marine dynamic condition changes caused by the sea level rise will also possibly change the port pool, channel in and out port, and the siltation

Table 14.5 Influence of Sea Level Rise of 50 cm on Seawalls in Yangtze River Delta Area (Yellow Sea Elevation in 1956, m)

Section		North of Yangtze River Estuary			Yangtze River Estuary Area			South of Yangtze River Estuary	
		Beiling Sluice to Dongan Sluice	Dongan Sluice to Dongzhaogang Sluice	South of Dongzhaogang Sluice	North Back of Yangtze River Estuary	Shadao Island in the River	South Back of Yangtze River Estuary	Chuansha Section	Nanhui Section
Seawall length/km		86.3	34.9	83.5	46.6	298.4	25.2	46.4	45.0
Status seawall elevation		8.5	6.9	6.8−7.8	6.6	4.5−6.5	6.2	4.9−6.6	6.4
The highest tide of history		6.63	4.92	4.74	4.78	4.04	4.11	4.01	3.63
Wave climbing height		1.5	1.5	2.00	1.00	1.00	1.00	1.50	1.60
Sea level rise of 50 cm	Possible maximum tide height	8.63	6.92	7.24	6.28	5.54	5.61	6.01	5.73
	Height over seawall top[a]	+0.13	−0.02	+0.44 to −0.56	−0.32	+1.01−0.96	−0.59	+1.11 to −0.59	−0.67

[a] *"+" means the tide level beyond the seawall top; "−" means the tide level below the seawall top.*

Table 14.6 Possible Flooding Influence of Sea Level Rise of 50 cm on Chinese Main Coastal Ports[a] (Yellow Sea Base Surface, m)

Port Name	Wharf Top Elevation	Historical Highest Tide Level	Possible Maximum Tide Level at Sea Level Rise of 50 cm	Over Wharf Top Height[b]
Dalian port	2.9−4.9	2.5	3.0	+0.01 to −1.9
Yingkou new port	3.4	2.7	3.2	−0.2
Qinhuangdao port	4.1	1.6	2.1	−2.0
Tianjin port	2.4−2.6	3.2	3.7	+1.3 − +1.1
Yantai port	2.9−3.2	2.7	3.2	+0.3 − 0
Qingdao port	3.2−3.8	3.0	3.5	+0.3 to −0.3
Shijiu port	3.4−12.3	2.8	3.3	−0.1 to −9.0
Lianyungang port	4.1	3.6	4.1	0
Nantong port	4.5	4.8	5.3	+0.8
Shanghai port	3.1−4.0	4.1	4.6	+1.5 − +0.6
Ningbo port	3.9−5.9	3.3	3.8	−0.1 to −2.1
Xiamen port	4.3	4.5	5.0	+0.7
Huangpu port	3.9	3.3	3.8	−0.1
Zhanjiang port	5.1	5.4	5.9	+0.8
Haikou port	3.1	3.3	3.8	+0.7
Sanya port	2.8	1.7	2.2	−0.6

[a]*The original data is provided by Mr. Zhou Lishan of Nanjing Geology and River Institute of Chinese Academy of Sciences.*
[b]*"+" means the tide level over the wharf top height, "−"means the tide level below the wharf top height.*

and scour balance of coastline near the port area, influencing the stability of berth and channel, and increasing the operating costs.

1.4.2 Prevention Countermeasures

The global sea level rise caused by climate warming and the relative sea level rise caused by many interacting factors for a specific region all need a global scientific basis and reliable countermeasure plan, and a prewarning system and prevention countermeasures to control and reduce the relative sea level rise. For the former, the coastal zone management subgroup of IPCC worked out three countermeasures in 1990 for the selection and comparison (IPCC, 1990).

① Retreat: leave the area that will be flooded by the seawater.
② Adaptability: add building height or support to prevent flooding by the sea level rise.
③ Protection: protection measures include building hard construction, such as seawalls, and building soft construction, such as artificial sand dunes, plants, and artificial beach.

The hard structure in the prevention measures refers to the height increase and consolidation of seawall and the construction of wave prevention wall in town; these hard buildings are high cost, they are difficult to be revised after building, they reduce the beach area, and adversely affect the downstream coast erosion. The current known best coast protection measure is to resume its natural state as much as possible, and allow the natural process of coastal zone to continue as usual without artificial intervention (Ren, 2000). The artificial beach is one coast protection measure to resume the original process of nature, which is applicable to the developed coast.

In the delta area with developed modern economy, the best measure to prevent sea level rise is the protection. For the specific coastal area, there are the following protection measures.

1.4.2.1 Strengthening Monitor Method for Sea Level Change

In order to obtain reliable research results that are close to the actual situation for Chinese coastal sea level change prediction, one important basic work is the accumulation and analysis of the direct observation data of sea level change. In order to obtain the true sea level change data, we must consider the relationship between sea level and land level change.

Firstly, we need to establish and complete the monitoring, early warning, and prevention decision system for the climate hazard. The current Chinese observation for the near sea level change is mainly based on the monitoring at each coastal tide station. The Chinese tide stations are mostly set on the coast or on islands, some of them are set at the river estuary or the river section, or set in some large ports; some stations have the observation data of more than 20 years. Under the complete verification of the historical data of the national 22 main tide stations, only 13 stations have the reliable or basically reliable data quality. This situation is not beneficial for the further research and prediction of future sea level change in China. Therefore, the improvement of data quality of tide stations is very important.

Secondly, the sea level change observed at tide station is the change values of the relative tide benchmark. The data observed at tide station is actually the superposing result of sea level change and land elevation change. In order to know the actual sea level change extent, we must carry out monitoring of the land regional structural rise and fall motion near the sea. Meanwhile, because the data obtained by the tide station observation is for a certain tide benchmark, but the research of the whole Chinese coastal sea level change requires the unified processing of the observation data at many tide stations, this requires many land structural rise and fall observation data as the calculation basis. Through the measurement of coastal land terrain deformation, we can clearly know the regional difference of the structural rise and fall motion at each Chinese coastal section; this has significant meaning for comprehensively analyzing the sea level rise and fall change in China.

Finally, on the land near sea, the distribution of very thick Quaternary sediment stratum, plus lots of exploitation of underground water, often caused the reconsolidation and compaction of Quaternary stratum, and this further causes the land subsidence. This phenomenon is mostly in the coastal cities or the industry-centralized areas such as Shanghai and Tianjin. The vertical deformation of this ground is not formed by the regional geological structure; it is caused completely by humans. Because the land subsidence area is adjacent to the sea, so it has close relationship with the sea level rise and fall change. Therefore, the monitor data of land subsidence is a requisite for the research of the sea level rise and fall change. In order to obtain the data, we need special monitoring equipment, namely the land subsidence observation target, which is “layer target” and “bed rock target.” The former’s sign post is set at the top of different sediment layers, and the latter’s sign post bottom is set at the bed rock top buried below the loose sediment layer. In order to ensure the measurement accuracy, the bed rock sign post of land subsidence area should be connected for measurement with the benchmark outside of the subsidence area.

Seen from this, the accurate number of the sea level rise and fall change must be unified to comprehensively analyze the weather station data, tide station data, land regional structure deformation data, and land subsidence observation data, so as to obtain the true sea level change value.

1.4.2.2 Revise Current Seawall Standard, Gradually Reinforce and Add Height of Sea Wall, Strengthen Management and Protection for Current Seawall

The Chinese current seawall elevations are mostly obtained by the addition of the historical maximum tide level, wind and wave height climbing in corresponding repeating periods and over safety as three parameters. For long term, the coast protection is limited by the coast and technical conditions, the seawall construction usually uses low standard plan with many hidden risks, and many places have the negative situation of "typhoon in every year, seawall collapse in every year, seawall fixing in every year." The outstanding problems in the Chinese coastal protection are: low standard of seawall, weak persistence ability, and shortage of comprehensive protection measures.

The current Chinese seawall standards have been self-made by each place from the 1950s to 1960s, usually based on the degree of importance reflected by cultivated land area and population index in the protection area. The seawall standard is divided into four grades; the design repeating periods are 10, 20, 50, and 100 years. Currently the seawall standard in China is mostly for 10—20 years, some low standards are even for less than 5 years. Some high standards have 50—100 years and even higher. Though some seawalls have wall height designed for 100—200 years as the high tide level, they are plant bank protection slope and simple stone block bank protection slope, the wall body is not stable with poor wind and wave persistent ability, and the seawall comprehensive standard is only for 20—50 years.

To change the current situation that the seawalls have generally low standard and weak protection ability, the key is to increase the investment. The existing seawall design standards should be properly revised to redefine the seawall grade and division basis, to improve the seawall resistance, and raise a general level of the seawall on the basis of existing reinforcement.

The seawall facilities not only ensure the sustainable and healthy development of the economy in the coastal area but also protect the people's lives and keep their property safe; meanwhile this is an important countermeasure to global change and sea level rise, and we must strengthen the management by the coastal law and improve the organizational structure.

1.4.2.3 Carrying Out Beach Nourishment to Reduce the Coastal and Beach Erosion

Ren (2000) estimated that 70% of the sandy beaches in the world are under erosion; in the United States, this may reach 90%. Because the sandy beach is an important tourism resource, which is very important for the coastal social economy, in recent decades moving sand to feed beaches (beach nourishment or artificial beach) has become the first measure for coastal management.

Beach nourishment includes rebuilding and recharging of sand as two approaches. The former refers to the moving of suitable sediment (sand) to resume the original width of the eroded beach to fulfill the requirements of tourism and entertainment, meanwhile to protect the beach from erosion of storm. Recharging of sand refers to the regular artificial sand supplement to maintain the beach profile. The artificial beach has the following advantages: more beautiful after widening of beach to promote tourism; hard structures such as jetties and approach embankments often have negative effects on the downstream, while the artificial beach has no such effect; building of seawall can't solve the coastal erosion problem for long term, because the beach in front of seawall will be eroded and disappear, the ocean powers (wave and current) will directly attack the root of the seawall making the seawall collapse, such as the Yellow River delta; artificial beach makes the coast free from the threat of erosion, but increases the price of coastal housing for the new development. See from the earlier discussion that in the future, with the increase of coastal populations in the world and more requirements for beach tourism and entertainment, the application of artificial beaches has good prospects.

1.4.2.4 Strengthening Scientific Research

The most important thing is to research and predict the sea level rise and its influenced rainfall and storm surge frequency and strength and other change rates; the scientific research on this aspect must be connected with the international sea level research, such as the global sea level observation system, IPCC, international geosphere-biosphere program, and mean sea level permanent office.

The sea level change is involved with many factors such as global climate change, marine environment change, regional crust change, and land subsidence caused by human beings. Therefore, we need to apply many kinds of scientific methods (including astronomical measurement) to obtain the accurate change date, and meanwhile apply many analysis methods to research its change rule, and determine its extent and space and time change characteristics. In this process, in addition to the improvement of the routine observation and research methods, we still need some high and new technical observation methods, and to connect it with other fields such as astronomy, geodesy, and geophysics.

With regard to the research content, we need to research the increase of estuary coastal storm surge intensity caused by the sea level change, seawater intrusion and inside seepage, soil liquefaction, increase of coastal erosion rate, estuary and river tough landform change, delta water system gradient becoming gentle, and more serious flood hazard. We also need to research a series of problems brought about by the change of base surface for city construction, such as flood prevention, sewage drainage, flood drainage, water supply, and water drainage and city traffic. For these problems, we need to put forward the corresponding prevention countermeasures. Because the study is comprehensive and involves a wide range of research, it is important to play a multidisciplinary, multicoordinated and multiparty research strengths.

1.4.2.5 Strengthening Public Information and Education

In the delta area, due to the human activity disturbances such as dam construction, banking, and artificial river channel, which reduce the times of delta ground flooding, there is big reduction of sediment, stream discharge, and nourishment into the ground. The wetlands have shortage of nutritive salt, the organic matter has greatly reduced production and can’t continue to increase the height and eventually disappears. The wetland loss or disappearance not only makes the economy suffer from the seriously adverse effects, but also makes it suffer from the more serious flooding threat. The change of the abandoned Yellow River and modern Yellow River delta coast in China is a vivid and powerful practical example of the human activity transforming the coast in the world. The relative sea level rise in some coastal areas has in small part suffered from natural factors; most of the rise is caused by human activity, for example, Shanghai and Tianjin have large relative sea level rise caused by the land subsidence by excessive exploitation of underground water. This is confirmed by the practice of recharge to reduce the land subsidence and further reduce the relative sea level rise. Therefore, strengthening the public information and education and improving the awareness of people to have a scientific view on sea level rise and all kinds of hazards caused by it have important effect for long term. In a word, we should emphasize people’s awareness of protection on natural environment and actively support this awareness.

2. SEAWATER INTRUSION

The seawater intrusion is the water invasion process and phenomenon by the moving of seawater or high-mineralized water to land freshwater reservoir layer under the changes of underground hydrodynamic conditions (Pan and Li, 2002). The coastal city is the area with highly concentrated population and rapid development of economy; its overrequirements for freshwater cause the excessive exploitation, and the underground water level continues to drop, the freshwater interface changes, and the seawater intrudes into the freshwater reservoir layer, underground water has high mineralization, and the water quality deteriorates.

Currently seawater intrusion has been found in hundreds of places in more than 50 countries and areas in the world; it is mainly distributed in the coastal plain, estuary delta plain, and island with developed social economy, such as Long Island in the United States, Hector Moss City in Mexico, and the coastal areas in Japan, Israel, the Netherlands, and Australia. The Chinese coastline is as long as 1.8×10^4 km, and it is one of the countries in the world with the longest coastlines, and the coastal areas are the focus of Chinese social and economic development strategy. However, because of the vulnerability of the natural environment in the coastal areas, and the complexity and variation of the geological environment, under the comprehensive action of natural conditions and human activity, all kinds of hazards occur there frequently. Especially since the 1980s, many sections in the Chinese Bohai Sea and Yellow Sea coast have seawater intrusion aggravation with different degree due to the excessive exploitation of underground water, such as Liaoning, Hebei, Shandong, Jiangsu, Tianjin, Shanghai, and Guangxi, of which the Laizhou Bay coast in Shandong province is the most serious. By the end of 1995, the seawater intrusion area in Laizhou Bay area had developed to more than 970 km^2 (Ma et al., 1998), the area with land underground water level below sea level and threaded by seawater intrusion had developed to more than 2400 km^2, and more than 400,000 people suffered water shortages. It also had caused salty conditions and abandonment of more than 8000 wells, irrigation ability loss of more than 40,000 ha of farmland, large-scale food supply production losses, and other serious results. The seawater intrusion into the freshwater layer directly causes the gradual deterioration of underground water environment, which decreased the limited underground freshwater resources, and causes regional environmental damage and an unbalanced ecosystem.

Currently, people have no unified thought on the definition of seawater intrusion, and there are even different ideas for the name and coverage range of this phenomenon. The foreign documents usually call it salinity intrusion, and the domestic documents define it as seawater intrusion, or seawater infect, seawater internal invasion, seawater underground intrusion, salty intrusion, saline water intrusion, saline water infect, and brine infect, in which "seawater intrusion" is relatively well accepted. The seawater intrusion can be defined as: because of the natural factor or human activity influence, the dynamic conditions of the underground water reservoir layer in the coastal areas have changes, which destroy the balance state between freshwater and seawater, resulting in the intrusion of seawater or the highly mineralized underground water, which has direct dynamic connection with the seawater along the water reservoir layer into the land, the interface of saline and freshwater continues to move to the land, which causes the damage process and phenomenon of freshwater resources (Pan and Li, 2002).

2.1 CURRENT STATUS OF SEAWATER INTRUSION IN RIVER DELTA AREAS IN CHINA

2.1.1 Current Status of Seawater Intrusion in Yangtze Estuary

The spring of 1979 was one of the most serious periods of seawater intrusion at Yangtze estuary. The Yangtze River had low water in 1978; the annual average flow at Datong station was only 21,400 m^3/s, which was the lowest value since 1925. The spring of 1979 was a drought season, the monthly average flow at Datong station in February was only 7010 m^3/s, the minimum flow measured at the Datong station on January 31 was only 4620 m^3/s, and there was a large amount of water pumping along the river; according to incomplete statistics, from April to September in 1979, there was river water pumping of 6.29×10^8 m^3 in Anhui province and river water pumping of 295.2×10^8 m^3 in Jiangsu; from January to March in 1979, the total water pumping along the river at the Datong station downstream achieved 45×10^8 m^3, so that the runoff reaching estuary was reduced and this resulted in the aggravation of seawater intrusion at estuary. The seawater at north branch had continuous flow backward into the south branch in Yangtze estuary, the seawater intrusion in the north port and the south port was strengthened, the whole Chongming Island was surrounded by the seawater, and the Yangtze estuary below Xuliujing suffered from the seawater intrusion for five months (Xu and Zhu, 1994). According to the actual data analysis, the chlorine value at Wusong water plant had the maximum of 3950×10^{-6} and the duration of chlorine value over 250×10^{-6} was as long as 64 days (January to March in 1979). This seawater intrusion's influence range extended more than 170 km from the entrance to the upstream, until the Wangyu estuary and Hupu estuary in Changshu of Jiangsu province. The counties along the river, due to the water pumping, were also influenced by the saline water, such as the inner rivers in Taicang, Kunshan, Jiading, and Qingpu. According to the investigation of the related department for 90 factories, the direct economic losses caused by this seawater intrusion were more than 14 million RMB. Some factories invested more than 8 million RMB to improve the water quality. In order to ensure the water quality, Baogang steel factory had to invest 120 million RMB to build the reservoir of 1300×10^4 m^3. According to the incomplete statistics, the cost to Shanghai for the desalting facilities was more than 1 billion RMB. In agriculture, because of the water pumping for fighting drought along the river, the saline water entered into the inner river, resulting in damage to the rice seeding, of which Taicang county's rice seeding success rate was only 60%, Chongming county had more than 1333 ha of rice loss due to the seawater intrusion. What was more serious was that many people drank the water with high chlorine and then suffered diarrhea, and patients with heart disease and kidney disease suffered even more serious effects to their health (Shen et al., 1990). Therefore, the seawater intrusion at Yangtze estuary had big effects on the industrial and agricultural production and people's lives.

In the spring of 1987 there was another serious seawater intrusion period (Xu and Zhu, 1994). From February 16 to April 10, 1987, a total of 11 stations simultaneously observed the same issues along the north branch, south branch, Beigang and Nangang in Yangtze estuary. During the observations, the run flow at Datong station was 7300–8000 m^3/s, showing that there was less water in low water season, resulting in serious seawater intrusion. The observation results are shown in Table 14.7. As seen in the table, we know: firstly, the seawater intrusion was bigger at the north branch than Beigang, which was bigger than Nangang. The maximum chlorine value at Santiao port of the north branch achieved $16{,}637 \times 10^{-6}$, which was close to that of the seawater. Chongtou had also achieved 7.869×10^{-6}. So the whole north branch was controlled by seawater. The Baozhen at Beigang and the Gaoqiao at Nangang had close location at the estuary profile, but the former's chlorine value achieved

Table 14.7 Actually Measured Chlorine Value Characteristics Index Statistics at Yangtze Estuary From February 16 to April 10, 1987

Place	Actually Measured Statistics Series/h	Maximum Chlorine Value ($\times 10^{-6}$)	Hours With Chlorine Value More Than 250×10^{-6}/h	Ratio of Hours With Chlorine Value More Than 250×10^{-6} and Total Statistics Hours/%	T_0
Santiao port	1440 (60 d)	16,637	1440	100	0/60 = 0.00
Qinglong port	1440 (60 d)	14,288	1209	84	10/60 = 0.17
Chongtou	1440 (60 d)	7,869	834	58	25/60 = 0.42
Baozhen	1440 (60 d)	5,825	1289	90	7/60 = 0.12
Nanmen	1440 (60 d)	2,945	1080	75	17/60 = 0.28
Xinjian	1440 (60 d)	1,599	524	36	40/60 = 0.67
Gaoqiao	1440 (60 d)	2,965	1108	77	15/60 = 0.25
Wusong	2880 (60 d)	3,110	880	30.5	86/120 = 0.72
Baogang	2160 (60 d)	1,705	831	38.5	55/90 = 0.61
Qianjingkou	1440 (60 d)	1,466	506	35	55/60 = 0.87
Xuliujing	1440 (60 d)	133	000	0	60/60 = 1.00

Note: $T_0 = T_1/T_2$, T_1 are the days with chlorine value less than 250×10^{-6} within one day and duration more than 4 h for water pumping. T_2 is the days of the actually measured statistics series of days.

5825×10^{-6}, and the latter's chlorine value was 2965×10^{-6}, they had almost one time of difference, the seawater intrusion at Beigang was less serious than Nangang. Secondly, if there were more than continuous 4 h a day with chlorine value less than 250×10^{-6}, we could pump water; then in this seawater intrusion process, the percentage of days we could pump water and the actually measured total days for the south bank was 100 at Xuliujing, which means we could pump water every day, 87 at Qianjingkou, 61 at Baosteel, 72 at Wusong, and 25 at Gaoqiao, and from upstream to downstream the days we could pump water were gradually reduced. For the northern bank at the south branch, it was 67 at Xinjian, 28 at Nanmen, 12 at Baozhen, also upstream to downstream, the days we could pump water were gradually reduced. For the north branch, it was 42 at Chongtou, 17 at Qinglong port, and 0 at Santiao port, which was also reduced at downstream and tended to be in shortage.

Except for Yangtze River estuary, other sea estuaries in Yangtze River delta area all have the tidal gates, so Yangtze River estuary is the only one suffering from seawater intrusion in this area. Yangtze River estuary is the mixing type estuary with salt- and freshwater; what plays the deciding effect on the seawater intrusion strength change is mainly Yangtze discharge flow and estuary tide as two factors. The seasonal change of Yangtze River flow and the periodical motion of estuary tide make the seawater intrusion change regularly.

Yangtze River estuary discharge flow into the sea is the leading factor to control the seawater intrusion strength at Yangtze River estuary (Yang and Zhu, 1993). In the flood season of Yangtze River, the runoff is very rich, and the river sections at Yangtze River estuary are basically controlled by the

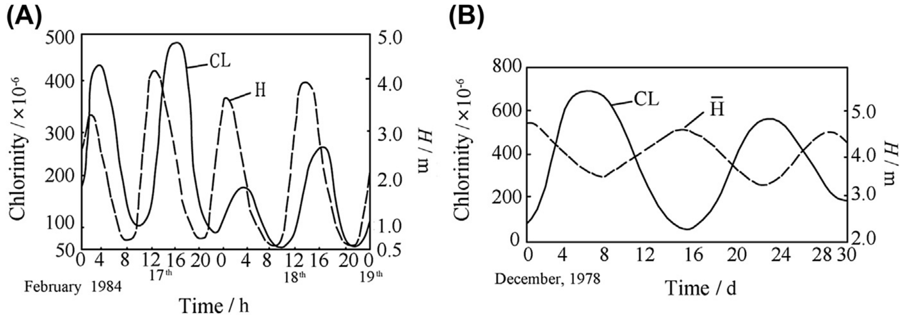

FIGURE 14.13

Chlorine value and tidal process line with time. (A) Gaoqiao station. (B) Wusong station.

freshwater. The chance of daily chlorine value more than 100×10^{-6} for many years at Wudsong estuary is less than 1%; while in the dry season, the runoff effect is obviously weakened, the tidal effect is relatively enhanced, and the seawater intrusion is more serious, the chance of daily chlorine value more than 100×10^{-6} for many years at Wudsong estuary can be above 40%. Affected by the tidal periodical rise and fall, the chlorine value in the water at estuary changes. In a typical year, there is good similarity between the chlorine value and tidal process line, just the chlorine value change is lag of the change of tidal level, and there is a certain phase difference between them (Fig. 14.13). While in the water-rich year of Yangtze River ($P = 20\%$), the strong runoff effect makes the corresponding relationship between the monthly change of chlorine value and the tidal change not obvious.

The saline water moving and chlorine value distribution at the south and north branch river section at Yangtze River have different characteristics. The north branch has small flow with strong tidal action, and general seawater intrusion strength is far stronger than the south branch; the chlorine value distribution gradually increases from the upstream to the estuary gate along the way. During the high tide period in the dry season, there is even seawater in the form of water exchange back charge from the north branch into the south branch. Although the seawater intrusion is not as serious as the north branch, as the main excretion of the Yangtze River runoff, the south branch's chlorine value distribution is very complex. Meanwhile due to the sea level rise influence, the seawater intrusion hazard at Yangtze River estuary will be aggravated. Yang and Zhu (1993) showed by the calculation that when the sea level rises 50 cm, the south branch has fall of 1×10^{-3} isohaline in the dry season and the intrusion distance of 5×10^{-3} isohaline will increase, respectively, 6.5 and 5.3 km from the current status. If the Yangtze River discharge flow is less than 11×10^3 m^3/s, the two isohalines will, respectively, go upstream to Gaoqiao and Xiaojiuduan. When the sea level rises 80 cm, the 1×10^{-3} and 5×10^{-3} isohaline intrusion distance will, respectively, increase about 9.8 and 8.1 km from the current status.

2.1.2 Current Status of Seawater Intrusion in Pearl River Delta

At the Pearl River estuary, the bottom salinity in dry season is between 30 and 33, and it is not very related, and the surface salinity in the waters of Modaomen estuary is obviously small. According to the coastal zone actual measured data, when the surface salinity at other estuaries is above 2, it is only 4–14 at the estuary nearby in the Modaomen waters (Zhou, 1998). In the contour line of salinity of

Pearl River, the isohaline of Modaomen bends to the outside, which is obviously influenced by the upstream runoff flow. Lingding River has strong tide due to the small flow of upstream water, also the bottom slope is flat and gentle, the seawater marches in from Lingding Bay. The situation in Yamen is similar with Lingding Bay.

Tide and runoff are important dynamic factors influencing the seawater intrusion at Pearl River estuary. In the estuary area, because the rainfall is not distributed evenly in the year, it forms the spring drought; at this time the river runoff is in the drought season, the seawater goes upstream, and the river channel salinity largely increases, with Humen having the widest influence range, and Jitimen, Yamen, Hongqimen, following behind it.

Zhou (1998), after analyzing the salinity value of the main representative stations, thought that the estuary desalination is the general trend. The factors for desalination are also tide and runoff. The changes of these two factors are: ① estuary extension, the increase of original fault runoff power; ② shallow sea siltation, the increase of seawater intrusion resistance. Because the siltation rate in shallow sea is bigger than the relative sea level rise rate at Pearl River estuary, Zhou thought that the influence of seawater intrusion on the Pearl River delta is gradually reduced.

2.1.3 Current Status of Seawater Intrusion in Laizhou Bay

The Laizhou Bay area in Shandong province refers to the coastal areas for eight counties (downtown) as Guangrao, Shouguang, Hanting, Changyi, Pingdu, Laizhou, Zhaoyuan, and Longkou with area of 10,000 km^2 and population of about 4.55 million. This is the coastal open area with developed economy, where the demands of industrial and agricultural production and people's lives for freshwater in the recent 20 years has cause the excessive exploitation of underground water and damaged the limit equilibrium between the original freshwater and seawater flow, resulting in the seawater or the ancient seawater lagging in the near sea underground intrusion into the inner land along the channels in the stratum in every way. The seawater intrusion in Liazhou area has big dynamic change and potential risk; it is also difficult to handle, which seriously influences the economy and social life in this area.

According to the related data (Zhuang et al., 1999), in recent 20 years, the seawater intrusion hazard on the eastern and southern coast of Laizhou Bay has been developing. The seawater intrusion area in 1989 reached 627.3 km^2, in 1995 it reached 762.5 km^2, and the underground water cone area with negative value was over 2000 km^2 according to the observation data from 1975 to 1995 in every county of Laizhou area for many years. Zhuang et al. (1999) divided the seawater intrusion hazard in this area into four development stages: original, development, aggravation, and relieve phases. (1) The initial stage was from 1876 to 1979. The seasonal salty change of water quality predicted the coming of seawater intrusion. (2) The development stage was from 1980 to 1985. The rainfall in this area from 1981 to 1986 was relatively small for many years, the industrial water demand was sharply increased, resulting in the salty water frontal surface fast moving to the land, and the seawater intrusion range rapidly increased several times. (3) The serious aggravation stage was from 1987 to 1989. These were three years of serious seawater intrusion in this area, the supplement of water resource was reduced to the historical minimum, while the industrial and agricultural water demand increased several times, resulting in the underground water negative total area in every county and city in this area reaching 1498 km^2 (1989), and the seawater intrusion range also increased to 627.3 km^2. (4) The relieve stage was from 1990 to 1995. At that time, the rainfall increased, people drew water from Yellow River and used some water-saving measures to prevent the hazards. Although the seawater intrusion hazard still developed, its impetus was controlled and its rate obviously slowed.

As seen from the previous discussion, the direct reason for the seawater intrusion hazard in Laizhou Bay is the human excessive exploitation of underground water.

Su et al. (2009) used the fuzzy mathematics method to evaluate the current status of seawater intrusion at the south bank of Laizhou Bay, and the evaluation result objectively reflected the comprehensive degree of the seawater intrusion in this area. The results showed that the general trend of seawater intrusion hazard degree at the south bank of Laizhou Bay gradually reduced from the coastal zone to the inner land; the seawater intrusion pollution degree at the south bank of Laizhou Bay was somehow enlarged, and the proportion of the seriously polluted area in the total polluted area was large, mainly concentrated in the west and center, and the east had small degree of pollution.

2.2 MECHANISM AND INFLUENCE FACTORS OF SEAWATER INTRUSION

2.2.1 Mechanism of Seawater Intrusion

The seawater intrusion into the underground water is the fluid dynamics process of the interaction and interactive restriction of salt- and freshwater. Under the natural state, the salt- and freshwater in the water reservoir layer keep a certain balance, and the coastal zone underground water level tilts from land to the ocean, and land underground water discharges into the ocean; these two keep the stable balance state. On the one hand, the salt- and freshwater have different density, and due to this density, the salty water will seep into the land, which makes the seawater intrude into the land water reservoir layer; on the other hand, because the land water reservoir layer's underground freshwater has high water head, namely the freshwater level is higher than the seawater level, the seepage of freshwater into sea can stop the intrusion of seawater into the land; it forms a transitional zone or critical surface with different width between these two, and it finally forms a dynamic balance. Under this balance status, the transitional zone or critical surface is basically stable, which can stop the seawater intrusion. However, once this balance is broken, the saltwater and freshwater critical surface is moved to establish the new balance. If there is a large exploitation of underground water that reduces the freshwater pressure, the critical interface will move to the land, and the original balance is damaged, and then the storage space of freshwater in the water reservoir layer will be replaced by the seawater and seawater intrusion will occur.

In fact, the intruding seawater is not static, and it intrudes the inner land at the deep and flows back to the sea at the shallow. Meanwhile, the land freshwater also has seepage into the sea, the mechanical dispersion between the saltwater and freshwater caused by the diffusion action of salinity and the uniformity of medium channel in the diffusion process makes a mixture transitional zone between the saltwater and freshwater. When the transitional zone thickness is much less than the water reservoir layer thickness, this transitional zone can be seen as the abrupt interface between the saltwater and freshwater. Usually this interface tilts to the inner land and keeps things relatively stable, but with the flood and ebb of sea tide and the rise and fall of the underground water in coastal zone, this interface of saltwater and freshwater has constant fluctuation. Jean and Hertz Berg analyzed and thought (Pan and Li, 2002) that under the natural conditions, the burial depth of the saltwater and freshwater near the coastal zone is equivalent to 40 times higher that of the freshwater level than the sea level height. During the underground freshwater exploitation, it often forms depression cone and reverse cone of saltwater intrusion near the exploitation well; if the exploitation is too much, the saltwater reverse cone is enlarged and rises to make the saltwater enter into the exploitation wells and pollute the water resource (Fig. 14.14).

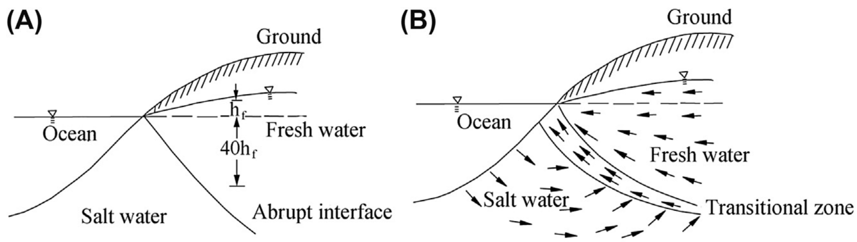

FIGURE 14.14

Flow process and interface change of freshwater and seawater in coastal water reservoir layer.
(A) Noncompatible interface of seawater and freshwater under hydraulic balance condition. (B) Flow process and mixture belt of freshwater and seawater in coastal water reservoir layer.

Essentially, the seawater intrusion is an environmental hazard phenomenon induced by human activity; it is shown in the specific stratum position through the saltwater and freshwater unbalance.

2.2.2 Influence Factors of Seawater Intrusion

The intrinsic factor of seawater intrusion is that there is a good hydraulic relation between the underground freshwater and seawater in the water reservoir layer in coastal area. The extrinsic factors that damage the saltwater and freshwater balance state to cause the seawater intrusion include hydrology, meteorology, relative sea level change, concentration ratio of saltwater and freshwater, freshwater runoff into the sea, tide concentration, and other natural factors, and the development and utilization of human activity with regard to the natural resources.

2.2.2.1 Hydrology Geological Condition

The hydrology geological condition is the leading environment of the occurrence and development of seawater intrusion; the hydraulic relation between underground freshwater and seawater in coastal area is the material basis for the seawater intrusion. The coastal plain stratum having seawater intrusion is mainly the Quaternary loose sediment with strong permeability, lacking a stable water separation layer between the underground freshwater and seawater, which is the main channel of seawater intrusion. When the underground water level is below the sea level for long term, the seawater rapidly intrudes into the land through the water reservoir layer and the seawater recharge occurs.

2.2.2.2 Topography Condition

Generally, the coastal plain is low and flat, and the underground water surface is shallow. Due to the excessive exploitation of underground water, the underground water level falls to form the negative area, which changes the underground water runoff supplement direction in the coastal area, resulting in the seawater intrusion.

2.2.2.3 Climate Condition

The underground water resource is mainly from the rainfall. If the climate continues to be dry, the underground water supplement has serious shortage, meanwhile the river runoff into the sea is reduced, which will intensify the seawater intrusion. The relative sea level rise caused by global warming and excessive exploitation of underground water can increase the upstream distance of tide along the river, strengthen the storm surge attack, and then induce the seawater intrusion.

2.2.2.4 Human Activity

The development and utilization of human activity on the underground freshwater resource is the important factor for the saltwater and freshwater balance state damage in the coastal zone. The contradiction between supply and demand for the water resource in the coastal area is becoming sharper; many areas have the underground water level fall with large scale in the coastal area due to the excessive exploitation of underground water for long term, which forms the underground water level negative area below the sea level; the seawater intrudes into the underground freshwater layer along the water reservoir layer and causes the seawater intrusion. The seawater feeding and tidal salt and other economic activities draw lots of seawater to the land and enlarge the supplement range of seawater to the underground freshwater. In addition, building of reservoirs, dams, and other irrigation facilities on the upstream areas of the rivers into the sea generally reduces the water flowing from river into sea, and the human activity of lots of sand mining and reducing river bed elevation in the estuary area intensifies the distance of tide upstream and makes both banks of river have seawater intrusion.

In a word, in the factors influencing seawater intrusion, the dry season and shortage of rain fall and water resources, are the background conditions; the water reservoir layer water conductivity and other hydrology geological characteristics are the basic conditions; and the unreasonable human activity is the inducing condition. The interaction results of these three may cause the coastal area to have seawater intrusion with large scale.

2.3 RISK OF SEAWATER INTRUSION

Seawater intrusion is the most common marine geological hazard in the coastal area in the world. The areas in the Chinese coastal area with the obvious seawater intrusion include Dalian in Liaoning, Qinhuangdao in Hebei, Laizhou Bay in Shandong, and Beihai in Guangxi; the national accumulated seawater area reaches about 1000 km^2, the maximum intrusion distance is more than 10 km, and the maximum intrusion rate is more than 400 m/a. The economic loss caused by this hazard is about 800 million RMB annually (Pan and Li, 2002).

The risks of seawater intrusion are mainly shown in the deterioration of underground freshwater quality, aggravation of water resource supply and demand contradiction, influence on industrial and agricultural production, and damage of natural ecosystem environment in the coastal areas.

2.3.1 Deterioration of Water Quality, Reduction of Irrigation Water Resource

The seawater intrusion creates a shortage of the underground freshwater resources, influencing the drinking water of residents and livestock in the coastal areas. Take the Laizhou Bay area as an example. In the last several dozens of years, more than hundreds of rivers have dried up, and even though a few rivers have water, they are seriously polluted, so the industrial and agricultural water supply depends on the exploitation of underground water. The seawater intrusion firstly increases the underground water chloride ion content, makes the mineralization higher, and makes it gradually lose the utilization value. On the one hand, the further excessive exploitation of underground water makes the underground water level fall again, and on the other hand we have to move to another place to exploit the underground water, resulting in the constant enlargement of seawater intrusion range. This creates a vicious spiral of underground water level fall—seawater intrusion—underground water salinization—underground water level fall again.

2.3.2 Soil Ecosystem Unbalance, Cultivated Land Resource Degradation

The soil ecosystem in the coastal area has unstable water and nutrition elements due to the climate and underground water content changes. After the seawater intrusion, the underground saltwater rises and enters into the cultivated layer along the soil capillary, resulting in soil salinization. When using high salinity water for irrigation for a long term, salts continuously accumulates in the soil surface, which makes physical properties of the soil becoming poor, microbial activity weakened, and organic matter decreased, at last results in decreased soil fertility.

2.3.3 Influencing Industrial and Agricultural Production

In the seawater intrusion area, water quality is deteriorated and soil is salinized, resulting in the paddy field area reduction and fry field area increase, the effective irrigation area is reduced, the cultivated land area is reduced, abandoned land area is increased, and the agricultural production is seriously influenced.

The industrial enterprises in the seawater intrusion area will also be influenced. Due to the water quality deterioration, the enterprises requiring high water quality have to open new water resources or use a long-distance remote water supply, which will not only add production costs but also possibly pollute the new open water resource and enlarge the seawater intrusion area. The enterprises without enough capital to open new water resources can only use the water polluted by seawater, resulting in serious rusting of production equipment, shortening of life, and speeding up of renewal cycle; meanwhile the product quality becomes poor and some enterprises have to move or close.

2.3.4 Influencing Population Quality and Social Stability

The seawater intrusion will reduce people's health. Due to the shortage of freshwater, lots of people in the seawater intrusion area often or for many years drink the saltwater, resulting in common local diseases. Many people have enlargement of the thyroid gland, dental fluorosis, fluorosis, brucellosis, and liver fluke disease. According to the related data, the eight counties and cities at Laizhou Bay area in Shandong province have 610,000 patients with fluorosis, plus other local diseases; there are a total of 680,000 of patients (Han, 1997). Scholars in Japan and the United States have also found that stroke, several chronic cardiovascular diseases, and cancers have close relationship with drinking excessive salinity water.

2.3.5 Deterioration of Natural Ecological Environment

The ecological environment in the coastal zone is fragile; its ecosystem is weak on the self-adjustment and buffer of disturbance resistance. The results of seawater intrusion make the salinity in soil increase and the halophytic plant communities such as *Suaeda salsa* gradually increase, their coverage can be up to more than 90% in the large range, so that the ecological environment of plant communities is changed from the terrestrial plant crops as the main to the saline alkali tolerance wild vegetation environment.

2.4 PREVENTION COUNTERMEASURES FOR SEAWATER INTRUSION

Because the excessive exploitation of underground water and other human activity are the main factors inducing or aggravating the seawater intrusion, the general principle for the seawater intrusion prevention is to make the underground water level in the coastal area higher than the sea level. The details include the increase of underground freshwater reservoir, effective utilization of water resources, carrying out the artificial recharge of underground water, building the flow impede and seepage barrier engineering to prevent the seawater from going upstream, improving the ecosystem environment, and strengthening the underground water monitor.

2.4.1 Reasonably Exploit Underground Freshwater Resources, Broaden Sources of Income and Reduce Expenditures

The prime cause of seawater intrusion is the regional water resource shortage and the excessive exploitation of underground water. Therefore, solving the freshwater problem is the main method to relieve the seawater intrusion. Seen from the supply situation of water resource in the coastal areas, the freshwater shortage is inevitable. And in the long term, drawing in water from other areas is the important strategy measure to control the seawater intrusion in the coastal areas. But seen from the short term, it is more practical to make the water resource supply and demand status become better through engineering measures and dispatch methods. We need to reasonably arrange the exploitation well, abandon the water pumping well near the interface of salt- and freshwater, scatter the exploitation, regularly stop the exploitation, or exploit the underground water by turn and shorten the water level resume time to prevent forming depression cone.

2.4.2 Implement Artificial Recharge, Introduce Freshwater and Restrict Saltine Water

Make use of recharge well, recharge corridor, and other facilities to carry out the artificial recharge to supply underground freshwater and improve underground freshwater level and flow velocity in the coastal areas, use freshwater to restrict saline water and force seawater to retreat. The artificial recharge has had obvious effects in China and many countries. The recharge water resources mainly include the surface water in the local rain season, outside water, and wastewater after treatment.

2.4.3 Barrier Water Flow

Barrier water flow includes setting of water separation wall, building of underground dam, farmland buried pipeline drainage, deep well drainage, and vertical well drainage. Through the setting of water separation wall, we can separate the freshwater and saline water, the detailed method is to fill in certain material in suspended state, such as the high-plastic clay slurry to make the suspended material fill in the soil pores to form the water-impervious barrier. The farmland buried pipeline drainage plays an obvious role in the alkali drainage, flood removing, stain prevention, and reduction of underground water level, and it is effective in the engineering flow barrier. Because of the timely drainage, the salt in soil is obviously reduced, so that changes the plant ecosystem environment. The deep groove drainage has been widely used in the treatment of depression flood saline alkali land and alkali modification process in Tianjin, and has made certain progress; it is effective as the seepage barrier measure (Tian, 1994). But because the deep groove drainage has the disadvantages of unstable slope and easy collapse, this affects the results of reduction of underground water level, prevention of stain and washing salt. The vertical well drainage is the effective drainage measure in the engineering drainage and farmland drainage. Through the seepage barrier and farmland drainage, we can improve the underground water quality, supplement the pressure-bearing water reservoir layer water quality, and improve the soft stratum compression condition.

2.4.4 Improve Ecosystem Environment

Through the building of irrigation engineering, adjustment of planting structure, forestation, and development of animal husbandry, we can establish the agriculture ecosystem economic system with reasonable structure, stable function, and high economic profit to improve the hazard persistence ability and relieve the adverse effects brought by seawater intrusion.

2.4.5 Establish Underground Water Monitor System in Coastal Area

Establish underground water dynamic monitor network in coastal area to carry out the water level and water chemistry monitoring, when necessary, with seawater hydrological dynamics monitor. According to the formation mechanism and intrusion rule of seawater intrusion, predict the seawater intrusion rate, scale, and hazard range, and then provide a scientific basis for the effective prevention of seawater intrusion.

3. LAND SUBSIDENCE IN COASTAL AREAS

3.1 DOMESTIC AND FOREIGN RESEARCH PROGRESS

Land subsidence refers to the ground elevation drop caused by ground surface shallow loose sediment compaction by the exploitation of underground water or other underground fluid; it is also called ground setting or depression (Pan and Li, 2002). The characteristics of land subsidence are the wide impact range and slow subsidence rate, which are often not easy to recognize, but it has big risk for the safety of buildings, city construction, farmland, and irrigation.

The land subsidence phenomenon was found as early as at the end of the 19th century and at the beginning of the 20th century, but because the subsidence was not big, so its risk was not clear and people didn't pay attention to it. After the 1930s, some cities in the world had more and more serious land subsidence, which became a slow and unrecoverable geological hazard, and then it caught the attention of people. The land subsidence is mainly in the cities on plain and inner continental basin with developed industry and oil and gas exploitation areas. For example, Las Vegas in Nevada, United States, began to exploit the underground water in 1905. Due to the constant fall of the underground water level, the land subsidence area has reached 1030 km^2, the accumulated subsidence extent in the subsidence central area has reached 1.5 m, and has made the wells 1.5 m higher than the ground; meanwhile, there are also wide distributed ground fissures with length and depth of dozens of meters.

The land subsidence in Japan from the 1950s to 1980s has been found in more than 50 cities and areas (Pan and Li, 2002). The land subsidence range in Tokyo is more than 1000 m^2 with the maximum subsidence of 4.6 m, and some areas are even below the sea level.

The exploitation of petroleum also produces serious land subsidence hazard. The Wilmington oil field of Long Beach city in California, United States, had the accumulated subsidence of 9 m from 1926 to 1968 with the maximum subsidence rate of 71 cm/a (Pan and Li, 2002). In addition, London in Great Britain, Moscow in Russia, Debrecen in Hungary, Bangkok in Thailand, the German coast, New Zealand, and Denmark also have land subsidence with different degree.

The Chinese land subsidence research began from the study on the land subsidence in Shanghai in the 1960s. In 1964, it was suggested that the excessive exploitation of underground water was the main reason for the land subsidence in Shanghai. In the 1990s, the local uneven subsidence in Shanghai was found, it was thought that the proportion of local uneven subsidence phenomena caused by large building, deep base pit, and metro should not be neglected in the microregional subsidence. Currently, there are a total of 46 cities (sections) and counties in Shanghai, Tianjin, Jiangsu, Zhejiang, and Shanxi province having the land subsidence with the total subsidence area of 48.7×10^4 km^2 (Pan and Li, 2002).

The Chinese land subsidence is mostly caused by the excessive underground water exploitation. See from the maximum accumulated drop depth of subsidence area and subsidence center, the more serious depression areas are in Tianjin, Shanghai, Suzhou, Wuxi, Changzhou, Xi'an, Fuyang, and Taiyuan, they all have the maximum accumulated subsidence above 1 m; for the maximum subsidence rate, Tianjin (the maximum subsidence rate is 80 mm/a), Fuyang in Anhui (the subsidence rate is 60−110 mm/a) and Taiyuan in Shanxi (114 mm/a) have the most serious situation (Pan and Li, 2002). The Chinese coastal land subsidence is mainly in the river delta and coastal plain. The Quaternary sediment layer is thick and has poor consolidation with fine particles and multilayers and strong compression; there are many underground water reservoir layers with poor supplement runoff condition, long exploitation time, and big intensity; they have concentrated towns with large population and developed industrial and agricultural production. The land subsidence in these areas first started by forming the subsidence cone in the city underground water exploitation center, and further extended to the periphery from the large area of subsidence with the town as the center.

The land subsidence caused serious consequences for Shanghai when the land subsided 1.76 m. But since the restriction of underground water exploitation, artificial recharge of underground water and adjustment of exploitation level in 1965, the land subsidence has basically been controlled. In 31 years from 1966 to 1996, Shanghai land subsided only 124.5 m with the annual subsidence of 4.0 m. From 1966 to 1990, the land annual average subsidence was only 2.5 mm, which was 1/44 of the annual subsidence as 110 mm. In the recent period, Shanghai land has had accelerated subsidence phenomenon. From 1991 to 1996, the downtown accumulated annual subsidence is 61.2 mm with the annual subsidence of 10.2 mm, the subsidence in these six years is equivalent to the total subsidence of the former 25 years, which is 2.5 times that of the annual subsidence in the former period. The factors influencing land subsidence acceleration have been engineering construction, shallow soil layers' further subsidence, middle and upper soil layer subsidence acceleration, and deep soil layer subsidence acceleration.

Tianjin is one of the cities that has the most serious land subsidence in China. For many years, due to the excessive exploitation of underground fluid, Tianjin has had land subsidence phenomenon of different degrees, forming five subsidence centers in downtown, Tanggu, Hangu, Dagang, and Haihe River downstream industrial zone. With the increase of underground water exploitation, the subsidence in Tianjin downtown is also aggravated; there was a record annual subsidence of 159 mm in the 1970s. In the 37 years from 1959 to 1996, the accumulated maximum subsidence had been over 2.7 m, and the area over 2 m was about 37 km^2, while the range above 1 m almost covered all the downtown (Wu and Jin, 1998). Currently the residual elevation in Tianjin downtown (refers to the Yellow Sea elevation) all are below 3 m, except Dingjiagu, Yixingbu, and Beimalu zone of above 3 m. After the implementation of the phase 1 land subsidence control plan of Tianjin in 1986, the land subsidence's malignant development was controlled. Especially since the 1990s, the annual average subsidence is now always about 14 mm, which is basically the microsubsidence trend (Fig. 14.15). According to the

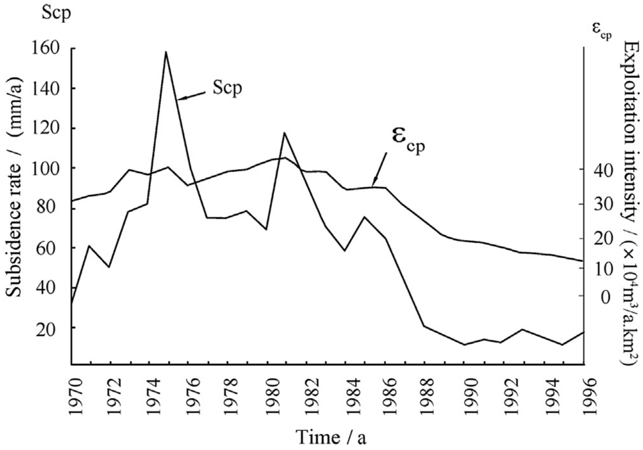

FIGURE 14.15

Figure of annual average subsidence rate (S_{cp}) and annual average exploitation intensity (ε_{cp}) change in Tianjin downtown.

actual measurement data, the annual average subsidence in the inner ring line is 9 mm; in the outer ring it is 17 mm; and in the periphery it is 47 mm (Wu and Jin, 1998).

The accumulated maximum subsidence in the 37 years from 1959 to 1996 reached 3.06 m, its surrounding old downtown has the negative elevation zone about 5 km^2 below the average sea level. After taking the subsidence control measures, within the monitor range of 200 km^2, the average subsidence in 1996 was 13 mm, and they were 10 and 8 mm, respectively, in built area and port area. The annual average subsidence in the monitor range of 270 km^2 in Hangu was 82 mm in 1985 before the treatment, and it was reduced to 42 mm in 1996, of which the annual average subsidence was as much as 56 mm in built area. Currently the ground elevation in the whole built area in Hangu is all below or close to the average sea level. The annual average subsidence in the monitor range of 295 km^2 in Dagang district was 50 mm in 1985 before the treatment, and it was reduced to 34 mm in 1996. The annual average subsidence in the monitor range of 330 km^2 in Haihe River downstream industrial district was 73 mm in 1985 before the treatment, and it was reduced to 43 mm in 1996 (Wu and Jin, 1998).

Seen from the previous discussion, the land subsidence in Tianjin is very serious; it was caused by the structural subsidence background plus the artificial excessive exploitation of underground water.

3.2 FORMATION MECHANISM OF LAND SUBSIDENCE

Early scholars of land subsidence put forward several different views about the mechanism of land subsidence, such as new tectonic movement, stratum shrinkage and natural shrinkage, ground static and dynamic load, and regional sea level rise, etc. A great deal of research has shown that the excessive exploitation of underground water is the external reason for the land subsidence; the existence of medium and high compression clay layer and pressure-bearing water reservoir layer are the internal reasons for the land subsidence (Pan and Li, 2002). So, many people think that the subsidence is caused by the excessive exploitation of underground water, petroleum and natural gas, brine, and the excessive load of high buildings.

In pressure-bearing water reservoir layer with pore water, the exploitation of underground water causes the reduction of pressure-bearing water level, which inevitably decreases the pore water pressure in the water reservoir layer itself and its upper and lower water separation layer. According to the effective stress principle, the total stress caused by the overlying load in soil is taken together by water and soil particles skeleton. The total pore water pressure taken by water and the effective stress taken by soil particles equal the total stress. If the soil layer internal stress is not changed during the water pumping process, the decrease of pore water pressure will inevitably increase the effective stress in soil, resulting in the reduction of pore volume and soil layer compression.

Because of the obviously different permeability performance, the aforementioned processes of pore water pressure decrease and effective stress increase in the sand layer and clay layer are completely different. In the sand layer, with the decrease of pressure-bearing water head and the discharge of the spare water, the effective pressure rapidly increases to the balance degree after the pressure-bearing water level reduction, so the sand layer compaction is “instantaneously” completed. In clay layer, the compaction process is very slow, which may take several hours, several years, and even dozens of years.

In comparison, the compression of sand layer under relative low stress is small, elastic and it can be formed, while the clay layer compression is relatively large, and it is mainly the nonelastic permanent deformation. Therefore, under the relative low effective stress increase condition, clay layer compaction plays the main role in the land subsidence; while in the process of water level back rise, the expansion springback of sand layer plays the decisive role.

3.3 INFLUENCE FACTORS OF LAND SUBSIDENCE IN COASTAL AREAS

Seen from the geological conditions causing land subsidence, the loose multilayer water reservoir system, pressure-bearing water reservoir layer with rich water, and compression thick clay layer that is normally consolidated or nonconsolidated within the exploitation range are the premise and material basis for the land subsidence. The artificial excessive exploitation of underground flow plus the new tectonic subsidence are the main influence factors for the coastal land subsidence, of which the subsidence caused by the excessive exploitation of underground water is the most outstanding. With the booming development of the Chinese coastal economy, the local land subsidence caused by building construction should also not be ignored.

3.3.1 Material Basis Causing Land Subsidence

Land subsidence is mainly caused by the exploitation of underground flow, which causes the soil compression, and the thick loose fine particle soil layers form the material basis for the land subsidence. The coastal area is distributed with very thick Quaternary sediment and Neozoic loose or nonconsolidated sediment; these sediments are mostly muddy clay with the water content more than 60%, the void ratio is big with low strength and strong compression, which easily produces the plastic flow. During the large excessive exploitation of underground water, the underground water pressure in the water reservoir layer is reduced, the weak combination of water pressure difference increases in the muddy clay water separation layer pore, which makes the pore water flow into the water reservoir layer, and the effective pressure increase, resulting in the compression deformation in the clay soil layer.

The stratum structure that is easy to have land subsidence is the loose soil layer structure with the sand layer and clay layer interbedding. With the exploitation of underground water, the pressure-bearing water level is reduced, the pore water pressure in the water reservoir layer itself and its upper and lower relative water separation layer is reduced, and the stratum compression causes the land subsidence.

3.3.2 New Tectonic Movement

The Chinese coastal areas, such as Bohai Sea and its coast, Fujian Quanzhou, Guangdong Nanao, and Hainan Qiongzhou, all had strong seismic activity, resulting in ground rise and fall. The Chinese eastern coastal zone is located at the west margin of the West Pacific tectonic belt. Since Quaternary, the new tectonic movement and the current tectonic movement in the hundreds of years is very strong. The North China plain, northern Jiangsu plain, and Yangtze River delta areas belong to the crust continuous subsidence area, and the structural subsidence increases the land subsidence value.

After the analysis of a large amount of tide data, Huang and Liu (1989) thought that the Dagu original point tend subsidence rate was 5.6 mm/a reflected by the Beipaotai (located at the north of Tanggu) tide station. They also calculated the downtown subsidence rate in 1931 was 4 mm/a according to one benchmark in Tianjin downtown. These data reflect the status in Tianjin before the large scale of underground water exploitation. Some geologists thought that the structural subsidence rate in Tianjin was about 2–4 mm/a, while the measurement personnel of Tianjin land subsidence control office through the benchmark measurement thought that the crust in Tianjin had stable subsidence with 1–3 mm/a rate in the 30 years (Tianjin Office for Controlling Ground Subsidence, 1997).

The strong seismic activity will cause the inherited subsidence. Tangshan strong earthquake once reached Tianjin and its coastal areas, and formed a subsidence center in Hangu area; the macro-investigation showed that partial sections had the subsidence over 1.5 m, including the base soil liquefaction and other hydrology factors, the benchmark measurement results showed that the maximum subsidence was hundreds of millimeters (Wang and Sun, 1994). Seen from this, if the instantaneous activity with large range and high strength is in the area with strong land subsidence, especially in the coastal area whose ground elevation is near the sea level, the risk will be very serious.

3.3.3 Global Sea Level Rise

The global sea level rise caused by climate warming makes the coastal land subsidence more outstanding on the original basis. The Chinese coastal areas all face the sea level rise problem. Because the sea level rise is only in millimeters, so this factor's influence is secondary. We can know from Table 14.3 in this chapter that the eustatic sea level rise rate of the Chinese three big rivers delta is 1.5 mm/a, the IPCC best estimation for the eustatic sea level rise rate for the three big deltas in 2030 is 4.5 mm/a. Though these sea level rise values are relatively smaller than the land subsidence in coastal areas (mainly Tianjin and Shanghai), after taking the underground water recharge measures to control the large scale of land subsidence, the many disastrous results of superposing these sea level rise values on the land subsidence should not be ignored.

3.3.4 Natural Subsidence of Soft Foundation

The Chinese coastal areas mostly have very thick and loose Quaternary sediment. These sediments have rich water content, high clay particles content, poor consolidation degree and most of them are not consolidated; before they are completely consolidated, they will inevitably have natural subsidence. Tanggu, Hangu, and Dagang in Tianjin have the Cenozoic sediment with the thickness of several kilometers because they are located on the Huanghua depression belt. In these sediments, the compressible clay layers account for more than 60%. The lag compaction of deep clay layers causes the land subsidence. According to the Holocene marine stratum ^{14}C dating data and the historical benchmark data from 1930 to 1953, the natural subsidence in Tianjin produced by the new tectonic movement and stratum compression is about 3 mm every year (Wu and Jin, 1998). This is not related to the land subsidence caused by the exploitation of underground flow, it is the constant and the secondary. But under the microsubsidence condition, the natural subsidence is also a constant that should not be ignored.

3.3.5 Excessive Exploitation of Underground Flow

The main factors of the land subsidence in Chinese coastal areas are the human excessive exploitation of underground flow for long term, such as the underground freshwater, petroleum, and natural gas. In China, the cities having outstanding land subsidence are Shanghai and Tianjin. These two cities are the forward positions of Chinese economic development, and they have many large industrial enterprises and large populations, which have large demands for the underground freshwater. In the past dozens of years, the economy and social life in Shanghai and Tianjin have been booming, but due to the long-term excessive exploitation of underground water, resulting in the land subsidence in city, some surprising situations have developed.

From 1921 to 1965 was the development period for the land subsidence in Shanghai; the central city land had average subsidence of 1.76 m with the maximum subsidence of 2.63 m, and the ground elevation was about 2 m below the Huangpu River high tide level (Liu et al., 1998a). In the 25 years from 1966 to 1990, after taking the restriction of underground water exploitation measures in 1962, in 1965 and 1968, respectively, carried out the underground water artificial recharge and adjustment of exploitation level and other measures, the land subsidence in Shanghai was basically controlled. In the 25 years the central city had average accumulated subsidence of only 62.4 mm and the annual average subsidence about 2.5 mm, which was only 6.4% of the former period. From 1966 to 1971, the land has had 18.1 mm springback, and from 1972 to 1990 the land had 44.5 mm microsubsidence with the annual average subsidence of only 2.3 mm.

The land subsidence factors in Tianjin are complex with many forms. There are both the regional land subsidence caused by the exploitation of pressure-bearing underground water and underground hot water, also the subsidence caused by the exploitation of oil and gas, also the local land subsidence caused by the underground engineering construction. But the main reason is the human excessive exploitation of underground flow for long term. The land subsidence has good corresponding relationship with the exploitation of underground water, and the land subsidence range continues to increase with the enlargement of depression cone. Since 1985, this city has been dedicated to land subsidence control, which has made the subsidence rate in Tianjin downtown decrease from 76 mm in 1985 before the treatment to 17 mm in 1996, a decrease of 77.63%; it has entered into the microsubsidence stage and is basically stable.

In summary, the long-term human excessive exploitation of underground flow is the leading factor to cause land subsidence. Land subsidence has a close relationship with the underground water exploitation and dynamic change:

① Land subsidence center has obvious consistence with the central area of underground water exploitation cone.

② Land subsidence area is basically consistent with the underground water centralized exploitation area.

③ Land subsidence isoline distribution direction is basically consistent with the underground water cone isoline distribution direction, and the land subsidence rate has good corresponding relationship with the underground fluid exploitation and exploitation rate.

④ Land subsidence and the compaction of every single layer are closely related with the pressure-bearing water level.

⑤ Development of land subsidence in many areas has been controlled through the artificial recharge or restriction of underground water exploitation to resume and lift the underground water level; land surface in some areas even uplifts. This further confirms the reason and resulting relationship between the land subsidence and the fall of water level or hydraulic pressure caused by exploitation of underground flow.

3.3.6 Local Subsidence Caused by Construction Engineering

Corresponding to the land subsidence caused by the exploitation of underground flow and tectonic movement, the land subsidence caused by city construction is local, and sometimes it is also irreversible.

The local subsidence caused by city construction engineering has the high buildings base engineering as the typical causes, such as base excavation, discharge, and pile sinking. The engineering measures with relatively obvious subsidence effect are excavation, discharge, shield driving, and pile sinking. If it is revealed that there is saturated sand layer with drift sand properties or saturated muddy soft soil with drift sand characteristics, during the excavation of base pit with large depth and area, this may cause the support structure to become unstable, so that there is land subsidence around the base pit. The tunnel and culvert excavation with large scale sometimes has more outstanding subsidence effect. The discharge is often as the auxiliary project engineering for the base pit excavation; its purpose is to predry the operation surface seepage, its mechanism is consistent with the land subsidence caused by the underground water exploitation.

The land subsidence caused by the city construction is closely related with the engineering construction progress; the subsidence is mainly concentrated in the strata with frequent and concentrated shallow engineering activities. After the building construction, the building load has long-term loading action on its underlying compression strata. So the local subsidence can last for a very long time, and it is difficult to resume the original ground elevation.

Liu et al. (1998a) thought that from 1992 to 1998, the subsidence caused by the engineering construction in Shanghai accounted for about 12% of the total land subsidence, but the local land subsidence caused by every engineering construction is very surprising, and the accumulated subsidence can reach as much as 100 mm.

In summary, the crust subsidence activity, natural consolidation of loose sediment, global sea level rise, and the soil layer compression caused by human exploitation of underground water or oil and gas resources will all have land subsidence, but the land subsidence from the hazard research perspective refers to the land subsidence caused by human activity, or the land subsidence caused by the human activity as the main and the natural power as the auxiliary.

3.4 RISK OF LAND SUBSIDENCE IN COASTAL AREAS

The damage and influence caused by land subsidence have many aspects. The main risks include the ground elevation loss and further ground water accumulation in the rainy season and the ability reduction of flood prevention and discharge; the lowland area enlargement and seawall height decrease in the coastal cities cause the seawater to flow backward; the port buildings are damaged; loading ability is reduced; the ground transport line and underground pipeline have twisting fractures; the city building base sinks and has suspended fracture; the bridge clearance is reduced, which influences navigation; the deep-well pipeline rises, well platform is damaged, and the city water supply and discharge system become invalid; and the depression in rural areas has flood accumulation, which reduces agricultural production.

3.4.1 Elevation Loss, Ability Reduction of Storm Surge Prevention

The elevation loss caused by ground subsidence is the maximum resource waste. The land subsidence in the coastal area makes partial areas have reduction of ground elevation, and they are even below sea level. Some coastal cities often suffer from the seawater intrusion, which seriously endangers the local people's production and lives. In order to prevent the sea tide threat, we have to invest much to increase height of ground and build antiflood walls or embankments. But just only increasing seawall height cannot bring a complete sense of safety.

According to the report from Tianjin Office for Controlling Ground Subsidence (1997), the Bohai Bay area is an area with frequent and serious storm surge; based on the historical records, in the last 100 years there was one storm surge every 4.7 years. After the liberation, due to the continuous subsidence of coastal land and the ground elevation loss, the ability of the antiflood wall to withstand the storm surge was reduced, and the storm surge hazard frequency increased to once in every 3.6 years, and the hazard has become more and more serious. The antiflood walls on Tianjin Tanggu have the accumulated subsidence of 239 mm from 1985 to 1996, and in the recent years, the average subsidence is also in double digits, see Table 14.8.

On August 2 and August 19, 1985, Tianjin coast was attacked by storm surge twice, the new port wharf was all flooded, the storage was flooded, and the direct economic losses were about 130 million RMB. According to the report of Tianjin Office for Controlling Ground Subsidence (1997), the extra-large storm surge attacked Tianjin coastal areas on September 1, 1992, which made with direct economic losses of 399 million RMB.

3.4.2 Ability Reduction of Flood Prevention

The ability reduction of flood prevention is another serious risk of land subsidence in coast cities. Because the ground elevation continues to be decreased, the serious siltation at river bed and estuary seriously reduces the river action; this not only puts the flood discharge in the flood periods at risk but also makes the nonsmooth discharge of surface water. Take Tianjin as an example; Haihe River is the important river channel for Tianjin's flood prevention, flood discharge, water reservoir, navigation, and tourism, and plays a very important role in the safety and ecosystem of Tianjin in the flood period.

Table 14.8 Antiflood Wall Average Subsidence Value (mm)

Section	1993	1994	1995	1996	Average Value (mm)
Tanggu section	18	22	7	13	15.00
Hangu section	41	38	23	27	32.25
Dagang section	22	29	6	20	19.25

According to the report of Tianjin Office for Controlling Ground Subsidence (1997), the downtown section of Haihe River is through the subsidence center; it had bank subsidence of 1.0–2.0 m, the Hebin Park near Tanggu section had subsidence of 2.8 m, plus the Haihe River gate had subsidence of more than 1.3 m (from 1959 to 1995), the siltation at river channel and estuary makes the flood discharge ability of Haihe River reduced from the original design of 1200 m^3/s to 250 m^3/s.

3.4.3 City Infrastructure Damage

The land subsidence often makes the ground and underground buildings have huge damage, such as building wall crack and collapse, high building suspension, deep well pipeline uplift, well platform damage, bridge pier uneven sinking, and water pipeline bending and leakage. The areas with strong land subsidence have the big accompanied horizontal displacement, and the huge shear force caused by the uneven horizontal displacement causes road deformation, railway distortion, bridge pier moving, wall fracture and collapse, high building support and truss bending and fracture, and oil well and other pipeline damage.

3.4.4 Port Facilities Invalid

The land subsidence makes the port lose validity and reduces the port goods loading ability. The city of Long Beach, California, abandoned its port and wharf due to the land subsidence. The port in Shanghai at which the ships anchor has the original elevation of 5.2 m, by 1964 it was reduced to 3.0 m; during the high tide, the river water surges on the ground and the goods loading work has to be stopped (Pan and Li, 2002).

3.4.5 Less and Less Bridge Clearance

The bridge pier sinks with the land subsidence, which makes for less and less bridge clearance. The Suzhou River in Shanghai originally had more than 2000 ships of different sizes sail on it daily, with the navigation of $(100-120) \times 10^4$ t. Due to the land subsidence, the bridge clearance has become less, and now big ships can't pass, and the medium and small ships have also been affected (Pan and Li, 2002).

3.4.6 Influence on Agriculture

Due to the land subsidence, the shallow underground water level has relative lift, and the farmland has flood discharge difficulty, which aggravates the soil secondary salinization and influences the farmland fertility and agricultural single production. In addition, there are down slopes formed for the farmland irrigation channels, which require big pumping station's discharge ability, resulting in the increase of agricultural costs.

The previous discussion only briefly introduces the risks caused by land subsidence; in fact, the risks brought by subsidence are great and more serious.

3.5 PREVENTION COUNTERMEASURES FOR LAND SUBSIDENCE IN COASTAL AREA

The land subsidence has close relationship with the excessive underground exploitation; only if there are the compressible strata below the underground water level will there be land subsidence due to the excessive exploitation of underground water. Once land subsidence occurs, it is difficult to handle, so what is important is to prevent the land subsidence.

Currently, the domestic and foreign technical prevention measures for the land subsidence are mainly the same; they include the establishment and completion of land subsidence monitor network, strengthening the underground water dynamic and land subsidence monitor work; creating new substitute water resources, promoting water saving techniques; adjusting the underground water exploitation arrangement, controlling the underground water exploitation; artificial recharge for the underground water exploitation level; performing the underground water total exploitation control; and planning the exploitation and target management.

3.5.1 Save Underground Water, Restrict Exploitation

Because the land subsidence is mainly due to the excessive exploitation of underground water, saving the underground water and restricting the exploitation of underground water become one of the main measures to prevent land subsidence. In order to reasonably exploit and use the underground water, Shanghai in recent years, has insisted on the principle of "strict control and reasonable exploitation" to strengthen the underground water development, utilization and management, and have made obvious progress. According to the statistical data of Shanghai water supply department, from 1996 to present, the whole city and suburbs have total compression and stop of 185 deep wells, and the underground water exploitation has reduced from 1.5×10^{12} m^3 in 1996 to 1.04×10^{12} m^3 in 1999, which has made the underground water exploitation resume to the level in 1980s; and in 1999, the whole city's average land subsidence was reduced 1.94 mm from that in 1998 (Pan and Li, 2002).

For the serious land subsidence status, Tianjin organized and carried out the phase I, II, III, and IV land subsidence control plan. Take the prevention as the main with the combination of prevention and treatment, together with broadening the sources of income and reducing expenditure, take the planned measures to stop well, block well, and adjust the underground water exploitation arrangement and level, which make the land subsidence obviously slow down. According to the preliminary statistics, the land subsidence rate in the downtown has reduced from the annual average of 76 mm in 1985 before the treatment to 17 mm in 1996, a slowdown of 77.63%, and it has entered into the microsubsidence stage and is now basically stable. The average subsidence rate in Tanggu was reduced from 82 mm in 1985 to 13 mm in 1996, a slowdown of 87%. The average subsidence rate in Hangu was reduced from 82 mm in 1985 to 42 mm in 1996, which was a reduction of nearly 50%. The annual average subsidence rate in Dagang district was reduced from 50 mm in 1985 to 34 mm in 1996. In the downstream industrial area of Haihe River, it was reduced from 73 mm in 1985 to 42 mm in 1996.

Therefore, the measures of saving water and restricting the underground water exploitation can greatly relieve the serious land subsidence status in the Chinese coastal cities, and effectively control the land subsidence.

3.5.2 Solve Substitute Water Resources, Compress Underground Water Exploitation

For the control and prevention of land subsidence, solving the problem of the substitute water resource and further compressing the underground water exploitation are the main measures. This is much more important for the coastal cities in China that face serious water shortages such as Tianjin. Tianjin government uses the cross-river water introduction project as introduction of the Luanhe River water into Tianjin. According to the report of Tianjin Office for Controlling Ground Subsidence (1997), by the end of 1996, the project of introduction of Luanhe River water into Tianjin had supplied 70.43×10^8 m^3 of water to Tianjin downtown, of which 5.45×10^8 m^3 is supplied to Tanggu district.

Table 14.9 Exploitation and Exploitation Strength Statistics Table For Tianjin Downtown (334 km^2)

Year	Exploitation ($\times 10^4 m^3$)	Exploitation Strength ($\times 10^4 m^3/a\ km^2$)
1985	8421	25.2
1988	5714	17.1
1991	3869	11.6
1996	2640	7.9

With regard to the water saving, Tianjin had carried out three large scale censuses for the city deep wells from 1981 to 1993 in order to figure out the deep well exploitation number in the whole city. According to the statistics for the Tianjin downtown and adjacent suburb areas with 440 km^2, there were 841 self-prepared wells in the whole city in 1981 with the annual exploitation of more than 91.67 million cubic meters, accounting for 13.6% of the water used in the whole city. After the phase I, II, and III subsidence control and well stop plan, by 1996, the downtown had stopped 637 industrial self-prepared wells, and Tanggu district stopped 175 wells, which made the underground water exploitation greatly reduced in the downtown and Tanggu; the plans also strictly restricted drilling wells in Dagang and Hangu. According to the report of Tianjin Office for Controlling Ground Subsidence (1997), because taking a series of measures such as "one water for many usages," recycling water using, compression of underground water exploitation, adjustment of exploitation level, and artificial recharge, the underground water exploitation and exploitation strength in the downtown have also been greatly reduced (see Table 14.9).

Since 1988, Tianjin Water Conservancy Bureau carried out the well stop transformation and water saving work for the industrial and mining enterprises in the city surrounding areas that have serious land subsidence, and one after another arranged 153 water-saving engineering projects, including cooling circulating water reuse, production water recycle and reuse, sewage recycle and reuse after treatment, water transport pipeline update and reform, and water supply equipment adjustment and correction. According to the report of Tianjin Office for Controlling Ground Subsidence (1997), with regard to the agricultural water saving measures, they reduced the water for every acre, built every kind of seepage prevention channel of 460×10^5 m, which greatly improved the water utilization rate.

3.5.3 Underground Water Artificial Recharges

Measures to prevent ground subsidence in addition to open source and limiting groundwater exploitation,the underground aquifer recharge is an effective measure, this point has been confirmed by the practice in Shanghai and Tianjin.

Tianjin, in order to effectively control the land subsidence, to make the underground water level rise year by year, has the city water saving office and Tanggu water saving office promoting the deep well recharge technique in many enterprises. According to the report of Tianjin Office for Controlling Ground Subsidence (1997), until 1996, only the downtown area of 334 km^2 had the recharge reaching $4317 \times 10^4\ m^3$ in 30 years, and annual average recharge was $148 \times 10^4\ m^3$, during which from 1985 to 1995, the recharge was $1440.1 \times 10^4\ m^3$, and annual average was $130.9 \times 10^4\ m^3$. The recharge was $14 \times 10^4\ m^3/a$ in Tanggu district, the water input reached $2500 \times 10^4\ m^3$ in 1995 in Dagang oil field. The downtown main sediment layer is the second water reservoir layer, because of the increased recharge and adjustment of exploitation level, the water level in this group rises year by year, the land in some areas has local springback trend. The current main subsidence part has moved to the strata below the third water reservoir layer.

Another effect of the deep well recharge in Tianjin is shown in the cooling and energy storage aspect, namely the exploitation in summer and recharge of water in winter. The average exploitation water temperature in summer is 8.5−10.0°C. Analyzed from the cooling effect, the underground water recharge of 1 m^3 equals to the water of 3 m^3 in summer. Only this can reduce the underground water exploitation of 381×10^4 m^3 for every year in Tianjin.

After the restriction of underground water exploitation measures in 1962, Shanghai in 1965 and 1968, respectively, carried out the underground water artificial recharge and adjustment of exploitation level, so that the land subsidence in Shanghai has been basically controlled. In the 25 years, the downtown land average accumulated subsidence was only 62.4 mm, and annual subsidence was about 2.5 mm. From 1966 to 1971, the ground had uplifted back 18.1 mm; from 1972 to 1990, the ground had 44.5 mm microsubsidence and the annual average subsidence was only 2.3 mm.

But the artificial recharge of underground water to prevent the underground subsidence is only a remedial measure, not a main measure. We should take prevention as the main measure during the treatment of land subsidence.

3.5.4 Complete and Supplement Land Subsidence Monitor

Land subsidence as a geological hazard has big risk for city construction. Because it develops very slowly, and it is not easy to be recognize in the short term, so it is not paid attention to by the related department; however this “chronic disease” has wide influence range and is difficult to treat, and it is often more serious than other city hazards. So we need to pay attention to the land subsidence investigation and subsidence monitor measures.

One of the main tasks of the land subsidence investigation is to figure out the hydrogeological conditions and engineering geological conditions, study the underground water resource distribution, movement, and storage rule, and analyze the internal conditions and external factors causing the land subsidence. In order to figure out the subsidence and water level change with different degree, Tianjin established a total of nine level marks, of which there are 64 stratum compaction observation holes, 18 underground water observation holes, and 44 clay layer pore water probes, making use of these level marks to periodically observe the engineering geological dynamic change data at soil layers with different depth in every area. In addition, Tianjin set the underground dynamic monitor network in the downtown, suburban county, and coastal area to periodically collect statistics and observations and water quality analysis for the water level and water amount. Meanwhile they carried out the exploitation investigation for 903 exploitation wells and 1850 km^2 range, which provided a reliable basis for the comprehensive analysis of land subsidence change and working out the land subsidence control measures.

The benchmark monitor work is the regular method to know the land subsidence change; it can objectively reflect the subsidence change at different places for different years. The subsidence monitor range in Tianjin includes downtown 540 km^2, Tanggu district 200 km^2, Hangu district 270 km^2, Dagang district 295 km^2, and downstream area of Haihe River 330 km^2; the total monitored area in 1996 reached 1635 km^2. Through the benchmark measurement monitor results, we can work out the subsidence contour line map for different districts, different years, and different scales, and calculate the land subsidence rate in different areas for different years, so as to provide reliable basic data for the scientific research and government decisions.

3.5.5 Strengthen Scientific Research

During taking the aforementioned measures to prevent the land subsidence, strengthening the scientific research and improving the research level are also very important. We can use computer techniques to improve the defects brought by the planned water using, water saving and other traditional human management, improve the macrocontrol ability, and make the underground water development and utilization have more automation management. Then we can establish the database of multifields for the special local characteristics to greatly improve the digitization of all of land subsidence's monitored data, and in a timely fashion master the underground water level, exploitation, and subsidence change.

3.5.6 Improve Construction of Laws and Regulations

We should strengthen the professional laws and regulations construction for land subsidence, set special fund for the land subsidence research and prevention, work out related laws and regulations to strengthen the water resource management and water-saving information and education, continuously improve the social water saving awareness, and create underground water management laws and regulations. We need to establish the technical files and exploitation files, train the related management personnel, check and register all the water users, carry out the water balance test for every kind of water user by different periods and different batches, ensure the planned water management, and charge extra fees for water users who exceed the plan.

4. CURRENT SITUATION AND DEVELOPMENT TREND OF HAZARDS IN CHINA RIVER DELTA AREAS

The Chinese delta areas have sea level rise, base surface uplift, producing backwater, causing heavy rain hazard, strengthening flood hazard frequency, making the self-discharge ability gradually weaken and disappear, the mechanical and electrical discharge proportion increase, discharge lift increase, and the electrical discharge total assembly machine increase. The sea level rise, tide level increase, and the flood discharge difficult increase, such as the tide level rise in Yangtze River and Huangpu River will directly influence the downstream discharge at Taihu River.

The Chinese delta areas have developed economy, and lots of industrial wastewater is discharged into the river, resulting in river pollution. The river sections with water quality of III class standard in the Pearl River delta have been over 60% (Fan, 1994), the black and smelly days for the water quality in Huangpu River of Shanghai have been increasing year after year, and the black and smelly range has been enlarged year after year, which seriously influences the city water supply. Shanghai has become one of the key cities that have a shortage of water with water quality type. The sea level rise, tide uplift, and sewage backflow will inevitably aggravate the river pollution.

The seawater intrusion is the common phenomenon in the Chinese estuary, and it is controlled by the river flow, tide level, and tide inlet. The river flow is small and the seawater intrusion has long distance. The sea level rise and tide level rise are also beneficial for the seawater intrusion. The Yangtze River Three Gorges Project, south water to north and water introduction along river will all decrease the river flow and strengthen the seawater intrusion at estuary. The seawater intrusion and sewage discharge will further deteriorate the river water quality; this is another environmental problem the Chinese delta areas face. The seawater intrusion at estuary has the lateral seepage and downstream seepage through the riverbed, which accumulates the soil salinity along the river, and the land is gradually salinized; this is more obvious in Tianjin area and it is also common in the river belt of Yangtze River delta.

The sea level rise, water depth increase, and wave increase will inevitably aggravate the coastal erosion. The influence of sea level rise on ports has many aspects. It reduces the port land relative elevation and floods the facilities, strengthens the wave action and makes the buildings have siltation change, reduces the port operation days, and deteriorates the operation condition.

The land subsidence is another serious environmental problem the delta areas face. Most Chinese delta areas are located in the crust subsidence areas, plus the sea level rise and the land subsidence caused by the excessive exploitation of underground water make the land subsidence problem in coastal areas more outstanding. It will inevitably reduce the storm surge resistance ability, reduce the city flood prevention ability, damage the infrastructure facilities, and make the port facilities invalid. The elevation loss reduces the clearance of bridges, resulting in interrupted water traffic.

Seen from the previous discussion, the sea level rise increases the possibility of seawater intrusion, and the land subsidence increases the relative sea level rise; the sea level rise makes the coastal cities that have land subsidence face more serious hazard threats, and the sea level rise, seawater intrusion, and land subsidence in the coastal areas have interacting influences and they interact as both cause and effect.

The following section briefly analyzes the sea level rise, seawater intrusion, and land subsidence in the Chinese three big river deltas: the Yangtze River delta, the Yellow River delta, and the Pearl River delta.

4.1 YANGTZE RIVER DELTA AREA

The Yangtze River delta area refers to Shanghai near the Yangtze River estuary and the coast of its adjacent Jiangsu and Zhejiang provinces, from Guanhe River estuary at north to Qiantang River estuary at south, including the depression below the high tide level of the downstream of Taihu River at south of the Yangtze River and Lixiahe River at north of the Yangtze River as two ground elevations.

The Yangtze River delta is located at the west bank of the Chinese southern Yellow Sea and northern East China Sea, it is formed by the Yangtze River sediment into the sea since Holocene, and the average altitude is about 3 m. There are tide blocks and seawalls along all the coastline, and the coast type is silty mud plain coast, which develops broad and typical tidal beach. There are more than 5000 m^2 of shoal (from seawall to the theoretical depth base surface) (Sun et al., 1997), of which the intertidal zone area accounts for more than 40% of the total shoal area, there are about 1000 m^2 of coast wetland distributed in the intertidal zone. Shoal and wetland have rich biotic resources and unique ecosystems, which are mainly salt fencing meadow and reed swamp and some shoal rare birds.

The Yangtze River located in this area is the largest Chinese river; the annual runoff into the sea is 9240×10^8 m^3, the maximum annual value reached $13,592 \times 10^8$ m^3 (1954), the minimum was 6969×10^8 m^3 (1972); the maximum flood peak flow reached 92,600 m^3/s; the annual sediment into the sea was 4.85×10^8 t (according to the actually measured data for many years at the Datong station) (Sun et al., 1997). The coastal tides in this area are mostly regular and irregular semidiurnal tides with the tide difference mostly more than 2 m, and both banks at the Yangtze River estuary are the Chinese coastal waters with the strongest tide action. This area is also the area with very strong typhoon storm surge hazard.

This area is the important industrial base in China, it has developed agricultural system, and more important is that it has many industrial cities. Shanghai, located at the Yangtze River estuary, is not only one of the important industrial, scientific, cultural, economic, and trade centers in China but also the biggest port city in China. Its GNP accounts for about 4% of China's economy, the cargo-handling capacity of seaports accounts for about one-half of the national coastal ports, and it plays a decisive role in the national economic development.

4.1.1 Sea Level Rise Trend and Influence Prediction

4.1.1.1 Sea Level Rise Trend

In the past 100 years, though the sea level rise in this area shows the regional characteristics, the general change trend is consistent with the global changes. Here we use the global sea level rise best estimation proposed by IPCC in 1995, namely between 18 and 21 cm in 2050 (the average rise rate is 3.0–3.5 mm/a) (Shi et al., 2000).

The Yangtze River delta and its adjacent areas under the interactions of structural subsidence, loose sediment compaction, and artificial exploitation of underground water have had big land subsidence rates in recent years. Xie (1996) proposed sea level–ground series concepts and its mathematics models; he used model fitting, theoretical estimation, and repeat benchmark measurement and analysis to obtain seven groups of data of the land subsidence trend in the long term and short term. According to the continuity of natural subsidence and the controllable assumption of artificial subsidence, the land subsidence rate best estimation of the difference sections in this area from 1990 to 2050 was obtained. Based on this, we can estimate the future sea level rise extent of the different sections in this area (Table 14.10) (Shi et al., 2000).

Seen from Table 14.10, there are large differences in the future relative sea level rise extent in this area; the Shanghai coastal rise extent from 1990 to 2050 reached about 50 cm, it was about 45 cm at the northern waters of the Yangtze River delta, while it was between 25 and 30 cm on the northern Jiangsu coastal plain and the north bank of Hangzhou Bay, the latter two places will rise 50 cm in 2100.

Table 14.10 Most Possible Future Sea Level Rise Extent Estimation For Yangtze River Delta and Adjacent Areas

Section	Global Average Sea Level Rise Rate/(mm/a)	Land Subsidence Rate/(mm/a)	Most Possible Rise Extent in 2030/cm	Most Possible Rise Extent in 2050/cm
Northern Jiangsu coastal plain	3.0–3.5	1.6	18–20	28–31
Northern part of Yangtze River delta	3.0–3.5	4.1	28–30	43–46
Shanghai	3.0–3.5	5.0	32–34	48–51
North bank of Hangzhou Bay*	3.0–3.5	1.1	16–18	25–28

**The north bank of Hangzhou Bay here refers to the west part of Caojing, Shanghai.*

4.1.1.2 Sea Level Rise Influence Prediction

4.1.1.2.1 Storm Surge. The storm surge is one of the main natural hazards in the Yangtze River delta area. The accelerated rise of sea level will increase the frequency and strength of storm surge; the sections with relative small tide difference have increased frequency higher than the sections with relative big tide difference. For the sections with big tide difference such as Xiaoyangkou station and Ganpu station, if the sea level rises 50 cm, the highest tide level in 100 years will become in 50 years; while on other sections with relative small tide difference, if the sea level rises 20 cm, the highest tide level in 100 years will become in 50 years (Shi et al., 2000). The sea level rise aggravates the storm surge hazard, will cause huge losses to the coast protection engineering and seawall protection areas. Currently, the seawall design in the whole area is for 100 years. In order to maintain this safety standard, the seawall must be increased in height with the increase of storm surge level. The relative sea level of northern Jiangsu plain will rise about 20 and 30 cm in 2030 and 2050, and the seawall should be correspondingly increased in height about 16—25 cm; the relative sea level of Shanghai and Yangtze River delta will rise 50 cm in 2050, then the seawall should be increased in height about 43 cm.

4.1.1.2.2 Tidal Flat and Wetland Loss. The tidal flat area here is more than 5,200 m^2, which are mainly distributed at the Yangtze River estuary and its northern part. Here, the coastal wetland area is about 1200 m^2, which are located at the middle and upper part of the tidal flat, and they have high production and rich biotic resources. Ji and others (1994) calculated the tidal flat and wetland losses caused by the sea level accelerated rise (Table 14.11). The calculation results show that the loss rate on different sections have big differences. The erosion coast has bigger loss rate due to the interaction of erosion and flooding. For example, the coast of abandoned Yellow River delta will have the sea level rise of 28—31 cm in 2050, and the tidal flat and wetland loss will reach 45.8%—46.8%. Seen from the whole area, in 2050, the tidal flat and wetland of erosion coast, stable coast, and slight siltation coast will, respectively, reduce 356.1—373.2 km^2 (loss rate 13.7%—14.4%) and 231 km^2 (44.3%). The influence of sea level rise on the siltation coast will be the reduction of siltation area.

Table 14.11 Tidal Flat and Wetland Losses Caused by Sea Level Rise in 2050

	Tidal Flat		Wetland	
Area	**Area/km²**	**Rate/%**	**Area/km²**	**Rate/%**
Abandoned Yellow River delta	144.0—147.2	45.8—46.8	120	100
Sheyang estuary to Doulong port	77.6—80.2	11.9—12.3	80	25
Doulong port to Dongzhao port	(85.9—95.1)	23.4—25.9	0	0
Offshore radiation sand bar	85.1—94.2	6.7—7.4	—	—
Yangtze River delta	47.5—49.5	15.0—15.6	30	37
Yangtze River estuary	(89.6—95.2)	61.6—65.4	0	0
North bank of Hangzhou Bay	1.9—2.1	4.2—4.7	1	100

The values in the brackets are the areas reduced by the siltation.

4.1.1.2.3 Coastal Erosion. The erosion coasts in this area are mainly the abandoned Yellow River delta coast, Lvsi coast at the north of Yangtze River estuary coast at the south of Nanhuizui in southern Yangtze River estuary, and the northern coast of Hangzhou Bay. Currently, though the Yangtze River in this area delivers lots of sediment into the sea every year, there is huge northern Jiangsu radiation sandbar protection and erosion sediment supply of the abandoned Yellow River underground delta, and the coastal erosion range continues to enlarge. With the increase of the accounting proportion of sea level rise factor, the coastal erosion range will continue to enlarge. It is predicted that when the sea level rises 50 cm, the proportion of erosion coastline in the total coastline in this area will be increased from the current 36% to about 50%. Several currently stable coastlines will gradually develop into erosion coast.

4.1.1.2.4 Flood Hazard. The most ground elevation in this area is only 2—3 m; only the area below 2 m of Lixiahe River area and downstream Taihu River are two depressions, at $1 \times 104\ km^2$. The sea level rise makes the high and low tide levels have corresponding lift in the tide-sensitive river channels, the tide uplift actions are strengthened, resulting in the discharge ability of depression being reduced, which aggravates the flood hazard. If the sea level rises 40 cm, the natural discharge ability of the depressions in the whole area will be reduced 20% (Shi et al., 2000), the discharge ability of Lixiahe River area will be reduced 15%. If the sea level rises 40 cm, under the current irrigation engineering condition, the Lixiahe River area will encounter the extra-large flood in 1991, Taihu River area will encounter the extra-large flood in 1954, and the accumulated flooding area in these two regions will reach $4{,}860\ km^2$. This situation will appear in the eastern depression of Taihu River before 2050 and in the lowland of Lixiahe River after 2050.

The current design standard of the antiflood wall in Shanghai downtown is to increase the height and consolidated for Huangpu Park Station referring to 5.86 m in 1000 years. If the sea level rises 50 cm, the high tide level as 0.1% frequency at Huangpu Park station will reach 6.36 m, and not only the antiflood wall will be in danger, but the downtown discharge ability will also be weakened 20%, which has big threat to Shanghai.

4.1.1.2.5 Seawater Intrusion. In addition to the Yangtze River estuary, other estuaries into the sea in this area all have antiflood walls, so the Yangtze River estuary is the only estuary suffering from the seawater intrusion in this area. Yang Guishan et al. (1993) analyzed and calculated that with the sea level rise and the decrease of Yangtze River flow into the sea, in the dry season, the duration of chlorine value at Wusongkou with more than 200×10^{-6} and 250×10^{-6} will have exponential increase. If the sea level rises 50 cm, the isohaline intrusion distance of Yangtze River estuary fall of 1 and 5‰ will be increased, respectively, 6.5 and 5.3 km, which will seriously threaten the production and life in Shanghai and its surrounding area, which also has adverse effects on the estuary sediment deposition and channel evolution.

Shi et al. (2000), according to the sea level rise extent and its influence consistence, made the influence zoning for this area. The comprehensive valuation showed: the most serious influence is on the Yangtze River delta and the eastern depression of Taihu River, especially Shanghai; followed by the north bank of Hangzhou Bay; the abandoned Yellow River delta takes third place; and the northern Jiangsu coastal plain and the lowland of Lixiahe River have the slightest influence. The Yangtze River delta area has large population and developed economy, the sea level rise has wide influence and big risk. We need to work out the corresponding prevention countermeasures to relieve the risk as much as possible based on the specific influence type and influence degree.

4.1.2 Seawater Intrusion Problem

As mentioned earlier, the Yangtze River estuary is the only estuary suffering from the seawater intrusion in this area. Yang Guishan et al. (1993) through their research thought that the influence degree of sea level rise caused by global warming on the Yangtze River estuary seawater intrusion mainly depends on the Yangtze River discharge into the sea and the sea level rise extent. The influence of sea level rise of 50 cm will mainly occur when the situation is flow less than 1.1×10^4 m^3/s; while when the sea level rise is more than 80 cm, it will produce serious influence when the Yangtze River flow is kept at 1.3×10^4 m^3/s. The influence is not obvious only if the flow is more than 1.5×10^4 m^3/s. See from the Yangtze River sea data for many years, in the dry season, the chance of monthly discharge flow of Yangtze River of less than 1.3×10^4 m^3/s can be over 60%, and the chance of less than 1.1×10^4 m^3/s can also be up to 40%, and the chance of more than 1.5×10^4 m^3/s is less than 18%. Therefore, we must pay attention to the influence of global sea level rise on the seawater intrusion at Yangtze River estuary in the dry season.

In order to ensure the social and economic development and people's water demand for living in the Yangtze River area, and face the seawater intrusion hazard aggravated by the sea level rise, we must make early considerations about moving the city water supply place upward or establishing the side beach salty water prevention and freshwater storage adjustment reservoir and other prevention measures. In addition, the block of north branch can increase the discharge flow at south branch, and completely eliminate the influence of saltwater recharge at north branch, which will also play an important role in the reduction of chlorine value in the waters above Wusongkou section at south branch, especially above the Baoshan section.

The estuary seawater intrusion aggravated by the sea level rise not only causes serious risk to the water supply at estuary area but also influences the ecosystem in the whole estuary area, such as estuary water power, water chemistry characteristics, migration sediment action of chemical elements, and the composition and numbers of biological species.

4.1.3 Land Subsidence Problem

The Yangtze River delta is one of the most typical areas of the Chinese land subsidence. The land subsidence of the Yangtze River area has the connection trend in the region. Nearly 10,000 km^2 in the area has obvious land subsidence phenomenon, and the subsidence range with the accumulated subsidence of 200–600, 600–1000, 1000–1400, 1400–1800 mm, and more than 1800 mm are, respectively about 4650, 1350, 300, 30, and 6.5 km^2 (Gong, 2005).

The Yangtze River delta is located in the crust movement slow subsidence area. From northern Jiangsu to Hangzhou Bay, the structural subsidence rate is 0.4–1.2 mm/a (Sun et al., 1997), Shanghai area is 1–2 mm/a. This area is also the serious local subsidence area due to the excessive exploitation of underground water. In which, on the land of Shanghai with about 6000 km^2, the area with the accumulated land subsidence of more than 5 cm from 1956 to 1965 had reached 500 km^2. After taking the control measures in 1956, the land subsidence was somehow relieved, and it even had some certain rise (see this chapter), but since 1972, the land subsidence rate was still big, the downtown average subsidence rate was 3 mm/a from 1972 to 1989. The land subsidence rate reached 6–7 mm/a in downtown and Pudong from 1985 to 1990, and from 1991 to 1996, the accumulated average subsidence was 61.2 mm and the annual subsidence reached 10.2 mm.

Since the 1960s, Suzhou, Wuxi, Changzhou, Hangzhou, Jiaxing, and Huzhou plain and Nantong have land subsidence one after another; almost the whole Yangtze River delta has the land subsidence.

The land subsidence in Yangtze River delta is with the large scale of the underground water exploitation; Suzhou, Wuxi, and Changzhou areas are the typical. In the recent 30 years, with the development of rural industries, the ground surface water has become polluted, the underground water greatly exploited, and the underground water level rapidly fell to form the regional depression cone. During the development process of depression cone, there is land subsidence. These two are not only consistent in time but also consistent in range. This fully shows that the excessive exploitation of underground water is the main reason causing the land subsidence in this area. By 2000, the second pressure-bearing water reservoir layer's depression cone distribution area in Suzhou, Wuxi, and Changzhou areas had reached 5356 km^2. The area with accumulated subsidence of more than 200 mm has reached 5000 km^2, the contour line of accumulated subsidence of 500 mm has connected these three cities with the maximum accumulated subsidence or more than 2 m. The subsidence center of Hangzhou, Jiaxing, and Huzhou plain is in Jiaxing, and by 2011, the land subsidence area with the accumulated subsidence or more than 100 mm was more than 2500 km^2, and the maximum accumulated subsidence in the center was 0.837 m. Currently the three places as Suzhou-Wuxi-Changzhou, Shanghai and Hangzhou-Jiaxing-Huzhou, no matter the underground water level depression cone and land subsidence area, are isolated and not connected. But the land subsidence has rapid development; if we don't take the effective measures, the underground water level depression cone and land subsidence area in the whole data area have the trend of connection. In recent years, because of following the exploitation restrictions, exploitation prohibition of underground water, underground water recharge, and other measures, the underground water level has gradually resumed, and the subsidence rate gradually fallen, but what needs to be paid attention to is that the subsidence range is still enlarged (Xue et al., 2003).

4.2 OLD YELLOW RIVER DELTA AREA

The old Yellow River delta and its adjacent areas include Beijing, Tianjin, and most areas in Hebei and Shandong; they play a decisive role in the Chinese politics, economy, and culture. In the natural environment, the old Yellow River delta with Tianjin as typical has complex geological structure, and the new tectonic movement is strong; only during the seismic activity period from 1966 to 1976, there were three strong earthquakes with magnitude more than 7. Regarding the climate, it belongs to the semidry area with the annual average rain fall of 500–700 mm, and most of the precipitation is concentrated in the rainy season in July and August, and with a lot of evaporation. Water resources are always the important factor restricting the economic development in this area. The coastal area in this area has flat terrain; the coast, especially the intertidal zone, has large saline alkali land. Due to the industrial and agricultural development, the water resources are in serious shortage, underground water pumping is common in this area, resulting in the large-scale fall of the underground water level, and there is large range of land subsidence that is difficult to control. In addition, the relative sea level rise also has brought about many environmental problems.

The coastal area in Tianjin in the old Yellow River delta area suffers from the strongest action and deepest influence of relative sea level rise, land subsidence, and other marine geological hazards. Tianjin coastal area is located at the west bank of Bohai Bay, which is composed of the three districts of Tanggu, Hangu, and Dagang. This area had early development with high degree of development, and it has currently become the production base for the petroleum and chemical industry, salt and salt chemical industry, and fishing and sea transport of Tianjin; 90% of the petroleum industry, 50% of the electric industry, and 25% of the chemical industry of Tianjin are distributed in this area. With the economic development and the construction of Binhai new area in Tianjin, the coastal area has become the foreign trade window of Tianjin, the sea gate of the capital, Beijing, economic and trade center of the North China, and the bridge to connect with the world economy. Because Tianjin coastal area is located at the convergence zone of sea and land, it is the frontline of sea attack. Therefore, at the same time of development and construction, it is vital to analyze and research the influence of marine geological hazard on the coastal area, understand and master its occurrence frequency and characteristics, and work out the general prevention countermeasures.

The main marine geological hazards in the Tianjin coastal area are sea level rise, seawater intrusion, and land subsidence.

4.2.1 Sea Level Rise Trend and Influence Prediction

4.2.1.1 Sea Level Rise Trend

The relative sea level rise of old Yellow River delta is the interaction result of the global eustatic sea level rise and the land subsidence. Ren (1993) thought that the eustatic sea level rise rate of old Yellow River delta in the 30 years from 1956 to 1985 was 1.5 mm/a, the land subsidence rate was 23 mm/a, so the relative sea level rise rate was 24.5 mm/a. According to the sea level rise trend, it is predicted that in 2030, the old Yellow River delta's eustatic sea level rise rate will be about 4.5 mm/a; the land subsidence rate has been much relieved due to the control measures in the recent years, and it is predicted that in 2030, it will be controlled at about 10 mm/a, so in 2030, the relative sea level rise rate will be about 14.5 mm/a, and it is predicted that in the 40 years from 1993 to 2030, the sea level rise will be about 60 cm.

4.2.1.2 Prediction on Sea Level Rise Influence

4.2.1.2.1 Storm Surge. The formation condition of the coastal storm surge in Tianjin is the coupled superposing of the high tide level and storm water increment of astronomical tide. When the actually measured tide level is more than 4.7 m, it often causes the storm surge hazard (Peng and Yang, 1994). The relative sea level rise causes the relative decrease of elevation, which will inevitably cause the reduction of flood resistance and tide prevention ability, the highest tide level in 100 years will become in 10 years, which will inevitably make the frequency and strength aggravate the storm surge hazard. The seawall standard in Tianjin is low, and most of them are embankments with the embankment elevation of 4.5–6.0 m (Peng and Yang, 1994), according to "Flood Prevention Plan of Tianjin," set it for "100 years," the seawalls generally require height increase of 1.3–1.8 m to prevent the storm surge hazard.

4.2.1.2.2 Coastal Erosion. Due to the human economic activity, there are many reservoirs built on the upstream, middle, and even downstream of rivers on the North China plain at the west bank of Bohai Sea, and there are tide blocks built at the estuary; these tide blocks have not been open for a long time, they block the sediment resources and have made the sediment into the sea zero in the recent 10 years, thus causing or aggravating the coastal erosion and retreat. On the Yellow River delta, because the reservoirs are built on the middle and downstream of Yellow River, there are 14 estuary reservoirs built in the estuary area, which causes the introduction of Yellow River water to discharge the siltation and the introduction of Yellow River water to supply some downstream big and medium cities such as Qingdao. On the other hand, since the Yellow River flowed into Bohai Sea in 1955, the main river channel initially went into the sea from the northern delta, and then gradually moved to the northeastern and eastern part to go into the sea; in 1986 it went into the sea from the southeastern part, and it is fixed by the engineering measures of oil field department. Therefore, there is erosion and retreat at the west and north margin of delta due to the gradual shortage of sediment resource. In the 10 years from 1976 to 1986, the average retreat rate reached 100−300 m/a (Han, 1994).

On the Tianjin coastal plain, because of the interruption of sediment resource of rivers into the sea, also the sediment resource has sharp reduction from Luanhe River in the north and Yellow River in the south, many coastal sections become erosion and retreat coast from the former accumulation and extension coast, which makes the seawall base to the sea eroded and puts it in danger. At Dashentang of Hangu, due to the land subsidence and shortage of sediment resource, in the recent 60 to 70 years, the coastline has been eroded back of 60−70 m (Han, 1994).

4.2.1.2.3 Flood Hazard. Lying in a low and flat terrain, Tianjin's altitude elevation is generally 2−5 m while most of it is below 4 m. The continuous rise of relative sea level makes this area in threat of flood hazard. Haihe River, the largest water system in this area, due to the relative sea level rise, has river bed and estuary seriously silted and the river action has large reduction. The surface drainage is not smooth, which will put the flood discharge in the flood period in risk.

4.2.1.2.4 Soil Salinization. Tianjin is located at the downstream of Haihe River waters, most of it has low and flat terrain, and the ground elevation is relatively low with very gentle gradient. The soil is mainly comprised by heavy soil and light clay. With the relative sea level rise, the river water level is relatively lifted; the highly mineralized river water and the intruded seawater have aggravated effect on land, resulting in the farmland salinization at both banks.

4.2.2 Land Subsidence in Tianjin Area

The land subsidence in Tianjin draws national attention. Since the 1960s, due to lots of underground water exploitation, plus the structural subsidence activity, there is land subsidence of large scale. With the influence of modern sea level rise, many environmental hazards caused by land subsidence have been shown.

According to the benchmark measurement results, Wang and Sun (1994) drew the characteristics of crust deformation evolution in Tianjin area from 1965 to 1988. The subsidence cone area in Tianjin area from 1965 to 1975 was less than 600 km^2, the subsidence centers are only downtown and Hangu, of which the downtown was outstanding with the maximum subsidence rate of 62.9 mm/s (result after balancing, the below are the same). Hangu was 44.1 mm/a. By 1979, the subsidence in the area had sharply increased to more than 3000 km^2. Tianjin, Hangu, and Wuqing subsidence centers were connected to form the large compound cone with the maximum subsidence rate in downtown reaching 89.5 mm/a. Hangu had the maximum deformation rate of 322.8 mm/a due to the superposing of the after-earthquake effects of Tangshan strong earthquake, Cangzhou subsidence center was 28.6 mm/a, Renqiu was 11.8 mm/a. From 1979 to 1983, the subsidence area further developed to more than 6000 km^2, based on the connected multisubsidence centers, there was Gu'an subsidence center developed at the north side, and its inside developed Tangguantun subsidence center, the subsidence rates of the subsidence centers were: Tianjin 113.3 mm/a, Hangu 118.0 mm/a, Tanggu 107.0 mm/a, Renqiu 40.0 mm/a, Tangguantun 68.3 mm/a, and Gu'an 4.6 mm/a. The whole subsidence area from 1983 to 1988 was more than 7000 km^2, and the annual subsidence rates of the subsidence centers were: Tianjin 56.5 mm/a, Hangu 76.1 mm/a, Tanggu 67.8 mm/a, Renqiu 77.1 mm/a, Tangguantun 54.5 mm/a, Cangzhou 74.5 mm/a, Baxian 57.4 mm/a, and Guan 36.0 mm/a. Due to the control of underground water exploitation, Tianjin downtown's subsidence showed obvious slowing down.

Beginning in 1986, Tianjin started to manage the land subsidence. The land subsidence rate in the central downtown and Tanggu downtown was controlled between 10 and 15 mm/a, which was basically under control. Especially in phase I (1986−1988), the land subsidence in the central downtown and Hangu downtown had very fast slowing down. By 1996, the annual average subsidence inside the central line was 9 mm, and in the outer line it was 17 mm. In the following more than 10 years, the annual subsidence in the central downtown and Tanggu were maintained at about 20 mm. The land subsidence in most areas had obviously slowed down, and the subsidence control effect in general was obvious. The subsidence of the maximum subsidence point was reduced fast, and the subsidence cone gradually disappeared (Dong et al., 2008).

Because of the land subsidence, the serious siltation of river bed and estuary of Haihe River makes the river action largely reduce. The original design is for 1200 flows, but now it is difficult for 400 flows to pass (Wang and Sun, 1994). This not only puts the flood discharge in the flood period in risk but also makes the swamp along the coast due to the nonsmooth surface discharge. In addition, the decrease of ground elevation and the formation of lots of water depression make the seawater recharge and the water table rise, which aggravates the soil salinization, causing the surface water quality to be polluted, and the whole city's water supply and discharge system is seriously influenced. In a word, the direct and indirect hazards due to the land subsidence in this area are serious.

4.3 PEARL RIVER DELTA AREA

Pearl River delta is located at the south of the Tropic of Cancer with the average temperature of 21−23°C, it belongs to the northern tropical monsoon climate with frequent tropical cyclone and heavy rain, and the runoff has obvious flood and dry up. The Pearl River delta is mainly collected and accumulated by Xijiang River, Beijiang River, Tanjiang River, Liuxihe River, and many other rivers, and on the plain, the river network is arranged in a crisscross pattern, the river network density is 0.68−1.07 km/km^2 (Li et al., 1994), and it is divided into eight estuaries that flow into the South China Sea.

The average runoff flow of the rivers of Pearl River into delta for many years is 3029×10^8 m^3, the average flow is 9584 m^3/s, the annual suspended sediment transport is 8735×10^4 t, and the annual average sediment concentration is about 0.28 kg/m^3. It has high flood peak and large flow, and there are five flood peaks in every year. The average tide difference at the estuary is 0.86 (Modaomen)−1.60 m (Humen). The average high tide level is 0.41−0.77 m (Pearl River base surface), and the actually measured highest tide level is 2.63 m (Pearl River base surface). Humen, which has the largest flood flow, has the annual average as 2288×10^8 m^3, and the total flood flow at eight estuaries is 3762×10^8 m^3 (Li et al., 1994).

There is land with area of 803.65 km^2 in the Pearl River delta below Pearl River base surface, and there is land area of 1469.53 km^2 as 0.4 m below the base surface elevation of Pearl River; there is land area of 2994.76 km^2 as 0.9 m below the base surface elevation of Pearl River. It has low and flat terrain, which is easy to suffer from the sea level rise and cause hazard.

The Pearl River delta is one of the areas with the fastest economic development in China, the total social output value and foreign trade exports are increased year by year with many large and concentrated towns. This area always has had close geopolitics, genetic, and economic relationships with Hong Kong and Macau. The strong economy of Hong Kong and Macau and the position as big trade port in the world play an important role in the economic development of the Pearl River delta.

The Pearl River delta area is the biggest hometown of overseas Chinese in China, and it has become the area with the most concentrated foreign trade enterprises in China. This area is the important foreign trade window in China, Guangzhou is the place where Chinese Export Commodities Fairs are held, and Shenzhen and Zhuhai have direct trade relationships with the countries throughout the world. The Pearl River delta area has good development prospects; it is predicted that is will become one of the areas with the most developed economy in China and even in the Asia Pacific region.

4.3.1 Sea Level Rise Trend and Influence Prediction

4.3.1.1 Sea Level Rise Trend

According to the actually measured data of Hong Kong and Macau tide stations, Huang et al. (2000a,b) obtained that the sea level rise of the Pearl River delta in the nearly 72 years from 1925 to 1996 was 1.8 mm/a; this rise rate can be seen as the eustatic sea level rise rate of the Pearl River delta area, which can be compared with the world records. With the comprehensive consideration of the eustatic sea level, sea level abnormal fluctuation, flood and tide level rise, terrain, and other factors, it is predicted that the relative sea level rise extent in 2030 is 22—33 cm. According to the best estimation of IPCC, with the consideration of the current land subsidence situation, the development trend and the control measures of government in the Pearl River delta, Ren Meie predicts that in 2030, the relative sea level rise will be 20—25 cm. After organizing related experts for investigation and research, the Department of Earth of Chinese Academy of Sciences predicted that the sea level of the Pearl River delta in 2050 will rise 40—60 cm (He, 1994).

According to the sea surface height data of the South China Sea observed by TOPEX and Jason-1 from 1993 to 2008 and the tide level data at the Guangdong coastal tide station from 1986 to 2008, Tang et al. (2009) calculated that the (absolute) sea level average rise rate of South China Sea in the recent 16 years was 4.5 mm/a, and the relative sea level rise rate of Guangdong coast in the recent 23 years was 2—3 mm/a, which was 1—2 mm/a lower than the absolute sea level of South China Sea.

The estimation for the relative sea level rise is uncertain, but the fact can't be changed, and many influences brought by the sea level rise should also not be ignored.

4.3.1.2 Prediction for Sea Level Rise Influence

4.3.1.2.1 Storm Surge Hazard. He (1994) selected five tide stations of the representative Guangzhou, Huangpu, Sishengwei (Dongguan), Nansha (Panyu), and Denglong Mountain (Zhongshan) located along the coast of the Pearl River estuary as the research objects; after analysis and calculation of the tide level data, he thought that if the sea level rises 40 cm, there will be many areas in every county along the coast of the Pearl River delta in the high water level about one-third of the time in every month; if the sea level rises 60 cm, it will approach the current actually measured historical highest tide level in one or two days in every month, and the seawalls of every county along the coast with the current building standards will be seriously threatened for several days of every month.

The sea level rise makes the storm surge hazard more serious in the Pearl River delta. If the sea level rises 40 cm, the storm surge level of 10-year frequency had reached the level of 50-year frequency, and the storm surge level of 20-year frequency can reach the current tide level of 100-year frequency; if the sea level rises 60 cm, then the storm surge level of 10-year frequency will be over the current tide level of 100-year frequency, and the storm surge level of 20-year frequency will be over the current 500-year frequency level and will be close to the tide level in 1000 years. In addition, the sea level rise will make the storm surge hazard extend to the deep Pearl River delta.

Currently the seawalls in the Pearl River delta can generally withhold the storm surge level in 20-year frequency. We can assume from this that after the sea level rise, if we don't take the seawall consolidation and height increase measures, then every county and city on the coast of the Pearl River delta will have serious storm surge hazard due to the sea level rise. Therefore, the design standard of seawall should be generally upgraded two levels.

4.3.1.2.2 Large Lowland Will be Flooded. The Pearl River delta has about 1500 km^2 (accounting for 23.76% of the plain) land elevation of 0.4 m higher than the current sea level; if the sea level rises in 2030, there will be large lowland flooded. There is land area of about 5000 km^2 (accounting for 23.76% of the plain) below the current highest tide level (Li et al., 1994). If the existing seawalls are not increased in height and consolidated, during the high tide large areas of plain in this area will be flooded.

4.3.1.2.3 River Channel Siltation. The river channels in this area are in the siltation state for long term, the current average siltation velocity is about 3 cm/a, and some local areas are more than 10 cm/a (Li et al., 1994), basically it has siltation in the flood season and erosion in the dry season. If the sea level rises dozens of centimeters in the middle of the 21st century, the erosion base surface will be uplifted, which will inevitably cause the aggravation of the ltation in parts of the river channel. The strong siltation section of river channel moves inward with the siltation velocity higher than the sea level rise velocity, which will have adverse effects on the water depth of partial shipping channel and port.

4.3.1.2.4 Drainage and Irrigation Difficulty, Environment Pollution. The farmland in the Pearl River delta always uses the flood and ebb for self-discharge and irrigation and the industrial and life sewage in the city are also discharged into the rivers making use of tide. Recently there has not been smooth discharge due to the sea level rise. If the sea level rises dozens of centimeters, the tide discharge and tide irrigation of farmland will not be possible, contrarily it will increase the difficult of city sewage discharge and will make the river water quality pollution more serious.

4.3.1.2.5 Seawater Intrusion. Currently the constant seawater (chlorine value is 1‰) intrusion has reached the line of Bitou-Taiping-Houjie-Zhupingsha-Huangpu-Hualong-Shiqi-Hengmen; in the dry season, it can reach the water plant in Xi village at southwestern Guangzhou, which is about 70 km away from Humen (Li et al., 1994). The maximum chlorine value in Huangpu reaches 5.93‰, and it reaches 13.6‰ at the Dongguan Sisheng station, which is about 28 km away from Humen. According to the calculation of Li Suqiong, if the sea level rises 70 cm, the seawater will go further 4 km. At that time, there will be new problems for the water plant layout, production, and water for life.

4.3.2 Seawater Intrusion Problem

Outside the Pearl River estuary, the bottom salinity in the dry season is between 30 and 33, which doesn't have much relationship, while the surface salinity is obviously small in the Modaomen waters (Zhou, 1998). The powers influencing the seawater moving upstream are the tide and runoff. Influenced by the upstream runoff, when the surface salinity at other estuaries is above 2, it only has 4−14 at the estuary in Modaomen waters. From the salinity isoline at the Pearl River estuary, we can also see the Modaomen salinity is bending outward. In the estuary area, because the rainfall distribution in the year is not even, it forms in the early spring, at this time, the river runoff is in the dry season, the seawater moves upstream, the salinity value in every river channel is greatly increased, with Humen having the widest influence range, and Jitimen, Yamen, and Hongqimen follow.

According to the saline and freshwater mixture spread principle at estuary, Li (1994) analyzed the possibility of sea level rise influence on the seawater intrusion of the Pearl River delta, calculated the distance change of the main channel's seawater intrusion at each waters during the high tide of future sea level rise and water level lift of 0.4—1.0 m, and obtained the following understanding: in the dry season, the seawater intrusion distance of the main Humen water channel of Pearl River has the average increase of 1.3—3.0 m with the maximum of about 4.0 m. That is to say that during the huge tide in winter, when the water level rises 1.0 m, the seawater will basically reach Guangzhou nearby; the seawater intrusion distance of Jiaomen water channel has the maximum increment of about 3 km, which can reach Nansha above about 25 km. The Modaomen of Xijiang River main channel has little intrusion distance; because of its maximum discharge runoff, the seawater under the action of uplift will have the maximum increment of about 3 km, namely reaching the Shenwan nearby above the fault of Denglong Mountain. The intrusion distance of seawater in Huangmao Sea has the maximum increment of about 5 km, namely the upper seawater can reach the middle Tanjiang River of Xijiang River branch. In addition, the research thought that the increment of seawater intrusion is bigger in the dry season than that in the flood season, and the maximum increment basically appears in the huge tide period in winter. If there is a maximum drought year and sea level rise, the water level is lifted, and the seawater intrusion degree will be strengthened.