# Flooding Hazards and Potential Risks due to Heavy Rain and Sea Level Change in Shanghai, China

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**ABSTRACT:** Current sea level change is mainly induced by global warming which is believed to increase the sea level if sustained for a sufficiently long period of time. Many coastal cities around the world have suffered adverse effects as a consequence of sea level change. Shanghai is a coastal city which is located on the estuary of the Yangtze River with an elevation ranging from 3 to 4 m. Its geological and climatic conditions make the city sensitive to flooding risk caused by heavy rain and sea level change. This paper analyses the recent sea level change and heavy rainfall in Shanghai. Regional rates of sea level change can be divided into i) the rate of eustatic sea level change; ii) tectonic movement of the continent; and iii) land subsidence in Shanghai. A correlation analysis shows that the number of local torrential rains and short duration torrential rains correlates with sea level change. Incidents including pluvial flooding, sea water intrusion and potential damage to coastal structures will be more serious if the rate of sea level change continues to rise. To protect the environment and to control economic losses, more countermeasures should be established to prevent the potential hazards.

**KEYWORDS:** Sea level change, Heavy rainfall, Flooding hazards, Shanghai

## 1. INTRODUCTION

With the increase in global temperatures as a result of the process of industrialisation and the greenhouse effect, many large cities in coastal regions in the world have experienced hazards, (such as pluvial flooding and coastal scouring), due to rising sea levels and heavy rainfall. Sustainable economic and social development of many coastal cities in China has been influenced by the adverse effects (such as pluvial flooding and seawater intrusion) of rising sea levels and heavy rainfall. For example, Shanghai is a coastal city which is located on the estuary of the Yangtze River and is bordered by the East China Sea to the east. It has an elevation ranging from 3 to 4 m (Chai et al., 2004, 2014; Shen et al., 2006, 2015a, b; Xu et al., 2008, 2013a,b; Wu et al., 2015a, b; Wang et al., 2013; Zhang et al., 2015). The Huangpu River, as a tributary of the Yangtze River, runs through Shanghai. The annual precipitation is about 1200 mm, of which 60% falls during the flooding season (Shen et al., 2005, 2011, 2013; Xu et al., 2009a, b 2012a,b, 2015; Wu et al., 2014, 2015c). The first month of the flooding season is referred to as 'Meiyu' in Shanghai, and in this time the rains may last for several days. This intensive rainfall normally commences at the end of May and lasts for four months and will induce hazards and economic losses. Although a lot of infrastructure, including drainage systems and pumping stations, has been constructed in Shanghai since the 1980s, serious pluvial flooding due to heavy rainfall still occurs (Hu, 2002).

Sea level change can cause a series of hazards and economic loss to coastal regions, including storm tides, coastal erosion, and seawater intrusion. Consequently much attention has been paid to the causes of sea level change. Sea level can be classified as the relative sea level and the eustatic sea level. Several factors contribute to a change in the eustatic sea level, such as climate change, air pressure, winds, steric effects, oceanic currents, rainfall, evaporation, continental runoff, and glacial runoff (Nerem et al., 2006; Han and Huang, 2008). Continental tectonic movement and human activity, such as urbanisation and groundwater withdrawal, can have an effect on the relative sea level. Most existing studies concentrate on just one or a few academic problems, such as climate change, thermosteric changes, tectonic movement and land subsidence due to human activities (Han and Huang, 2008). With the low elevation of Shanghai, many hazards due to sea level change have occurred. Very few analyses have focused on the relationship between the sea level change and heavy rainfall. In this paper, a correlation analysis between the sea level change and heavy rainfall is discussed.

The objectives of the paper are to: i) describe the sea level change and the heavy rainfall in Shanghai; ii) discuss the correlation between the sea level change and the heavy rainfall; iii) discuss hazards due to the sea level change and the heavy rainfall.

## 2. METHODOLOGY

In order to summarise the recent sea level change and heavy rainfall in Shanghai, relationship between heavy rainfall and sea level change and the impact on heavy rainfall due to sea level change will be analysed synchronously. Meanwhile, the flooding hazards and potential risks due to sea level change and heavy rainfall have impact on the sustainable system and infrastructures of the coastal cities.

In this paper, we propose the sea level anomalies may have an effect on the frequency and precipitation of heavy rainfall. The main methods adopted in this study included collecting the data of sea level change and frequency of different heavy rainfalls in the last thirty years. After that, the correlation between the sea level change and the frequency of different heavy rainfalls were analyzed. Then the severity geo-hazards, such as flooding hazards, seawater intrusion and potential risks to the coastal structures, may occur and get worse if no countermeasures are taken and the trend of heavy rainfall and sea level change continues. To mitigate the impacts, useful countermeasures for Shanghai will be suggested in this paper for the sustainable system and the resident life.

## 3. SEA LEVEL CHANGE ALONG THE COAST OF SHANGHAI AND CHINA

The current rise in sea level is mainly induced by global warming and this is believed to have been contributing to rising sea levels over a long period of time (Bindoff et al., 2007). The global sea level has been rising at a rate of 1.5±0.5 mm/yr during the last century (Church et al. 2001), while the rate from 1993 to 2003 was 3.1 mm/yr. Excluding the influence of crustal tectonic movement and land subsidence, satellite-based estimations suggest that sea level rise increased to an even faster rate of 2.8±0.4 mm/yr during the last decade (Cazenave and Nerem, 2004). According to the China Ocean Bulletin (2015), the average rate of sea level rise was about 3.0 mm/yr from 1980 to 2015, which is far higher than the global average rise rate. Figure 1 shows the sea level variation around the Chinese coast. Internationally, the mean sea level is defined as the average sea level from 1975 to 1986. As shown in the figure, the highest sea level on record reached 122 mm above mean sea level in 2012. The sea level in China from 1980 to 2015 has fluctuated but has had an upward trend, and has increased sharply in recent years.

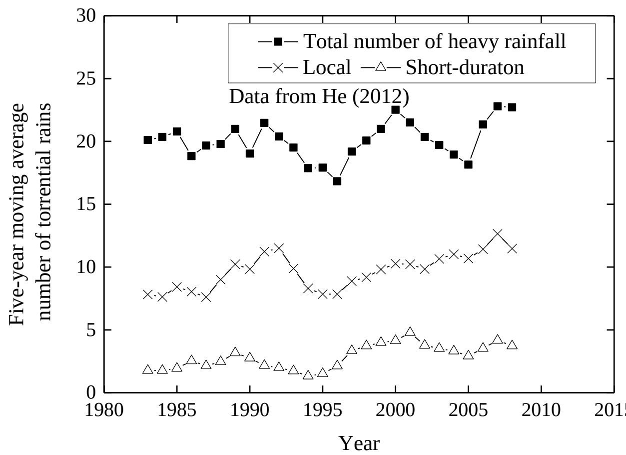


Figure 1 Average of sea level variation of China

Shanghai is a typical coastal city in China, located on the Yangtze River delta, with the East China Sea to the east and Hangzhou Bay to the South. The regional rate of sea level change in Shanghai can be expressed as follows:

$$V_r = V_e + V_t + V_0 \tag{1}$$

Where $V_r$ = regional rate of sea level change; $V_e$ = rate of eustatic sea level change; $V_t$ = tectonic movement of the continent; $V_0$ = land subsidence in Shanghai. Figure 2 shows the variation in the eustatic sea level in comparison to the mean sea level from 1985 to 2015. Before 2010, the variation between actual eustatic sea level and the mean sea level fluctuated within a range of 30 mm to 80 mm. After 2010, the eustatic sea level began to increase sharply. The highest sea level recorded is 120 mm above the mean sea level, occurring in 2014. The tectonic movement in Shanghai is about 1 mm/yr. Due to the deltaic soft deposit on which Shanghai stands, land subsidence is also a key factor which should be taken into account in the regional rate of sea level change. Figure 3 shows the cumulative subsidence in Shanghai from 1965 to 2010. The cumulative subsidence rate in the urban centre increased to 12.9 mm/yr after 1995 and the cumulative regional rate of sea level change Vr increased to almost 17 mm/yr. There will therefore be a significant risk to the coastal regions if the regional rate of sea level rise continues to increase.

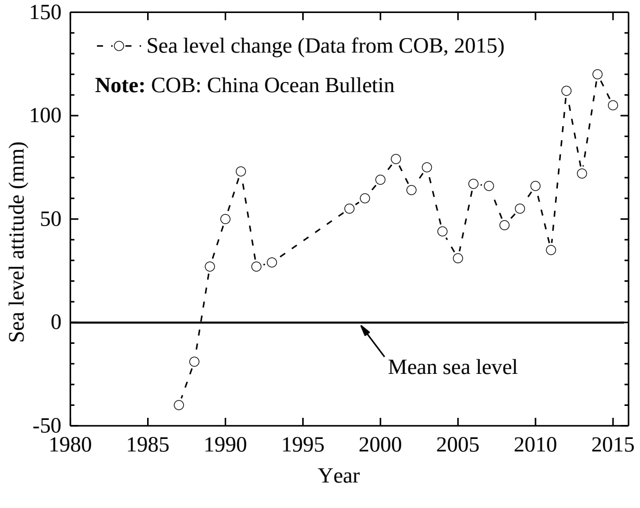


Figure 2 Eustatic sea level variation in Shanghai

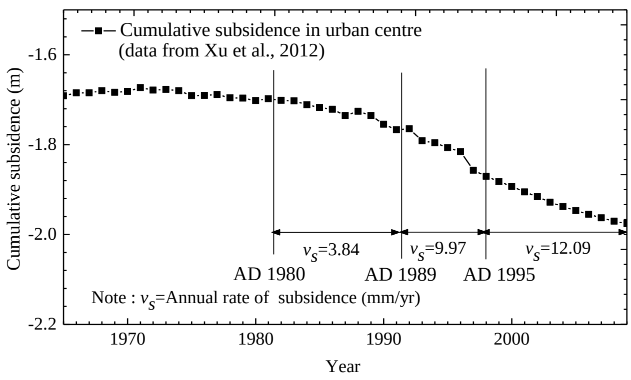


Figure 3 Cumulative subsidence from 1965 to 2010 in Shanghai

## 4. HEAVY RAINFALL IN SHANGHAI

Figure 4 shows the locations for the monitoring stations. Heavy rainfalls in Shanghai are formed by small and medium scale weather system. In this paper, the definition for the duration time of the heavy rainfall is as follows: beginning with the first meteorological station begins to rain, ending with the last meteorological station stops to rain, while precipitation larger than 30 mm in 12 hours will be defined as torrential rain._According to meteorology, based on the cumulative precipitation, heavy rainfall can be divided as three stages: i) rainstorm (cumulative precipitation equal to 30 ~ 59 mm/day); ii) heavy rainstorm (cumulative precipitation equal to 60 ~ 99 mm/day); iii) extraordinary rainstorm (cumulative precipitation equal to or larger than 100 mm/day). In Shanghai, rainfall with accumulated precipitation equal to or greater than 30 mm within 12 hours is defined by the local government as torrential rain. In order to show the affected area, local torrential rain is defined as covering an area of less than or equal to 20% of the area of Shanghai. To indicate the storm period, short duration torrential rain is defined as lasting less than 6 hours ($D_t \leqslant 6$ hours).


Figure 4 Locations of the meteorology monitoring stations

Figure 5 shows the five-year averaged curves of torrential rain frequencies in Shanghai from 1981 to 2010 (He, 2012). The number of torrential rainfall events shows a stable trend, with a range from 18-23 per year from 1981 to 2010. But, the number of local torrential rains and short-duration torrential rains has an increasing trend. The local torrential rains increase from 6 per/year to 9 per/year, while the short duration torrential rains increase about 1.8 per year from 1980 to 2010. On the other hand, the torrential rainfalls are commonly focused in the month from May to September. Table 1 shows the monthly distribution of the torrential rain intensity in Shanghai from May to September from 1980 to 2010. The number of heavy rainfall commonly focused in July and August. Currently, despite the difficulties for the anticipation of the heavy rainfalls, it is necessary to investigate the possible impacts on the rainfall, such as climate change and sea level change. After the analysis between the rainfall and the possible impacts, more useful countermeasures can be proposed to prevent the pluvial flooding disasters caused by heavy rains.

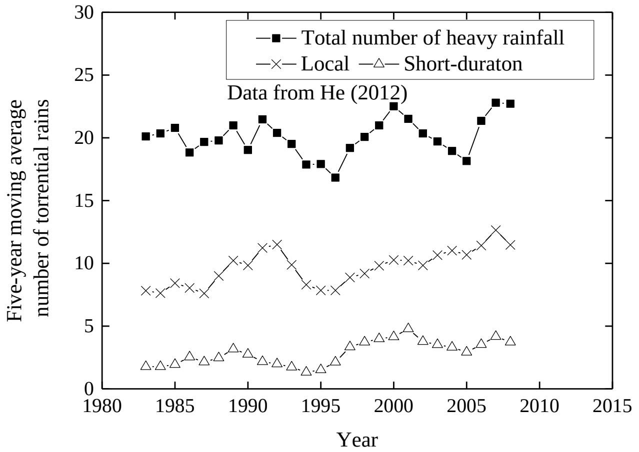


Figure 5 Five-year moving average number of torrential rains from 1980 to 2010

Table 1 Monthly distribution of torrential rain intensity from 1980 to 2010 (Number) (Data from He and Zhao, 2009)

| Month | Total | Extraordinary rainstorm | Medium rainstorm | Rainstorm |
|---|---|---|---|---|
| May | 44 | 3 | 13 | 28 |
| Jun. | 99 | 17 | 31 | 51 |
| July | 120 | 20 | 25 | 75 |
| Aug. | 155 | 17 | 46 | 92 |
| Sep. | 71 | 13 | 16 | 42 |

## 5. CORRELATION BETWEEN HEAVY RAINFALL AND SEA LEVEL CHANGE

An alternative mechanism contributing to heavy rainfall in Shanghai is associated with rising global temperatures. The change in eustatic sea level due to global warming may have an effect on the number and the intensity of the heavy rain events. Based on the observed results at eleven weather stations, Figure 6(a) shows the sea level change and the number of local torrential rainfalls. Figure 6(b) shows the sea level change and the number of short duration torrential rainfalls.

As shown in the figure, the variation in the number of local torrential rainfalls and short duration torrential rainfalls shows almost the same trend as the sea level change. There are good correlations between the sea level change and different types of torrential rains, namely local torrential rain and short duration rain. The decrease in the number of local torrential rainfalls is thought to be related to an effect associated with quasi-stationary frontal systems during the Meiyu period, which has reduced the number of rainstorms. The number of local torrential rainfalls may be correlated with the sea level change. Figure 7(a) shows the relationship between the five-year moving average number of local torrential rainfalls and the eustatic sea level change. The values are mainly focused within the range of y=0.26x and y=0.12x, and there were only four exceptional events, in the years 1985 to 1988. Figure 7(b) shows the relationship between the five-year moving average number of short duration torrential rains and the eustatic sea level change. The values are mainly focused within the range of y=0.10x and y=0.04x, and again there were only four exceptional events, in the years 1985 to 1988. As shown in Figure 6, the contribution to the frequency of local torrential rain and short duration rain appears positively correlated with sea level change. The main reason can be divided as follows: i) aforementioned tidal water increase due to sea level change; ii) sea level change will induce the temperature increment along the coastal area. In the warm sector area of Shanghai, this convective precipitation induced by strong convergence and cyclonic curvature will increase the frequency for local torrential rain and short duration rain.

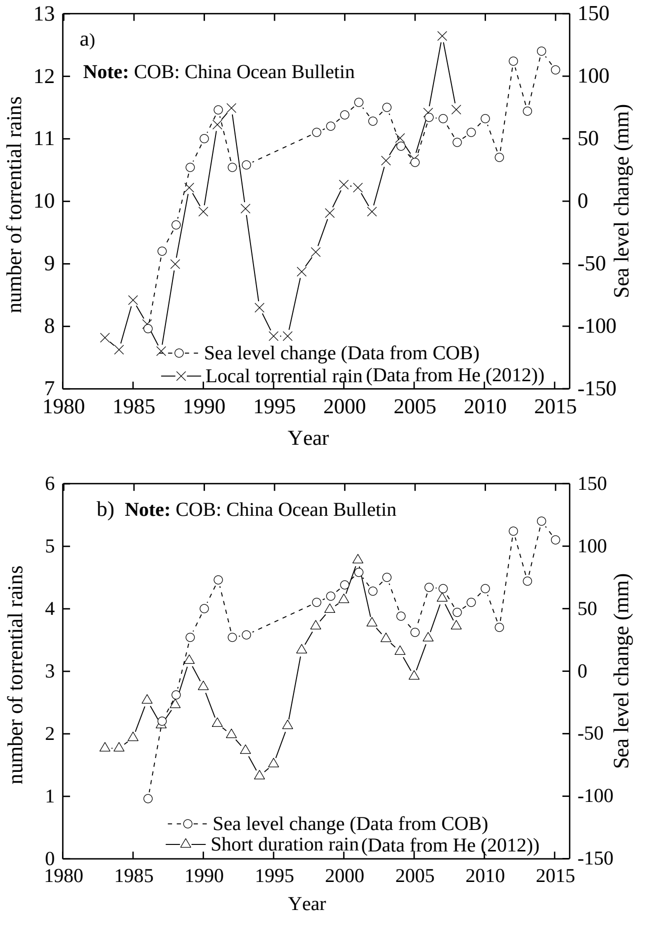


Figure 6 Sea level changes and five-year moving average number of torrential rains

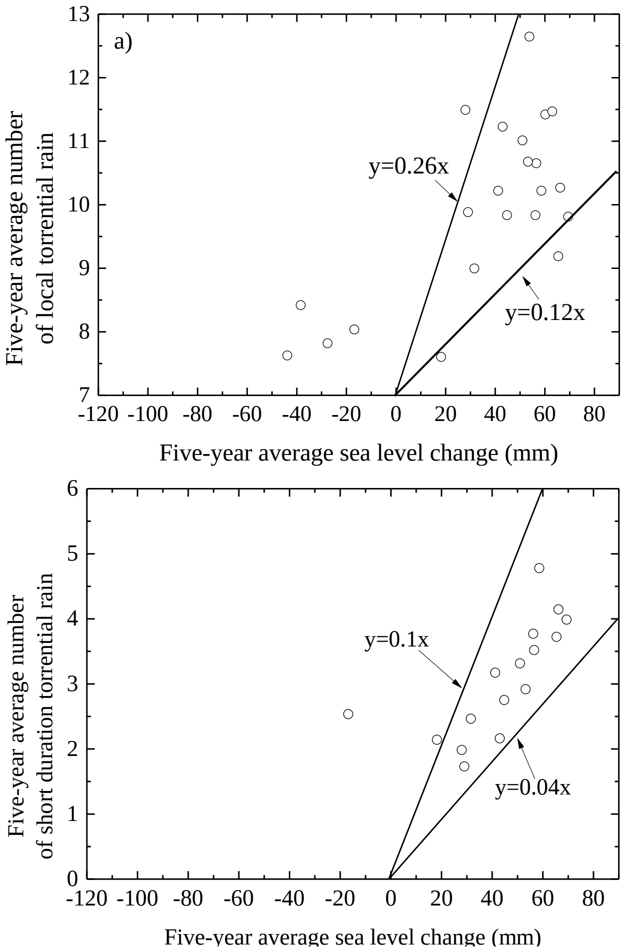


Figure 7 Relationship between the number of torrential rain and sea level change

## 6. HAZARDS DUE TO HEAVY RAINFALL AND SEA LEVEL CHANGE

### 6.1 Pluvial flooding

The mechanism of pluvial flooding in Shanghai is based on the current and previous research results (e.g. Hu, 2002). Under normal conditions, some of the rainwater is stored temporarily in the storage system, and the excess is discharged into the sea through the drainage system. If the excess rainwater cannot be discharged properly, pluvial flooding occurs. In this paper, the impact of pluvial flooding due to heavy rainfall is evaluated by considering the number of reported flooded road sections, $N_R$. Table 2 shows the impact stages of pluvial flooding. The impact of the flooding increases from stages I to IV.

Two parameters of rainfall properties, the maximum precipitation, Pm, and the average Figure 8 intensity, $I_a$ ($I_a = P_m / D_t$), are used to analyse the pluvial flooding. Figure 7 shows the relationship between $I_a$ and $P_m$ for 54 heavy rainfall events in Shanghai during the last fifteen years. In these rainfall events, the $P_m$ of flooding events is mainly concentrated in a range from 50 mm to 150 mm, while the $I_a$ is within a range of 5 mm/h to 60 mm/h. If $P_m$ is smaller than 50 mm or $I_a$ is smaller than 5 mm/h, few pluvial flooding events will occur even with heavy rainfall (which would correspond to impact Stage I). But if Pm is larger than 150 mm, or $I_a$ is larger than 60 mm/h, the current capacity of pluvial flooding resistance in Shanghai cannot prevent a flooding event. For example, due to the low elevation, when high intensity of short duration rainfall ($I_a$ > 60 mm/h) or long duration rainfall ($P_m$ > 150 mm) occurs, the formation of ground runoff due to pluvial flooding will induce the road traffic blocking, power failure and large economic loss. Figure 9 shows pluvial flooding on September 13th, 2013. The $P_m$ and $I_a$ of this pluvial flooding are 137 and 68.5, respectively. More than 80 roads and districts were inundated. Based on the observed data at meteorological station in Xuhui District，another torrential rainfall with the precipitation larger than 117.5 mm from 7 am to 8 am ($I_a$=117.5 mm/h) occurred on August 25th, 2008. Many roads were inundated and daily life of the local residents was seriously disturbed. As shown in Figure 5, the regional sea level change has the same increasing tendency as the number of local torrential rains, and as the short duration torrential rains. If the regional sea level change continues increasing, this kind of heavy rainfall will increase. It is therefore essential to improve the drainage system capacity in order to prevent this kind of pluvial flooding event (which would correspond to impact Stage IV).

Table 2 Impact stage of pluvial flooding event

| **Impact stage** | **Number of sections of inundated road reported by media** |
|---|---|
| Stage I | "A few" or $N_R \leq 3$ |
| Stage II | "Less than 10" , "More than 10" or $4 \leq N_R \leq 11$ |
| Stage III | From "Less than 20" to "more than 40" or $12 \leq N_R \leq 50$ |
| Stage IV | From "More than 50" to "More than 200" or "Extensively water-logged" or $51 \leq N_R$ |

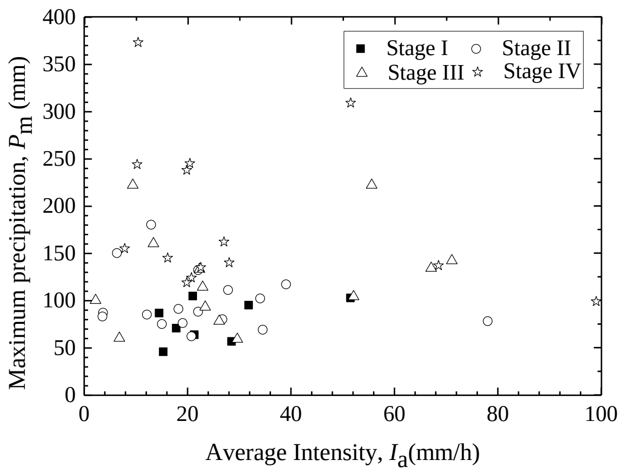


Figure 8 Relationship between $I_a$ and $P_m$ in the rainfall event causing pluvial flooding from 2001 to 2015

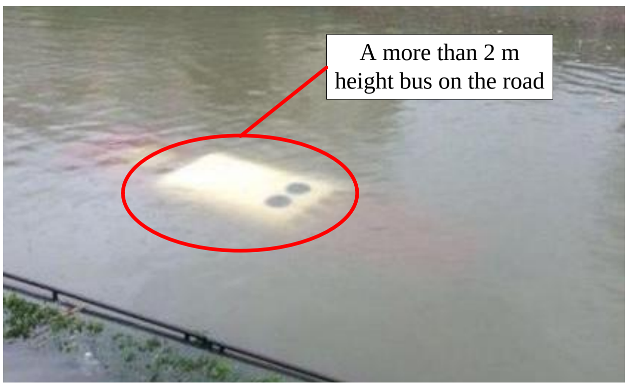


Figure 9 Flooding occurred in 2013 after raining for a few hours (Photo online: http://news.xwh.cn/news/system/2013/10/09/010401470.shtml )

### 6.2 Seawater intrusion

Coastal erosion is considered to be one of the most significant consequences of sea level change for coastal cities. Due to the low elevation and the silty-muddy soil along the coastline, about 48 km of the coastline of Chongming Island has suffered coastal erosion. Figure 10 shows a photograph of coastal erosion in Chongming Island in 2015. Based on data from the China Ocean Bulletin, the erosion rate of its coastline is about 7 m/year. If the coastal erosion continues, areas of tidal flat wetland will be submerged. This will lead to damage to coastal defence structures, such as breakwaters and the main harbour. Moreover, the sustainable system for local residents will be disturbed. A further Issue is that of saltwater intrusion caused by sea level change, which will affect the fresh water supply and soil salinization in Shanghai. The area of Coastal saline soils is about 15 percent of the total area in Shanghai. The area is mainly disturbed in the intertidal zone outside the dam or the newly reclamation zone inside of the dam, such as in the north branch of Chongming Island.


Figure 10 Coastal erosion in East Chongming Tidal Flat (Photo Online: http://www.mlr.gov.cn/zwgk/tjxx/201303/t20130322_1194292.htm)

The bad physical and other properties of this kind soil make it difficult for agriculture and daily life. During periods of drought, the reduction in the volume of runoff will result in sea water flowing upstream, causing an intrusion of salt water, which will pollute the groundwater and salify the river beach soil. At present, 70% of fresh water supplies for Shanghai come from reservoirs and tributaries in the Yangtze estuary, and a sea level rise will lead to a shortage of fresh water. For example, in 1978, due to the drought causing a reduced volume of water in the Yangtze River, severe seawater intrusion occurred from the winter to the following spring. The chlorine content of the supplementary water source at the Wusong estuary was higher than the allowable industrial water standard and this situation lasted for two months, and Chongming Island was inundated by the sea for almost six months. Zhang et al. (1997) estimated that the period that the seawater intrusion lasts for will increase to almost the entire year, if the sea level rise increases by 50 ~ 100 cm.

### 6.3 Potential damage to the coastal structures

Tidal regime is also very important for a coastal city, especially during heavy rainfall occurs. Sea level change will induce the tidal water level increased. The increasing tidal water level will increase the frequency of the torrential rainfall due to storm tide. Based on the database observed by the meteorological station in Shanghai, the tidal regime due to tropical cyclone will more easily induce the local torrential rain and short duration rain. Moreover, the both increasing of tidal regime and torrential rainfall will react on the sea level change and induce the potential risks to the coastal structures. The current average elevation of Shanghai is about 3-4 m above sea level, and is only 2 m in some areas. Figure 11 shows the highest tides observed at Huangpu Park Station in the urban centre of Shanghai. The tide has shown an increasing trend since the 1960s. All the highest tides in the past 100 years have been above 4 m. The highest tide on record occurred on August 19th, 1997, and was 2 m higher than the average elevation.

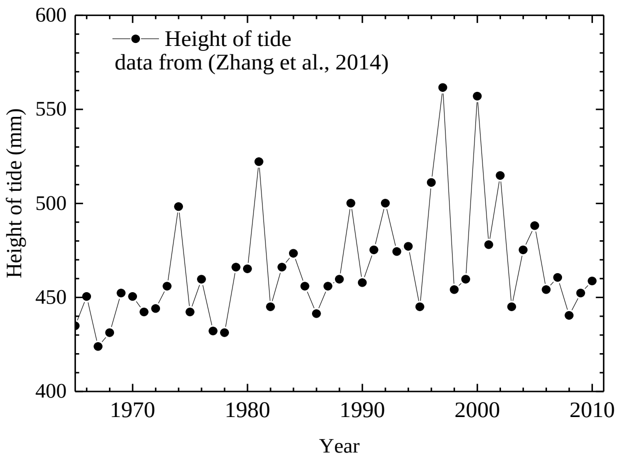


Figure 11 Maximum height of tide

Figure 12 shows a photograph of the Suzhou River, a tributary of the Huangpu River. The floodwall was raised three times and its height now reaches 5.2 m. However, based on the China Ocean Bulletin (2015), the average sea level rise is about 3 mm/yr. The tectonic movement of the continent and the land subsidence rate in Shanghai are 1 mm/yr and 9 mm/yr, respectively. If the regional sea level rise continues, the maximum tidal level will exceed the current highest value, and many potential engineering problems will occur. For example, the clearance of the bridges on the Suzhou River will be reduced due to the regional sea level rising, and this will have a serious effect on the navigability of the river. The sea level rise will shorten the recurrence interval of the extreme high water level, and the sea water will easily overtop the breakwaters. This will change the ranking of the coastal defence structures, in terms of the magnitude of flooding which they can withstand. For example, the flood control wall in Shanghai has reduced in rank from protecting against a one-in-1000 year flood to protecting against a one-in-200 year flood. As shown in Figure 13, in June 2015, a short duration rainfall occurred in Shanghai, and the water level near the Hongkou Port increased significantly and rapidly flooded the land and the bridge near the Hongkou Port. Thus further issues should be focused on controlling the adverse effects induced by regional sea level change. More countermeasures should be established to prevent the potential hazards.

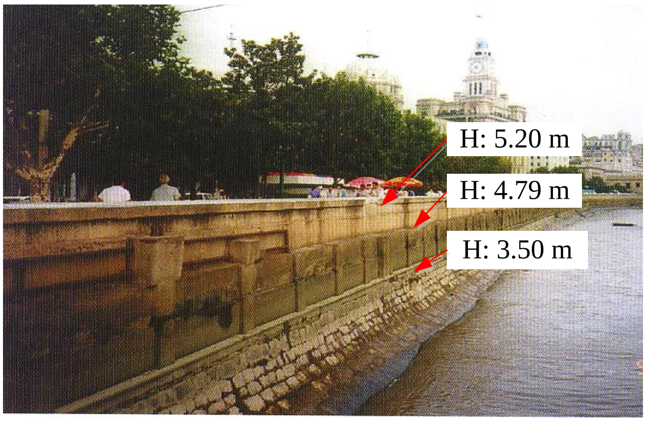


Figure 12 Photo of floodwall along Suzhou River

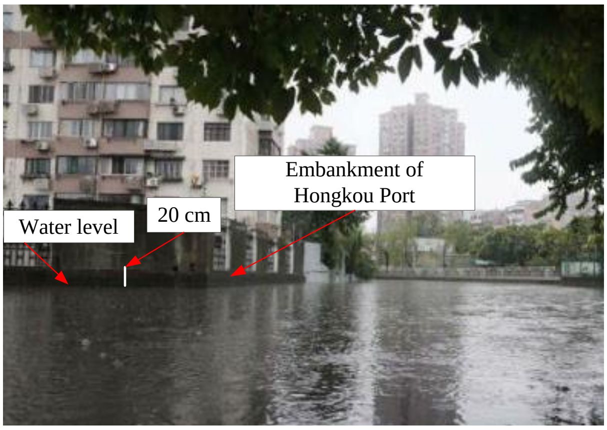


Figure 13 A short duration rainfall in June 2015
(Photo Online:http://
www.jfdaily.com/minsheng/new/201506/t20150617_1604856.html)

## 7. CONCLUSIONS AND COUNTERMEASURES

Sea level change and heavy rainfall pose a significant risk for coastal areas. Shanghai is a coastal city, with an average elevation of about 3-4 m, so that it is sensitive to sea level change and heavy rainfall. The correlation between sea level change and heavy rainfall within the last 35 years in Shanghai has been analysed. In order to mitigate the hazards and potential risks due to sea level change and heavy rainfall, countermeasures are be recommended. Based on the analysis, the following conclusions can be drawn:

(1) The regional rate of sea level change in Shanghai can be divided into: i) the rate of change in eustatic sea level; ii) tectonic movement of the continent; iii) land subsidence of Shanghai. The regional rate of sea level change $V_r$ has increased to almost 17 mm/yr. A significant risk will be posed for coastal regions if the regional rate of sea level rise continues to increase.

(2) The number of torrential rainfall events shows a stable trend, while the local torrential rainfall and short duration rains shows an increase from 1981 to 2010. The torrential rainfall is concentrated in the Meiyu period, from May to September. After analyses 54 heavy rainfall, $P_m$ of flooding events is mainly concentrated in a range from 50 mm to 150 mm, while the Ia is within a range of 5 mm/h to 60 mm/h.

(3) Based on the observed results at eleven weather stations, the variation in the number of local torrential rains and short duration torrential rains have a similar trend to that of the sea level change. The values plotted to show the relationship between local torrential rain and the sea level change are mainly focused in the range of y=0.26x and y=0.12x, with only four exceptional events, in the years 1985 to 1988. The values plotted to show the relationship between short duration torrential rain and the eustatic sea level change are mainly focused in the range of y=0.10x and y=0.04x, with only four exceptional events, in the years 1985 to 1988.

(4) Pluvial flooding, sea water intrusion, and potential damage to coastal structures are all related to the sea level change and to heavy rainfall. In recent years, the above hazards have not been mitigated and have become more severe in Shanghai, which will cause more inconvenience and danger to the residents' lives and cause more economic losses. The proposed methods includes, monitoring and establishment of database system for sea level change and heavy rainfall, improving the water storage capacity and drainage system for torrential rainfalls, Increasing the defend ability of coastal structures. Furthermore, more useful and advanced countermeasures, such as Sponge city construction,are necessary to mitigate the risks caused by sea level change and heavy rainfall.

## 8. ACKNOWLEDGEMENTS

The research work described herein was funded by the National Nature Science Foundation of China (NSFC) (Grant Nos. 41372283), and National Basic Research Programme of China (973 Programme: 2015CB057806). These financial supports are gratefully acknowledged.

## 9. REFERENCES

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C. K., Talley L. D. and Unnikrishnan, A., (2007) Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp408-419, 996.

Chai, J. C., Shen, S. L., Zhu, H. H. and Zhang, X. L. (2004) "Land subsidence due to groundwater drawdown in Shanghai". Geotechnique, 54, Issues 2, pp143-147.

Chai, J.C., Shen, S.L., Ding, W.Q., Zhu, H.H., and Cater, J.P (2014). Numerical investigation of the failure of a building in Shanghai, China, Computers and Geotechnics, 55(2014), 482-493.

Chambers, D.P., Ries, J.C., Urban, T.J., 2003. Calibration and verification of Jason-1 using global along-track residualswith TOPEX.Mar. Geod. 26, 305.

Cheng, J., Yang, K., Zhao, Y., Yuan, W., and Wu, J. P. (2007) "Variation of River System in Center District of Shanghai and Its Impact Factors During the Last One Hundred Years". Scientia Geographica Sinica, 27, Issues 1, pp85-91. (in Chinese)

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T.,Qin, D. and Woodworth, P. L., (2001) "Changes in Sea Level, in Intergovernmental Panel on Climate Change, Third Assessment Report". Cambridge Univ. Press, New York, pp639-694.

Han, G. Q., and Huang, W. G., (2008) "Pacific decadal oscillation and sea level variability in the Bohai, Yellow, and East China Sea". Journal of Physical Oceanography, 38, Issues 12, pp2772-2783.

He, F. F. and Zhao, B. K. (2009) "The characteristics of climate change of torrential rains in Shanghai region in recent 30 years". Advances in earth science, 24, Issues 11, pp1260-1267.

He, F. F. (2012) "Characteristics of torrential rain in Shanghai from 1980s". Proceedings of Urban Meteorology Forum - Urban and Climate Change, Shenzhen, pp10-17. (in Chinese)

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Liu, X.Y., Liu, Y.G., Guo, L., Rong, Z.R., Gu, Y.Z., & Liu, Y. H. (2010) Interannual changes of sea level in the two regions of East China Sea and different responses to ENSO. Global and Planetary Change, 72: 215-226.

Ma, L., Xu, Y. S., Shen, S. L., and Sun, W. J. (2014). "Evaluation of the hydraulic conductivity of aquifer with piles". Hydrogeology Journal, 22, Issues 2, pp371-382.

Nerem, R. S., Leuliette, Éric, Cazenave, A., (2006) "Present-day sea-level change: a review". C. R. Geosci. 338, pp1077-1083.

Qing, S., Zhang, Y. S., Hu, E. H. and Lu, C. H. "Potential impacts of sea level rise on the economy and environment in the Yangtze River delta and the countermeasures thereof". Resources and

Environment in the Yangtze Valley, 1997, 1, Issues 6. (in Chinese)

Shen, S. L., Chai, J. C., Hong, Z. S., and Cai, F. X. (2005). "Analysis of field performance of embankments on soft clay deposit with and without PVD-improvement". Geotextiles and Geomemberanes, 23, Issues 6, 463-485.

Shen, S. L., Xu, Y. S., and Hong, Z. S. (2006) "Estimation of land subsidence based on groundwater flow model". Marine Georesources and Geotechnology, 24, Issuess 2, pp149-167.

Shen, S. L., and Xu, Y. S., (2011) "Numerical evaluation of land subsidence induced by groundwater pumping in Shanghai". Canadian Geotechnical Journal, 48, Issues 9, pp1378-1392.

Shen, S. L., Ma, L., Xu, Y. S., and Yin, Z. Y. (2013) "Interpretation of increased deformation rate in aquifer IV due to groundwater pumping in Shanghai". Canadian Geotechnical Journal, 50, Issues 11, pp1129-1142.

Shen, S. L., Wu, H. N., Cui, Y. J., and Yin, Z. Y. (2014) "Long-term settlement behavior of the metro tunnel in Shanghai". Tunneling and Underground Space Technology, 40, pp309-323.

Shen, S. L., Wang, J. P., Wu, H. N., Xu, Y. S., Ye, G. L., (2015a) "Evaluation of hydraulic conductivity for both marine and deltaic deposits based on piezocone testing". Ocean Engineering, 110, 174-182.

Shen, S. L., Wu, Y. X., Xu, Y. S., Hino, T., and Wu, H. N. (2015b) "Evaluation of hydraulic parameter based on groundwater pumping test of multi-aquifer system of Tianjin". Computers and Geotechnics, 68(2015), 196-207.

State Oceanic Administration, People's Republic of China (2015). China Ocean Bulletin (COB) 2015. Online: http://www.soa.gov.cn/zwgk/hygb/zghpmgb/201603/t20160324_50508.html

Wang, J. P., Xu, Y. S., Ma, L., and Shen, S. L. (2013) "An approach to evaluate hydraulic conductivity of soil based on CPTU test". Marine Georesources and Geotechnology, 31, Issues 3, pp242-253.

Wu, H. N., Huang, R. Q., Sun, W. J., Shen, S. L., Xu, Y. S., Liu, Y. B, and Du, S.J. (2014) "Leaking behavior of shield tunnels under the Huangpu River of Shanghai with induced hazards". Natural Hazards, 70, Issuess 2, pp1115-1132.

Wu, H. N., Shen, S. L., Liao, S. M., and Yin, Z. Y. (2015c) "Longitudinal structural modelling of shield tunnels considering shearing dislocation between segmental rings". Tunneling and Underground Space Technology, 50, pp317-323.

Wu, Y. X., Shen, S. L., Xu, Y. S., and Yin, Z. Y. (2015a) "Characteristics of groundwater seepage with cutoff wall in gravel aquifer. I: Field observations". Canadian Geotechnical Journal, 52, Issues 10, pp1526-1538.

Wu, Y. X., Shen, S. L., Yin, Z. Y., Xu, Y. S. (2015b) "Characteristics of groundwater seepage with cutoff wall in gravel aquifer. II: Numerical analysis". Canadian Geotechnical Journal, 52, Issuess 10, pp1539-1549.

Xu, Y. S., Shen, S. L., Cai, Z. Y. and Zhou, G. Y. (2008) "The state of land subsidence and prediction activities due to groundwater withdrawal in China". Natural Hazards, 45 Issuess 1, 123-135.

Xu, Y. S., Shen, S. L., & Du, Y. J. (2009a) "Geological and hydrogeological environment in Shanghai with geohazards to construction and maintenance of infrastructures". Engineering Geology. 109, Issuess 3-4, pp241-254.

Xu, Y. S., Zhang, D. X., Shen, S. L., and Chen, L. Z. (2009b) "Geological disasters and prevention measures along the coastal region of China". Natural Hazards, 49, Issuess 3, pp479-500.

Xu, Y. S., Ma, L., Shen, S. L. and Sun, W. J. (2012a) "Evaluation of land subsidence by considering underground structures penetrated into aquifers in Shanghai". Hydrogeology Journal, 20, Issuess 8, pp1623-1634.

Xu, Y. S., Ma, L., Du, Y. J., and Shen, S. L. (2012b) "Analysis on urbanization induced land subsidence in Shanghai". Natural Hazards, 63, Issuess 2, pp1255-1267.

Xu, Y.S., Huang, R.Q., Han, J., and Shen, S. L. (2013a) "Evaluation of allowable withdrawn volume of groundwater based on observed data". Natural Hazards, 67, Issues 2, pp513-522.

Xu, Y. S., Shen, S. L., Du, Y. J., Chai, J. C., and Horpibulsuk, S. (2013b) "Modelling the cutoff behavior of underground structure in multi-aquifer-aquitard groundwater system". Natural Hazards, 66, Issues 2, pp731-748.

Xu, Y. S., Yuan, Y., Shen, S. L., Yin, Z. Y., Wu, H. N., and Ma, L. (2015) "Investigation into subsidence hazards due to groundwater pumping from Aquifer II in Changzhou, China". Natural Hazards, 78, Issues 1, pp281-296.

Zhang, H., Li, Q. F., Yu, M. X., Ren, J. L., and Li, P. C. (2014) "Frequency Analysis of Annual Maximum Tide Level in Huangpu River in Times of Intense Change". Water Resources & Power, 32, Issues 7, pp1-5. (in Chinese)

Zhang, N., Shen, S. L., Wu, H. N., Chai, J. C., and Yin, Z.Y. (2015) "Evaluation of performance of embankments with reinforcement on PVD-improved marine clay". Geotextiles and Geomembranes, 43, Issues 6, pp506-514.