Review article

Emerging flood risks and challenges in a Chinese delta: the case of the Pearl River Delta

Abstract

By the 2050s, more than 120 million people are predicted to settle in the Pearl River Delta (PRD), which covers urbanised coastal cities like Hong Kong, Shenzhen and Guangzhou. Cities in the PRD are important to China in terms of their socio-economic contributions. From recent evidence, this strongly urbanized area is vulnerable to, and currently experiencing increased incidences of, coastal and urban flooding. Flood risk is increasing in low-lying coastal areas due to rapid urbanization and increasing flood hazards exacerbated by climate change, including frequent intensive rainstorms, sea-level rise, typhoons and surges. This threatens large populations and their economic assets causing severe socio-economic and ecological impacts in the PRD cities. Current flood risk management (FRM) in the delta is still predominately focused on using traditional techno-fixes and infrastructure paradigms and lacks sufficient strategic planning and flood protection to develop adequate flood resilience. Recent urban floods, enhanced by storm surges and intensive rainstorms, affected multiple PRD cities, and draws attention to flood risk as a major challenge in the PRD's coastal cities. This review encourages development of long-term FRM practices with provincial and municipal authorities working together more closely to develop better-integrated regional FRM strategies for the PRD.

Keywords: Urbanization, climate change, flood risk and hazards, sustainable flood risk management

1. Introduction

Currently, more than half the Asian population lives in coastal areas, especially in vulnerable deltas and coastal cities. More than 325 million inhabitants have settled in coastal low-lying flood prone areas in East Asia alone (Chan *et al*., 2018; Chan *et al*., 2012; McGranahan *et al*., 2007). Many of these coastal areas are projected to become more vulnerable to flood hazard due to future climate change (e.g. sea-level rise), with millions of people and their economic assets exposed to floods and storms (Ward *et al*., 2011). Yet, in the next few decades, in most of these areas (deltas, estuaries, coastal zones and coastal cities), the population will continue to increase due to growing employment and economic opportunities (Seto, 2011). Population growth in the Pearl River Delta (PRD) region, for example, is forecast to rise from some 50 million people to over 120 million by 2050 (Yeung, 2010). Increasing socioeconomic wellbeing will amplify both the vulnerability and adaptive capacity of such areas to future floods, with increasing urban populations and greater financial capital invested in costal floodplain areas.

The 4th and 5th Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) predict that global sea level will rise at least between 0.18 and 0.59 metres by 2100 (Bindoff *et al.*, 2007; IPCC, 2013), whilst others suggest the rise may be three-fold higher (up to 1.9 metres) if the global temperature rises faster than expected, and glaciers melt more quickly (Vermeer and Rahmstorf, 2009). Wilby and Keenan (2012) expect the frequency, intensity and duration of extreme precipitation events to increase because of climate change.

Unfortunately, many Asian coastal areas already suffer an increasing frequency of typhoons, storm surges and rainstorms from the West Pacific (Webster *et al.*, 2005). These regional experiences apply in the PRD, with the Hong Kong Observatory (HKO) expecting annual mean sea-level (MSL) to rise more than 20cm by 2050 (Woo and Wong, 2010). The HKO also report that the frequency of intense rainfall from storms (i.e. typhoons) in the PRD has been increasing over the last 50 years (Lee *et al.*, 2010).

Large cities in the PRD's coastal flood-prone areas (including Hong Kong, Shenzhen and Guangzhou), have recently experienced coastal and urban surface water flooding. In 2008, 2009 and 2017, three coastal floods occurred in the Tai O town and other low-lying areas in Hong Kong from storm surges (caused by Typhoons Hagupit, Koppu and Hato respectively) (Chan et al., 2018; Chan *et al.*, 2013ab). Intensive rainstorms can quickly exceed urban drainage capacity leading to surface water flooding. In Guangzhou, an intense rainfall (99.1mm/hr) recorded on 7th May 2010, resulted in damage to more than 200 vehicles, and the main railway station in the city centre being inundated (Zhang and Ouyang, 2011). Similarly, more than 400mm rainfall was recorded within 12 hours on 22nd July 2010 in Hong Kong, causing three fatalities by drowning in the Lam Tsuen River, North New Territories (Chan *et al.*, 2010). Recently, on 14 June 2017, Typhoon Merbok caused intensive rainfall of 81mm over 24 hours and affected many roads through surface water flooding in Shenzhen (China Daily, 2017).

There are several interpretations and understandings of flood hazard and risk. Hazard is an event or agent with the potential for harm to vulnerable systems, whilst risk takes into consideration the probability of being exposed to the hazard and the likely damage (losses) that ensue. It is commonly accepted that flood hazard differs from flood risk, which measures the chance or probability of an expected (flood) event with the potential for negative consequences for society (Slobodan, 1999). While a hazard may be substantial, the risk associated with it may be insignificant if there is little chance of being exposed to it.

Hutter (2006) defined flood risk as a product of the chance or probability of an expected event and the consequences (impacts) associated with that event. Consequences here relate to the degree of harm suffered by a receptor (the entity that may be harmed by a flood – such as people, their houses and properties) during a flood event. On the other hand, flood risk can also be understood as the combination of the flood exposure, vulnerability and hazard (Samuels, 2006). While the definition of flood risk is continuously developing, in this review, we also determine flood risk as the combination of hazard, exposure and vulnerability (Schanze, 2006; Samuels, 2006; Hutter and Schanze, 2008).

Flood hazard here is defined through its probability and severity. Among other factors, exposure may depend on the population and economy that may be exposed to flooding (Carter *et al.*, 2013). Vulnerability is considered as the extent of harm, which is closely linked with flood exposure, and the resilience (impact response and adaption response) from the flood hazard (Balica *et al.*, 2012). Susceptibility may be understood as the elements exposed within the system, including the relative 'damageability' of people, property and materials during floods (Penning-Rowsell and Chatterton, 1977). For example, susceptibility may be related to the social context of flood damage, such as the level of vulnerable populations (e.g. elderly people, children and people with disabilities) or if any possible measures or tools are (e.g. flood risk mapping and flood warning system) available that could increase or reduce flood hazards (Yang *et al.*, 2018). Resilience in this case, may be understood as the capacity of any kind of system, community, society or environment, potentially exposed to flood hazards, to adapt by resisting to change, in order to maintain an acceptable level of functioning (Pelling, 2003; Zevenbergen *et al.*, 2020).

Measures that may increase resilience can lower vulnerability, such as an adequate level of flood protection measures, a reduced recovery time (so that the city can function and recover quickly after a flood event – e.g. hospitals and temporary emergency accommodation), and the awareness of, and preparedness to, flooding. A system at risk is more vulnerable when it is at higher exposure, and it is more susceptible to its impacts. However, the system will be less vulnerable when the resilience is higher, and exposure is lower.

Flood risk in the PRD is likely to increase substantially in the coming decades, and flood hazard increases due to climatic change, such as global MSL rise, and increasing frequency of storm surges and the intensity of rainstorms. In addition, the rapid socio-economic trends such as fast expansion of population and the economy (i.e. assets) have increased the circumstance of flood risk such as increasing the flood exposure and vulnerability in the delta during the last few decades. The PRD is already subject to coastal floods from storm surge, high-intensity rainfall-enhanced urban surface water or urban pluvial flooding (Chan *et al.*, 2018; Chan *et al.*, 2013ab; Chan *et al.*, 2012).

We recognise that there are several conceptual definitions of flood risk as discussed above. In this paper, we adopt the conceptualisation of Samuels (2006) that defines flood risk as the combination of flood exposure, vulnerability and hazard. This conceptualisation is common in key literature in the field (see Table 1) including in influential works on flood management (Carter *et al.*, 2013; Balica *et al.*, 2009, 2012; Pelling, 2003; Tapsel *et al.*, 2002; Penning-Rowsell and Chatterton, 1977).

Table 1 is about here

This study investigates the geography of the PRD and provides a detailed review of the previous and current conditions of flood risk and the challenges to deliver future flood risk management practices in the delta. More specifically, this paper also reviewed many grey literature and governmental documents (see Appendix 1) to investigate the current flood risk and challenges, with the aim for further exploration of developing long-term flood risk management strategies for the PRD, and extending this to other Chinese deltas.

2. Geography of the Pearl River Delta

2.1 Geographical aspects of the delta

The PRD is an extensive low-lying floodplain of about 42,800 km^2 at the mid-south of Guangdong Province in southern China, located between latitude 21°30'N and 23°42'N, and longitudes 112°26'E and 114°24'E (see Figure 1). It is the second largest river delta in the People's Republic of China (after the Yangtze River Delta). The PRD is formed by sediment deposition of the Pearl River and its three major branches, the West River (Xijiang), North River (Beijing) and East River (Dongjiang) (Zhang et al., 2008).

Figure 1 is about here

The channel topography of the PRD is complex with a highly branched, dendritic, bifurcating and coalescing river-network. The hydrology at the PRD is influenced by the interaction of Pearl River runoff and sea tides from the South China Sea. The PRD is dominated by a sub-tropical monsoon climate with abundant precipitation. The average annual precipitation is around 1600 to 2600 mm (Yang *et al.*, 2010). About 80 % of annual rainfall is distributed within the wet season during April to September from the impact of the East Asian Monsoonal circulation. Cyclonic effects, such as typhoons, occur most frequently from June to October (Weng, 2007). Land subsidence is a common issue in deltas, with no exception to the PRD. The west part of the PRD has subsided a metre below MSL (Huang *et al.*, 2004) (see Figure 2). The deltaic area is subsiding mainly from compaction/decomposition of the alluvium sediment layer, which contains a large amount of organic rich Mollisols (Zhang *et al.*, 2008). These types of soil are unstable and widely spread in the PRD. Mollisols may trigger subsidence from cracking and collapsing of the ground. In the meantime, expansive soil contains large amounts of montmorillonite. These soil (clay) minerals swell and compress with the accumulation or loss of water. Such mechanism leads to ground cracking and land subsidence in deltaic areas (Xu *et al.*, 2009).

Figure 2 is about here

Syvitski *et al.* (2009) reported that the Western PRD will be particularly exposed to coastal flooding, relating to the consequences of land-subsidence. For example, Zhuhai and Zhongshan (both are located in the West PRD) have been subsiding. Global sea-level rise and land subsidence has caused both extensive submergence and saline-water/brackish intrusion (with salinity from 250 mg/litre to over 3000 mg/litre). During the dry season every year, the freshwater supply to 15 million inhabitants in the region (i.e. Zhuhai, Zhongshan and Macau) could be affected by salinity problems for up to six months (Luo *et al.*, 2007). Lack of good quality freshwater available after intrusion has led to huge amount of groundwater being extracted. The water table is thus further lowered which in turn has again escalated land subsidence in the West PRD cities (Xu *et al*., 2008; Li and Damen, 2010).

2.2 Socio-economic development

The PRD includes 11 cities, nine of which (Shenzhen, Dongguan, Guangzhou, Foshan, Jiangmen, Zhongshan, Zhuhai, Zhaoqing and Huizhou) are located in Guangdong Province, and two are special administrative regions (SARs), Hong Kong and Macau. The region comprises about 56,000 km^2 land area and in 2010 had a population of 55 million (Yeung, 2010).

In the late 1970s, the Chinese Government established and promoted the "*Open door and economic reform policy*", aimed to transform the region as a manufacturing hub (Lin, 2011). One of the core strategies was to develop Shenzhen as a special economic zone (SEZ) in 1980. This designation gave SEZs a remit to focus on international trade, and through tax and foreign joint venture incentives encouraged strong foreign investment in manufacturing (e.g. semi-conductors, textiles and food). The SEZ concept also benefitted from an advantageous geographical location, with container ports and well connected logistic (national railway and highway) networks (i.e. Beijing – Shenzhen railway) for exporting products (Yeh and Li, 1999).

The SEZ has positively influenced other cities in the PRD region in attracting overseas investment and promoting international trade. Hong Kong has played significant roles in developing the PRD as the "*Gate of China*". Many foreign co-operations locate their business terminals in Hong Kong, because of the strong link to Britain (and all Commonwealth countries) through similar legislative and trading systems under the colonial jurisdiction. Hong Kong and Shenzhen (and the Shenzhen hinterland in East PRD) are geographically connected, both cities have forged a mutually beneficial relationship as "*front shop, back factory*" (Yeung, 2011). This mechanism works well as Hong Kong provided plenty of capital, skills, business experiences and global networks. Shenzhen and other PRD cities used to have relatively cheap labour and land available during the early 1980s. According to the Guangdong Provincial Government Report (2006), Hong Kong investors contributed about 80 % of direct investment in the PRD. The PRD only occupies about 0.57 % of land area, with 4.2% of the total population in the country for about 56 million people in 2010. By 2017, the GDP of the PRD reached over 9,720 billion Renminbi (RMB – official currency of the People's Republic of China) with an average annual rate of 17.8% increasing from the 1980s (Table 2) (Guangdong Statistics Yearbook, 2017). Liu et al. (2018) reported that the PRD has contributed further at about 9.12% of the national gross domestic product (GDP) in 2015 that accounts for about 30 % of foreign direct investment, and some 40 % of national exports.

Table 2 is about here

The PRD is known as the "World's Factory" and an "economic miracle" (Shen, 2014). The trend of economic development is further strong growth under the Greater Pearl River Delta development plan 2030, with further integration with neighbouring provinces (Cheung 2012). As a result, a large labour force was urgently required to support this industrialisation and development. Migrants from rural China, attracted by employment opportunities, drove the expansion of cities, which grew rapidly. For example, the population of Shenzhen grew from about 0.33 to 7.5 million from 1979 to 2014, more than a 20-fold rise (Shen, 2014). Similarly, the population of Guangzhou grew from about 5.6 to 12 million people from 1982 to 2014 (Zanuttigh *et al.*, 2015; GD-info, 2014). The total population of the PRD has increased from 0.9 to 55.2 million from the late 1970s. The UN-HABITAT (2008) noted that the populous coastal cities in the PRD will further merge to form mega-metropolis regions (e.g. Hong Kong – Shenzhen – Dongguan; Guangzhou – Foshan – Zhongshan; Zhuhai – Macau), with the population predicted to reach over 120 million by 2050s.

In the light of these economic reforms in the PRD, the economy has been largely dominated by secondary (manufacturing – textiles and electronics) and tertiary (logistics, tourisms and finance) industries, which account for 47.3 and 50.3 % of the economy respectively. Primary sectors (agriculture and aquaculture) have declined significantly (from 25.8% to 2.4%) within three decades (from 1978 to 2008) since the "*Open Door*" policy was established (Yeung, 2010). In parallel, landuse in the PRD became heavily urbanised. Agricultural land has been converted to industrial, commercial and residential areas from 1982 to 2000 for more than 3374 km^2 (Ouyang et al., 2006).

The urban area has expanded by more than 3000 km^2; the urbanisation rates in major cities reach up to 80 to 100 % in 2010s (refer to Table 2). Rapid population and economic growth encourage a large demand for land for developments in the PRD. The availability of land is scarce, the municipal authorities have to convert agricultural lands, or create new lands by coastal reclamation. More than 10 % of the urban areas in Hong Kong were generated from reclamation during the 1980s to 1990s (Nicholls, 1995). Recently, the Shenzhen municipal government has initiated a large coastal reclamation project for the Qianhai Bay in Bao'an and some areas in the Futian coastal wetland, which originally functioned as a natural conservation and flood-storage area (Chan *et al*., 2014). The PRD is naturally exposed to large storms (cyclones/typhoons). The region has suffered from sea surges and inundations in recent years. Due to on-going pressure of demographic changes, plus the influence of future climate change, the likelihood of flooding is increasing.

3. Exploration of flood risk in the PRD

Flooding is unavoidable in deltas and it is a natural process due to the geographical (deltas are located on floodplains), hydrological and geomorphological conditions (connected with inland rivers, catchment with lake, coast or sea). However the same conditions in deltas also provide flood-prone and thus enriched water storage and agricultural systems (e.g. wetland; paddy rice field) (Scholz, 2011). On the other hand, because of the urbanisation and development of deltas, flood impacts to humans and their properties can be badly impacted. The PRD is exposed to sub-tropical monsoons and land subsidence in its coastal flood areas. Since the late 1970s, rapid socio-economic development has further intensified coastal development. These combined factors have likely exaggerated flood risk in the PRD. In the following sections, we examine in more detail, the flood hazard, exposure and vulnerability (section 3.1) and the consequent increasing flood risk in the region (section 3.2).

3.1 Review of flood hazards and impacts in the PRD

In this review, we adapt the framework on understanding flood risk by Samuels (2006): *Flood risk = Flood (Hazard x Exposure x Vulnerability).* Thus flood risk can be understood as the product of the flood hazard, the assets (magnitude and value) that are exposed to that hazard, and their vulnerability. Uncertainties and risks also associated with the "resilience" as it helps us to understand the ability to "resist" when exposed in flood events. In this section, we will provide our critical review on each item as the subsections as follow.

3.1.1 Review of flood hazard

One of the main elements for understanding flood risk (Schanze, 2006) is flood hazard which could be understood as the probability of flood occurrence, with a potentially damaging effect for a given time period and location (Koks *et al.*, 2015). Vulnerability is caused, in part, by anthropogenic changes to the deltaic zone, inter-connected with the coastal and fluvial system. Flood exposure indicates the degree of predisposition of the PRD suffering from flood hazard including inland and coastal flooding (Balica *et al.*, 2012). The PRD is located in a sub-tropical climatic zone and influenced by sub-tropical monsoonal or cyclonic effects (typhoons, surges and intense rainstorms) every summer (May to September) (Zhu *et al.*, 2003). This means the delta (its inhabitants and economic assets) is exposed to inland (fluvial and urban surface water) and coastal flood hazards.

3.1.2 Review of flood exposure

Fluvial floods frequently occur from the upper stream of the three major tributaries of the Pearl River, and inland flood hazard is primarily related to rainstorms. About 80 % of annual rainfall is distributed during the wet season (May to September), and is above 2000 mm in this period (Chan *et al.*, 2018). The peak discharge accumulated in the Pearl River Basin and flows into the South China Sea via the PRD. PRD coastal cities including Guangzhou, Foshan, Zhongshan and Dongguan are located in the western, northern and eastern areas of the Pearl River Estuary that also suffers from this fluvial flood hazard (Figure 1). For example, a devastating flood event in 1915 with a 1-in-200-year return period, was the worst fluvial flood event in the PRD, resulting in large-scale, month-long precipitation in the middle and upper parts of North and West Pearl Rivers. Floodwater overtopped and breached riverbanks and levees. Guangzhou, at the outlet of the three tributaries, was inundated for seven days and suffered widespread damage. More than 935,000 ha of farmland were damaged, 100 thousand people were killed or injured, and some 6 million homes were lost (Chan *et al.*, 2014).

More recently, over the period of 8th to 17th June 1994, fluvial flooding occurred in the northern PRD (North River area) after an intense rainstorm (> 600 mm precipitation) from Typhoon Russ, with 102 deaths, 2000 injuries, and the inundation of more than 9,000 villages, 23,000 houses and 100,000 ha of farmland. Total economic loss was 3.2 billion RMB (at 1994s rate) in Foshan and Northern Guangzhou (Wong and Zhao, 2001). Embankments and dykes along the North River collapsed, prompting questions about whether existing flood protection measures can meet future needs. Other fluvial flood events that caused riverbank and levee breaches due to excessive precipitation occurred in 1931, 1949, 1982 and 2006 in the PRD (Zhang *et al.*, 2011a).

Intense precipitation affects populous cities in the region, particularly during the typhoon and rainstorm period that may possibly overload the urban drainages. The rate of urbanisation of the PRD cities is high (Table 1), and rural land has frequently been converted for urban use. These cities are highly reliant on their urban drainage systems to offload peak discharges. Most of the lands and roads have been converted to concrete; the hydrological functions of soil-water percolation and absorption are largely diminished. Typhoons and large magnitude sub-tropical rainstorms often affect several cities at once in the PRD. That means surface flooding can occur across multiple cities (across the East and West of PRD) during typhoon (enhanced rainstorm) or torrential rainstorm event. These rainstorms are normally above 100mm/24hr with some reaching 300-500mm/24hr (see Table 3) and occur frequently (once or twice per year). Such general PRD figures however, mask the variation across the region and for individual cities.

Table 3 is about here

Typhoon and torrential rainstorms in the PRD, more easily cause severe surface water flooding in cities because rapid urbanisation and development have decreased the time needed to produce high surface runoff, to the extent that land drainage systems cannot cope with the urban stormwater discharge. For instance in Shenzhen, the runoff coefficient increased by 13.4% and the maximum flood discharge increased 12.9% on average (from 1980 to 2000) (Shi et al., 2007). Low-lying, poorly drained areas or districts in these cities are likely to be more frequently exposed to surface water flooding or waterlogging.

The intensity and areal coverage of the rainstorm is large and sometimes affects multiple cities simultaneously. For example, during the period of 7^{th} to 14^{th} May 2010, rainfall intensity of 100mm/24hr (1-in-5 year event) was recorded and triggered waterlogging in Shenzhen on 13^{th} May 2014. That event caused economic damages of more than 80 million RMB, and led to the evacuation of approximately 3,000 people with more than 25,000 people affected in some way (Figure 3). For the same storm, the cities of Dongguan, Hong Kong and Guangzhou were also heavily impacted (peak rainfall reached f 99.1mm / hour in Guangzhou and over 500mm was recorded for the week, approximately a quarter of annual rainfall). Four towns and districts were inundated in Dongguan, causing 8 casualties according to the Dongguan municipal water bureau. Sever surface flooding also occurred in towns of Yuen Long and

Sheung Shui in the low-lying flood prone areas of the North New Territories, Hong Kong (Liu, 2014). On 7th May 2010

Figure 3 is about here

The Hong Kong Observatory (HKO) (the government meteorological institution of Hong Kong Special Administrative Region (HKSAR)) typically reported more than 1,700mm of rainfall from May to September in Hong Kong, Shenzhen and the East PRD. They also found that the return period of intense rainstorms (mainly over 100mm/hr) has shortened from 37 years to 19 years over the last century (Lee *et al.*, 2010). The intensity of short-term (hourly) intensive rainfall has increased from 110mm to above 140mm from 1984 to 2010, a trend projected to continue according to the HKO who expect the annual precipitation and extreme rainstorms to increase over the next century. Hong Kong has recorded heavy rain (with more than 200 mm/24hr) during the wet season every year since 2000, which increases the number of flash floods and poses a major problem for urban drainage systems. More than 400mm precipitation (about 20 % of the average annual rainfall) was recorded within 12 hours on the 22nd July 2010 with a flash flood causing three deaths in the Lam Tsuen River Catchment, a flood prone area in the North New Territories of Hong Kong (Chan *et al.*, 2013a; Chan *et al.*, 2010).

Intensive rainfall is a key factor for increasing inland flood hazards, particularly for urban surface water flooding or waterlogging (which happens when rainwater does not drain away through the normal drainage systems or soak into the ground consisting of mostly concrete or tarmac surfaces but flows over the ground instead) (Environment Agency, 2014). This suggests that existing drainage systems cannot cope with the rate of urban development. Local drainage system in older towns have often not been replaced as large areas have been rendered impermeable under rapid urbanisation. Severe waterlogging and urban fluvial flooding occur because surface runoff and current drainage/river channel capacities are insufficient to carry intense peak discharge from rainstorms (Chan *et al.*, 2018; Chan *et al.*, 2013a). As a result, large populations and their assets are becoming more exposed and vulnerable to inland floods (refer to Table 3).

The PRD is also vulnerable to and suffering from coastal flooding. More than 3,720 km^2 of coastal land has been affected by land subsidence, particularly in Macau, Zhuhai, Zhongshan, Shenzhen and Guangzhou. Subsidence can be triggered by (human-induced) construction on

Mollisol soils, which are often unstable with an organic rich profile, have a calcareous base and become saturated easily (Xu *et al.*, 2009). Rapid urbanisation has forced municipal governments to undertake reclamation to meet huge demands. It is noticeable that the provincial government has established a regional coastal development plan 2030, and further implemented a large reclamation project in the entire PRD estuary bay area (Ma, 2012). In some areas, reclamation has extended the coastline 1 km seawards in the last decade (Hay and Mimura, 2006). Unfortunately, most reclaimed land has been converted from coastal wetlands (i.e. mangroves), which acted as a buffer to seawater intrusion and provided hydrodynamic attenuation of the tidal cycles (Hoozemans *et al.*, 1993). Reclamations also modify estuarine morphology, by introducing dry land where previously only wetland existed, which may likewise affect tidal dynamics in the PRD (Zhang, 2009). Recent research demonstrated that mean sea-level rise in the PRD has risen by 26mm per decade from 1954 to 2009, with a significant increase during the 1990s (Zhang *et al.*, 2011b) (Figure 4).

Figure 4 is about here

Woo and Wong (2010) further projected that the sea-level would rise some 200 mm by 2050s. That potentially will expose more than 2,000 km^2 of coastal low-lying areas to tidal inundation in the PRD. Storm surges driven by typhoons *Hagupit and Koppu* in 2008 and 2009, and also the recent typhoon Hato in August 2017, inundated the low-lying coastal areas in Hong Kong (e.g. Tai O town in Lantau Island, Lei Yu Mun in the East Kowloon and Heng Fa Estate in the Hong Kong Island), with over 100 properties in both events. Typhoon Hato caused 16 causalities (drown from the coastal flood) and 153 were injured in the PRD cities including Macau, Zhuhai, Zhongshan, Dongguan, and Guangzhou. (USA Today, 2017). Forty-one storm surges of two to three metres were recorded in the PRD from 1991 to 2005 (Zhang et al., 2011b). The HKO recorded over 10 surges higher than 1.5 metres from 1954 to 2009 in Hong Kong alone (HKO, 2013). Typhoon Wanda in 1962 was a particularly severe event that generated a surge reaching over four metres average MSL (Yim, 1996). In the PRD, populous cities such as Hong Kong are exposed to coastal and inland flooding; typhoons may enhance an intense rainfall and surge all at once in some occasions. Likewise, the majority of total population of 7.5 million in Hong Kong is settled in flood prone areas, which are distributed about 24 % of the total land use of the city. The urbanisation rate is 100 % of these developed (residential and commercial) areas (Yeung, 2010), which means the city is highly reliant on drainage to offload flood discharges. Urban drainage systems have to handle substantial hydrological discharge from surface runoff since a rapid landuse change occurred by urbanisation.

Under intensive rainstorms and high tides, some low-lying and poorly drained areas are frequently affected by the combined effect of coastal and pluvial flooding (see Table 4). High tides cause seawater backlash to submerge urban drainage outlets and reduce the drainage ability thus compounding surface water flooding or waterlogging in urban areas. For example, coastal pluvial flooding was enhanced by Typhoon Utor, with a surge at +4.0 MSL plus an intense rainstorm with 166.7 mm/24hr in July 2001 in Sheung Wan (major business district in Hong Kong).

Table 4 is about here

Rapid and on-going development means that an increasing number of people and their economic assets are likely to be influenced by flooding (Jongman *et al.*, 2012). Several regional development reports forecast that the PRD will have a population of about 60 million by 2030, and 120 million by 2050 (Ma, 2012, Cheung 2012, Canton, 2011). The PRD now is a huge economic hub (ranked 4th in total GDP and economic power in East Asia). The delta now has iconic features on socio-economic developments, such as the international financial and logistics centres in Hong Kong (e.g. the Hang Seng Stock Market Exchange – top 5 stock market globally, international ports and airports), Shenzhen (e.g. high technological development centres, Shenzhen stock market and international port), Guangzhou (e.g. large vehicle factories, international ports and airports) and Macau (tourism).

Other PRD coastal cities (e.g. Zhuhai, Zhongshan, Foshan and Dongguan) are all developing rapidly, and offering large powerhouses of industrial production (e.g. manufacturing); and supporting roles of economic development. Some advantages such as providing budgetary office space (on rental costs compare to HK, GZ and SZ), cost of employment, etc. These features are tightly aligning with the major hubs from Guangzhou, Shenzhen and Hong Kong (the major financial centres in the PRD) and integrated with the logistics and other services in the PRD (Liu *et al.*, 2013). Therefore, the increasing growth of populations and assets are currently protected by various structural and non-structural measures that are part of the flood management strategy. Conversely, some of them have none or only limited flood defence and control measures, and the exposed populations are more often subject to inland and coastal floods with the consequent disruption, economic losses and loss of life.

The hydrology and geography of some of the PRD's coastal cities is complex due to its deltaic nature (i.e. major outlets of three main tributaries of the Pearl River). For example, more than 1300 urban channels (with the total length of 5597km) can be found in Guangzhou (Pan *et al*., 2010). Most of them are connected with the South China Sea, thus the city is fully exposed to fluvial and coastal flood risks during the wet season (Zanuttigh *et al*., 2015). The costs of construction and maintenance for such large waterfront areas (i.e. riverside and coasts) by hard-engineered measures is massively expensive (i.e. 1 km of sea cost up to 10 million Euros). Therefore, the costs of upgrading the infrastructure is about 7-10 million Euros per km for the 1-in-100 year flood protection standard from the Dutch experience (Jonkman *et al*., 2013). GZ Water (2014) reported that less than 4% of Guangzhou (in terms of the city's land area) is protected to at least 1-in-100 year flood frequency. Unfortunately, most flood-prone areas (about 77%) are protected only for the 1-in-20 year standard or below (see Table 5). More importantly, the drainage of many urbanised districts and areas (i.e. Tianhe, Liwan, Baiwan, Haizhu, in Guangzhou) are currently engineered with less than a 1-in-10 year protection level (Chan *et al*., 2014). Therefore, some old towns or districts are protected only for 1-in-1 year standard according to the current drainage plan of the Municipal Governments in the Delta, and still yet to upgrade the system (Xia *et al*., 2017; Zhang and Ouyang, 2011), meaning the resilience of urban flooding is rather inadequately low. In light of frequent typhoons and rainstorms, coastal and fluvial flood measures with low protection level are vulnerable and at risk to be breached (Zhang *et al*., 2013). Urban surface water flooding/waterlogging occurs because the existing urban drainage system cannot cope with the peak discharges. Astronomical expenditure is required to improve much of the infrastructures to safer standards (approximately 52 billion UK Sterling, equivalent to 520 billion RMB in Guangzhou). The current urbanization rate (in excess of 82%) means that a large and diverse urban population has spread over across the city boundary already with possible additional economic implications for infrastructure improvement. Flood defences by hard-engineered approaches alone are therefore perhaps not economically sustainable under foreseeable climatic and socio-economic changes.

Table 5 is about here

3.1.3 Review of flood vulnerability

For the flood vulnerability, Hallegatte *et al*. (2013) has warned that PRD's coastal cities like Guangzhou, Shenzhen and Hong Kong are highly vulnerable. (Guangzhou now is ranked at the most vulnerable city exposed to flooding, Shenzhen is ranked the ninth and Hong Kong ranked as the 20th for the global vulnerable coastal cities).

A review of current FRM and climate change adaptations approaches in the region shows that traditional engineering approaches are still popular (Chan *et al*., 2018). No particular practices and measures are proposed to address vulnerability other than engineering infrastructures. Authorities in the region, which have not fully evaluated exposure and vulnerability (susceptibility and resilience). Assessments of the number of people that have been affected (i.e. casualties and injured) and their economic losses (i.e. farms, fishponds, etc.) by previous flood events are not within the public domain. Currently, there are lacking information on susceptibility, e.g. no focus on vulnerable groups like disabilities and elderly people before, during and after flooding. Chui *et al*. (2006) reported that the Hong Kong and Shenzhen flood management authorities have adopted advanced flood modelling tools for evaluating inland and fluvial (including urban channels) flood hazards. Unfortunately, this information is not available to the public (Chan et al., 2012). The public seems unable to check flood risks from flood information and prepare for a flood. Developers are not obliged to consider flood risk before they submit the new development plans, which means more new buildings may be located on reclaimed riverine waterfronts and floodplains (e.g. Lok Ma Chau Loop in the New Territories, Hong Kong) (Chan *et al*., 2014; Chan *et al*., 2013a). Without further improvements, the PRD cities are expected to become more vulnerable to flooding. The Guangzhou municipal government disputes such findings. Nevertheless, as we discussed above, evidence indicates that Guangzhou, Shenzhen and other coastal cities in the PRD are increasingly suffering from surface water, coastal and fluvial flooding.

Furthermore, the urbanised areas have diversely developed all along the coasts in the PRD. Large reclamation projects, as the South coast of Guangzhou, West coast of Shenzhen, East coast of Zhongshan, Macau and Zhuhai, etc. for the future regional development of the PRD Bay Area, will be implemented to satisfy the increasing demand of population growth (Guangdong Province Housing & Urban – Rural Department, 2011). We argued that future flood exposure in the PRD and its coastal cities will continuously and rapidly increase (UN-

HABITAT, 2008), where more people and their properties are expected to be located on the low-lying flood prone or newly reclaimed areas that are more exposed to multiple flood hazards, and vulnerable in the deltaic environment.

3.1.4 Review of flood resilience

The definition of "*resilience*" was introduced by Holling (1973), and there are many interpretation of this term, popularly resilience to be understood as, a systems ability to resume functionality in the wake of a perturbation (McClymont et al., 2020). There are significant contributions reducing flood risk and uncertainties, we still witnessed frequent and severe floods occurred, and enhanced serious consequences, and flood resilience is an essential element in the FRM nowadays. Samuels et al. (2010) indicated that social dimension is vitally important as floods cause harms to human and caused risk, so as caused conflicts with human developments and activities, the social dimension on resilience that the ability of resisting floods or remaining unchanged on the systems. These will be helpful for implementing the strategies of flood recovery and adaptation approaches to deal with flood risk. Indeed, Zevenbergen *et al.* (2020) also indicated that the FRM is gradually shifting from a traditional to a more resilient approach. In this review, we have only identified the frameworks of resilience on "*Engineering resilience*" (using resilient construction design and technologies to adapt and reduce the probability of failure from floods); "*Resistance*" (using flood protection such as flood embankments, seawall, floodwall, channelisation, etc.); "*Ecological resilience"* (the ability of the system to enhance quick recovery after floods) and "*Socio-ecological or Adaptive resilience*" (enhance persistence learning and adaptive capacity transformation).

In this study, we have found that there is no guidance on flood recovery measures (e.g. clean up properties scheme, home return strategies after floods, public health guidance after floods, etc.) that means the ability of bounce back and recover from floods are currently lacking via the case of previous coastal floods in the PRD (Chan *et al.* 2014). Whilst, we also found that the engineering resilience is rather low, as most of the PRD cities (e.g. Shenzhen, Guangzhou, etc.) only equipped at 1-in-1 to 1-in-5 years return period protection levels on their land drainage or urban drainage measures (Chan *et al.*, 2018, Chan *et al.*, 2013). Currently, there is lacking of flood risk mapping and relative information available to the communities in the PRD cities, so as private insurers also hesitate to offer insurance package and premiums to clients, especially for the areas that have been flooded severely (e.g. Tai O town, Hong Kong; Lo Wu, Shenzhen, Macau, etc.) (Lo *et al.*, 2020; Chan *et al.*, 2018).

3.2 Upcoming challenges on flood risk in the PRD

Based on the reviewing of flood hazard exposure and vulnerability in the last section (3.1), flood risk is increasing due to social (i.e. potential demographic changes) and natural (i.e. climatic changes) factors.

The PRD is a densely populated area that is home to more than some 50 million inhabitants; with an estimated GDP of USD 690 billion (the GDP per capita is much higher than the PRC's national average). The socio-economic development is growing strongly, and it is expected that the populations and GDP will increase at least two-folds within the next few decades (Hanson *et al.*, 2011). Large developments have been located on low-lying and flood-prone coastal cities along the PRD estuary that are connected to wetlands (areas should be naturally flooded). The municipal and provincial authorities have made efforts to mitigate exposure and vulnerability. However, these approaches are too much dependent on traditional flood control (hard engineering) measures, which may not be enough to address actual flood risk. We have found that in the PRD, large coastal areas do not have enough protection and less than 10 % of the coastal areas are protected against events with 1-in-50 years return period or by better resilient measures (Yang *et al.*, 2014). Some municipal governments (e.g. Guangzhou and Hong Kong) have initiated some plans to address climate change and improve flood measures. Guangzhou would like to improve their urban drainage protection level to reach a more resilient or higher protection level improving up to 1-in-10 to 1-in-20 years by 2030.

However, these projects will not be completed overnight, so the city will continue to suffer the risk of surface water flooding into the next two decades. Swiss Re (2014) has undertaken a research study to estimate current risk from natural hazards in urban areas across 616 cities globally. Their results showed the PRD ranked top among all metropolitan areas due to the size of population that will be potentially affected by storms, storm surges and river floods (Table 6).

Table 6 is about here

For the PRD, Swiss Re (2014) estimated the potential economic value of working days lost (relative to its national economy) by river and coastal flooding. A large metro population is unable to reach work during river and coastal flood events. In this respect, the PRD area is ranked the highest for the value of working days lost by storm surges. The economic losses (by the value of working days lost) could reach up to 1 – 2 % of the region's annual GDP for a (urban inland or coastal) flood event generated by strong typhoons. Zhang (2009) projected whether a sea-level rise of 30cm occurs by 2030, then a 1-in-100-year storm surge event would inundate over 80 % of the delta, with an estimated one million homes flooded, and economic losses exceeding 232 billion RMB.

In fact, more than 86 % of the PRD coastal area are currently relying on flood protection infrastructures (dykes and embankments, etc.), of which only a limited proportion could withstand a 1-in-100-year event. We do not disregard the role of hard engineering measures, since the PRD region has used dykes and river channel diversion for flood protection since the Ming Dynasty (about AD 15th century) (Weng, 2007). Current engineering measures evidently were shown as insufficient to mitigate the increasing flood risk (hazards, high exposure and vulnerabilities) in the region, specifically in the urbanised coastal estuarine areas exposed to multiple flooding.

Alarmingly, recent strategic planning of Guangdong's regional government addresses neither existing flood risks nor the possible effects of future climatic change. Ng (2012) criticised the fact that regional climate change adaptations are currently still under-developed across the PRD, where only Hong Kong has completed the "*Climate Change Feasibility Study*" in 2010 by the Government. Even that study was targeted at the public consultation level (with rather lower participation level) (EPD, 2010). The practice has only offered rather limited consideration of implementing policies to address inland and coastal flood issues. Past (coastal flood) events have also shown that no single institutions is specifically responsible for coastal flood mitigation.

In Hong Kong, the Drainage Service Department (DSD) mainly deals with inland flood problems. Two surge-led coastal flood events (by Typhoon Hagupit and Koppu) further illustrated ad hoc approaches that are not based on strategic long-term plans that can take into account climate change projections. Zhou and Cai (2010) noted other PRD coastal cities; also do not address coastal flood risk and climate change adaptations issues (i.e. integrate climate change projections into their FRM). Yang *et al*. (2014) and Chan *et al*. (2014), for example, note that the Guangzhou and other municipal governments in the PRD have not addressed climate change in the current FRM policies (i.e. 13th- Five year's development plan) and practices (National Flood management protocol and Guangzhou Integrated Water Resources Management Plan (2005 – 2030), etc.) (GZ Water, 2014). Other evidence shows that there are currently lacking relevant flood management policies at all spatial levels (regional, provincial, municipal, towns and districts). Thus, the municipal governments have yet to integrate with spatial planning (see Appendix 1, for relevant documents used in this review) in the PRD, which indicates a lack of responsive actions to address climate change (i.e. adaptations) in the existing FRM practices (Chan *et al.*, 2013ab).

While other adaptation and response measures are still undeveloped, there is lack of emergency contingency plans and strategies, specifically targeting for social vulnerable groups – e.g. elderlies and disabilities, post-flood aid/support schemes and flood insurance programs. Integrated FRM approaches incorporating "soft" protection measures such as flood warning, risk-mapping and post-flood contingency/emergency plans are important to address vulnerability and improving resilience. Such findings are similar in Hong Kong, Shenzhen, Guangzhou and other PRD coastal cities in this study, as current flood management is still highly focused on a one-dimensional approach based on traditional engineering (as discussed). We demonstrated that flood risk is increasing in the PRD by using the flood risk framework (refer to Table 1). Accordingly, inland and coastal flood hazards are increasing by incessant urbanisation and climatic change.

Flood exposure and vulnerability are increasing according to the findings on more intensive rainstorms (HKO, 2013), global sea-level rise (IPCC 2013; IPCC 2007), and frequent typhoons during the summer season (Chan *et al.*, 2013ab). In the meantime, large coastal settlements and their assets continue with more than 42.4 million people exposed to flood risk (Swiss Re, 2014). The susceptibility is high, and the resilience is still low, due to factors such as lack of practices of post-flood recovery and arrangements, and the current urban pluvial flood protection standards (i.e. land drainage system) is low (between 1-in-1 to 1-in-5 years return periods in the PRD cities) as discussed in section 3.1 previously (Chan et al., 2014) (see Table 7).

Overall, we emphasise that the PRD and its cities are facing tough challenges, with a lack of holistic FRM policy existing against a canvas of increasing exposure and emerging climate change threats.

Table 7 is about here

4. Conclusions and recommendations

The PRD is a coastal region with a large population that has become a global hub of socio-economic activities. Cities within the delta will further integrate with nearby metropolis (e.g. Hong Kong-Shenzhen-Dongguan, Guangzhou-Foshan-Zhongshan, Macau-Zhuhai), to exhibit a population of over 120 million by 2050 (UN-HABITAT, 2008).

Rapid population growth and high-flying economic performance also mean that the region is exposed to inland and coastal flood impact risks. Climate change and sea-level rise enhance the likelihood of intensive rainstorms and storm surges delivered by the Western Pacific and sub-tropical cyclonic effects (e.g. typhoons and sub-tropical storms). Climate change, extreme rainfall, surges and sea-level rise will increase the potential occurrence of flooding (hazard). Large populations and their assets will be exposed to flooding, especially the low-lying urban and populous areas/cities.

In this review, we have demonstrated that flood risk has escalated in the PRD (Table 7). It was found that the region suffers from limited implementation of inclusive strategies addressing flood risk (and its components hazard, exposure and vulnerability). Evidence suggests traditional "hard" engineered flood protection measures remain a favourite option although they are practiced in a disjoint manner (understandably, as hard infrastructures are still important to reduce flood hazard and exposure and increase resilience).

However, the PRD is large and it is extremely costly to build highly resilient flood measures to protect a large coastal flood prone area (Table 6). The governments are keen to practice mitigation of flood risk, which currently is not economically sustainable. The flood hazard exposure is increasing in the PRD and its populous coastal cities, against a backdrop of unabated rates of population and economic growth, emphasising how integration of climate change adaptation and more sustainable flood risk management practices can be tackled.

For the way forward, we recommend that FRM practices such as land use planning, awareness building and post-flood recovery measures are improved to enhance resilience and lower flood risks. In terms of governance and policy arrangements, we particularly suggest that the government should consider establishing deltaic management practices across the delta. We find that currently action on flood hazard exposure and vulnerability in the PRD lacks any climate change adaptations. We suggest collaboration between the Central/National Government in Beijing, the Guangdong Provincial Government and all municipal governments of the PRD cities to legislate the regional flood risk management plans regarding the effects from large-scale storms and typhoons. We have found that the effects on climate change and flood hazards normally are not affecting solely one city in the PRD, but could damage several cities in the same event, which may prove problematic, as sea-level rise, extreme rainstorms, surges and typhoons will visit the PRD more frequently. We recommend that the meteorological departments and bureaus in the PRD share metrological data (e.g. rainfall, storm tracks, pressure, etc.) and that the governments may further develop better flood warning and meteorological track systems to improve flood awareness, preparedness and prevention against flood disasters and mitigate flood risk.

The increasing flood risk in cities of PRD, is not the result of climate change per se, but is combined with the rapid urbanisations and developments since the late 1970s. The way that cities in PRD were developed, have not been considered intensively in addressing urban floods and climate change issues. Unsustainable urban development causes adverse reduction of natural adaptive capacity (e.g. soil-water infiltration) to cope with stormwater and urban discharges. Traditional engineering infrastructures and approaches are not sufficient to cope with the current situation, also with future uncertainties. Thus, we also recommend here that the governments should co-ordinate and develop a strategic “soft” flood risk management that encourages decreased vulnerability and integrates FRM with urban planning and climate change adaptation. We encourage the inclusion of these integrated governance arrangements and policy improvements, as these practices have yet to be implemented in the PRD. These suggestions should be useful to mitigate flood risk in the PRD and to be adopted in other deltas elsewhere, particularly in Asia facing similar issues of increasing flood risk affected by the pressure of urbanisations, socio-economic developments and climate change.

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Appendix 1. Relevant grey literature documents on flood risk management, urban planning and climate change issues in the PRD

Categories-Policy document	**Year**	**Document**	**Types of floods**	**Location**	**Highlights**	**Publisher/ Publishing organisation**
Flood risk management	2014	Guangzhou Water White Paper	Fluvial, pluvial and coastal flooding	Guangzhou	Emphasising the importance of flood risk mitigation in Guangzhou in all kind of flooding	Guangzhou municipal water bureau
Flood risk management	2013	Flood Defence and Rainwater Discharge Plan (2010-2020) (FDRD)	Fluvial, pluvial and coastal flooding	Guangzhou	Strengthening flood defence infrastructure, preventing the loss of tide and rainwater discharge	Guangzhou municipal water bureau
	2012	Overall Plan of Guangzhou Rainwater Discharge System(2008-2020)(RDS)	Fluvial flooding	Guangzhou	Rainwater discharge plan	Guangzhou municipal water bureau
	2007	Canals and Waterways Renovation Program 2005-2020 (CWR)	Fluvial and Pluvial flooding	Guangzhou	Canals dredging, maintanance of river channels, environmental and ecological enhancement, waterlogging and urban discharge	Guangzhou municipal water bureau
	2011	Drainage Service Department Annual Report of 2010–2011	Fluvial and Pluvial flooding	Hong Kong	Overall strategies on current flood risk management in Hong Kong	Drainage Service Department, HK Govt.
	2010	ADVICE NOTE NO. 1: (APPLICATION OF THE DRAINAGE IMPACT ASSESSMENT)	Pluvial flooding	Hong Kong	Technical guidance on drainage standard and instructions of urban drainage construction	Drainage Service Department, HK Govt.
	2006	The development of a comprehensive flood	Fluvial and Pluvial flooding	Hong Kong	Overview of the flood management strategies in Hong Kong	Drainage Service Department, HK Govt.

		prevention strategy for Hong Kong				
	2001	Drainage Master Planning for Land Drainage Flood Control in Hong Kong.	Fluvial and Pluvial flooding	Hong Kong	Overall strategies on current flood risk management, the level of urban flood protection and drainage standard improvement in Hong Kong	Drainage Service Department, HK Govt.
	2019	Shenzhen flood management plan	Fluvial , coastal and Pluvial flooding	Shenzhen	Overal strategies on current flood risk management plans in Shenzhen	Shenzhen Municipal Water Bureau
	2015	Zhongshan flood protection and prevention plan	Fluvial, coastal and pluvial flooding	Zhongshan	Flood disasters prevention and preparedness in Zhongshan city	Zhongshan Municipal Water Bureau
	2018	Dongguan flood protection plan	Fluvial and Pluvial flooding	Dongguan	Addressing urban floods and other pluvial floods issue in Dongguan city	Dongguan Municipal Water Bureau
	2017	Foshan Drainage control guidance	Pluvial and urban floods	Foshan	Providing drainage guidance and information in Foshan city	Foshan Municipal Water Bureau
	2015	Zhuhai flood prevention and protection plan	Pluvial, fluvial and coastal floods	Zhuhai	Flood disasters prevention and preparedness in Zhuhai city	Zhuhai Municipal Water Bureau
	2016	Macau flood management plan	Pluvial and inland urban floods	Macau	Rainwater and stormwater management and urban floods strategies	Macao government (iacm.gov.mo)
Urban planning	2017	Guangzhou Sponge City Plan2016-2030	Fluvial, pluvial and urban floods	Guangzhou	Integrating urban flood risk management by the establishment of Sponge City program and adopted the landuse planning strategies	Guangzhou municipal urban Planning Bureau
	2016	Guangzhou Master Plan 2010-2020	Fluvial, pluvial and urban floods	Guangzhou	Overall rural and urban development, which concentrates on economic development, land uses, and infrastructure construction, etc	Guangzhou municipal urban Planning Bureau
	2005	Guangzhou Master Plan 2000-2010	Fluvial, pluvial and urban floods	Guangzhou	Overall rural and urban development in Guangzhou, which concentrates on economic development, land uses, and infrastructure construction, etc. in the city	Guangzhou municipal urban Planning Bureau
	2016	Foshan water maangement plan under the 13-5 planning strategies	Urban floods	Foshan	Urban planning and water management issues	Foshan municipal urban planning and water bureau
Climate Change	2010	Sea-level rise and storm surge—impacts of climate	Coastal floods	Hong Kong and Shenzhen Bay areas	Overall strategy about the climate change on sea-level rise	Hong Kong Observatory

		change on Hong Kong.				
	2010	Agreement No. CE 45/2007 (EP): A Study of Climate Change in Hong Kong—Feasibility Study.	All flood issues related to climate change	Hong Kong	General guidance on climate change including all aspects, such as urban temperature, energy, housing and wate rissues, but indicated some suggestoins on addressing future floods that related to climate change	Hong Kong Govt. Environmental Protection Department

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