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Advancing index-based climate risk assessment to facilitate adaptation planning: Application in Shanghai and Shenzhen, China

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Abstract

One of the key issues in climate risk management is to develop climate resilient infrastructure so as to ensure safety and sustainability of urban functioning systems as well as mitigate the adverse impacts associated with increasing climate hazards. However, conventional methods of assessing risks do not fully address the interaction of various subsystems within the city system and are unable to consolidate diverse opinions of various stakeholders on their assessments of sector-specific risks posed by climate change. To address this gap, this study advances an integrated-systems-analysis tool - Climate Risk Assessment of Infrastructure Tool (CRAIT), and applies it to analyze and compare the extent of risk factor exposure and vulnerability over time across five critical urban infrastructure sectors in Shanghai and Shenzhen, two cities that have distinctive geo-climate profiles and histories of infrastructure development. The results show significantly higher level of variation between the two cities in terms of vulnerability levels than that of exposure. More specifically, the sectors of critical buildings, water, energy, and information & communication in Shenzhen have significantly higher vulnerability levels than Shanghai in both the 2000s and the 2050s. We further discussed the vulnerability levels of subsystems in each sector and proposed twelve potential adaptation options for the roads system based on four sets of criteria: technical feasibility, flexibility, co-benefits, and policy compatibility. The application of CRAIT is bound to be a knowledge co-production process with the local experts and stakeholders. This knowledge co-production process highlights the importance of management advancements and nature-based green solutions in managing climate change risk in the future though differences are observed across the efficacy categories due to the geographical and meteorological conditions in the two cities. This study demonstrates that this knowledge co-creation process is valuable in facilitating policymakers' decision-making and their feedback to scientific understanding in climate risk assessment, and that this approach has general applicability for cities in other regions and countries.

Keywords: Climate risk assessment; Megacities; Resilient urban infrastructures; Subsystem; Knowledge co-creation process; China

1. Introduction

Climate change poses an ongoing challenge to society, with the potential for adverse consequences arising from increasing climate-related hazards such as flooding and heat waves. The

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Intergovernmental Panel on Climate Change (Reisinger et al., 2020) conceptualizes climate risk as a result from dynamic interactions of social and environmental processes, from the combination of physical hazards and the vulnerabilities of exposed elements (Cardona et al., 2012; Reisinger et al., 2020). For example, while it is well acknowledged that a good understanding of current and future climate risks is essential for the planning, design, and management of new and existing infrastructure systems to respond to climate risks in the future, the risk assessment is challenged not only by the uncertainty in terms of magnitude and likelihood of occurrence, but also by social economic development in infrastructure, technology and other system transitions.

One of the key issues in urban climate risk management is to develop climate resilient infrastructure, as it not only ensures the safety and sustainability of urban functioning systems, but also helps to combat the adverse impacts such as direct and indirect losses arising from extreme climate hazards (Dawson et al., 2018; OECD, 2018). Previous studies have paid attention to critical urban infrastructure sectors such as transport, water, energy and telecommunications (Bhattacharyay, 2010; Millward, 2007; Straub, 2008) and conducted assessments on how these sectors are impacted by extreme climate hazards (Dawson et al., 2018). For example, Suarez et al. (2005) assessed the potential climate change impact on transport networks in the Boston Metropolitan area where the system was severely impacted with delays and lost trips.

It is well-recognized in the literature that the design, implementation and operation of resilient urban infrastructures need to take into account the potential risks and uncertainties associated with the exposure and vulnerability to climate change throughout their lifetimes, given the complexity and interdependence between different infrastructure systems in urban cities (Dawson et al., 2018). As reviewed by Nguyen et al. (2016), conventional assessments have primarily focused on physical factors such as geophysical dynamics or physical impacts. It is imperative for researchers to take into account other factors such as policy orientation, the urgency of the climate threat, the geographical and temporal scope of the analysis, the reliability of future climate impact projections, knowledge from the expertise and other relevant resources, and diverse opinions of various stakeholders on their assessments of sector-specific risks. In this line, index-based assessment can help identify and prioritize sectors, raise awareness, and can be part of the policy decision-making process. Of course, by taking into accounting so many factors and diverse opinions, the index-based method has to give up complicated quantitative modelling process. On the other hand, the results produced by the index-based method can effectively facilitate broader communication with government officials and the public because indexes can be understood and compared more easily than the results produced by complicated quantitative modelling process. Tate (2013) outlines the three sequential steps of vulnerability index construction: the selection of indicators, normalization of indicators to a common scale, and aggregation to a final value. The selection of indicators is driven by theory and data based on existing scientific knowledge or statistical relationship with observed vulnerability outcomes.

Compared with the conventional methods of assessing risks that have limited focus on the interaction of various subsystems within the city system (Adger et al., 2018), index-based assessment goes beyond the physical components of the infrastructure system and incorporates the implications that any disruption would have on the services that the infrastructure system provides (Fussel and Kelien, 2006; Yohe and Tol, 2002). Review on index-based assessment of climate risk also highlights the need to account for decision contexts and system boundaries (Hinkel, 2011; Birkmann, 2006). This practice represents a holistic approach to establish linkages and relationships between data, and combine them in a meaningful way as stakeholders and decision-makers from all relevant sectors take into account different rationalities, concerns and interests of the various institutions and the public at large, in addition to the scientific data which captures a list of complex and interacting parameters from existing databases. This approach has emerged as a new mainstream in climate risk assessment and management, which emphasizes the generation of useable science for decision-making through sustained and meaningful dialogue between scientists, policymakers, and other stakeholders (Clark et al., 2016; Meadow et al., 2015). It facilitates the incorporation of stakeholders' latent knowledge into the overall scientific synthesis and builds stakeholders' capacity in the utilization of the project outcomes for decision-making (Clark et al., 2016). What to note as well is that the majority of such works have been mainly emerged in the developed economies (Jeuken and Reeder, 2011), and there is still a shortage of studies that consolidate diverse opinions of various stakeholders on their assessments of sector-specific risks posed by climate change and aggregate these opinions into intuitive and comparable radar (spider) charts and tables in emerging economies such as China. This study aims to fill this important niche.

To achieve this goal, this study advances an integrated-systems-analysis (Soroczynski, 2002) tool — Climate Risk Assessment of Infrastructure Tool (CRAIT) — to analyze and compare the extent of risk factor exposure and vulnerability over time across five critical urban infrastructure sectors in Shanghai and Shenzhen, two economic and innovation centers of China with distinctive geo–climate profiles and long versus short history in infrastructure development, and to explore potential adaptation policies in these two cities. A successful application of the CRAIT is bound to be a knowledge co-creation process. The notion of knowledge co-creation puts an emphasis on the generation of useable science for decision-making through sustained and meaningful dialogue between scientists, policymakers, and other stakeholders (Clark et al., 2016; Meadow et al., 2015; Liu et al., 2019). The tool first facilitates communications between scientists and local experts (and stakeholders) about the best available climate information and the initial assessments of how key infrastructure sectors are affected by climate change in heavy rainfall events. Then it enables the dialogues on calibrations and evaluations of plausible adaptation strategies among experts, stakeholders, and decision-makers from key infrastructure sectors. By this way, we show an effective knowledge co-development process with multi-stakeholders in synthesizing the existing local information, expert opinions, and scientific tools, and in supporting well-informed and proactive infrastructure planning to mitigate the risks posed by future climate change. This approach has general applicability for cities in other regions and countries.

2. Data and methods

2.1. Study area

We chose Shanghai and Shenzhen, the two key metropolitan cities in the Yangtze River Delta (YRD) and the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) respectively. The choice is based on the dominant role of the two cities in the regional economic development of the YRD and the GBA, and also on the increasing climate risks the two cities have faced and will continue to face in the future.

As the largest coastal city and economic center in China, the infrastructure systems in Shanghai have been developed and tested in the last two hundred years. By contrast, Shenzhen is growing from a fishing village before the 1980s to a megacity. Its infrastructure systems are new but not yet well-tested. While both Shanghai and Shenzhen face the risks of heatwaves (Yang et al., 2015), rising sea level and increasing frequency and intensity of rainstorm (de Dominicis et al., 2020; Jian et al., 2021), the following differences are worth noting. As illustrated in Fig. 1, Shanghai sits on the low-lying coastal zone of eastern China with an average elevation of 3−4 m above sea level. It is surrounded on three sides by water bodies including the Yangtze River Estuary, the Hangzhou Bay, and the East China Sea. The Huangpu River passes through the main urban area of the city. The specific geological profile in combination with the aging urban drainage facilities makes urban waterlogging have been the main climate risk in the city (Hu et al., 2019). By contrast, typhoons and rainstorms have high intensity and frequency in Shenzhen because it is located 1200 km south of Shanghai. Shenzhen's terrain has noticeable undulations, and its river courses have a large slope. Furthermore, Shenzhen's drainage pipe network facilities are relatively new and has not been tested by extreme events. As a result, Shenzhen is more prone to storm surge and the formation of upstream floods in a short time which often cause huge losses because of the complex terrain (Shi et al., 2007; Yan et al., 2019).

As shown in Table 1, the rainfall amounts of the highest five-day precipitation (RX5day) and of the extremely wet days (R95p) in Shenzhen are much higher than those in Shanghai in the baseline and future climates. Furthermore, the increments of R95p in Shenzhen under both RCP4.5 and RCP8.5 are significantly higher than those in Shanghai, indicating a more significant increase in short-term heavy rainfall in Shenzhen in the future. Additional summary information on mean temperature and precipitation and their changes, and on the number of hot days and its changes in Shanghai and Shenzhen

Table 1
Extreme precipitation and changes in Shanghai and Shenzhen between the baseline (1981−2010) and the middle of the 21st century (2031−2060).

Index	City	Baseline	2031−2060	
			RCP4.5	RCP8.5
Rx5day (mm)	Shanghai	100.2	119.3	136.9
	Shenzhen	225.5	256.7	220.9
R95p (mm)	Shanghai	334.5	313.8	389.1
	Shenzhen	464.6	671.4	568.1

Note: RX5day refers to the highest five-day precipitation total amount, and R95p denotes the annual precipitation from daily precipitation >95th percentile (i.e., the extremely wet days). These are the projections of the UK Met Office's PRECIS-2 model, which is a high-resolution regional climate model driven by the UK Met Office, HadGEM2-ES (Dong et al., 2020).

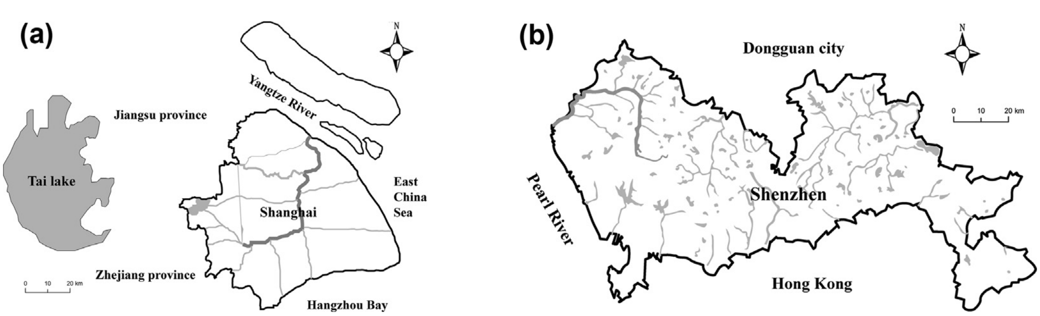

Fig. 1. Geographical features of Shanghai and Shenzhen.

between 1981–2010 and 2031–2060 are presented in Tables A1 and A2.

With the observed and foreseeing climate change impacts, both cities are under pressure to take strategic priority in climate risk assessment and policy-making. The State Council of China issued a Circular on enhancing the treatment of urban waterlogging on April 25, 2021 (State Council, 2021), in which both cities are on the targeted list as both have suffered severe waterlogging in recent years and are required for flood control improvement to establish a system which combines the operation of water systems and drainage pipe networks in urban areas with surrounding rivers, lakes, oceans and reservoirs, for effective urban water drainage and waterlogging control by 2025. Therefore, these two cities can not only offer interesting case studies for undertaking climate risk assessment but also facilitate the identification of appropriate adaptation measures for megacities.

2.2. CRAIT and data collection through knowledge co-creation process

The Climate Risk Assessment of Infrastructure Framework (CRAIT) has been developed to include all components of climate risk to enable planners and/or policymakers to understand how climate change might impact the infrastructure system within a city either during the initial stages of development for a new infrastructure project, or during the maintenance and redevelopment of existing assets and identify suitable adaptation options. The initial version of CRAIT was jointly developed by Arup Group, SOAS University of London, and local collaborators in Shanghai in 2016/2017 for cities in the Yangtze delta region of China (https://www.arup.com/projects/yangtze-river-delta). The initial version facilitates the identification of the key hazards and the most exposed infrastructure system in the city, and the assessment of the current and future climate resilience of these systems. Information on current and future hazards is required to complete the assessment (Sun et al., 2019). In addition to the vulnerability and exposure assessment by the initial version, the current version of CRAIT further considers the entire cascade of climate risk assessment, entails more quantitative analysis, and explores the adaptation measures (Fig. 2).

The CRAIT tool includes a variety of adaptation options derived from an extensive literature review (e.g. HM Treasury, 2015; Quinn et al., 2017). This initial step allows us to build a list of adaptation actions by reviewing a long list of potential measures based on previous research, covering green solutions, grey solutions, and management solutions (Kabisch et al., 2017). Secondly, we further our review and included adaptation measures that have been implemented in sectors and regions, such as C40 Cities and McKinsey (https://www.c40.org/news/c40-mckinsey-focused-adaptation/), the Climate-ADAPT Search (https://climate-adapt.eea.europa.eu/metadata/adaptation-options), PIARC (World Road Association) (www.piarc.org/ressources/publications/8/23557,SpecialProject-ClimateChange-EN.pdf), Rail Adapt of International Union of Railways (https://uic.org/IMG/pdf/railadapt_final_report.pdf) to our list, eventually considering about 37 possible measures. These adaptation measures include a range of plausible policy, physical and operational related measures.

It is worth noting that we do not intend to have an exhaustive list because presenting a pre-set long list of measures would hinder the dialogue process with experts. Instead, the consultations with experts and incorporation of their professional judgement allowed the researchers and field experts to co-produce a list of measures that are relevant to both the infrastructure types and climate events being assessed, and to understand the relative feasibility levels of these measures. We engaged in discussion and consultation with local infrastructure experts, to refine the list and comment on three dimensions of these measures: no or low regret solutions and win–win measures to ensure that the list was meaningful. There are twenty adaptation measures in the CRAIT model (Table A3), twelve of them were identified through online interviews and consultations with stakeholders in May 2021. In the CRAIT tool, the efficacy of each option is assessed against the four sets of criteria: technical feasibility, flexibility, co-benefits, and policy compatibility. The CRAIT tool also takes into account all costs related to developing, implementing, and maintaining the adaptation option and identifies the tipping point or ‘sell-by date’ to adopt the option. This process is particularly useful in engaging multiple stakeholders into the dialogue for resilient decision-making in response to climate change mitigation and adaptation (Clark et al., 2016; Meadow et al., 2015).

An option with a high technical feasibility may use current practice design techniques that are well known and tested, whereas that with a low technical feasibility may require new and/or cutting-edge technical skills and expertise that have not been tested before. Flexibility is concerned with the degree to which an option is adaptable to uncertainty in future climate. Co-benefits are the additional positive outcomes provided by an option, beyond the primary intended benefits. Policy refers to whether adaptation options align with and/or complement existing policies, or potentially conflict with them. The CRAIT tool also takes two additional factors into account. First, the cost of these adaptation options if implemented. This includes all costs related to developing, implementing, and maintaining the adaptation option (e.g. capital, operational, maintenance and repair costs). Second is the tipping point, which scales the urgency of options to be adopted, or ‘sell-by date’, which indicates the temporal dimension when these adoption options are to be taken into action. Table 2 presents the evaluation results of the 12 adaptation options for the roads systems in Shenzhen and Shanghai.

Forty seven experts, twenty-one of whom are based in Shanghai and the rest in Shenzhen, who have comprehensive

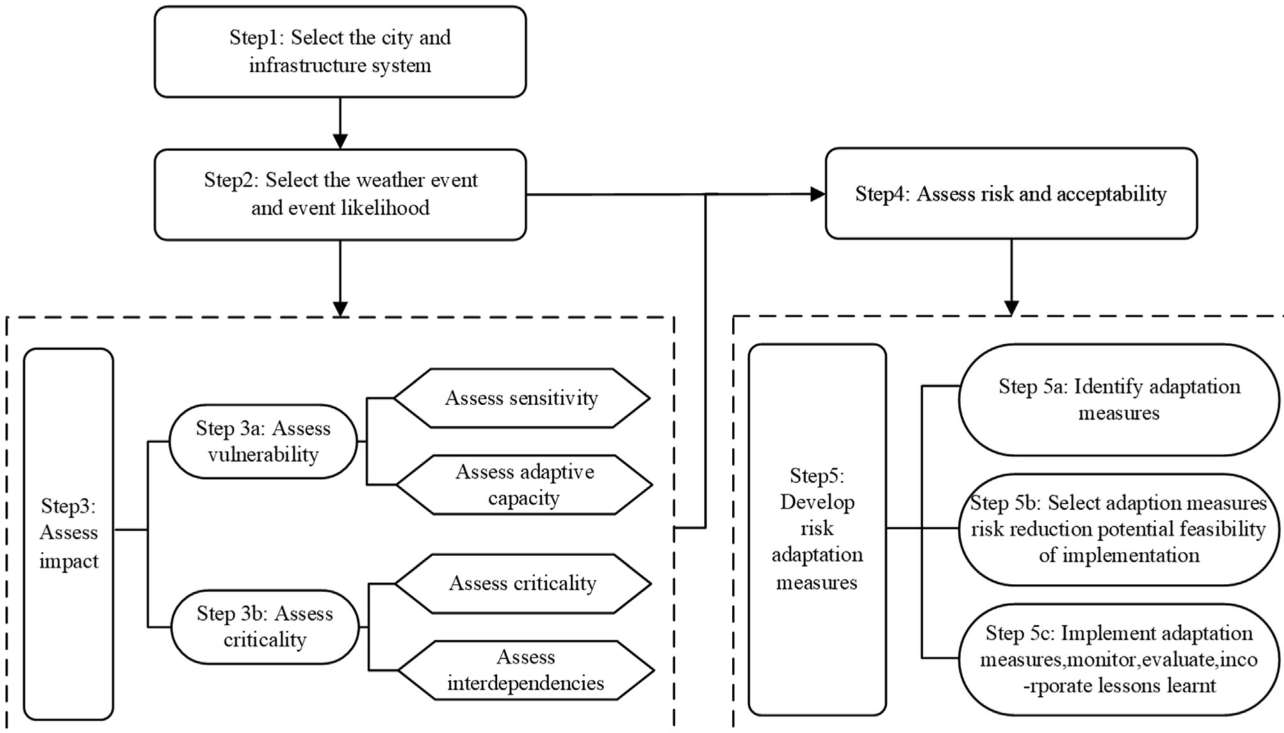

Fig. 2. Flow chart of climate risk assessment of infrastructure tool.

industry experience and a high awareness of climate change risks in these two cities, participated in a series of focus group meetings as well as in-person and online interviews. The questionnaires we used in these meetings and interviews are presented in Tables A4-A6. The list of participants, together with their affiliation, post, areas of expertise, interview location, interview methods, and interview date, is summarized in Table A7. The focus group meetings for Shanghai's case were undertaken in February and March 2017 while those for Shenzhen were carried out in September and October 2020. Further follow-up in-person and online interviews were conducted in May 2021. The experts hold positions as senior engineers, departmental directors and policymakers in the five key infrastructure sectors including transportation, water, energy, ICT and critical buildings in the two cities.

Thirty-two valid questionnaires were collected during and after the focus group meetings, 14 of which are from the groups in Shanghai and 18 from those in Shenzhen. Based on their evaluations on the extent to which the performance of the infrastructure asset in assessment can be compromised by current versus future climate hazards, we were able to have the input in the Exposure assessment and to produce exposure scores. The climate hazard for each infrastructure asset with the greatest Exposure score, identified as the ‘critical climate hazard’ was carried through in the Vulnerability assessment. In this stage, the participants provided their evaluations on a list of questions in relation to planning and design, operation and maintenance, and future vulnerability in Table A5, which helped to produce the most relevant climate hazard (e.g., heavy rain for Shanghai and Typhoon for Shenzhen) outlooks in these two cities. The third stage of the infrastructure assessment is the assessment of system vulnerability. In the tool, we grouped individual assets into ‘systems’ to represent the key infrastructure sectors to cross-check the interdependency of each infrastructure system against the others. The options of low, medium or high interdependency produced an overall score of inter-dependency for each infrastructure system. Based on the CRIAT tool, we are able to capture and identify the top adverse climate hazards in Shanghai and Shenzhen across the infrastructure systems. We focused on rainstorms, typhoons, and urban floods caused by heavy rainfall.

As illustrated in Fig. 2, the CRIAT tool first communicates the best available climate information and the initial assessments of the tool on how transportation, critical buildings, water, information and communications technology (ICT), and energy sectors (in Shanghai and Shenzhen) are affected by climate change in heavy rainfall events. Then the tool facilitates the calibrations and evaluations of plausible adaptation strategies through the knowledge exchange workshops and interviews with experts, stakeholders, and decision-makers from these five key infrastructure sectors. By this way, we demonstrated an effective knowledge co-development process with multi-stakeholders to synthesize the existing local information, expert opinions, and scientific tools in infrastructure planning, with the aim to mitigate the risks posed by future climate change. This approach has general applicability for cities in other regions and countries.

Table 2
Evaluation results of the 12 adaptation options for the roads systems in Shenzhen and Shanghai.

Category	Adaptation option	Technical feasibility		Flexibility		Co-benefit		Policy compatibility		Sell-by date		Cost	
		SH	SZ	SH	SZ	SH	SZ	SH	SZ	SH	SZ	SH	SZ
Green solutions	1. Increasing water retention capacity and slowing infiltration through natural or bioengineered systems	+++	+++	0	0	++	+++	+++	+++	>2020	>2020	+	+
	2. Realigning natural water courses	+++	+	++	++	++	++	+++	+++	>2020	>2020	+	+++
Grey solutions	3. Implement climate change increments on construction standards of drainage systems and flooding defense walls	+	++	0	+	+++	+++	+++	+	>2020	>2050	+++	+
Management solutions	4. Allowing for alternative routes in the event of a road closure	+++	+++	+	+	+	+	+	+	Any time	Any time	0	0
	5. Mapping of flood hotspots	+++	+++	+++	+++	+++	+++	+++	+++	>2030	>2025	++	++
	6. Production of Surface Water Management Plans, Local Flood Risk Management Plans etc.	+++	+++	+++	+++	+++	+++	+++	+++	>2020	>2020	+	+
	7. Implementation/broadening of emergency warning systems in the instance of extreme weather including detection, analysis, prediction, and warning dissemination followed by response decision-making and implementation	+++	+++	+++	+++	+++	+++	+++	+++	>2020	>2025	++	+
	8. Improved communication methods for network users in the event of emergency	++	+++	++	++	+++	+++	+++	+++	>2020	>2025	++	+
	9. Develop strategies to minimize the impact of operational failures caused by extreme weather conditions (special timetables, rerouting models), and provide replacement of services if needed (e.g., bus transport)	+++	+++	+++	+++	+++	+++	+++	+++	>2025	>2020	+	+
	10. Model climate impacts on existing and planned assets	++	++	++	++	++	++	++	++	>2025	>2025	+	+
	11. Increase frequency of maintenance schedules	+++	+++	+++	+++	+	+	+	+	>2020	>2050	+	+
	12. Integrate smart technologies, telemetry and remote sensing technology and data management systems into flood risk management	+++	+++	+++	+++	+++	+++	+++	+++	>2030	>2025	+++	+++

Notes: SH–Shanghai, SZ–Shenzhen; 0, +, ++, +++ indicate from 0, low, medium, to high level of the relevant evaluation.

3. Results and discussion

As mentioned above, the CRIAT tool allows us to capture the climate risk in terms of exposure and vulnerability in Shanghai and Shenzhen. Fig. 3 shows the levels of exposure and vulnerability in the five key sectors: transportation, water, energy, ICT and critical building. The level of exposure and vulnerability is ranged from 0 to 3, representing the extent of exposure and vulnerability from small to large. In the following sections, we will present the climate risk assessment in each infrastructure sector, followed by a comparison between the two cities.

3.1. Transportation sector

Fig. 3 shows that the current exposure level of the transportation sector in Shanghai is higher than that in Shenzhen. Shanghai has one of the most comprehensive public transport systems in China, and the Port of Shanghai is the world's busiest container port. However, as data and local experts suggest, Shanghai also bears high risk from extreme climate hazards such as flooding because of its specific geological profile as presented in Section 2.1, which often results in transportation disruptions. The outlook for the 2050s does indicate a noticeable change of both exposure and vulnerability in the sector in the two cities. The exposure level will be reduced in Shanghai, thanks to the expectations of local experts and stakeholders that the infrastructure investment in Shanghai, together with the increasing construction standards to mitigate climate change.[1] However, the vulnerability level will increase mainly because of sea level rise and land subsidence (Hu et al., 2019). By contrast, the levels of both exposure and vulnerability in Shenzhen are expected to increase mainly owing to the expected intensification of socio-economic activities in the city and expected increase in the intensity of typhoon landfall events in the GBA (Wang and Toumi, 2021; Wang et al., 2021).

The transportation sector includes major roads, tube and light rail, railway systems, civil airport and ports. Fig. 4 further examines the vulnerability levels of these five major subsystems in the transportation sector. It shows that the vulnerability levels in Shenzhen are more or less equally distributed across the five major subsystems and are relatively low, with a moderate increase between the 2000s and the 2050s. By contrast, the major roads systems in Shanghai are highly vulnerable and their vulnerability level will increase in the future. Similar extents of vulnerability increase are expected for the systems of tube and light rail, and ports, although the base levels of vulnerability in these two subsystems are lower than that in major roads systems. The civil airports and railway systems are very strong, largely free from the threat of flooding.

3.2. Critical buildings sector

The two cities exhibit quite different features in this sector. The current exposure level in Shenzhen is remarkably higher than that in Shanghai (Fig. 3). This difference can be attributed to the following three sets of factors. First, a larger proportion

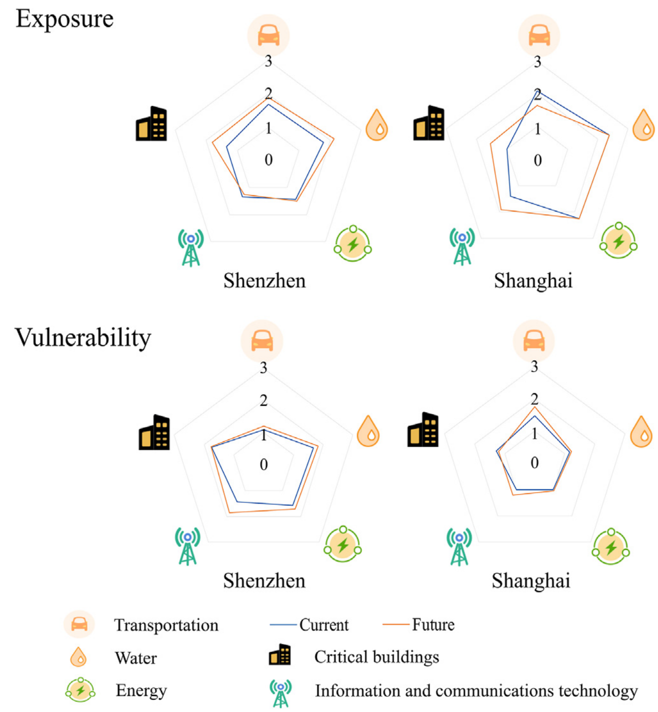

Fig. 3. Exposure (upper panel) and vulnerability level (lower panel) of climate hazard risks in the five major infrastructure sectors in Shanghai and Shenzhen, from the 2000s to the 2050s.

of land area in Shenzhen is hardening surface; second, there has been a much more rapid growth in underground space and number of high-rise buildings in Shenzhen; and there exists a large number of slope-cutting houses in Shenzhen. It is expected that the exposure levels of this sector will increase by a large margin in both cities, although the reasons for such increase are not the same (Table A8). In Shanghai, the top reason is the uneven land subsidence and sea level rising, whereas in Shenzhen, the top reason is the increasing intensity of typhoon landfall events.

Despite the increase in the level of exposure between the 2000s and 2050s, the future level of vulnerability will remain more or less the same as the current level in both Shenzhen and Shanghai, with a slight decrease in Shanghai (Fig. 3). There are three main reasons for this observation. First, the answers in the Planning and Design category of the vulnerability module indicate that the planning and design processes in the sector of two cities typically carry out relatively rigorous environmental and climate risk assessment, with due considerations to risk increments posed by future climate change and with keen attention to flood protective facilities (such as flood control walls). Second, the answers in the Operation and Maintenance category of the vulnerability assessment show the presence of regular monitoring and maintenance mechanisms for maintaining the performance and ensuring the effective operation of the flood protective facilities; the presence of emergency response and recovery mechanism for ensuring the rapid reconstruction when the system no longer functions; and the presence of upgrading programs and plans to accommodate urban climate trends and

[1] In 2012, the Shanghai Water Authority decided to spend 25 billion CNY to upgrade the city drainage system with wider pipes. By 2016, Shanghai has over 400 major pump stations, 82 pump vehicles and over 100 flood prevention teams. In 2016, Shanghai started to build China's largest deep-water drainage system beneath Suzhou Creek. Meanwhile, the city is launching the 40 billion CNY investment in its River Flood Discharge Project from Taihu Lake to the mouth of Huangpu River at Wusong, stretching over 120 km.

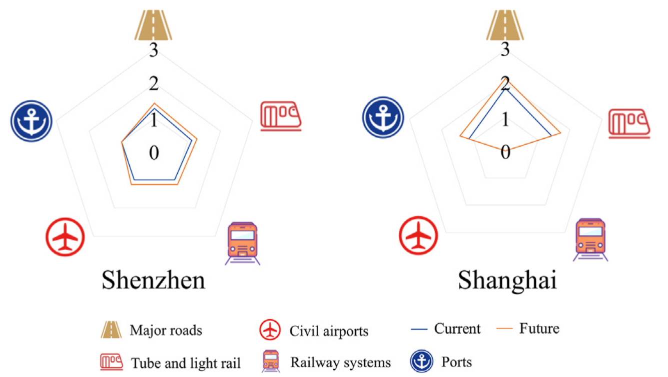

Fig. 4. Vulnerability level of climate hazard risks in the transportation sector in Shanghai and Shenzhen, from the 2000s to the 2050s.

population growth. Third, the answers in the Future Vulnerability category show good awareness of future climate hazards, and the existence of climate expert consultation processes which take into account climate change and exposure. Of course, it is worth noting that the vulnerability level in Shenzhen is higher than that in Shanghai both at present and in the 2050s.

The critical building sector includes police stations, fire-fight stations, emergency shelters, hospitals and schools/kindergartens, which provide critical public services to the societies. Fig. 5 compares the difference at the subsystem level between the two cities. In Shenzhen, the category of police stations has been labelled with relatively high vulnerability, whereas that of emergency shelters is associated with minimal vulnerability. While the vulnerability levels of the hospital category and schools/kindergartens category are the same in Shenzhen and Shanghai, the vulnerability levels across other three subsystems in Shanghai are relatively low, in comparison with those in Shenzhen. By the 2050s, there will be a potential increase in the vulnerability level of emergency shelters in Shenzhen, while the subsectors of fire-fight stations and emergency shelters will become less vulnerable. This contrast indicates that the collective assessments of experts in Shanghai are more optimistic on the capacity of these two subsectors in responding to future climate change than their counterparts in Shenzhen.

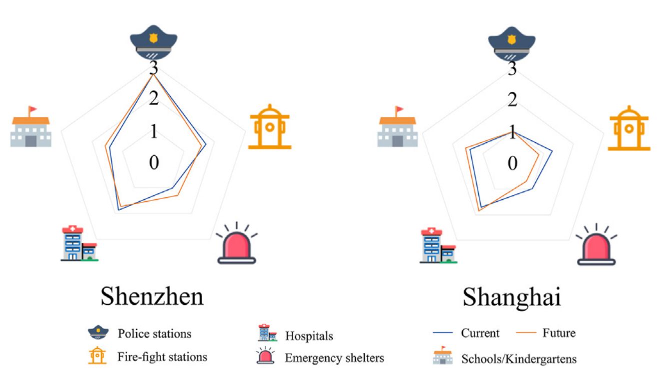

Fig. 5. Vulnerability level of climate hazard risks in the critical buildings sector in Shanghai and Shenzhen, from the 2000s to the 2050s.

3.3. Water sector

The water sector includes portable water system, wastewater system including treatment facilities, reclaimed water system including treatment facilities, major pumping stations, waterway system, and flood defenses. The current overall exposure level of the water sector in Shenzhen is lower than that in Shanghai by a grade margin of 0.6. The outlook for the 2050s does indicate an increase in Shenzhen, approaching the stable exposure level in Shanghai (Fig. 3). The vulnerability level of the water sector in Shenzhen is higher than that in Shanghai at present and will continue to be higher in the 2050s. Between the 2000s and the 2050s, the vulnerability level of the water sector in Shenzhen will increase by a small margin, while that in Shanghai will increase by a very small margin (Fig. 3).

In Fig. 6 we can see that the vulnerability levels of individual water subsystems in Shenzhen are more or less evenly distributed between the ranks of 1.5 and 1.8 in the 2000s. By contrast those in Shanghai are significantly lower with the only exception of the portable water system. In the 2050s, the vulnerability levels in Shenzhen will increase by varying margins from very small to moderate, with the waterway system, major pumping stations, and reclaimed water system leading the increase, while those in Shanghai will largely remain unchanged.

3.4. ICT sector

The ICT sector includes data centers, module offices, and tower/base stations. Fig. 3 shows that its current exposure level in Shanghai is similar to that in Shenzhen. The outlook for the 2050s indicates that the exposure level in Shenzhen will have a slight decrease while that in Shanghai will have a noticeable increase, resulting in a big difference between the two cities. Concerning the vulnerability level, Shenzhen has a higher level at present than Shanghai. By the 2050s, the lead by Shenzhen will extend because the extent of increase in the vulnerability level in Shenzhen is larger than that in Shanghai.

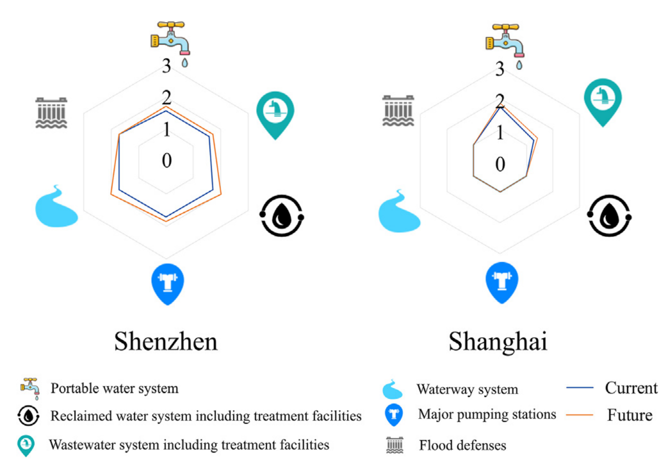

Fig. 6. Vulnerability level of climate hazard risks in the water sector in Shanghai and Shenzhen, from the 2000s to the 2050s.

Fig. 7 compares the vulnerability levels across the three subsystems. The distributions of the vulnerability levels across the three subsystems in the 2000s are similar in the two cities, with the shapes of two equilateral triangles. However, the vulnerability level in each of the subsystems in Shenzhen is noticeably larger. In addition, the extent of the vulnerability increases between the 2000s and the 2050s in Shenzhen will be larger than that in Shanghai. In Shanghai, noticeable increase will be present in the sub-sector of tower/base stations only.

3.5. Energy sector

The energy sector includes power stations, transmission networks, substations, and distribution networks. From Fig. 3 we can see that the current exposure level of the energy sector in Shanghai is much higher than that in Shenzhen and such relative positions will keep unchanged between the 2000s and the 2050s. With regard to the vulnerability level, surprisingly, a switch of the relative positions is observed in the two cities, with Shenzhen occupying a higher position than Shanghai both at present and in future.

Fig. 8 presents the vulnerability levels of the four subsystems. It shows an even distribution near the medium level in Shenzhen and an even distribution near the low level in Shanghai in the 2000s. By the 2050s, the evenly expanded vulnerability levels in Shenzhen will still be little lower than 2 and the less evenly expanded vulnerability levels in Shanghai will continue to be 1 except distribution networks (to be 1.14).

4. Results and discussion on adaptation options

For the identification and evaluation of adaptation options, we opted to focus on the roads system in Shanghai and Shenzhen. This infrastructure system has the most direct and visible connection to both surface flows and drainage systems. Meanwhile, roadblocks caused by floods and typhoon hazards result in the disruption of the transportation system directly.

From Table 2 we can see that of the 12 adaptation options, nine can be featured as management solutions, two nature-based green solutions, and one traditional grey engineering solution. It means that for the roads systems in Shenzhen and

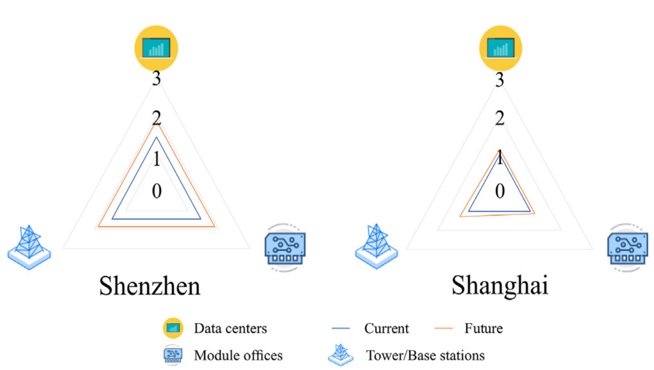

Fig. 7. Vulnerability level of climate hazard risks in the Information and communications technology (ICT) sector in Shanghai and Shenzhen, from the 2000s to the 2050s.

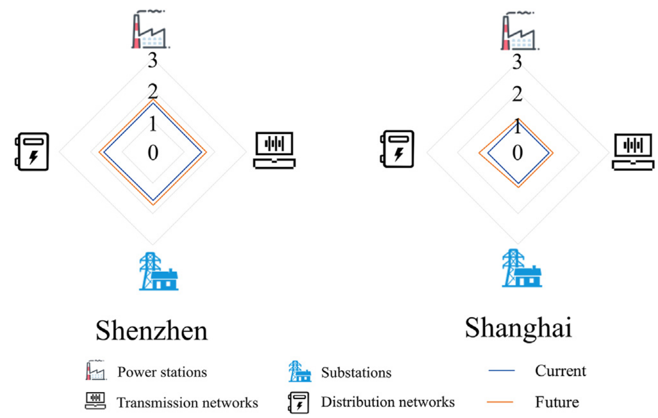

Fig. 8. Vulnerability level of climate hazard risks in the energy sector in Shanghai and Shenzhen, from the 2000s to the 2050s.

Shanghai, the experts in the sector are looking forward to implementing many adaptation options in the management field and they expect that such management advancements can play very significant roles in the future for managing climate change risk. A cross city comparison of these management options shows quite consistent levels of technical feasibility, flexibility, co-benefits, and policy compatibility between the two cities, with the only exception on technical feasibility of option 8. Of these nine management options, six (5−9 and 12) are highly compatible with the policy priority in using smart technologies for monitoring, data management, earlier warning, and planning. In terms of operational management, experts in both cities have emphasized the importance of emergency flood management (options 4, 6, 7, and 9) and an increasing frequency in maintenance (option 11). Interestingly, the communication across different sectors (option 8) is also highlighted, as an imperative part in increasing the efficacy of these adaptation policies.

The adoption of nature-based green solutions in flood management has been advocated and implemented in a stepwise fashion by policymakers in both cities. However, the differences exist in the efficacy categories of co-benefit (option 1) and technical feasibility (option 2). These differences are largely attributed to the geographical and meteorological conditions in the two cities as acknowledged by experts. For example, the difference in option 2 reflects the fact that Shenzhen has more natural water routes than Shanghai, the natural conditions of all water routes are degenerating, and it is more technically difficult and costly to realign natural water courses. Yet, the key difficulty in Shanghai roots in its existing drainage system, for which nature-based green solutions will have limited role to play (Hu et al., 2019). The city, especially in the center, has been heavily dependent on the drainage system with over 200 years of history. It is rather challenging to have a substantial change in the current system and therefore local policymakers may take an incremental approach (Option 3).

Costs associated with the options add an important dimension to the overall feasibility assessment. For example, in a short-time period, local policymakers in both cities are likely to focus on developing nature-based solutions (options 1 and 2), as well as upgrading their emergency flood management plans (option 6). While experts in Shanghai regard better communication and liaison across different departments and bureaus (option 8) and advancement of emergency warning systems (option 7) as immediate options, their counterparts in Shenzhen put a ‘sell-by date’ for these two options in 2025. Though smart technology has been seen as a critical strategic priority in integrating with current flood risk management (option 12), it is considered to be costly and may take a longer time to put into action.

5. Conclusions and discussion

This study demonstrated the advantages of the Climate Risk Assessment of Infrastructure Tool (CRAIT) in facilitating policymakers' decision-making and the feedback to scientific understanding in climate risk assessment. First, the tool enables the incorporation of the latest high-resolution climate data produced by the UK Hadley Center's PRECIS-2 regional climate model to present quantitative assessments of hazards and high-level estimates of changes in extreme weather events. This audience-friendly presentation allows stakeholders in the knowledge co-creation process, as facilitated by the CRAIT. to focus on adaptation policy considerations, instead of debating over the selections of hazards and climate events. Second, compared with the previous assessment framework (Sun et al., 2019), it details how vulnerability and criticality need to be taken into account in the key infrastructure sectors, at both the general system and the detailed sub-sector levels. This enables urban planners to more comprehensively and efficiently evaluate the critical factors contributing to the resilience of the urban infrastructure systems to the increasing risk and hazard caused by climate change. Third and mostly importantly, this index-based climate risk assessment tool can help to explore and compare the benefit and cost ranks of potential adaptation options for stakeholders.

We applied the CRAIT to Shanghai and Shenzhen, the two representative megacities in the Yangtze River Delta and the Pearl River Delta regions in China. Departing from previous work in developing and applying the index-based assessment framework (Sun et al., 2019) which permitted the application to a rather general level, this study analyzed and compared the extent of hazard exposure and vulnerability over time across five critical urban infrastructure sectors and then zoomed onto a specific sector − road infrastructure − to assess the climate risk and proceeding with policy options. The results show that the variation of vulnerability levels between the two cities are significantly larger than that of exposure. The sectors of critical buildings, water, energy, and ICT in Shenzhen have significantly higher vulnerability levels than Shanghai at the present and in the future (the 2050s). It is mainly because the much more rapid intensification of socioeconomic activities, more frequent typhoon attacks and the expected increase in the intensity of typhoon landfall events in Shenzhen (and the GBA) than in Shanghai. For example, Shenzhen has experienced a much more rapid growth in underground space and the number of high-rise buildings, and moreover, there exists a increasing number of slope-cutting houses in Shenzhen, which do not exist in Shanghai. These differences also lead to the variations in the adaptation measures that stakeholders and policymakers from the two cities have recommended.

By combining meteorological modelling results and expert engagement via the CRAIT, the results support the exploration of a wide variety of climate risks in a dynamic way, connects short-term targets and long-term goals. It demonstrated a useful way for policymakers to identify short-term actions while keeping options open for the future. It showed that by taking into account the cost-benefit balance, the approach built in the CRAIT is able to identify policies that are feasible. The engagement with policymakers as key stakeholders in climate risk management, has always been a real source given their experience in urban planning, flood risk management and other climate mitigation policymaking and implementations. It is because adaptation policies, which can be influenced by central government's strategic planning, need to take local contexts into account seriously for being more effective. There is no one size fits all, therefore, local policymakers do need to evaluate their existing climate risk assumptions, assess the potential likelihood of climate change, and consider different aspects based on status quo and anticipated targets.

While this study provided first-hand insights into a knowledge co-creation process in the effort to strengthen urban infrastructures’ resilience to climate risk and hazard, we acknowledge that there are few limitations that future research needs to address. First, the variations in the risk assessment between the two case cities tend to be converging over time from a long-term perspective. This could be due to the unpredictability or conservative estimations towards longer-term future from the participated stakeholders. Second, the two chosen cities are relatively advanced in infrastructure development and climate mitigation practices. Infrastructure experts and stakeholders in these two cities would tend to be more optimistic in their assessment of future climate risks and more, if not over, confident in evaluating the effectiveness of adaptation options. It is worth applying the CRAIT approach to other less-developed cities, where similar works would produce more remarkable variations.

Declaration of competing interest

The authors have declared no conflicts of interest for this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2022.02.003.

References

Adger, W.N., Brown, I., Surminski, S., 2018. Advances in risk assessment for climate change adaptation policy. Philos. Trans. A Math. Phys. Eng. Sci. 376. https://doi.org/10.1098/rsta.2018.0106.

Bhattacharyay, B., 2010. Estimating Demand for Infrastructure in Energy, Transport, Telecommunications, Water, and Sanitation in Asia and the Pacific: 2010–2020. https://doi.org/10.2139/ssrn.1678417.

Birkmann, J., 2006. Part I: Basic principles and theoretical basis. In Birkmann, J. (Ed.), 2006. Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. United Nations University Press, Tokyo Japan, pp. 9−77.

Cardona, O.D., van Aalst, M.K., Birkmann, J., et al., 2012. Determinants of risk: exposure and vulnerability. In: Field, C.B., Barros, V., Stocker, T.F., et al. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, pp. 65−108. https://doi.org/10.1017/cbo9781139177245.005.

Clark, W.C., van Kerkhoff, L., Lebel, L., et al., 2016. Crafting useable knowledge for sustainable development. Proc. Natl. Acad. Sci. U.S.A. 113, 4570−4578. https://doi.org/10.1073/pnas.1601266113.

Dawson, R.J., Thompson, D., Johns, D., et al., 2018. A systems framework for national assessment of climate risks to infrastructure. Phil. Trans. Math. Phys. Eng. Sci. 376, 20170298. https://doi.org/10.1098/rsta.2017.0298.

de Dominicis, M., Wolf, J., Jevrejeva, et al., 2020. Future interactions between sea level rise, tides, and storm surges in the world's largest urban area. Geophys. Res. Lett. 47. https://doi.org/10.1029/2020gl087002.

Dong, G.-T., Jiang, Z.-Y., Tian, Z., et al., 2020. A technical report on projected changes in extreme precipitation and temperature in the Yangtze River delta region during the 21st century. Earth Space Sci. 7, e2019EA001024.

Hu, H., Tian, Z., Sun, L., et al., 2019. Synthesized trade-off analysis of flood control solutions under future deep uncertainty: an application to the central business district of Shanghai. Water Res. 166, 115067. https://doi.org/10.1016/j.watres.2019.115067.

Jeuken, A., Reeder, T., 2011. Short-term decision making and long-term strategies: how to adapt to uncertain climate change. Water Governance 1, 29−35.

Jian, W., Li, S., Lai, C., et al., 2021. Evaluating pluvial flood hazard for highly urbanised cities: a case study of the Pearl River Delta Region in China. Nat. Hazards 105, 1691−1719. https://doi.org/10.1007/s11069-020-04372-3.

Kabisch, N., Korn, H., Stadler, J., et al., 2017. Nature-based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Springer Nature, Cham, Switzerland. https://link.springer.com/content/pdf/10.1007%2F978-3-319-56091-5.pdf.

Liu, J., Bawa, K.S., Seager, T.P., et al., 2019. On knowledge generation and use for sustainability. Nat. Sustain. 2, 80e82.

Meadow, A.M., Ferguson, D.B., Guido, Z., et al., 2015. Moving toward the deliberate coproduction of climate science knowledge. Weather, Climate, and Society 7 (2), 179−191. https://doi.org/10.1175/WCAS-D-14-00050.1.

Millward, R., 2007. Private and Public Enterprise in Europe: Energy, Telecommunications and Transport, 1830–1990. Cambridge University Press, Cambridge.

Nguyen, T.T.X., Bonetti, J., Rogers, K., et al., 2016. Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. Ocean Coast. Manag. 123, 18−43.

OECD (Organisation for Economic Co-Operation and Development), 2018. https://doi.org/10.1787/4fdf9eaf-en.

Quinn, A.D., Jack, A., Hodgkinson, S., et al., 2017. Rail Adapt: Adapting the Railway for the Future. A Report for the International Union of Railways (UIC).

Reisinger, A., Mark, H., Carolina, V., et al., 2020. The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Shi, P.-J., Yuan, Y., Zheng, J., et al., 2007. The effect of land use/cover change on surface runoff in Shenzhen region, China. Catena 69, 31−35. https://doi.org/10.1016/j.catena.2006.04.015.

Soroczynski, T., 2002. Integrated Systems Analysis and Sustainable Development. International Congress on Environmental Modelling and Software. https://scholarsarchive.byu.edu/iemssconference/2002/all/188.

State Council, 2021. Govt to Enhance Treatment of Urban Waterlogging. http://english.www.gov.cn/policies/latestreleases/202104/25/content_WS60852f92c6d0df57f98d88a8.html.

Straub, S., 2008. Infrastructure and Growth in Developing Countries: Recent Advances and Research Challenges. World Bank Policy Research Working Paper Series. https://ssrn.com/abstract=1080475.

Suarez, P., Anderson, W., Mahal, V., et al., 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. Transport. Res. Transport Environ. 10, 231−244. https://doi.org/10.1016/j.trd.2005.04.007.

Sun, L.D., Tian, Z., Zou, H., et al., 2019. An index-based assessment of perceived climate risk and vulnerability for the urban cluster in the Yangtze River Delta Region of China. Sustain. Sci. Pract. Pol. 11, 15. https://doi.org/10.3390/su11072099.

Tate, E., 2013. Uncertainty analysis for a social vulnerability index. Ann. Assoc. Am. Geogr. 103, 526−543.

Treasury, H.M., 2015. The Aqua Book: Guidance on Producing Quality Analysis for Government. HM Government, London. https://www.gov.uk/government/publications/the-aqua-book-guidance-on-producing-qualityanalysis-for-government. (Accessed 10 July 2017).

Wang, S., Toumi, R., 2021. Recent migration of tropical cyclones toward coasts. Science 371 (6528), 514−517.

Wang, S., Toumi, R., Ye, Q., et al., 2021. Is the tropical cyclone surge in Shanghai more sensitive to landfall location or intensity change? Atmos. Sci. Lett. 22 (10), e1058. https://doi.org/10.1002/asl.1058.

Yan, H., He, X., Lei, Y., et al., 2019. Land use-induced change in trophic state of Shenzhen Bay (South China) over the past half-century. Mar. Pollut. Bull. 145, 208−213. https://doi.org/10.1016/j.marpolbul.2019.05.046.

Yang, L., Scheffran, J., Qin, H., et al., 2015. Climate-related flood risks and urban responses in the Pearl River Delta, China. Reg. Environ. Change 15, 379−391. https://doi.org/10.1007/s10113-014-0651-7.

Yohe, G., Tol, R.S.G., 2002. Indicators for social and economic coping capacity-moving toward a working definition of adaptive capacity. Global Environ. Change 12 (2002), 25−40.