



# Delta management in evolution: a comparative review of the Yangtze River Delta and Rhine-Meuse-Scheldt Delta

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Received: 20 January 2020 / Accepted: 7 October 2020 / Published online: 31 October 2020  
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## Abstract

This paper aims to compare the Rhine-Meuse-Scheldt Delta in Europe and the Taihu Basin part of the Yangtze River Delta in China from a long-term historical perspective. Urbanized deltas are among the most prosperous and populated regions in the world, but also the most vulnerable. To cope with growing uncertainty, their systematic comparison has become instrumental in building mutual learning on the theory and practice of spatial planning and water resource management in such vulnerable contexts. Based on a systematic comparative mapping approach of Delta Urbanism with critical review of policies, this research highlights important similarities between these two deltas in terms of physical characteristics, dense occupation, and management history evolving from a decentralized polder-based system to a centralized control model, and a recent adoption of integrated and adaptive water management strategies. On the other hand, the comparison reveals distinct management focuses in current delta plans, as well as contrasting approaches to public participation and historical hydraulic landscapes. It is found from this comparative study that, beyond the socio-cultural specificities that can explain the distinct management practice of each region, the systematic use of mapping as a visualization and communication tool would facilitate integrative and adaptive delta management.

**Keywords** Delta urbanism · Integrated water resource management · Spatial planning · Mapping · Visualization · Taihu Basin

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## 1 Introduction

### 1.1 Urbanized deltas: prosperous and vulnerable

Deltas are amongst the most prosperous and densely populated places on Earth. Offering unique advantage for cultivation and water transportation, deltas have attracted human activities and settlements since early ages. Many deltas have been developed into flourishing agricultural and trading regions over time, resulting in some of the largest and fastest growing metropolitan regions in the world today (Saito 2001; Woodroffe et al. 2006; Shields 2008; Meyer and Nijhuis 2014). It is estimated that deltas are home to more than 7% of the global population (Day et al. 2016).

While densely populated and economically prosperous, urbanized deltas are extremely vulnerable. Because of their low elevation and impact of the surrounded lands, rivers and sea, deltas are by nature exposed to both riverine and tidal flood hazards (Nicholls 1995; Chan et al. 2012). In addition to natural factors, the vulnerability of urbanized deltas has been aggravated by human interventions and occupation. Several reports showed how large scale infrastructural works aimed at improving flood control, transportation, urban development and agricultural production have negatively impacted the natural mechanism of delta formation and resulted in increased coastal erosion, land subsidence, salinization of groundwater and ecological degradation (Meyer 2013; Welch 2017; Haas 2014). Most of these natural and human-induced risks are expected to be exacerbated due to rising sea-level and changing precipitation regimes as a consequence of climate change (Kabat and Vellinga 2011; Nichols and Cazenave 2010).

These intricate challenges demonstrate how aspects of spatial planning, water management and environmental protection are particularly intertwined in urbanised deltas. It requires a coordinated and integrated approach to deal with present issues and cope with future challenges.

### 1.2 Conceptualizing urban deltas

Urbanized deltas are very complex regions due to their natural dynamics and intense concentration of activities. To shed an insight into them, several models were developed to conceptualize deltas and to describe their transformation. Among these, a dual ‘co-evolutionary’ model conceives the development of deltas as the result of a constant interchange between natural environment and artificial (engineering) interventions (Welch 2017; Wang and Boelens 2018).

A similar but slightly more sophisticated model is the notion of ‘Delta Urbanism’ developed by a dedicated research group at the Delft University of Technology in the Netherlands. Combining the complex system theory (Mitchell 2009) and the layered cartographic reading of landscapes (McHarg 1969), Delta Urbanism conceptualizes urbanized deltas as a dynamic overlay of three layers of systems: the natural background, the infrastructural networks, and the occupation (Meyer and Nijhuis

2013). While each of these layers has its own logic and dynamic, they interact and mutually influence each other, most of the time in a non-linear and unpredictable way.

In this model, the historical evolution of deltas is conceived as a succession of ‘regimes’ or states of equilibrium within which a balance among nature, infrastructures and activities was established. Impacted from time to time by changes in the socio-economic context, technological innovations, or climate change, the balance among the three layers is disrupted. This can lead to different types of responses: resistance, resilience, or adaptation (Bucx et al. 2014).

According to Meyer and Nijhuis (2014), a majority of urbanized deltas in the world are currently in a transition phase. Stressed by the conflicting needs of protecting the socio-economic activities, restoring the ecological function, and anticipating the unpredictable consequences of climate change, most urbanized deltas need to adopt adaptive management strategies. It is in this context that the comparison of urbanized delta regions across the globe represents an insightful way to exchange fundamental knowledge and practical experience.

### 1.3 Learning by comparing

A series of recent major flooding disasters, such as hurricane Katrina in New Orleans in 2005 and storm Sandy in New-York in 2012, exposed to the world the limits of traditional hard-engineering infrastructures to protect coastal and deltaic urban areas. In response, the systematic comparison of deltaic regions from around the world has been increasingly considered as an exploratory method to gain insight into this. Initiated around the comparison of the Mississippi Delta with similar regions (Campanella 2010), the comparative appraisal of urbanized deltas has been theorized as a method thereafter (NRC 2013), experimented in various contexts (Tosi 2013; Bucx et al. 2014; Meyer and Nijhuis 2014; Welch 2017), and gave birth to dedicated international research platforms such as the Delta Alliance International.

As a research method, the comparative analysis of deltas can be multiple or paired (NRC 2013). Comparison across multiple cases allow for quantitative assessments (Bucx et al. 2014; Jeuken et al. 2014), while paired comparisons allow for more in-depth qualitative analogies, including a highlight of similarities and differences in terms of natural conditions, historical evolution and challenges, or management approaches (Glantz 1988; Meyer et al. 1998; Meyer and Nijhuis 2013; Zevenbergen et al. 2018). Although two deltas are never exactly the same, the parallel analysis and description of deltaic regions can contribute to mutual learning, such as the exchange of knowledge, the transfer of best practices, as well as lessons learned from failures. Also, by seeking similarities and stressing contrasts, the comparison of deltas can highlight the distinctive characteristics of each region, and hence inform decision-making on place-specific strategies.

## 2 Two comparable deltaic regions

### 2.1 Selection of the study areas

This paper brings in perspective two emblematic delta regions: the Rhine-Meuse-Scheldt Delta (RMS) situated in Europe and the Taihu Basin (TB) part of the Yangtze River Delta (YRD) in China. The two regions share a number of similarities with respect to their natural environment, historical evolution, socio-economic profiles and environmental challenges (Table 1). Both deltas are also regarded in international comparisons as the best practice of flood control and resilience (Bucx et al. 2014).

In paired comparative studies, the RMS Delta is often referred as a model of technological innovation and integration of water management and spatial planning (van Koningsveld et al. 2008; Zegwaard et al. 2019). In contrast, the YRD has not yet been subject to such systematic documentation and comparative analysis in the international literature, even though its infrastructure and management are considered as the most sophisticated in Asia (Bucx et al. 2014).

The territory of the RMS Delta, also known as the Low-Countries, covers a large share of the Netherlands and parts of Belgium. Due to the complex geomorphology of the delta and the inconsistent appellation of its river system, there is no conventional definition in the literature of the geographical boundaries of the RMS Delta. Different calculation methods evaluate its area between 20,000 km<sup>2</sup> (Meyer and Nijhuis 2014) and 25,000 km<sup>2</sup> (Tockner et al. 2009). To compare it with Taihu Basin, this research defines the RMS Delta region as the coastal zone with an altitude below 10 m above sea level (a.s.l.), and focuses exclusively on its Dutch part to reflect on national-level data and policies. As a result, the study area under investigation in this research covers 21,242 km<sup>2</sup>.

Likewise, the YRD is an ambiguous appellation that generally refers to the vast economic megacity region spanning across the four provinces of Shanghai, Jiangsu, Zhejiang and Anhui. Its geographical boundaries vary according to different studies and reports (Xu and Yeh 2010; Zhang et al. 2011; Zhu et al. 2016; The State Council of the PRC 2018). In this comparative study, the research area focuses on TB, a clearly defined drainage basin that corresponds to the most intensively urbanized part of the YRD. TB covers 36,895 km<sup>2</sup>, out of which 91% (around 33,414 km<sup>2</sup>) corresponds to a plain with an altitude less than 10 m a.s.l.

### 2.2 Methods of comparison

This research uses a combination of methods to describe and compare TB and the RMS Delta.

Firstly, literature review was conducted to explore the evolution of each study area in terms of spatial evolution and water management. Sources comprised both formal written sources such as papers, books, reports and chronicles, and graphic documentation such as ancient maps, paintings and photographs.

**Table 1** Comparative summary of physical, socio-economic and water features of the RMS and TB regions

	RMS	TB
River catchment area	243,000 km <sup>2</sup> (delta-alliance RMS)	1.8 million km <sup>2</sup> (Yang et al. 2015)
River water discharge (annual average)	85 km <sup>3</sup> /YR (Rijkswaterstaat 2005) <sup>a</sup>	900 km <sup>3</sup> /YR (Yang et al. 2015)
River sediment load	1.52 MT/YR (Rijkswaterstaat 2005) <sup>b</sup>	145 MT/YR (Yang et al. 2015) <sup>c</sup>
Delta area	Evaluated between 20,000 km <sup>2</sup> (Meyer and Nijhuis 2014) and 25,347 km <sup>2</sup> (Tockner et al. 2009) (ASTER 2011)	Taihu Basin: 36,895 km <sup>2</sup>
Total area < 10 m a.s.l.	21,242 km <sup>2</sup> (equivalent to 51% of the country's total area) (ASTER 2011)	33,414 km <sup>2</sup> (equivalent to 91% of Taihu Basin, and to 0.4% the country's total area) (ASTER 2011)
Land/water surface ratio <sup>d</sup>	69%/31% (ASTER 2011; OSM 2019)	71%/29% (ASTER 2011; OSM 2019)
Ratio of urban land cover (%)	Evaluated between 7.9% (Corine Land Cover 2012) and 17% (Meyer and Nijhuis 2014)	22% (TBA 2014)
Population living within the area < 10 m a.s.l. In 2019 <sup>e</sup>	11 million (equivalent to 63% of the country's total population) (ASTER 2011; CBS 2019)	57 million (equivalent to 4% of the country's total population) (ASTER 2011; NBSC 2018)
Average population density within the area < 10 m a.s.l. In 2019 [inh/km <sup>2</sup> of land surface]	519 inh/km <sup>2</sup> (National average = 521) (ASTER 2011; CBS 2019)	2,180 inh/km <sup>2</sup> (National average = 145) (ASTER 2011; NBSC 2018)
Gdp contribution of the area < 10 m a.s.l. <sup>f</sup>	71% (ASTER 2011; CBS 2019)	11.6% (TBA 2014)
Freshwater availability per capita [m <sup>3</sup> /person year]	600 m <sup>3</sup> (Delta Programme 2019)	350 m <sup>3</sup> (National average = 1998) (Ge et al. 2017)
Source of freshwater production	40% from surface water/60% from groundwater (Sjerps et al. 2017)	100% from surface water, with emergency groundwater reserves (TBA 2014)

<sup>a</sup>Calculation of water discharge in the RMS Delta: Rhine:  $2000 \text{ [m}^3/\text{s]} + \text{Meuse: } 230 \text{ m}^3/\text{s} + \text{Scheldt: } 120 \text{ m}^3/\text{s} = 85 \text{ km}^3/\text{year}$

<sup>b</sup>Note on sediment load in the RMS Delta: among the three rivers that feed the delta, the Rhine contributes to more than 80% of the total water discharge in the delta due to its catchment, but to less than 5% of the 1.52 million tons of sedimentation due to its long and flat profile

<sup>c</sup>Calculation of sediment load in the YRD:  $500 \text{ MT/YR}$  (in the 1950s) decreased by 71%<sup>g</sup> = 145 MT/YR (adapted from Yang et al. 2015)

<sup>d</sup>The land/water surface ratio in the area < 10 m a.s.l. was estimated by the authors by combining data from ASTER (2011) and (OSM 2019)

<sup>e</sup>The total population and population density in the area < 10 m a.s.l. was estimated by the authors by combining data from ASTER (2011) with the most detailed population statistics available on a municipal level in the Netherlands (CBS 2019) and county level in China (available from the Provincial Bureaus of Statistics of Jiangsu <https://tj.jiangsu.gov.cn/2019/nj03/nj0306.htm>, Zhejiang <https://zjzjmspublic.oss-cn-hangzhou-zwzynet-d01-a.internet.cloud.zj.gov.cn/> and Shanghai <https://tj.sh.gov.cn>.)

<sup>f</sup>The GDP contribution of the area < 10 m a.s.l. in the NL was estimated by the authors by combining data from digital elevation map (ASTER 2011) with economic statistics on a provincial level (CBS 2019), corrected by a factor of ratio of population living under 10 m a.s.l. In TB, the latest data available is provided by (TBA 2014)

**Fig. 1** Two comparable delta regions: the RMS Delta and TB regions share several commonalities in terms of **a** historical polder-based development, **b** landscape finely intertwining water, farmland and settlements, and **c** water quantity and quality challenges. (sources: (a) left: partial image of ‘Het Grootslag’, Anonymous 1606, copyright Stadhuis Enkhuizen; right: partial image of ‘Prosperous Suzhou’, 1759, public domain image, available at Wikipedia, [https://en.wikipedia.org/wiki/Prosperous\\_Suzhou](https://en.wikipedia.org/wiki/Prosperous_Suzhou); (b) and (c) left: national-water-plan-2016–2021 (NWP 2015); right: authors)

Secondly, a detailed and critical review of the most recent water management plan was conducted for each study area: the National Water Plan 2016–2021 (NWP 2015) for the RMS Delta, and the 2014 Taihu Basin Comprehensive Masterplan 2012–2030 (TBA 2014) for TB.

Thirdly, a systematic mapping of both regions was developed. Applying the technique of layered spatial analysis (McHarg 1969), mapping is particularly relevant in the frame of Delta Urbanism as it enables decomposing and comparing regions layer by layer in a systematic way (Nijhuis and Pouderoijen 2014). In addition, as an agent of visualization, mapping makes it possible to transcribe and interrelate information and data of different nature in a spatialized way (Corner 1999) as well as to establish a common language between stakeholders with different cultures and background (Carton 2007) (Fig. 1). The information collected from the review of the literature and management plans has been assembled, synthesized and translated graphically through mapping. Using a frame of 300 km × 300 km and data from open source international GIS databases (ASTER 2011; OSM 2019), a series of original maps were then produced to compare the RMS and TB study areas. A first set of maps provides an overview of the physical features in terms of natural background, infrastructural network, and occupation (Fig. 2). They are followed by paired maps representing the administrative management units (Fig. 3), and a summary of the main water and spatial challenges and the responses of the management plans (Fig. 4).

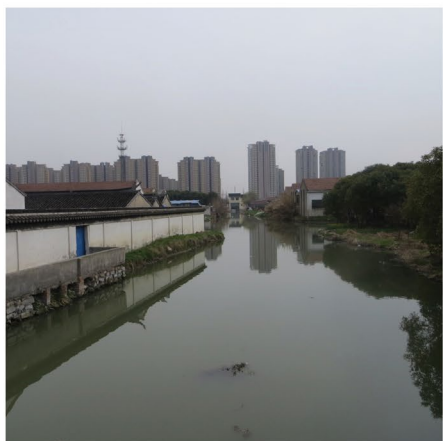
Finally, interviews were conducted to compensate the shortage of accessible data in TB study area. Interviewees included twenty experts from the government, research institutes, water boards and planning bureaus, and practitioners working in the region.

## 2.3 Comparing features

Applying the layered spatial analysis method of Delta Urbanism, Fig. 2 proposes a systematic comparison of the RMS Delta and TB in terms of (a) natural background, (b) infrastructure network, and (c) occupation (population density). The spatial analysis is complemented by data collected from various sources and the result has been summarized in Table 1.

### 2.3.1 Natural background

The formation of a delta is determined by the combined influence of river sediment input, wave energy, and tidal dynamics (Bradshaw and Weaver 1995). From this point of view, Table 1 shows that TB is, as a part of the YRD, a river-based delta. The catchment area, average water discharge and sediment load of the Yangtze River



**Fig. 2** Systematic comparison of the RMS Delta and TB in terms of **a** natural background, **b** infrastructural network, and **c** occupation (population density) (Sources: (a) authors, adapted from (OSM 2019) and (ASTER 2011) and (Zhu 2014); (b) adapted from (OSM 2019); (c) adapted from <https://luminocity3d.org/WorldPopDen/>, D. Smith, CASA UCL, 2016)

are respectively seven, ten and one hundred times more important than those of the Rhine, the Meuse and the Scheldt rivers together (Rijkswaterstaat 2005; Yang et al. 2015). The RMS Delta is mainly sea-dominated due to sand banks formed by strong tidal and marine currents (Rijkswaterstaat 2005).

Despite these distinct morphogenetic origins as described above, the two deltas share a relatively similar geomorphological layout. Figure 2a indicates the altitude of the two regions using grey and yellow colors according to three thresholds: the area below 10 m a.s.l. which is conventionally defined as the low elevation coastal zones potentially impacted by sea-level rise (McGranahan et al. 2007); the zones less than 5 m a.s.l., which is considered a common indicator to assess the exposure of delta regions to flooding risk (Meyer and Nijhuis 2014); finally, the areas below 2 m a.s.l. for TB (Zhu 2014), and areas below sea-level for the RMS Delta, which are evidently the most vulnerable. The comparison of maps reveals that both regions are flat plains, characterized by central lowlands bordered by slightly elevated coastal barriers formed by sand (RMS) or alluvial deposits (TB).

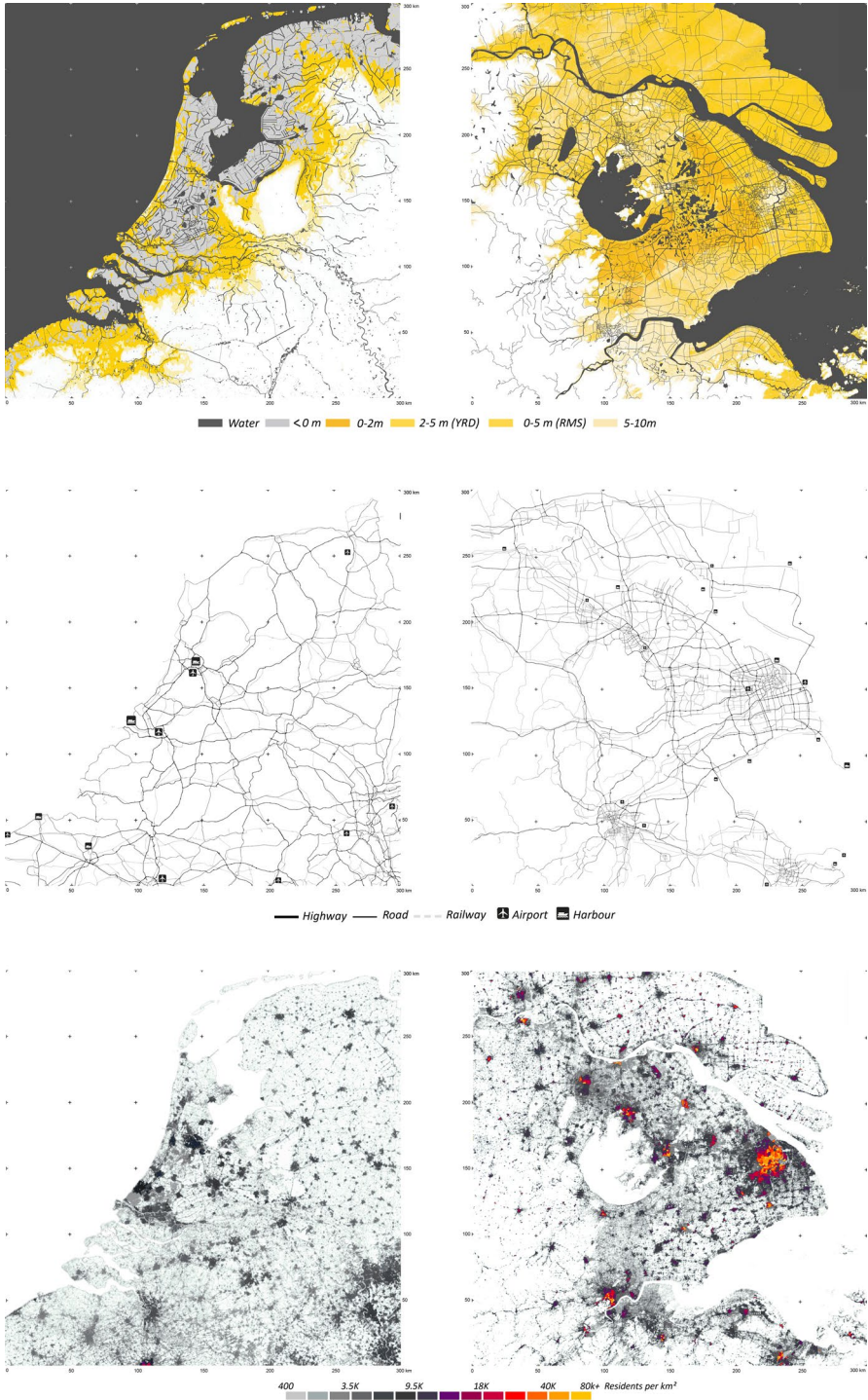
Another common feature of the deltas' natural background is the very fertile soil—composed of clay, sand and peat layers in the RMS Delta (Delta Alliance 2019) and of clay and silt in TB—as well as a dense water system. Water is present in both deltas in the form of estuarine river mouths, lagoons or lakes, alluvial wetlands, and an intricate network of creeks and small canals. These natural conditions—flat terrain, fertile soil, and abundance of water for irrigation and transport—explain the early and flourishing development of agriculture in both regions.

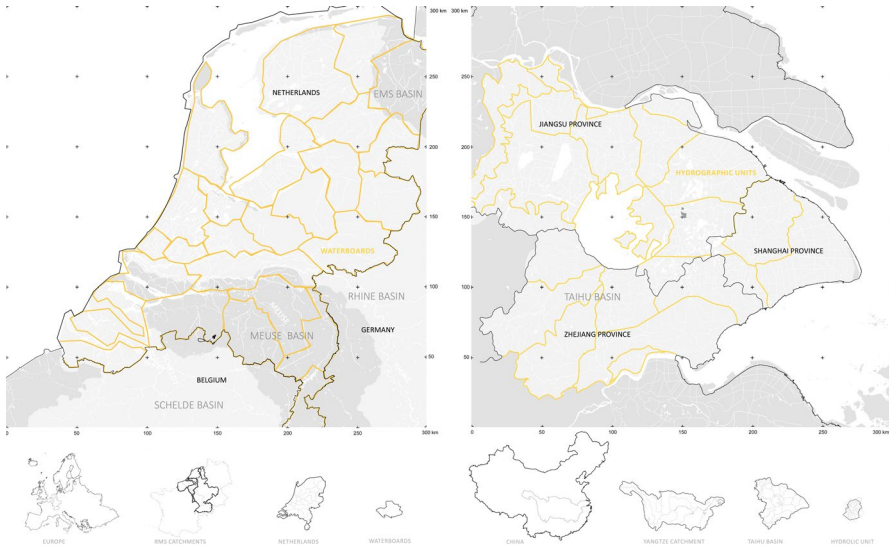
### 2.3.2 Cultural landscape: polders

Halfway between natural background and infrastructure, the construction of polders has been instrumental to the reclamation of land, management of water and development of agriculture in both delta regions. In the RMS Delta, isolated cases of small polders have been recorded since the tenth century. From the seventeenth century, the development of drainage techniques using windmill-powered pumps made polder construction evolve towards a territorial land reclamation system (van de Ven 2004). As a result, 26% of the Netherlands' current land is reclaimed from the sea and lies below sea level (AHN 2019). This portion of land is home to 3.93 million people, equivalent to 23% of the total population (Hoes and Hut 2015).

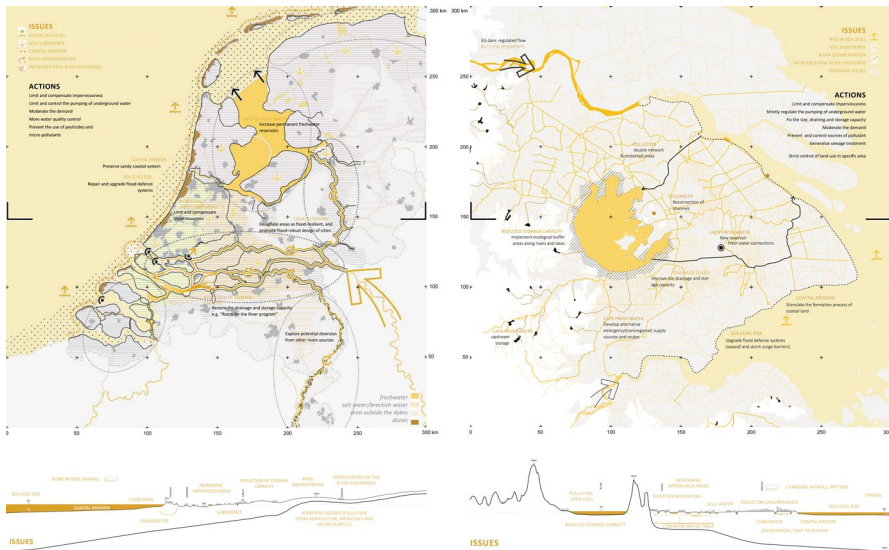
In TB, similarly, the construction of polders has been fundamental to the gradual consolidation and prosperous development of the delta region (Nolf et al. 2019). From the early reclamation of lakes since 500 BC until the contemporary construction of large-scale polders, successive types and generations of polders have shaped the agricultural landscape, regulated the water flows and determined the locations







**Fig. 3** Hydrographic, administrative and management entities of the RMS Delta and TB—situation in 2016 (source: authors)



**Fig. 4** Schematic maps and territorial cross-sections visualizing the main water challenges and responses of the latest water management plan of the RMS Delta and TB regions (Sources: left: adapted from (NWP 2015: Fig. 4); right: authors; cross-sections: authors)

and morphologies of villages and towns (Zheng 1987; Xie 2017). In total, 2539 polders today cover around 28.8% of the total basin area (Huang et al. 2017).

Although the polders explain the structure of rural landscapes and pre-modern cities in the two deltas (Hooijmeijer et al. 2005; Nolf and Vannoorbeeck 2018), they have not been considered as equivalently important in contemporary water management approaches. In the RMS Delta, polders have long been the subject of inventories and conservation programs aimed at preserving part of their cultural and historical features (Vervloet et al. 2003; Janssen and Knippenberg 2008; Steenbergen et al. 2009; de Boer 2020). In TB, in contrast, the historical value of the polder system has only been recognized recently by researchers, but has not yet been formally incorporated into the landscape conservation programs.

### 2.3.3 Infrastructure networks

In terms of infrastructure, the RMS Delta and TB are major maritime gateways of their regions and they host the largest ports of Europe (Rotterdam and Antwerp) and the world (Shanghai) respectively. In addition to sophisticated hydraulic infrastructures that regulate the water system, the two regions are covered with a very dense network of roads, motorways, railways and subways that ensure a distributed accessibility throughout the entire plain. Since good transport infrastructure can facilitate socio-economic activity, these two delta regions contribute to a significant share of their own national economy. The study area of the RMS Delta occupies 51% of the national territory and contributed to 71% of the GDP of the Netherlands in 2019 (CBS 2019); TB covers 0.4% of China's total surface, but contributes to 11.6% of its GDP (TBA 2014).

Nevertheless, the infrastructure networks in the RMS Delta and TB differ in terms of layout. Figure 2b shows how the RMS is characterized by a polycentric radial structure interconnecting numerous urban and logistical centers. TB, in contrast, the infrastructure networks is characterized by a grid of motorways that densify around Shanghai. While more or less completed and stable in the RMS, the network of infrastructures in TB is still expanding rapidly, catalyzed by the recent construction of bridges across the Yangtze and Qiantang estuaries and the relocation of the offshore harbor.

### 2.3.4 Occupation

In terms of occupation, the land cover of both deltas is dominated by agriculture, followed by a high percentage of urban land estimated to 22% in TB (TBA 2014), and varying in the RMS Delta from 7.9% to 17% according to different measurement methods (Corine Land Cover 2012; Meyer and Nijhuis 2014). Occupation can also be defined by the density of population. The combination of elevation data (ASTER 2011) with population statistics (CBS 2019) shows that the total amount of people living below 10 m a.s.l. in the RMS Delta can be estimated to 11 million, which is equivalent to 63% of the country's total population and corresponds to an average density of 511 inhabitants per km<sup>2</sup>. In TB, the total amount of inhabitants living in the area below 10 m a.s.l. was 57 million in 2018, which was equivalent to 4% of

China's population and corresponded to an average density of 2180 inhabitants per km<sup>2</sup> (ASTER 2011; NBSC 2018).

Figure 2c represent more precisely how these human concentrations are distributed spatially (Smith 2016). In the case of the RMS Delta, except the 'Randstad' conurbation of main cities along the coast and a constellation of middle-sized cities, a large part of the population is spread homogeneously in a continuous and low dense pattern that covers the entire region. It should be noted that the dispersed occupation of the RMS Delta is a long-standing phenomenon favored by the high productivity of the soil, the high accessibility by water and early roads, as well as a governance model traditionally supporting decentralized political organizations (Boelens 2014).

In TB, human occupation is also characterized by spatial dispersion. Next to Shanghai (24 million inhabitants) and a series of highly interconnected cities of 1 to 5 million inhabitants, the so-called rural areas of TB are also densely and evenly populated. Historical studies show that the dispersion of population in TB is the result of an initial dense network of rural settlements, which had been consolidated from the 1950s to the 1980s by a series of government-led industrialization programs aiming at an *in-situ* urbanization of the countryside (Fei 1939; Friedman 2005; Zhang 2018).

### 3 Delta management: comparing the evolution, challenges and responses

#### 3.1 Management levels and units

The 'low elevation coastal zone' (less than 10 m a.s.l.) of the two delta regions under investigation in this paper span across several administrative territories, and their water management depends on an overlay of authority layers (Fig. 3).

At the highest level, the management of the RMS Delta depends on three International River Basin District Commissions respectively for the Rhine, the Meuse and the Scheldt.<sup>1</sup> Established in 2002 as part of the European Water Framework Directive (EU 2000), these commissions coordinate issues relating to water resource allocation, regulation and quality control across national boundaries. At the national level (in the Dutch part only), the Ministry of Infrastructure and Water Management defines a National Water Plan that includes a 'structural vision on infrastructure and space'. Being revised every six years, the vision is then translated into concrete management plans and programs at national, basin and sub-catchment levels, where local water boards ensure the implementation process. Complementarily to the hierarchical organization, a transversal Delta Commission established in 2008 is in charge of stimulating public consultation

<sup>1</sup> The RMS Delta depends from three International River Commissions: Rhine (ICPR) [www.iksr.org](http://www.iksr.org); Meuse Commission (IMC) [www.meuse-maas.be](http://www.meuse-maas.be); Scheldt (ISC) [www.isc-cie.org](http://www.isc-cie.org).

and cross-sectoral collaborations in the delta area, as well as preparing an annually updated Delta Programme (Delta Programme 2009; Boezeman et al. 2013).

For TB, the highest managing authority is the Changjiang (Yangtze) Water Resources Commission, which was recently overseen by the new Ministry of Ecological Environment. This authority produces comprehensive masterplans for the monitoring, planning and management of water resources of the entire Yangtze River catchment. The latest version of the plan covers the period 2012–2030. At the scale of TB, the Taihu Basin Water Resource Authority is in charge of water resource monitoring, management and planning in TB since 1984. More locally, water is managed by eight hydrologic units that were outlined according to the topographical and water system features, administrative boundaries, and the distinctions of water management measures (Wang 2006). The Taihu Basin comprehensive masterplan (2012–2030) adheres to the combined governance at both the basin and sub-units levels, and it clarifies the specific strategies respectively for each unit via adapting to the local water conditions and the benefits of local hydraulic departments.

This comparative overview of delta management units is, however, limitative. It only provides a snapshot of current management organizations that have been in constant evolution. To address the mutual learning objective ambitioned in this paper, it appears more instructive to look at management practices from an evolutionary perspective, as a succession of ‘regimes’. The following examines how, in different phases, management practices in each delta have shifted their priorities, adopted new paradigms, developed new instruments and reorganized their structures to cope with changing conditions.

## 3.2 Evolution of delta management in the RMS delta

### 3.2.1 Phase 1 (before the 1950s): decentralized and organic self-management

Originally, the management of water and space in the RMS Delta was distributed among a myriad of polders. For each polder, a small dedicated water board was in charge of constructing, controlling and maintaining the dikes, sluices, and mill infrastructure (Raadschelders and Toonen 1993). From the seventeenth century, the upscaling of the polder system coincided with an upgrading of water boards into autonomous socio-economic and political entities with their own tax and judicial systems. Although the number of water boards was reduced by merging them from 2650 in 1950 to 21 today (DWA 2017), they still have a strong influence on the decentralized management philosophy of the delta and the country, according to Boelens (2014).

### 3.2.2 Phase 2 (1950s–1990s): centralization and resistance

From the nineteenth century, the creation of centralized and country-level public works ministries such as the ‘Agency for Public Works and Water Management’, known today as *Rijkswaterstaat*, has been instrumental to the formation of the Dutch

nation-state (Bosch and van der Ham 1998; Meyer 2016). It was nevertheless a devastating flood in 1953 and an ambitious coastal defence program developed in response in 1958 that definitely triggered a shift to a centralized system based on a paradigm of resistance (Gerritsen 2005). Known as the Delta Works, the coastal defence program entailed the construction a new seawall dike system equipped with storm surge barriers and transport infrastructure. The works not only completely reconfigured the natural function of the delta and its management, but also enabled and stimulated a new wave of urbanization in the delta plain, based on the road system and largely independent of the logics of water (Meyer and Nijhuis 2013).

### 3.2.3 Phase 3 (1990s–2000s): integration and work with nature

Celebrated for several decades as a heroic demonstration of human power over nature and as an agent of national identity and unity (Meyer 2016), the Delta Works have gradually come under criticism for their high maintenance cost, negative ecological impact, and inability to respond to new flood risk originating from peak river discharges (Disco 2002; Ysebaert et al. 2016). In response, new approaches were put forward since the 1990s by promoting preventive, integrative and environment-friendly alternatives that combined flood protection with land-use planning and nature-compatible design solutions (Kabat et al. 2009; van Buuren et al. 2011). Concrete projects, including the ‘Room for the River’ program (2006–2015), have been accompanied by institutional reform, such as the integration of spatial planning and water management competences under the same ministry.

### 3.2.4 Phase 4 (2008- on): climate change and adaptive management

In the latest phase of development, a growing awareness of climate and socio-economic change has motivated the profound revision of instruments and approaches. Influenced by the concept of Complex Adaptive System, existing institutions and legal frameworks were made more open and flexible (Dammers 2014). In addition, new planning instruments were created, such as the National Water Plan which would be revised every 6 years since 2009, and a Delta Program which would be updated annually. The adaptive philosophy of the Delta Program is reflected in key principles such as the synchronization of investment agendas from different sectors (e.g., flood risk management and freshwater supply), and the preparation of alternative planning strategies (Adaptive Delta Management 2017).

## 3.3 Evolution of delta management in Taihu Basin

### 3.3.1 Phase 1 (before 1949): polder-based management

The construction of rudimentary polders has been recorded in TB since 500 BC (Miao 1982; Zhao and Liu 2003). However, it is the construction of the Grand Canal during the Tang Dynasty (618–906) that is generally associated with the birth of water management in the region. By regulating the tumultuous flows of water that

repeatedly inundated the delta plain, the Grand Canal enabled the development of a large-scale polder system known as *Tangpu*, which in turn facilitated the growth of agriculture in the entire plain (Zheng 1987). From the thirteenth century, the centralized system fell into decay and fragmented into an organic system of small and self-managed polders. This decentralized polder model nevertheless enabled agriculture and urbanisation—including the famous water towns—to continue to prosper until the nineteenth century (Xu 2006).

### 3.3.2 Phase 2 (1949–1984): rationalization of the polder landscape

Shortly after the foundation of the People's Republic of China in 1949, a major flood disaster devastated Taihu Basin in 1954. This disaster, breaking eighty percent of the small polders in the plain's area, revealed the vulnerability of the inherited decentralized system (Wang 2006). Similar to the reaction of Dutch authorities to their 1953 flood, the newly created Chinese Ministry of Water Resources set up a vast protection and rationalization plan for the delta region, followed in the next decades by several infrastructure works and programs of polder merging that combined flood defence, water supply and food security objectives (Fang et al. 1997).

### 3.3.3 Phase 3 (1984–2002): comprehensive control plans, industrialization and generic urbanization

In the 1980s, new commissions were created for the seven major river basins and sub-catchments of China to coordinate local flood control, water resource management and infrastructure projects.<sup>2</sup> Founded in 1984, the Taihu Basin Authority played a major role in the development of a Comprehensive Water Control Plan (1991–2000) that, in response to another major flood disaster in 1991, systemized the use of concrete embankments, gates, valves, and pumps. By effectively reducing the frequency of floods, the mechanization of the water system has enabled the massive development generic forms of urbanization independent from the logics of pre-existing water landscapes (Nolf et al. 2019). At the same time, the segmentation of the network of canals and lakes led, together with the intensive development of polluting industrial activities, to a significant deterioration of the ecological quality and ecosystem functioning in the region (Xie et al. 2017; Zhang et al. 2017; Chen et al. 2018; Xu et al. 2019).

### 3.3.4 Phase 4 (2002–2014): gradual integration and environmental concern

From 2002, successive revisions of the Chinese Water Law were undertaken to promote more integrative and preventive approaches to water management (NPC 2002; Cosier and Shen 2009). These reforms coincided with a pollution disaster in Taihu Lake that caused a major water supply crisis and revealed the critical importance of

<sup>2</sup> The seven large river basins of China are Changjiang (Yangtze), Yellow River, Huaihe, Haihe, Pearl River, Song-Liao, and Taihu.

maintaining water quality (China Dialogue 2007; Qin et al. 2010). The latest Taihu Basin Comprehensive Masterplan (2012–2030) reflects these environmental concerns with an explicit emphasis on water security, pollution control, and ecological restoration (TBA 2014). The plan also mentions aspects of management and communication, such as a ‘improving the consciousness of disaster control in the society’, without actually suggesting how to implement them (TBA 2014).

### 3.4 Comparing the evolution: parallel trajectories

The historical review of management approaches in the two delta regions reveals a comparable succession of ‘regimes’. In both cases, an initial organic and decentralized management model based on polders was replaced, in response to a major flood disaster, by a centralized and comprehensive water control model in the mid-twentieth century. Focused on flood defence and infrastructure works, water management in this period was at the same time instrumentalized as an agent of national identity and unification. The works not only consolidated the two regions as coherent territories and facilitated their urbanisation, but also severely impacted the natural formation of the deltas and their ecological function. At the turn of the twenty-first century, growing environmental concerns led to a paradigmatic shift from resistance to resilience, with the adoption of integrated water resource management principles and a decentralization approach of water management responsibilities (Wesselinck et al. 2015). While TB reached the phase of integration recently, the RMS Delta has already moved to the next level of adaptive delta management (Dammers 2014).

The similar evolution, albeit each time pioneered by the Dutch case, could be interpreted as parallel trajectories in which the RMS Delta plays an exploratory role for TB. From this perspective, the Chinese delta region can learn not only from successful experiments conducted in its Dutch counterpart, but also from obstacles and failures, such as the unexpected post-realization maintenance costs of the ‘Room for the River’ program that had not been fully anticipated (Warner and van Buuren 2011).

### 3.5 Comparing current challenges and responses

Figure 4 visualizes and compares spatially the water challenges currently faced by each delta and the strategies proposed in response in their latest management plan. Borrowed from the Dutch National Water Plan (NWP 2015), the map of the RMS uses graphic textures and diagrammatic symbols to represent the current water issues and the strategies adopted in response. The map of TB was produced by the authors using the same graphic codes as the RMS Water Plan map to visualize the main water challenges and the written recommendations of the Taihu Basin Masterplan. The two maps are each supplemented by a territorial cross-section produced by the authors, offering an additional perspective to the challenges.



**Table 2** Summary of the RMS Delta's main water issues, their causes, and the strategies and actions adopted in response by the Dutch National Water Plan (2016–2021), evaluated in terms of solicited system-layers: natural background (N), infrastructural network (I), and occupation (O) layer. (Source: authors, adapted from NWP 2015)

Main water issues	Main causes or driving factors ( <i>italic = linked to climate change</i> )	Strategies/actions	System layers activated			
			N	I	O	
Flood from the sea	Coastal erosion due to tidal energy <i>Sea-level rise</i> <i>Sea storms</i>	Repair and upgrade flood defence systems (seawall and storm surge barriers) Preserve and reinforce sandy coastal barriers with sand replenishments		x		x
Flood from the rivers	Peak river discharges due to: <i>More intense rainfalls</i> Increased impervious areas Reduced storage capacity River sedimentation	Restore the drainage and storage capacity of the river and canal system: e.g., 'Room for the River' program Dyke improvement: e.g. increase of dyke height Limit and compensate imperviousness		x		x
Local flooding	Land subsidence due to the excessive pumping of underground water Limited storage capacity in urban areas due to soil sealing	Limit and control the pumping of underground water Limit the consequences of flooding: designate areas as flood-resilient, and promote flood-robust design of cities				x
Lack of fresh water	Excessive demand due to population growth <i>Seasonal disparities in supply</i> Lowering groundwater resources Salinization of intake points	Moderate the demand through tariffs and information campaigns, adjust the distribution during low water, and encourage the reuse of water Further increase permanent freshwater (lake) buffers Explore potential diversion from other rivers sources Scale up erosion control dams			x	x
Water quality	Nonpoint source pollution from agriculture, medicines and micro-plastics	Non-point source pollution control Prevent the use of pesticides and micro-pollutants				x

See Sect. 4.2 for more details

**Table 3** Summary of TB's main water issues, their causes, and the strategies and actions adopted in response by the Taihu Basin Comprehensive Masterplan (2012–2030), evaluated in terms of solicited system-layers: natural background (N), infrastructural network (I), and occupation (O) layer (Source: adapted from TBA 2014, complemented by interviews of experts)

Main water issues	Main causes or driving factors ( <i>italic = linked to climate change</i> )	Strategies/actions	System layers activated		
			N	I	O
Flood from the sea	Coastal erosion due to reduced supply of sediments Sea-level rise <i>Typhoon</i>	Upgrade flood defence systems: seawall and storm surge barriers Stimulate the natural process of coastal formation with sediment trapping infrastructures	x	x	x
Flood from the rivers	Peak river discharges due to: <i>More intense rainfalls</i> Increased impervious areas Reduced storage capacity River sedimentation	Compensate and reduce imperviousness through programs like the Sponge City initiative (2014-on) Improve the drainage and storage capacity of the plain through the dredging of rivers, canals and lakes, and the construction of new 'flooding roads'	x	x	x
Local flooding	Land subsidence due to the excessive pumping of underground water Limited storage capacity in urban areas due to soil sealing	Strictly regulate the pumping of underground water Fix the total draining and storage capacity of the water system: no landfill is allowed, unless a compensatory waterbody is created elsewhere	x	x	x
Lack of fresh water	Excessive demand due to population growth <i>Seasonal disparities in supply</i> Lowering of the water table Salinization	Designate areas as flood-resilient and design 'flood-robust cities' Moderate the demand: reduce consumption, use more efficiently and recycle water, water saving facilities, etc Designate reserves and protected zones for water functions (intake, cleaning, etc.) Create new fresh water upstream storage and reservoirs for seasonal storage and (transregional) emergency water supply routes	x	x	x

Table 3 (continued)

Main water issues	Main causes or driving factors ( <i>italic = linked to climate change</i> )	Strategies/actions	System layers activated		
			N	I	O
Water quality	Lack of wastewater treatment Polluting land uses (agriculture and industries) Stagnant waters, due to the flat terrain and fragmentation of the water network	Generalize sewage treatment Prevent and control strictly sources of pollutant discharge Strict control of land-use in specific water functional zones with 'The Three Red Lines' policy: e.g., forbid polluting industrial and agricultural activities in a 5 km radius around Taihu Lake's shoreline		x	
		Reconnect the network of drainage channels, with a distinct channel system dedicated to the drainage of waste water ('double water network')			x
		Implement ecological buffer areas along rivers and lakes (e.g., wetland (re)construction around Taihu Lake)		x	x

See Sect. 4.2 for more details

In addition to the maps, Table 2, 3 summarize the main water issues, the driving factors, the strategies and the actions proposed in the water plan of each delta. The causes and driving factors are listed independently, even though some factors are intricately interconnected, such as sea-level rise, coastal erosion and salinization. However, their one-by-one enumeration helps to disentangle the complex mechanisms at work in the deltas and to identify the factors linked to climate change.

## 4 Discussion

### 4.1 Common challenges and human-driven factors

The numerous water issues identified in the RMS Delta and TB water management plans indicate that the balance between the three systems (i.e., natural background, infrastructure networks and occupation) is unstable and requires continuous adaptations. As summarized in Table, 2, 3, the water issues in both contexts are essentially linked to flooding, lack of fresh water resources, and water pollution. Some of these issues—such as flooding or stagnant water—are inherent to the natural vulnerability of these low-lying plains with limited storage and drainage capacity. The majority of other issues, however, can be interpreted as the consequence of human-driven factors.

A first group of human-driven factors impacting the delta are linked to interventions on the river and estuarial systems. In the case of the Yangtze, it has been estimated that the implementation of more than 50,000 dams in its entire catchment since the 1950s (including the recent Three Gorges Dam built in 2003) has caused a 70% reduction of silt discharge in total (Yang et al. 2015), which in return aggravates coastal erosion and salt water intrusion in the delta (Li et al. 2012). In the RMS, the implementation of storm barriers and dikes as part of the Delta Works has disrupted natural sediment fluxes and negatively affected derived ecosystem services, and thus requires additional maintenance and management efforts (van Wesenbeeck et al. 2014; Ysebaert et al. 2016).

A second group of human-driven factors are related to the occupation of the delta itself. In both regions, the excessive runoff due to soil sealing and land subsidence due to excessive pumping of ground water have been, although now closely monitored, aggravating the risks of flooding and salinization of aquifers (NWP 2015; Shi et al. 2012). In terms of water pollution, no existing study makes it possible to compare the two regions according to a same water quality index. However, local reports indicate that the overall water quality in the RMS Delta has ‘improved substantially in recent years’, with the exception of the persistence of medicines, micro-plastics and chemicals (NWP 2015). In TB, in contrast, the water quality remains severe due to point pollution source from untreated industrial and sewage outlets, and nonpoint pollution source from agricultural nutrients and waterway transportations (TBA 2014; Yao et al. 2015; Lin et al. 2015).

The issue of water quality in the deltas is particularly critical given the high demand for fresh water from the dense population and intensive agricultural and industrial activities. Produced by 40% from surface water in the RMS Delta (Sjerps

et al. 2017), the fresh water availability per capita in this region is around 600 m<sup>3</sup>/person year (Table 1). This amount has until now been sufficient to meet the annual demand but may become scarce in case of droughts (Delta Programme 2019). In TB, all water supply is produced from rivers and lakes as the exploitation of groundwater has been prohibited since 2005 to prevent land subsidence. However, it has been estimated that in the period 2003–2016 more than 70% of surface water in TB could not meet the national standards for drinking water (TBA 2014; Lou et al. 2019). As a consequence of pollution, despite abundant natural precipitations and natural reservoirs, the annual amount of fresh water per capita in TB is limited to 350 m<sup>3</sup>/person year, equivalent to half of the demand (TBA 2014; Ge et al. 2017). In return, this requires considerable and extra investments in terms of water inflows.

Climate change, finally, as an indirect but significant human-driven factor, will aggravate current risks. Tables 2, 3 highlight in particular how the rise of sea-level and the changing rainfall patterns will exacerbate seasonal disparities in water supply and increase the frequency and intensity of flooding in both delta regions.<sup>3</sup>

## 4.2 Comparing the responses in system-layers

Tables 2, 3 review the measures of water management plans in response to water challenges. In the form of policies, regulations, or physical transformations, these responses solicit the three system-layers of natural background, infrastructural network, and occupation, either independently or in combination.

*Natural background* The strategies and actions involving the natural background are essentially aimed at restoring and reactivating the natural mechanisms of formation and regulation of deltas. Applied to address both issues of water quantity (flood risk management) and to control and improve water quality, the reactivation of the natural system is best exemplified in TB with the reconstruction of wetlands and the reconnection of canals and rivers networks. In the RMS, ‘natural’ measures consist of the replenishment with sand of the coast and the ‘Room for the River’ program that reclaims the drainage and storage capacity of the river system. It must be noted that the ‘natural’ strategies in the highly artificialized contexts of TB and the RMS are not aimed to substitute the existing engineered infrastructural system, but rather to complement it to increase its flexibility and resilience.

*Infrastructural network* In both deltas, measures focused on infrastructure prevailed in the years 1950–80 with the construction of dikes, seawalls, storm surge barriers, and reservoirs. Today, these infrastructures must be upgraded to respond to new risks associated with climate change and changing demands. In TB, hard engineering solutions remain the dominant paradigm, with the creation of additional

<sup>3</sup> In the RMS Delta, climate change scenarios forecast a 25–80 cm rise in sea levels by 2085, and an increase by 12.5% (Rhine) and 20% (Meuse) of peak discharge in the rainy season, and drier summers with low discharges diminished by 40% to 50% (NWP 2015). In the YRD, the rate of sea-level rise in the delta was 2.4 mm per year in 1981–2015 (Wang et al. 2018a, b). In 2000, it was estimated that relative sea level around the YRD would rise 25–50 cm by the year 2050 (Shi et al. 2000). The annual precipitation in the YRD will increase by 1–10%, and flooding frequency and intensity will increase by 5%–8% (Gu 2011).

drainage channels and reservoirs to address issues of flood risks and water supply. In the RMS Delta, existing water infrastructures are essentially repaired and scaled up, while complemented by ‘soft’ engineering solutions related to the occupation of the land.

*Occupation* In the densely populated TB and RMS regions, a large number of strategies are focused on the occupation of the delta and its resources. In both deltas, specific regulations and tariffs targeting a moderated consumption of water are accompanied by land use regulations aiming at limiting imperviousness and pollution. Restrictive planning measures preventing polluting agricultural and industrial activities are complemented by proactive measures designating flood-resilient areas and fostering the design of flood prone forms of urbanization—such as the Sponge City program in TB (Chan et al. 2018).

### 4.3 Contrasted approaches to historical landscapes and public participation

Besides the many similarities, the comparison of water management plans in the two deltas also stresses significant differences. Some differences are logically related to the type of challenges faced by in each context, with a stronger emphasis on flooding issues in the RMS Delta, and water quality issues in TB. Beyond these structural motives, other differences are reflecting distinct cultural approaches.

A first major difference relates to the consideration of historical hydraulic landscapes in contemporary management approaches. As mentioned above, the traditional system of polders and dikes in the RMS Delta is recognized and protected not only as cultural landscape (Janssen 2009; Steenbergen 2009), but also as the heart of contemporary ecological and water management strategies. In contrast, the polder system of TB has been, to date, largely ignored. Except a few very recent studies (Guo 2016; Xie 2017; Xie and Nolf 2020), the centuries-old landscape is generally ignored by current agriculture land consolidation or ecological restoration programs. This gap is an invitation to better understand the decentralized and adaptive logics of indigenous agriculture landscape and urbanism, and to explore how these logics could potentially find new relevance today (Yuan 2016).

A second main difference resides in the role of public awareness and participation. The benefits of public participation have since long been acknowledged in the European context (Blomqvist 2004), and are reflected in the planning of the RMS Delta by a vivid culture of communication, public consultation and debates supported by a profusion of didactic brochures, interactive websites, and open access databases.<sup>4</sup> In contrast, delta management in TB remains limited to a univocal, one-way form of communication. Although participation and transparency have been formally encouraged from 2002 by the Chinese Revised Water Law and is mentioned in the latest Masterplan of TB (TBA 2014), Chinese bureaus remain reluctant to sharing information and reports with the public and other departments (Yang and Griffith 2010).

<sup>4</sup> See for instance [www.onswater.nl/](http://www.onswater.nl/) or websites related to specific programs: <https://www.ruimtevoorderivier.nl/>; <https://www.platformparticipatie.nl/>.

This major difference can be explained by the status of land. In the Netherlands, the ownership and use of land is defined by a multitude of owners and actors. The active involvement of every stakeholder in a participatory and co-productive process is thus a prerequisite to any change (Chen et al. 2019). In the Chinese context, land is owned and regulated by the state, which makes public participation only accessory. However, according to some previous researches, the lack of participation and transparency of public authorities in water management and planning in China weakens the legitimacy of law enforcement by authorities, which can potentially trigger public resistance (Yang et al. 2013).

## 5 Conclusion

This paper addressed the question of delta management in the RMS Delta and the TB part of the YRD. Combining the systematic comparative mapping approach of Delta Urbanism with historical analysis and critical policy review as a methodology, this research unveils important similarities between the two regions in terms of physical features, intense occupation, water challenges and human-driven factors at the origin of these challenges. In addition, the parallel retrospective of water management practices in each delta reveals a comparable succession of phases characterized by a distinct paradigm: an initial decentralized polder-based management; a centralized control model in the mid-twentieth century; integrative and resilient strategies at the turn of the twenty-first century; and lastly, in the case of the RMS Delta only, an adaptive management model. In both cases, the paradigm shifts were each time motivated in response to a disaster, but also took advantage of new technological means and implied a governance reform. These observed similarities are nuancing the presumed opposition between a European bottom-up and a Chinese top-down approach that previous research tended to over-emphasize (Yang and Griffith 2010; Yang 2013; Zhou and Zhao 2017). On the other hand, the review reveals distinct management priorities in the current delta plans in the RMS and TB—focused respectively on flood control and water pollution-, as well as contrasting approaches to public participation and conservation of historical hydraulic landscapes. These contrasts can be explained by not only fundamental differences in terms of land ownership and control, socio-cultural tradition, but also distinct development stages.

This cross-regional comparison of the RMS Delta and TB validates the usefulness of Delta Urbanism methods to inform a knowledge-based management and planning of deltas (Welch 2017). The similarities identified in this paper will lead to potential exchanges of good practices, even though these transfers should be envisaged with respect to the socio-cultural specificities of each delta (Zegwaard et al. 2019). Conversely, the contrasts identify possible areas of improvement and stress the distinctive characteristics of the two regions.

Beyond the mutual learnings, this comparative research highlights the fundamental importance of mapping as an instrument of integrated and adaptive delta management. Mapping and visual communication are at the heart of delta management and planning in the RMS Delta case, as exemplified by the richly illustrated

National Water Plan (NWP 2015). In the TB Masterplan of 2014, in contrast, the communication mode is limited to a textual and technical language, even though the content described implies strong interplays of water management, spatial planning and environmental planning. Additionally, since 2014, recent programs such as the Sponge City program and the ambitious reorganisation of responsibilities under two new Ministries of Ecological Environment (MEE) and Natural Resources (MNR) are revolutionizing the sectoral approach that prevailed in China (Chan 2018; China Dialogue 2018).

In the new organizational context of natural resource planning in China, an intense collaboration will henceforth be required between stakeholders from different sectors, administrative authority levels and expertise domains (Nolf and Xie 2020). This research, by proposing a spatial visualization of water challenges and strategies in TB, is the first experiment of its genre in China. It is hoped that similar mapping practices can be systemized in the future for analyzing and adapting planning and management of delta regions.

**Acknowledgements** The research presented in this paper has benefited from the support of the Jiangsu Province Program of Science and Technology (BK20151244), the Young International Scientist program of the National Science Foundation of China (51550110235), the Research Development Fund of Xi'an Jiaotong-Liverpool University (RDF-14-03-23), the Zhejiang Provincial Natural Science Foundation (LY19E080001) and the Fundamental Research Funds for the Central Universities (2019QNA6023). We thank the anonymous reviewers for their careful reading of the manuscript and their many insightful comments and suggestions.

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