Catena 238 (2024) 107904

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

The changing Changjiang River estuarine-coastal ocean continuum in the anthropocene

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ARTICLE INFO

Keywords:
Changjiang River estuarine-coastal ocean continuum
Human perturbation
Ocean warming
Regime shift
Ecological environment

ABSTRACT

The Changjiang River estuarine-coastal ocean continuum is a well-studied system that is undergoing significant changes due to human activities and climate change. While research has improved our understanding of its ecological importance, the changing external forces present challenges that require integrated knowledge. Here, we provide a comprehensive summary of the natural and man-made stresses on the continuum and identify knowledge gaps for future study. The construction of dams has led to a decrease of approximately 70 % in sediment loads from the Changjiang River, resulting in seabed erosion and a reduction in organic carbon and pollutant reservoirs in the continuum. In contrast, nutrient fluxes from the Changjiang River have shown increasing trends since the 1960 s, leading to changes in nutrient conditions and ecological processes in the continuum. These changes have altered the biomass and community structure of phytoplankton, leading to frequent harmful algal blooms and shifts in dominant species from diatoms to dinoflagellates. We also outline the impacts of coastal engineering and wetland reclamation, which have altered coastal geography, destroyed wildlife habitats, and weakened the filtering effect on pollutants. Additionally, ocean warming has increased threats to the ecosystem, exacerbating harmful algal blooms and facilitating the release of semi-volatile pollutants. In our review of the ecological processes in the continuum, we categorize the changes into three stages: the 1950 s to mid-1980 s (initial state), mid-1980 s to early 2000 s (ecosystem destruction begins), and early 2000 s to the present (critical transition in the continuum). Future research should focus on understanding the ecological responses to these changing processes in the estuarine-coastal ocean continuum. As other continuum ecosystems worldwide may be at different stages, studying the response of the Changjiang River estuarine-coastal ocean continuum will provide a comprehensive case study.

1. Introduction

The world's 25 largest river catchments, which make up about half of the Earth's land surface. The major rivers themselves play a crucial role in transporting freshwater and particulate materials to the ocean (Milliman and Farnsworth, 2011). These rivers also form important interfaces between land and ocean, known as large-river delta-front estuaries, where material fluxes have a profound impact on marine biogeochemical cycles and ecosystem health (Bianchi and Allison, 2009). However, these estuaries are currently facing major challenges due to human activities and climate change. As a result, there is a growing focus on marine ecological protection, with the United Nations even assigning a separate Sustainable Development Goal (SDG 14) to address this issue.

To understand the current ecological changes in these estuaries, it is important to study their past conditions (Reusch et al., 2018). Coastal wetland reclamation, for example, has led to the loss of salt marshes and mangroves (Sun et al., 2015; H. Yang et al., 2017; Choi et al., 2018), while the influx of terrestrial nutrients and pollutants from rivers has dramatically changed the coastal ocean environment. This has resulted in nutrient over-enrichment, altered nutrient ratios, and negative impacts on phytoplankton structures and the overall ecological environment (Paerl et al., 2006; Danielsson et al., 2008; Jiang et al., 2014; Wang et al., 2019). These changes have often led to increased eutrophication, harmful algal blooms, hypoxia, and acidification in coastal areas (Heisler et al., 2008; Cai et al., 2011; Davidson et al., 2012; H. Li et al.,

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https://doi.org/10.1016/j.catena.2024.107904
Received 14 December 2023; Received in revised form 1 February 2024; Accepted 13 February 2024
Available online 16 February 2024
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2014; Reusch et al., 2018; Zhang et al., 2019).

Furthermore, the construction of large dams has also had an important environmental impact on estuarine regions (Syvitski et al., 2009; Yang et al., 2011; Maloney et al., 2018; Liu et al., 2022). These dams trap large amounts of sediment, leading to coast retreat and seabed erosion. In addition, the concentration of dissolved silicon (DSi) showed decreasing trend due to dam construction (Dai et al., 2011), especially for the TGD (Jiang et al., 2014; Liang and Xian, 2018). In contrast, the effect of reservoir construction on the retention of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) is limited (Dai et al., 2011; Yang et al., 2023). Overall, the combined pressures from human activities and climate change pose a serious threat to the ecology of estuarine ecosystems and can have severe consequences. In order to mitigate these impacts and protect estuarine ecosystems, it is crucial to understand the past and present dynamics of these systems and develop effective conservation strategies.

As the largest river in the Eurasia Continent, the runoff of the Changjiang River is of great significance to the ecological environment of the estuarine-coastal ocean continuum. However, the stability of the Changjiang River estuarine-coastal ocean continuum has been greatly impacted by human activities and climate change, leading to changes in coastal morphology and the marine ecological environment (Fig. 1). The construction of large-scale reservoirs in the Changjiang River basin has sharply reduced sediment flow to the Changjiang River estuarine-coastal ocean continuum, altering its geomorphic stability and material circulation (Yang et al., 2018a; Gao et al., 2017, 2019). Additionally, there has been a notable increase in the discharge of terrestrial nutrients, such as nitrogen and phosphorus, into the Changjiang River estuarine-coastal ocean continuum over the past 50 years. This has resulted in a severe deterioration of the coastal environment, including increased eutrophication, harmful algal blooms (HABs), and hypoxia (Chen et al., 2007; Cai et al., 2011; Dai et al., 2011; H. Li et al., 2014). Furthermore, large amounts of land-based pollutants have been discharged into the Changjiang River estuarine-coastal ocean continuum, making it an important sink for pollutants (Qi et al., 2014; Wang et al., 2016b; Li et al., 2017; Li et al., 2012; Lin et al., 2013; Wang et al., 2016a, 2017a). The reclamation of coastal wetlands has encroached upon the spawning and nursery grounds of fishery species and has also altered the community structure of plants, macrobenthos, and microorganisms, weakening the filtering effect of wetlands. Additionally, the sea surface temperature (SST) of the Changjiang River estuarine-coastal ocean continuum has gradually increased in the past 50 years (Cai et al., 2016), which may exacerbate HABs and hypoxia (Jiang et al., 2014) and even lead to the release of semi-volatile/volatile chemicals (Komprda et al., 2013). Therefore, the Changjiang River estuarine-coastal ocean continuum provides an excellent opportunity to study the response of estuarine ecosystems to the combined effects of climate change and human activities.

Considerable research has been conducted on the environmental changes of the Changjiang River estuarine-coastal ocean continuum over the past few decades. However, most of these studies have focused on individual factors of change and have not considered the interactive relationships between different factors. This limited approach often leads to one-sided conclusions. Estuarine ecosystems are highly complex, as they involve the interaction of land, ocean, and atmosphere. Any anomalies at these interfaces can have a severe impact on the stability of the system. For example, the river basin, estuary, and coastal ocean form a comprehensive conveying system that transports terrestrial materials from the continent to the Changjiang River estuarine-coastal ocean continuum. Understanding the changes in this system and their internal relationships is crucial for comprehending the evolving environment in the Changjiang River estuarine-coastal ocean continuum. Additionally, other factors such as reclamation and ocean warming need to be taken into account, as they further contribute to the deterioration of estuarine ecosystems. Despite the importance of this field, there is a lack of internationally available reviews on the topic and remained knowledge gaps.

This paper presents a comprehensive review of the ecosystem in the Changjiang River estuarine-coastal ocean continuum. We examine the changes in sediment and nutrients in the river over time and analyze their impact on the estuarine-coastal ocean environment. We also investigate the effects of reclamation, pollution, and ocean warming on this ecosystem. Based on our findings, we identify regime shifts in the ecosystem since the 1950 s and highlight four areas that require further

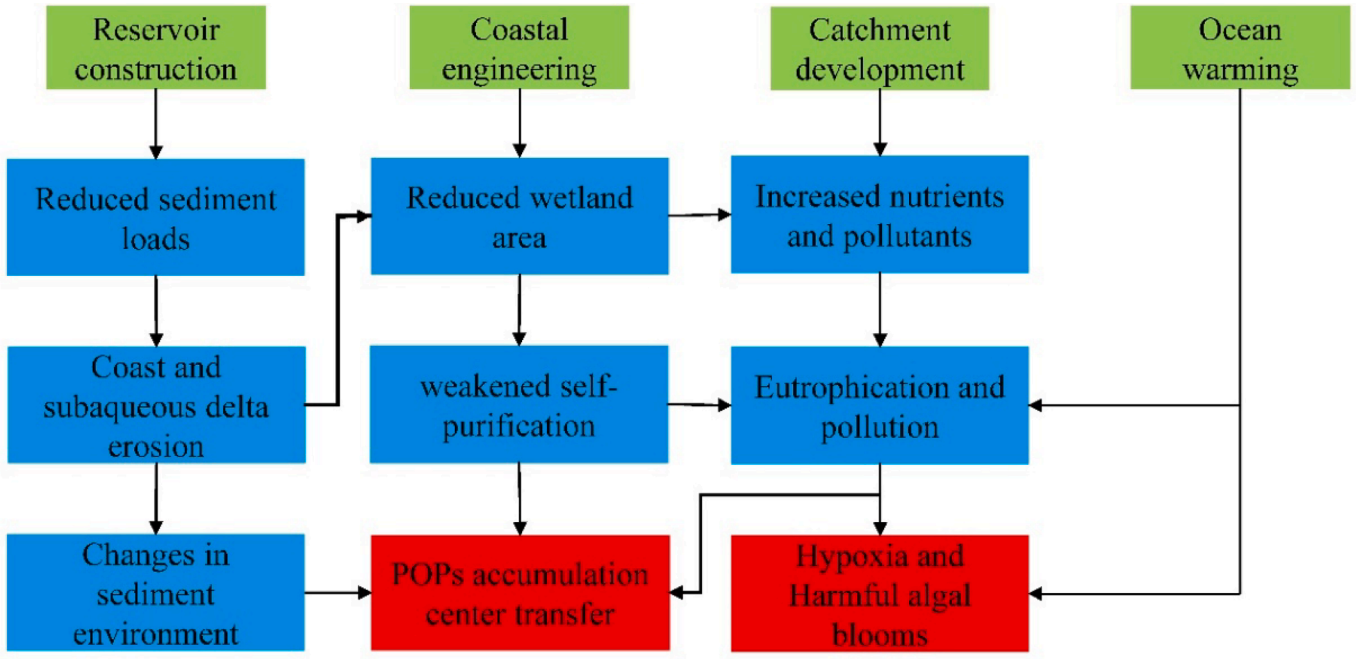


Fig. 1. Conceptual framework of the changing Changjiang River estuarine-coastal ocean continuum: the green boxes represent critical human activities and climate change that will affect the ecosystem of the continuum; the blue boxes represent perturbations in the continuum from human activities and climate change; the red boxes represent the critical variations in the continuum.

investigation. This integrated review offers a holistic understanding of the ecological environment in the Changjiang River estuarine-coastal ocean continuum, which can provide valuable insights for other regional seas.

2. Regional setting

The Changjiang River Estuary is a large-river delta-front estuary that receives a large amount of sediment from the Changjiang River basin. The Changjiang River is a 6370 km long river with a catchment area of 1.80×10^6 km^2, which is about 20 % of Mainland China's area (Fig. 2a, Yang et al., 2006). The Changjiang River basin is a prosperous region with a population of approximately 400 million people and contributes 42 % of China's GDP (Yang et al., 2006). It is also an important grain-producing area. Highly urbanized and industrialized regions, such as Jiangsu, Shanghai, and Zhejiang Provinces, are located near the coastal zone of the Changjiang River Estuary (Fig. 2b). The agricultural and industrial activities in the river basin and coastal zone result in the discharge of large amounts of nutrients and pollutants into the Changjiang River estuarine-coastal ocean continuum, impacting its ecological environment (Dai et al., 2011; Wang et al., 2016).

A huge amount of sediment is discharged into the estuary, with approximately 40 % of this sediment being trapped in the estuary to create the Changjiang subaqueous delta mud deposit (CSDMD) (Fig. 2b, Liu et al., 2007; Gao and Collins, 2014). The mud deposits consist mainly of clayey silt and extend over 800 km southward from the CRE (Fig. 2b), and the south part called Zhe-Min coastal mud belt (Fig. 2b). The oceanic circulation in the estuarine-coastal ocean continuum is primarily influenced by the Changjiang diluted water, the Zhe-Min coastal current, and the Taiwan warm current (Fig. 2b). The Changjiang diluted water is formed by the mixing of freshwater from the Changjiang River with offshore water, and it is characterized by low salinity and low density (Chang et al., 2014). The Zhe-Min coastal current flows along the coasts of Zhejiang and Fujian Provinces and is influenced by the East Asia monsoon, moving northward in summer and southward in winter (Yuan and Hsueh, 2010). The Taiwan warm current originates in the Taiwan Strait and is affected by the Kuroshio Current from northeastern Taiwan, flowing northward in the eastern region of the Zhe-Min coastal current (Zhu et al., 2004). The Zhe-Min coastal current and Taiwan warm current create a shearing effect that limits the export of sediment from the Changjiang River to the outer shelf, resulting in the formation of a mobile mud belt (Fig. 2b, Liu et al., 2007; Xu et al., 2012).

3. Variations in the Changjiang river-estuarine-coastal ocean continuum

In the past 15 years, several studies have examined the changes in sediment loads from the Changjiang River. These studies have shown a gradual decrease in sediment loads after the 1970 s (Yang et al., 2011; Guo et al., 2019). Previous research has indicated that the changes in sediment loads in the tributaries are closely linked to dam operations (Gao et al., 2018; Guo et al., 2019), with dams in the main river having a particularly important impact on sediment delivery (Gao et al., 2018; Yang et al., 2018b; Guo et al., 2019). Since 1950, more than 50,000 dams have been constructed in the Changjiang River basin, resulting in the trapping of a large amount of sediment from the upper reach (Yang et al., 2011; Fig. 3b). For instance, the Three Gorges Dam (TGD), the largest dam in the basin, has trapped a total of 1699 Mt of sediment between 2003 and 2017 (Guo et al., 2019). The sediment flux at the Yichang gauge (upper stream control gauge), Hankou gauge (middle stream gauge), and Datong gauge (Changjiang River basin control gauge) indicates that riverbed erosion has occurred in the middle-lower reaches following the impoundment of the TGD (Fig. 3a, c). After the impoundment of TGD, the Changjiang-derived sediment loads drastically decreased by ~ 74 % in 2006–2017 compared to 1950–1985 (Guo et al., 2019).

The sediment load of the Changjiang River has drastically decreased, but the water discharge showed no significant decreasing trends since 1953 (Zhao et al., 2015). As a result, the suspended sediment concentration in the Changjiang River has also decreased (Fig. 3d). At the

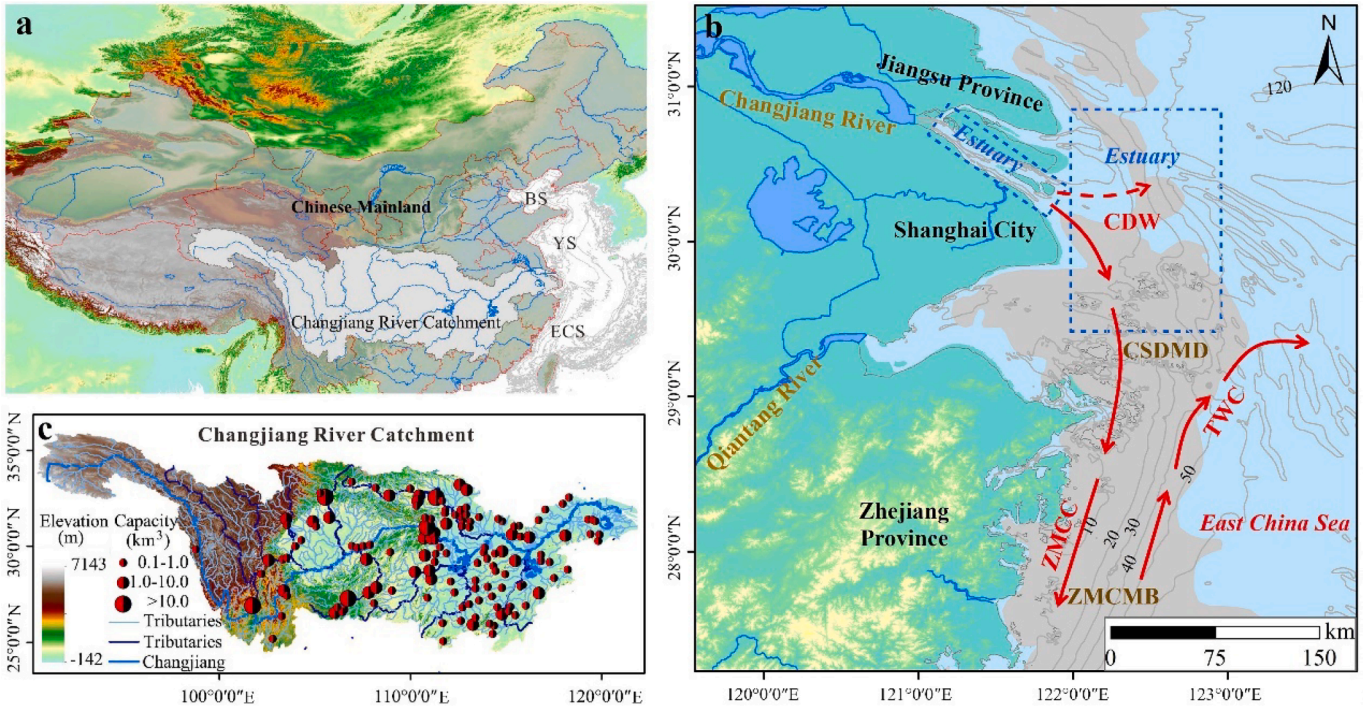


Fig. 2. Basic overview of the study area: a) geographical location of the Changjiang River catchment; b) ocean circulation patterns in the Changjiang River estuarine-coastal ocean continuum; c) reservoirs in the Changjiang River catchment. BS represents Bohai Sea, YS represents Yellow Sea, ECS represents East China Sea, CDW represents Changjiang dilute water, ZMCC represents Zhe-Min coastal current, TWC represents Taiwan warm current, CSDMD represents Changjiang subaqueous delta mud deposit, ZMCMD represents Zhe-Min coastal mud deposit; the blue dotted square represents the Changjiang River Estuary (Jiang et al., 2014).

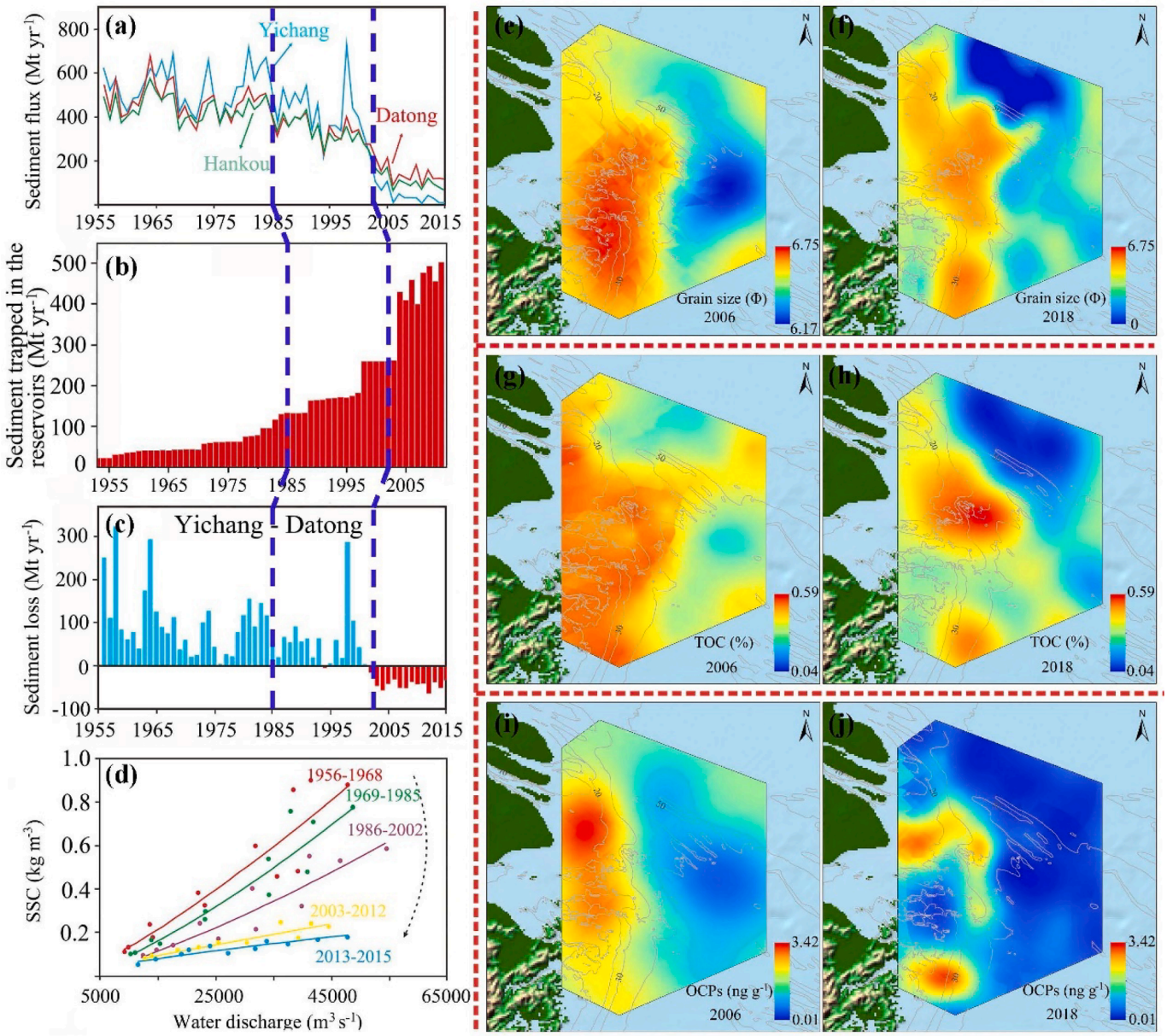


Fig. 3. Temporal changes in sediment flux, suspended sediment concentration (SSC), riverbed accretion/erosion, and dam capacity (Gao et al., 2014; Yang et al., 2018): a) sediment flux at Yichang, Hankou, and Datong gauging stations; b) SSC at Yichang, Hankou, and Datong gauging stations; c) suspended sediment loss between Yichang and Hankou; d) cumulative capacity of large dams/reservoirs; e, f) mean grain size of surface sediments in the Changjiang River estuarine-coastal ocean continuum in 2006 and 2018; (g, h) total organic carbon content of surface sediments in the Changjiang River estuarine-coastal ocean continuum in 2006 and 2018; i, j) organochlorine pesticide concentration of surface sediments in the Changjiang River estuarine-coastal ocean continuum in 2006 and 2018.

Datong station, the suspended sediment concentration was 0.59 kg m^{-3} during 1956–1968 and decreased to 0.14 kg m^{-3} after 2012, a decline of 77 % (Yang et al., 2018b). This decrease in sediment concentration has led to sediment starvation in the middle-lower reaches of the Changjiang River, causing increased erosion in the river channel, particularly in the middle reaches (Yang et al., 2011; Luo et al., 2012; Lai et al., 2017). Prior to the construction of the TGD, the sediment load at Yichang station was higher than that at Hankou station, indicating sediment accumulation in the middle reaches (Yang et al., 2011). However, after the construction of the TGD, there has been evidence of channel erosion below the dam (Yang et al., 2014; Yang et al., 2018b). The composition and sources of sediments discharged into the CRE have also changed due to dam construction.

The evolution of river delta systems is primarily influenced by the amount of sediment carried by the river and the sediment that is retained in the deltaic areas (Gao et al., 2007). Previous research has shown that a sediment load of approximately 300 million tons per year is necessary to maintain a stable sedimentary environment in the subaqueous delta of the Changjiang River (Gao, 2007; Yang et al., 2011). However, the actual sediment discharge into the estuarine-coastal ocean continuum from the Changjiang River has been much lower, averaging around 132 ± 40 million tons per year between 2003 and 2019. This large shortfall in sediment supply has led to a decrease in the growth of coastal salt marshes and an increase in erosion in the subaqueous delta front (Yang et al., 2011; Zhao et al., 2018). Bathymetric data collected between 1981 and 2012 for the North Branch of the Changjiang River Estuary has revealed severe degradation in this region following the construction of the TGD (Luo et al., 2017). Similarly, a study on the South Branch of the estuary has identified two large erosion zones along the 10-meter isobaths in the subaqueous delta front, as well as the

landward retreat of the 15-meter isobaths between 1997 and 2010 (Zhu et al., 2016). Yang et al., (2018a) have calculated the bed shear stress and determined that erosion has occurred under normal and extreme hydrodynamic conditions, indicating that the uppermost 10–20 m of the subaqueous delta are at high risk of erosion in the coming decades (Yang et al., 2018a).

The sediment grain size in the estuarine-coastal ocean continuum has also undergone great changes, for example, the sand-mud boundary has retreated landward due to the erosion of the mud fraction (Luo et al., 2012). The surface sediment grain size in the estuarine-coastal ocean continuum has become coarser over time, with a decrease from 8 Φ in 1982 to 7 Φ in 2006, 6 Φ in, 2012, and 4 Φ in 2018 (Fig. S1 and Fig. 3e, f; Yang et al., 2018a; Wang et al., 2020a). Additionally, the clay component of surface sediment has decreased from an average of 38 % in 1982 to 5 % in 2018 (Fig. S2, Yang et al., 2018a; Wang et al., 2020a). This indicates that a large amount of fine-grained sediment has been scoured and transported southward, weakening the estuary's function as a sediment sink (Gao et al., 2017, 2019). Radionuclide dating results show a clear decrease in the deposition rate in the estuarine-coastal ocean continuum, from over 4 cm yr^{-1} to less than 1 cm yr^{-1}, and the disappearance of the depocenter (Gao et al., 2019). Furthermore, the surface sediment grain size in the entire estuarine-inner shelf area of the East China Sea has also shown a tendency towards coarsening (Fig. S3, Wang et al., 2020b). Therefore, seabed erosion has not only occurred in the CRE and adjacent waters but also across the entire estuarine-inner shelf area of the East China Sea.

Although the function of estuarine-coastal ocean continuum as a sediment sink has weakened or eliminated, its role as a transfer station remains unchanged (Gao et al., 2017). This critical transition has converted the estuarine-coastal ocean continuum from a sink to a source, impacting its ability to bury sediment-associated materials such as organic carbon and pollutants (Wang et al., 2018, 2020a, b). Terrestrial

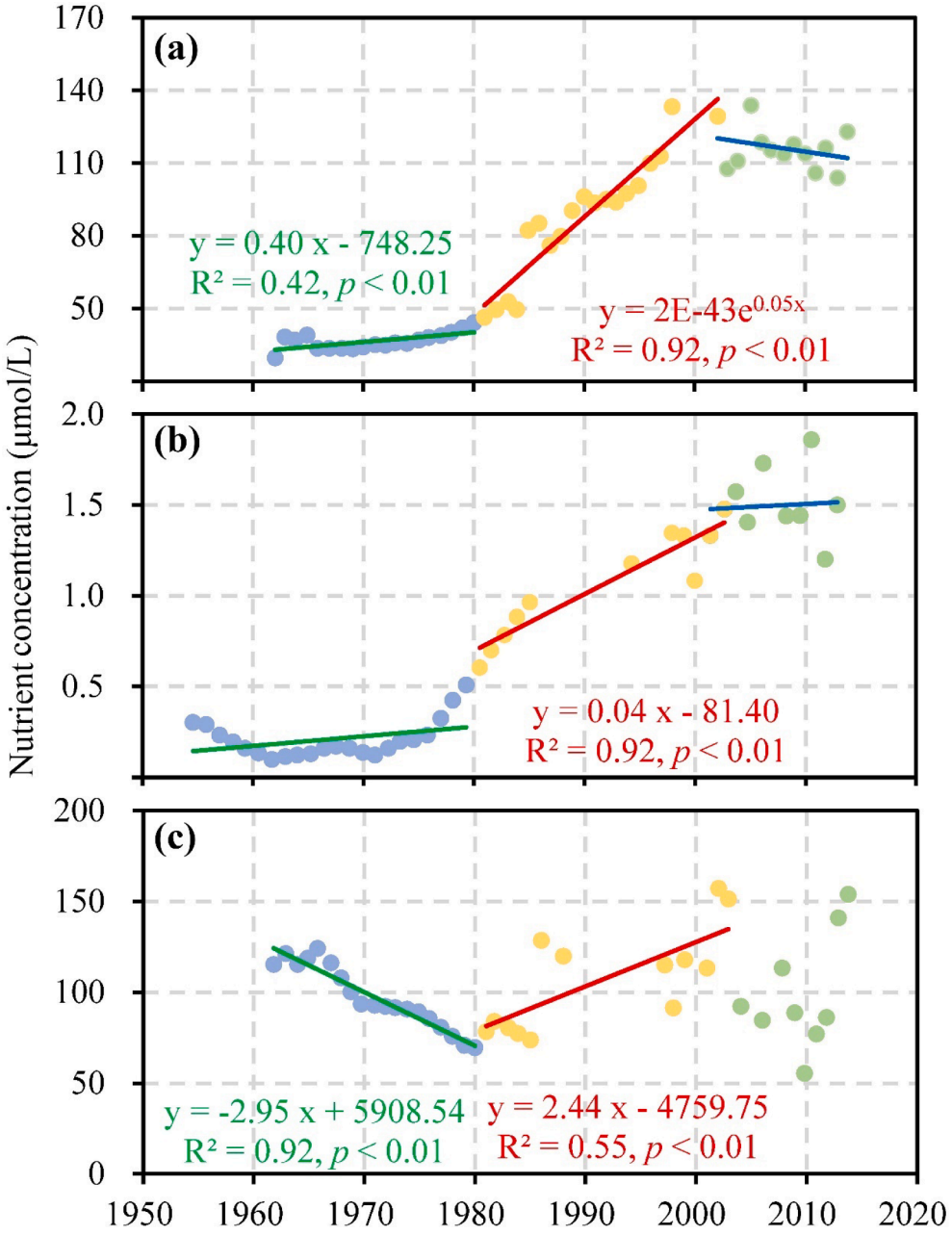


Fig. 4. Temporal variations trends of riverine materials discharged into the ECS. a) dissolved inorganic nitrogen (DIN) concentration; b) dissolved inorganic phosphorus (DIP) concentration; c) dissolved silicon (DSi) concentration (Data from Zhou et al., 2008; Dai et al., 2011; Jiang et al., 2014).

biomarkers, including *n*-alkanes, polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides (OCPs), have also shown similar variations due to the influence of river damming (Wang et al., 2020a, b; Wang et al., 2022). The depocenter of organic carbon and OCPs in the estuarine-coastal ocean continuum was relatively larger in 2006 compared to 2018 (Fig. 3g-j). In contrast, the variation in these sediment-associated materials in the inner shelf is relatively small due to the southward transport of fine-grained sediment. Therefore, the shift in the depocenter has greatly affected the transport and burial of sediment-associated materials. The deposition flux of organic carbon in the estuarine-coastal ocean continuum has decreased from 2.50 Mt yr^{-1} in 2006 to 1.17 Mt yr^{-1} in 2018, representing a decline rate of 53 % (Wang et al., 2020c). Similar declining trends have been observed for other sediment-associated substances such as PAHs and OCPs (Wang et al., 2020a, b). These results can be attributed to the reduction in riverine sediment supply and the loss of fine-grained sediment offshore due to seabed erosion. It is important to note that these findings have important implications for the biogeochemical cycle of organic carbon and pollutants in the Changjiang River estuarine-coastal ocean continuum.

4. Increasing nutrient fluxes and its environmental implications

Rivers transport both solid particles and dissolved matter, including nutrients (such as nitrogen, phosphorus, and silicon), to the ocean. The use of chemical fertilizers in agricultural production has led to an increase in nutrient flux into the Changjiang River estuarine-coastal ocean continuum (Dai et al., 2011). The variations in nutrient concentrations (DIN and DIP) can be divided into three stages: an initial stage before 1980 s with slight increasing trend, a drastic increase until early 2000 s, and a slow increase in phosphorus concentration and a slow decrease in nitrogen concentration after early 2000 s (Fig. 4a, b). The variation trend of DSi exhibits a decreasing trend before 1980 s, and then an upward trend until the 2000 s (Fig. 4c). After 2000 s, the DSi concentration sharply decreased, which may be attributed to the sedimentation

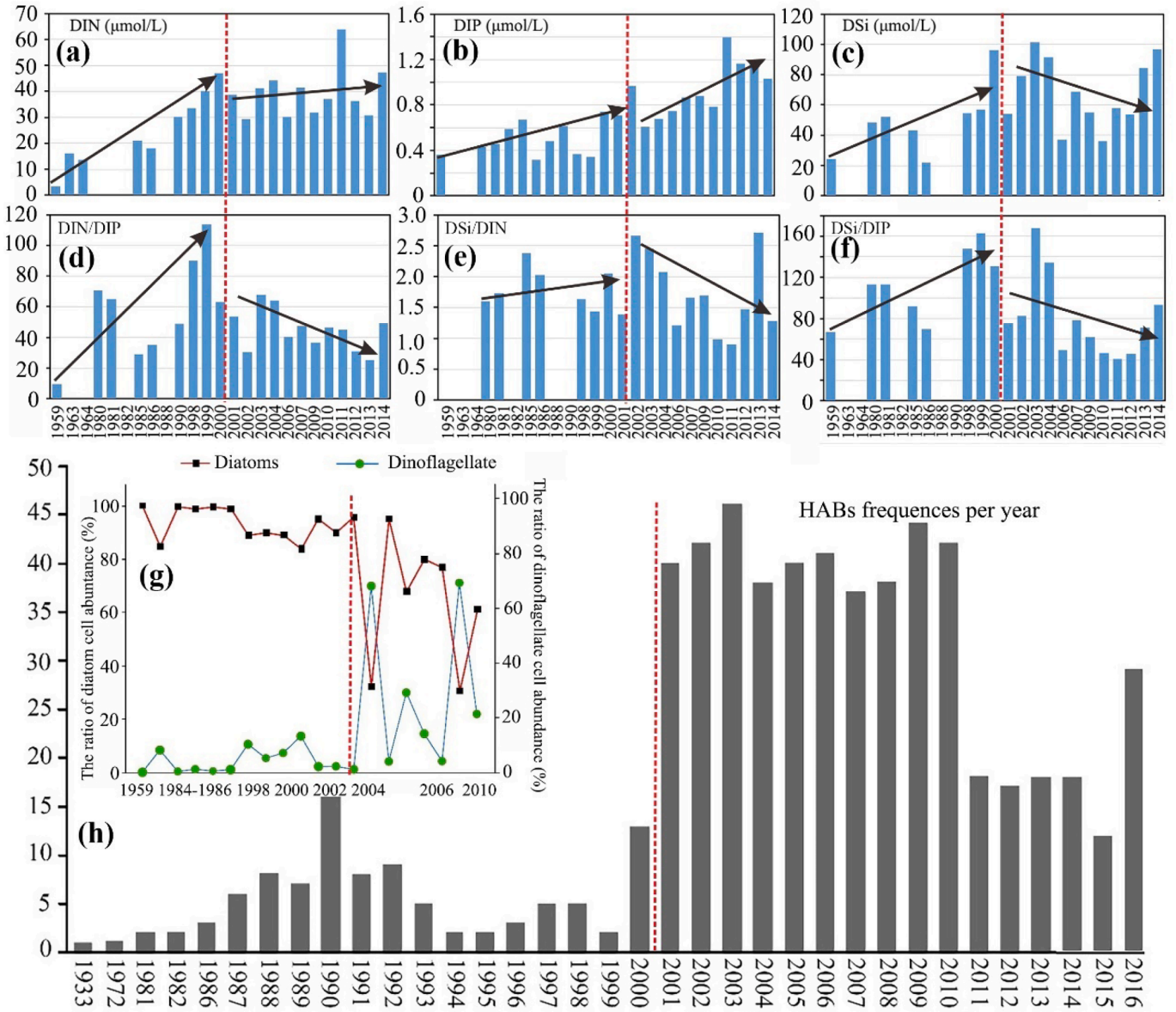


Fig. 5. Temporal variation trends of nutrient concentrations and ratios in the Changjiang River Estuary: a) DIN concentration; b) DIN:DIP ratio; c) DIP concentration; d) DSi:DIN ratio; e) DSi concentration; f) DSi:DIP ratio (Data from Zhou et al., 2008; Jiang et al., 2014; Li et al., 2014); Temporal variations in phytoplankton community and chlorophyll-a in the East China Sea: g) percentage of diatoms and dinoflagellates (H. Li et al., 2014); h) occurrence frequency of HABs in the East China Sea.

of biogenic silica in the reservoirs (Ran et al., 2016). The implementation of fertilizer reduction plans in China has stabilized and reduced fertilizer use (Fig. S4), which may be the main reason for this trend. Soil conservation projects in the upstream of the river basin have effectively reduced soil erosion and the flux of fertilizer into rivers (Liao et al., 2012). In addition to terrestrial inputs, mariculture also releases large amounts of nutrients into the marine environment (J. Wang et al., 2020). The rapid growth of marine aquaculture has led to a doubling of nutrient inputs from feed into the marine environment, with a calculated molar nitrogen-to-phosphorus ratio of about 15:1 (J. Wang et al., 2020).

The concentrations of DIN and DIP in the Changjiang River Estuary have shown a gradual increase (Zhou et al., 2008; Jiang et al., 2014; H. Li et al., 2014; Liang and Xian, 2018). In the 1960 s, the concentration of DIN was relatively low, around 15 μmol/L. It gradually increased to 20 μmol/L in the 1980 s and further increased to 45 μmol/L during the 1990 s-2000 s, remaining stable until the 2010 s (Fig. 5a). DIP concentrations in the estuarine-coastal ocean continuum followed a similar increasing trend before the 2000 s but did not stabilize after that (Fig. 5b). DSi concentrations showed high fluctuations with no clear trend (Fig. 5c). The DIN/DIP ratio increased rapidly in the 1980 s and 1990 s, then gradually decreased until 2014 (Fig. 5d). The DSi/DIN ratio was relatively stable before the 2000 s and then decreased quickly (Fig. 5e). The variation trend of DSi/DIP was similar to that of DSi/DIN (Fig. 5f).

The changes in nutrient concentrations and ratios in the estuarine-coastal ocean continuum will inevitably affect the biomass and species of phytoplankton. Previous studies have shown a clear increase in phytoplankton abundance and surface chlorophyll-a levels from the 1950 s to the 2000 s (Wang et al., 2006; Zhou et al., 2008; Jiang et al., 2014). The changes in nutrient inputs have influenced both the biomass and community structure of phytoplankton (Jiang et al., 2014; Xiao et al., 2018). Diatom abundance in the estuarine-coastal ocean continuum has decreased, while dinoflagellate abundance has notably increased (Zhou et al., 2008; Jiang et al., 2014). High DIN/DIP ratio will limit diatom growth, but dinoflagellates grow rapidly and become more dominant (Edwards et al., 2012; Irwin et al., 2015; Zhou et al., 2017), leading to changes in the overall phytoplankton community structure. Analysis of previous data indicates that diatoms were the dominant species in the estuarine-coastal ocean continuum before the 1990 s, accounting for over 90 % of the community (H. Li et al., 2014). However, by 2006, the percentage of diatom species had decreased to less than 40 % (Fig. 5g).

Another serious ecological problem caused by eutrophication is the occurrence of HABs (Qi et al., 2017; Wang et al., 2018; Zhang et al., 2019), which has been documented since the 1930 s with a bloom of *Trichodesmium spp* (Zhou et al., 2008). The frequency of HABs has shown an increasing trend, particularly in the 2000 s, although it has slightly decreased after 2010 (Fig. 5h). This temporal trend is slightly delayed compared to high nutrient concentrations in the estuary due to lag effects in the ecosystem. On average, HABs occur about 33 times per year in the East China Sea, but during 2003–2007, the rate exceeded 50 times per year (Yu et al., 2017). Additionally, there has been a notable shift in the dominant species causing HABs in the East China Sea from the 1990 s to the 2000 s (Yu et al., 2017). Dinoflagellates have gradually become the dominant species, posing a greater threat to ecosystem health compared to diatoms.

Eutrophication poses a severe threat, primarily by reducing the level of dissolved oxygen (DO) in bottom waters due to the decomposition of dead phytoplankton (Diaz and Rosenberg, 2008; Zhu et al., 2011). When the DO level drops below 2 mg/L (63 μmol/L), it creates a hypoxic condition, altering the natural redox state of the marine environment (Wang et al., 2016). The Chesapeake Bay is a well-known hypoxic zone, with reports dating back to the late 1950 s (Cai et al., 2011; Conley et al., 2011; Chen et al., 2017). The hypoxic area in the bay increased until 2003 and has since gradually decreased, following a similar trend to HABs. Despite the reduction in hypoxic area, the DO level has continued to decline in recent years (Fig. S5). The annual cycle of hypoxia aligns with eutrophication, peaking in August after developing in late spring and early summer, and weakening in autumn (Wang et al., 2012). A recent study found a correlation between hypoxia and chlorophyll-a, suggesting that a chlorophyll-a concentration of > 3.0 mg/L is necessary for hypoxia formation (Chen et al., 2017). This symbiotic relationship between eutrophication and hypoxic zone development indicates that eutrophication is an important driver of hypoxia.

5. Coastal engineering and wetland reclamation

Engineering construction and wetland reclamation in the coastal zone pose a serious threat to coastal wetlands, leading to degradation of coastal ecosystems, geological disasters, and environmental deterioration. Several studies (Mackinnon et al., 2012; Bai et al., 2015; Guo and Jiao, 2007; J. Li et al., 2014; Duan et al., 2016) have highlighted this issue. The coastal wetland of the East China Sea, including the Changjiang River Estuary, is the largest in China, covering an area of 2.07×10^6 ha (Guan, 2012). Unfortunately, these regions, being highly developed, have experienced drastic coastal wetland reclamation. To visualize the temporal changes in land reclamation, remote sensing images of the Changjiang River estuarine-coastal ocean continuum from 1981 to 2017 were used to identify the reclamation regions (Fig. 6a, b).

Estuarine hydraulic engineering projects and reclamation have been found to substantially impact estuarine hydrodynamics and shoal morphology (Chu et al., 2013; Wei et al., 2017; Wang et al., 2017b; Zhao et al., 2018). Since the 1950 s, approximately 1100 km^2 of intertidal wetlands have been reclaimed in the Changjiang River Estuary (Du et al., 2016). A study using multi-temporal remote sensing images from 1974 to 2014 found that the coastline of the Changjiang River Estuary has extended seaward since 1974, with an average land area increase of 871 km^2 at a rate of 21.8 km^2 per year (Wang et al., 2017b). However, the factors influencing the increase in subaerial delta area varied. The Chongming East Shoal experienced natural processes dominated by riverine sediment load, which correlated with the rate of coastline changes and net accretion area (Chu et al., 2013; Li et al., 2014; Wang et al., 2017b). On the other hand, the Hengsha Shoal and Nanhui East Shoal saw increased land area mainly due to human activities that increased the accretion rate (Du et al., 2016).

The Deep Waterway Project, the largest estuarine hydraulic engineering project in China, was carried out in the North Passage from 1998 to 2010. This project involved dredging over 300 million cubic meters of sediment, with approximately 130 million cubic meters of sediment being deposited on the Hengsha Shoal (Luan et al., 2016). As a result, the Hengsha Shoal experienced accelerated growth (Wang et al., 2017b). The construction of training walls also altered the estuary dynamics (Wu et al., 2018), causing sediment accumulation on various shoals including the Chongming East Shoal, Hengsha Shoal, and Jiuduan Shoal (Wei et al., 2016; Zhu et al., 2016; Wang et al., 2017b). The implementation of this project led to increased erosion rates in areas located seaward of the North Channel, North Passage, and South Passage (Zhu et al., 2016). The morphodynamic evolution of Jiuduan Shoal, the largest uninhabited island in the region, revealed continuous expansion of its area from 1998 to 2014, as the construction of the Deep Waterway Project induced sediment deposition on its northern and southern edges (Wei et al., 2016).

Engineering construction and wetland reclamation activities have negative impacts on fishery species by encroaching on their spawning and nursery grounds and altering the structure of the macrobenthos community (Borja et al., 2011; Wang et al., 2014; Yang et al., 2017; Lv et al., 2016; Liu et al., 2018). For instance, the Changjiang River estuarine-coastal ocean continuum serve as crucial spawning and nursery grounds for *Larimichthys polyactis*, a commercially important fish species that has supported the fishery industry in China and Korea for many years (Liu et al., 2018). The large-scale reclamation activities are expected to disrupt the hydrodynamics of nearshore waters, leading to

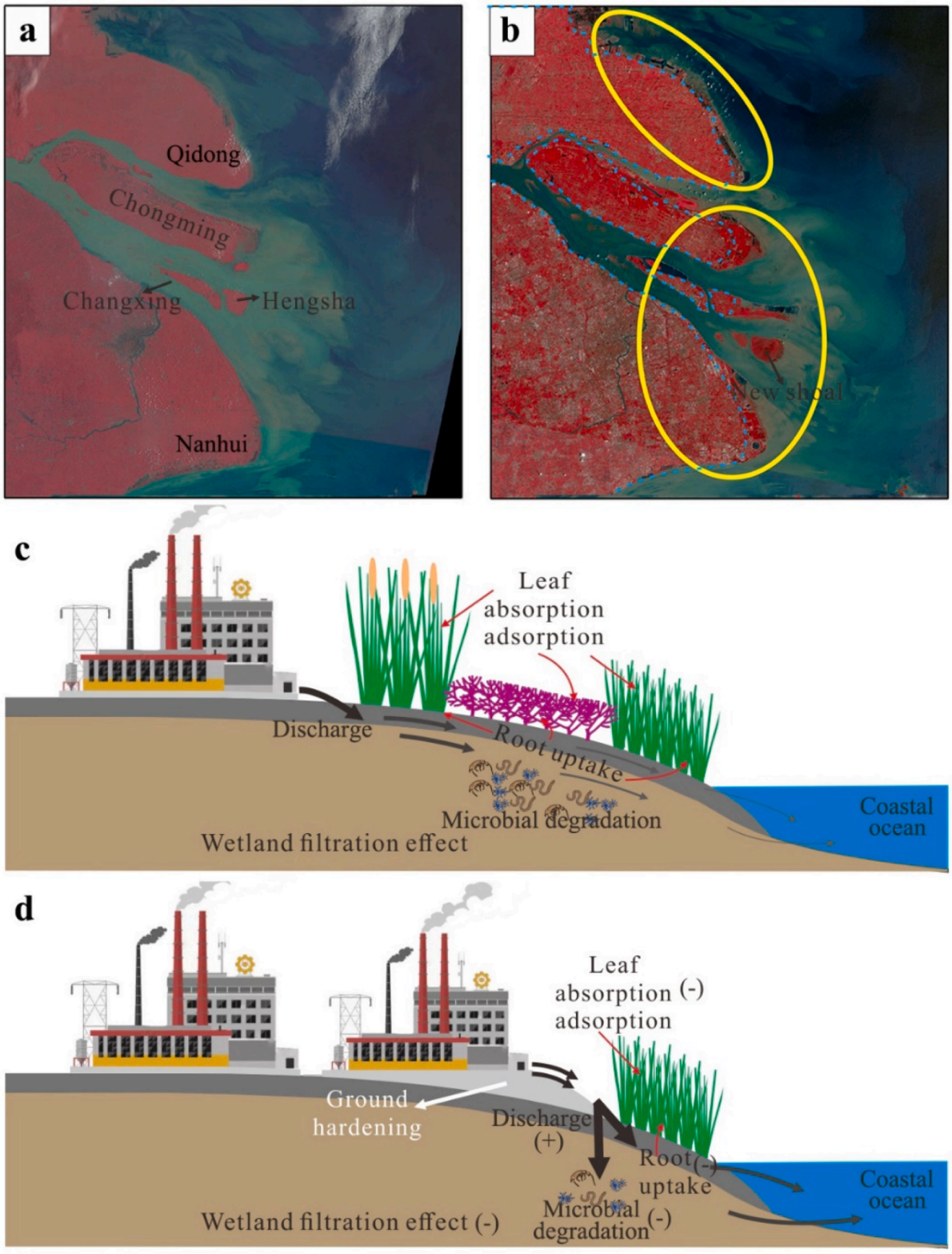


Fig. 6. Coastal wetland reclamation in the Changjiang River Estuary. Landsat satellite image of the estuary in 1981 (a) and 2017 (b); blue dot line in panel b showed coastline of 1981 and solid yellow line indicated reclamation. The fate of POPs in the estuarine wetland before and after reclamation (wetland filtration effect of POPs), including leaf absorption/adsorption, root uptake, microbial degradation, export to the coastal ocean; "+" represent strengthen, "-" represents weaken.

excessively high concentrations of suspended sediment (Wang et al., 2014). This can have severe detrimental effects on fish eggs and larvae, as well as influence the migration patterns of marine organisms. Furthermore, the reclamation activities have also altered the characteristics of coastal wetlands, such as moisture content, salinity, and soil granularity, which negatively affect the habitats of macrobenthos (Wang et al., 2014; Liu et al., 2018).

The Changjiang River Estuary are crucial for the East Asian-

Australasian Flyway, providing essential breeding, stopover, and wintering sites for millions of waterfowl (Ma et al., 2002; H. Yang et al., 2011; Mackinnon et al., 2012; Iwamura et al., 2014; Bai et al., 2015). However, intensive reclamation has led to a drastically decline in waterbird habitats and populations (Bortels et al., 2011; Mackinnon et al., 2012; Zou et al., 2016). This has resulted in changes to the coastal wetland landscape and the destruction of natural vegetation patterns (Gan et al., 2009; Ma et al., 2009; Zang et al., 2017). Artificial habitats, such as paddy fields and aquacultural ponds, have replaced the original habitats and now dominate the area. Between the 1980 s and 2000 s, the artificial habitats in the Chongming Eastern Shoal nearly doubled, while more than 65 % of natural habitats were lost (Ma et al., 2009). This habitat destruction has caused waterbirds to either die or seek alternative habitats nearby, resulting in a decrease in waterbird populations. A survey conducted in the Chongming Eastern Shoal showed no change in the number of waterbird species between the 1980 s and 2000 s, but more than half of the species experienced a decline in population (Ma et al., 2009). For example, the Tundra Swan (*Cygnus columbianus*) population decreased from 3000 to 3500 individuals in 1986–1989 to only 51 individuals in the winter of 2000/2001 (Ma et al., 2002).

Wetlands are not only important habitats, but they also act as natural filters for pollutants (Fig. 6c), earning them the nickname “kidneys of the Earth”. Coastal wetlands, which lie between land and ocean, play a crucial role in preventing the transport of pollutants from land to sea (Cao and Wong, 2007; SOA, 2013; Jiang et al., 2015). However, extensive reclamation of these wetlands is changing this dynamic, leading to the direct discharge of pollutants into the ocean (Fig. 6d). The removal of wetland vegetation reduced the leaf adsorption and absorption of pollutants (Huang et al., 2018), and also weakened the rhizosphere absorption capacity (Fig. 6c, d; Bagheri et al., 2020). Furthermore, hardening of the ground will change the hydrological conditions of the wetland, which in turn will affect the microbial community (Hussain et al., 2023), thereby reducing the microbial influence on the fate of POPs (Fig. 6c, d; Jiang et al., 2022). This reclamation

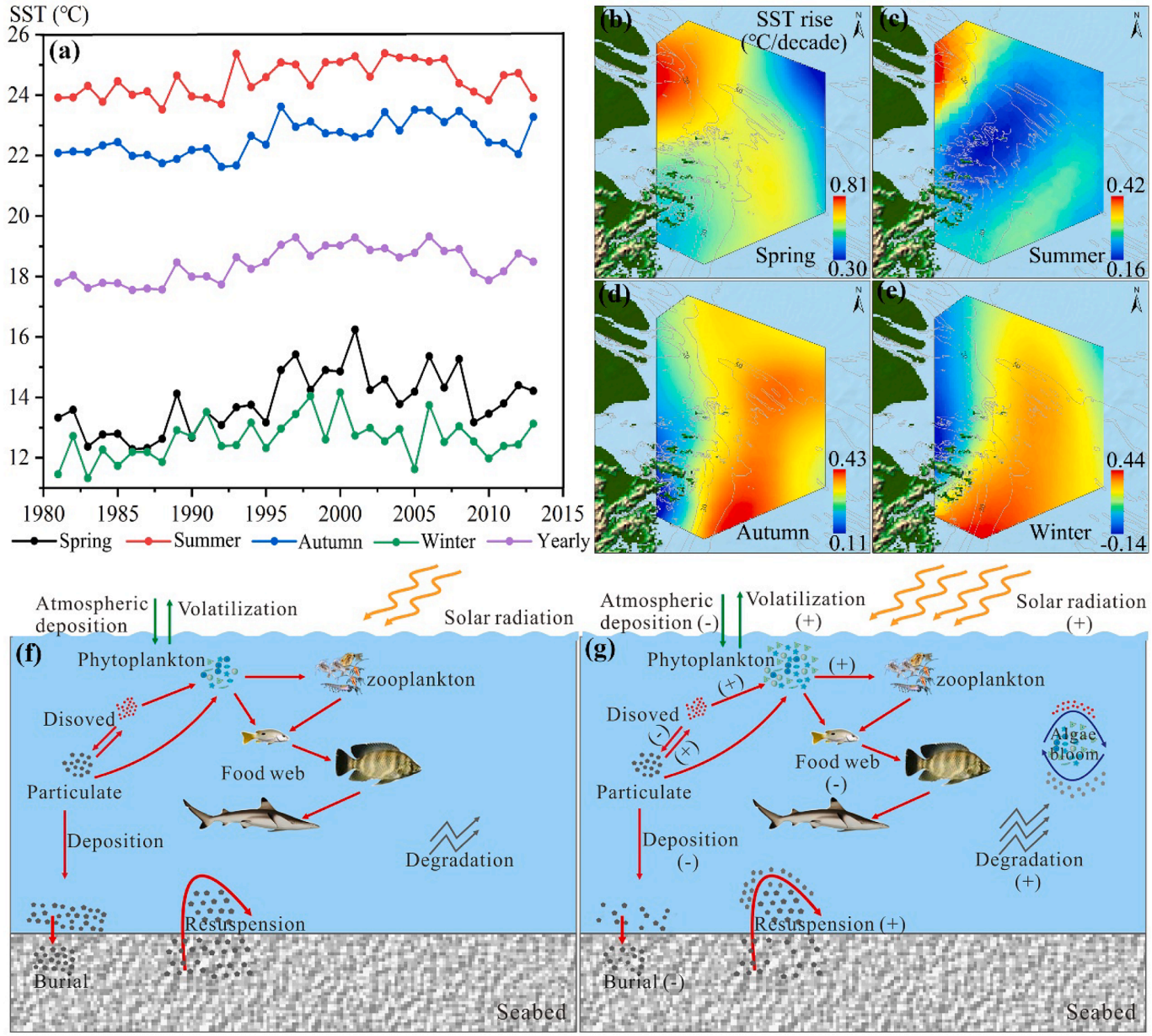


Fig. 7. Distribution patterns of seasonal and yearly mean surface seawater temperature (SST) in the Changjiang River Estuary over the past three decades (1982–2014): (a) Time series of yearly and seasonal SST, (b-e) spatial patterns of SST rising trends in spring, summer, autumn, and winter; The variations in ecosystem of the estuary before (f) and after ocean warming (g). (SST data from https://www.esrl.noaa.gov/).

process converts wetlands into farmland and construction sites (Zang et al., 2017), inhibiting their filtering capabilities and turning them into sources of contamination (Pan and Wang, 2012; Liu et al., 2011). For instance, the conversion of the Chongming Eastern Shoal into farmland resulted in higher levels of heavy metal accumulation in the soil compared to its previous state as a coastal forest (Zheng et al., 2016). The excessive use of fertilizers in reclaimed land also increases the discharge of nitrogen and phosphorus into the coastal ocean (Cao et al., 2003, 2005). Additionally, urban expansion and harbor construction in reclaimed areas contribute to contamination, with the increase in population and waste discharge, including wastewater and solid waste, and the risk of oil pollution from ship oil leaks. All of these human activities directly contribute to the discharge of pollutants into coastal waters.

6. Ocean warming in the Changjiang River Estuary

Global warming poses a serious threat to the East China Sea ecosystem (Hays et al., 2005; Belkin, 2009), leading to increased sea surface temperatures (SST), particularly in the Changjiang River estuarine-coastal ocean continuum (Fig. 7, Belkin, 2009; Cai et al., 2016). Ocean warming can impact regional hydrodynamics and vertical stratification through interactions between the ocean and atmosphere, resulting in noticeable changes to the physical environment of the Changjiang River estuarine-coastal ocean continuum (Belkin, 2009; Tang et al., 2009). The continuum has experienced rapid and persistent warming since the 1970 s, surpassing global and large-scale regional warming trends (Rhein et al., 2013; Cai et al., 2017).

In order to better understand the changes in SST over the past few decades, we collected seasonal SST data of the Changjiang River estuarine-coastal ocean continuum from 1982 to 2014. Our analysis revealed a clear warming trend in the Changjiang River estuarine-coastal ocean continuum throughout all seasons during this period (Fig. 7a-e). The average annual SST for the continuum also showed a warming trend, increasing at a rate of 0.14–0.48 ℃ per decade (Fig. 7a). This rate is higher than that observed in other Chinese marginal seas and even the global oceans (Rhein et al., 2013; Cai et al., 2017). Furthermore, we compared the trends between different seasons and found that the warming was most pronounced in spring and winter, while summer and autumn showed slower warming trends (Fig. 7b-e). The fastest warming was observed in spring in the continuum, with a rate of 0.56–0.78 ℃ per decade (Fig. 7b). This suggests that the SST in the estuarine-coastal ocean continuum increased by 1.62–2.34 ℃ over the past three decades. However, it is important to note that the warming trend started to slow down and even stagnate after reaching a peak in 2002 (Fig. 7a). This phenomenon is consistent with the global-warming hiatus observed in recent years (Kerr, 2009).

The rapid increase in temperature is creating favorable conditions for phytoplankton blooms (Hays et al., 2005; Gobler et al., 2017; Xiao et al., 2018). Phytoplankton are highly sensitive to temperature changes (Xiao et al., 2018), with diatoms thriving in lower temperatures and being inhibited by higher temperatures. Dinoflagellates, on the other hand, are less affected by temperature and can tolerate higher thermal conditions. This warming trend is likely the main cause of eutrophication and the shift in phytoplankton community structure (Fig. 5g). In the Changjiang River estuarine-coastal ocean continuum, ocean warming has led to a shift in dominant species from temperate-subtropical/eurythermal to subtropical–tropical/eurythermal taxa (Jiang et al., 2014). Furthermore, a large number of organic pollutants, specifically semi-volatile chemicals, can be emitted into the atmosphere from the ocean due to the impact of ocean warming (Ma et al., 2011). Previous research has shown that the seasonal warming in the Changjiang River estuarine-coastal ocean continuum leads to the release of PAHs and OCPs from seawater into the atmosphere (Ji et al., 2015; Jiang et al., 2018).

7. The changing Changjiang River estuarine-coastal ocean continuum

The studies mentioned above indicate that there has been a system regime shift of the Changjiang River estuarine-coastal ocean continuum due to human activities and climate change (Fig. 8). Based on the characteristics observed, we can roughly divide the ecological environment of the continuum since the 1950 s into three stages, which clearly demonstrate a critical transition in the ecosystem.

The first stage, from the 1950 s to the early 1980 s, can be considered an initial period with minor human disturbance (Fig. 8a). During this time period, the main channel and most of the tributaries of the Changjiang River are limited affected by human activities. However, some individual tributaries started to experience the impacts of human activities, such as the construction of the Danjiangkou Reservoir on the Hanjiang River, which began in 1978. The use of fertilizers was also minimal during this period (Fig. S4), resulting in low nutrient discharge into the Changjiang River estuarine-coastal ocean continuum (Fig. 4). Wetland reclamation in the Changjiang River Estuary was relatively limited during this time (Fig. S6). The second stage, from the early 1980 s to the early 2000 s, witnessed a gradual increase in human disturbance (Fig. 8b). Large-scale reservoir construction started in the upper tributaries, including the Yalong, Jialing, Min, and Wu Rivers. This led to a decrease in sediment loads discharged into the Changjiang River estuarine-coastal ocean continuum due to reservoir interception, which could affect the accretion rate of the subaerial and subaqueous delta (Yang et al., 2018a; Gao et al., 2019). The agricultural and industrial economy in the Changjiang River basin experienced rapid development during this period, resulting in an increase in nutrient and pesticide discharge into the Changjiang River estuarine-coastal ocean continuum (Fig. 4, Fig. S4 and S7). The ecological environment of the continuum deteriorated to some extent, particularly with enhanced eutrophication and HABs, which also caused a gradual decrease in DO levels (Fig. S5). Additionally, the rate of global ocean warming increased rapidly, further exacerbating the deterioration of the ecological environment in the Changjiang River estuarine-coastal ocean continuum (Fig. 3). Coastal reclamation in the CRE also accelerated during this period (Fig. S6).

The critical transition of the ecological environment in the Changjiang River estuarine-coastal ocean continuum occurred in the third stage, which we define as the period after the early 2000 s to the present (Fig. 8c). During this stage, the construction of reservoirs, such as the TGD and cascade reservoirs in the Jinsha River, drastically altered the sediment transport process in the Changjiang-East China Sea conveying system. This led to a sharp reduction in sediment, causing seabed erosion in the Changjiang subaqueous delta mud deposits and the northern part of the mud belt in the inner shelf of the East China Sea. As a result, the depocenter in the estuarine-inner shelf area of the East China Sea shifted (Gao et al., 2019; Wang et al., 2020a). These changes in riverine inputs and sedimentary environment affected the spatial patterns of carbon and pollutants, reducing their burial potential in the continuum (Wang et al., 2018, 2020a, b, 2022). Nutrient and pollutant levels discharged into the continuum remained high during this period, leading to the continuous deterioration of the ecological environment, including increased hypoxia and eutrophication (Fig. 5 and Fig. S5). Furthermore, despite suggestions that global warming may have stalled after 1998, coastal regions continued to store heat (Fig. 7), further damaging the ecological environment. Additionally, the intensity of wetland reclamation in the Changjiang River Estuary did not decrease during this period (Fig. S6).

8. What should we pay attention to in the future?

8.1. Response of sediment burial patterns to geomorphic system state changes

Previous studies have shown that changes in sediment discharge

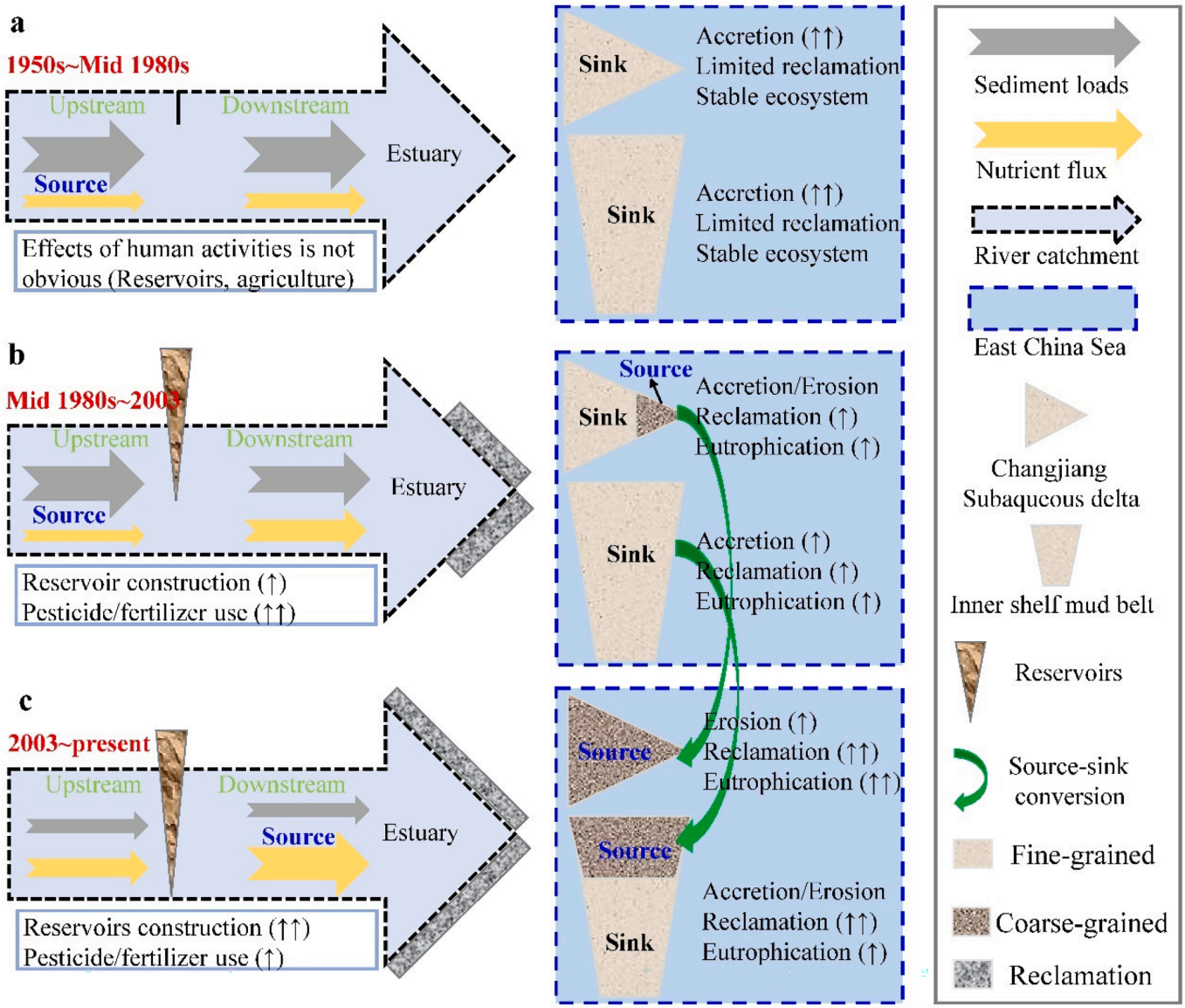


Fig. 8. Regime shift in the ecological environment of the East China Sea: a) relatively primitive state of Changjiang-East China Sea 'S2S' conveying system; b) regime shift of the ecological environment in the East China Sea; c) new steady state of the East China Sea after the regime shift.

have led to alterations in the geomorphic system state (Maloney et al., 2018; Gao et al., 2019). These changes have had an important impact on sediment transport processes, burial patterns, and the characteristics of surface sediments in the Changjiang River estuarine-coastal ocean continuum (Yang et al., 2018b; Gao et al., 2019). Additionally, these changes have implications for the burial patterns of materials associated with sediments (Gao et al., 2017; Wang et al., 2020a-c). For instance, the transport and burial changes can affect the fate of organic matter, such as organic carbon and organic pollutants, which are primarily absorbed onto fine-grained sediments (Wang et al., 2020a, b). The entrainment of organic matter in resuspension-deposition loops can accelerate its selective degradation process, while variations in sediment grain size and components can influence the protection of organic matter by the mineral matrix (Bao et al., 2016, 2018; Blattmann et al., 2019; Hemingway et al., 2019). These factors ultimately impact the burial process of organic matter in marginal seas and the global organic matter cycle (Wang et al., 2020c). However, research on these factors is currently limited, as most studies focus on the transition of the geomorphic system state. Therefore, it is crucial to shift the research focus towards understanding the ecological effects resulting from the transition of the geomorphic system. This will enhance our knowledge of source and sink processes in marginal sea environments under the context of global change.

8.2. *Reclamation weakens the filtering effect of wetlands*

Coastal reclamation has transformed natural wetlands into impervious hard ground and constructed wetlands, such as farmland and aquaculture ponds (Zang et al., 2017). This change in land use has altered the physical and chemical properties of the soil, including permeability, particle size, and mineral composition (Wang et al., 2014; Wissing et al., 2014; Zhang et al., 2018), which has an important impact on the wetlands' ability to filter pollutants. For instance, the construction of impervious hard ground disrupts the hydrological processes in wetlands, converting subsurface flow to surface flow and directly affecting the wetlands' capacity to degrade pollutants. Moreover, the change in land use also affects the microbial population and community structure in the soil, further influencing the wetlands' ability to remove pollutants. However, the specific impact of different wetland types on the transport of pollutants from land to sea remains unclear. Therefore,

future research should focus on understanding how wetland hydrological processes, vegetation, and microbial growth contribute to pollutant removal. Accurate knowledge of these processes is essential for a comprehensive assessment of the role of wetlands in pollutant removal, especially in the context of ongoing coastal wetland reclamation.

8.3. Biological pumping of pollutants

Marine microalgae in normal marine environments can impact the biogeochemical processes of persistent organic pollutants (POPs) through biological pumping (Galbán-Malagón et al., 2012; Nizzetto et al., 2012; Casal et al., 2017). This phenomenon has been observed in both marine and freshwater ecosystems (Tao et al., 2017). Microalgal blooms, characterized by increased phytoplankton biomass, absorb or adsorb a large number of dissolved or particulate POPs in the water, disrupting the balance of POPs exchange between water and particles (Galbán-Malagón et al., 2012; Shi et al., 2017). During algal bloom extinctions, dissolved POPs are released into the seawater, while organic particles adsorbed onto POPs are deposited onto seabed sediments, effectively removing PAHs (Nizzetto et al., 2012; Shi et al., 2017). This process, known as the biological pumping of POPs, plays a crucial role in regulating the occurrence, forms, and biogeochemical processes of POPs in the marine environment. Algal blooms can also affect the level of dissolved or particulate organic matter in seawater, which in turn influences the characteristics and biogeochemical processes of POPs due to their lipophilicity and hydrophobicity (Shi et al., 2017; Tao et al., 2017). Given that microalgal blooms and POPs pollution are severe issues in the East China Sea, studying the biological pumping effect of POPs in this area is essential. Therefore, more attention should be given to understanding the fate of POPs in the coastal ocean through biological pumping.

8.4. Secondary release of POPs caused by ocean warming

Seawater is an important source of POPs in the atmosphere (Lin et al., 2012, 2015; Li et al., 2017). Lin et al. (2015) found that most river-derived POPs discharged into the Changjiang River estuarine-coastal ocean continuum are not deposited in seabed sediments but instead volatilize into the atmosphere through air-seawater exchange. This exchange depends on the physicochemical properties of the POPs (such as vapor pressure, Henry's law constant, and partition coefficients) and environmental factors (such as temperature, precipitation, winds, and currents) (Dachs et al., 2002; Steemler and Lammel, 2009). Previous studies have shown that the physicochemical properties of POPs are influenced by temperature and can be described by linear relationships (Wania et al., 1998; Jantunen and Bidleman, 2006). Positive linear regression relationships between vapor pressure/octanol–air partition coefficients and temperature indicate that higher temperatures enhance the volatilization of pollutants (Ma et al., 2016). Lamon et al. (2009) demonstrated that a 1 °C increase in temperature can increase the volatility of a typical POP by 10–15 %.

Global climate change is altering environmental factors, leading to changes in the physicochemical properties of POPs. There is growing evidence that climate change is causing the release of POPs at local, regional, and global scales (Ma et al., 2011; Fan et al., 2023). From 1958 to 2014, SST in the Changjiang River estuarine-coastal ocean continuum increased by approximately 1.71 °C, with a winter warming rate of 0.3 °C per decade and a summer warming rate of 0.15 °C per decade. These warming rates have exceeded the global average since the 1980 s (Cai et al., 2017). Additionally, there have been marine heat waves occurring in the continuum due to ocean warming (Holbrook et al., 2019). These extreme high temperatures may further enhance the release of pollutants. The frequency of marine heat waves in the East China Sea has been higher than 3 per year, increasing by 1–2 per decade from 1982 to 2018 (Yao et al., 2020). The rapid warming and increasing frequency of heat waves in the Changjiang River estuarine-coastal ocean continuum have created favorable conditions for the secondary release of OCPs from the ocean. Therefore, it is crucial to understand the process of secondary release of POPs in marginal seas under the context of global warming. Such understanding is essential for accurately comprehending the biogeochemical cycling of POPs, and it warrants sufficient attention in relevant studies.

CRediT authorship contribution statement

Zhe Hao: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Min Xu:** Writing – review & editing, Formal analysis. **Xinqing Zou:** Writing – review & editing, Formal analysis, Conceptualization. **Chenglong Wang:** Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by the Natural Science Foundation of China (Grant Nos. 42106056) (C.W), the Natural Science Fund for colleges and universities in Jiangsu Province (23KJB170009) (Z.H.), the China Postdoctoral Science Foundation (2021 M691504) (C.W.), the Fundamental Research Funds for the Central Universities (Grant No. 0209-14370407) (X.Z.).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.107904.

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