Three Gorges Dam Alters the Footprint of Particulate Heavy Metals in the Yangtze Estuary

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Abstract: Two scenarios were selected to simulate the situation before the closure of the Three Gorges Dam (TGD) in 1996 (Scenario 1) and after the completion of the Three Gorges Project in 2010 (Scenario 2). A modified polar co-ordinated segmented quantification method was proposed to quantify the heavy metal footprint excursion in Scenarios 1 and 2 and further evaluate their influence on the six sensitive targets in the Yangtze Estuary. Scenario 3 was utilised to analyse the negative effects of the footprint range on the spatio-temporal overlap of the Chinese sturgeon juveniles arriving in the estuarine reserve, set in the TGD-altered biological rhythm. Each scenario comprises four simulation sites from March to September, including three major urban sewage outlets, named Bailonggang (BLG), Zhuyuan (ZY), Shidongkou (SDK), and the upstream pollution source, represented by Xuliujing (XLJ). The results showed that the increased discharge in the dry season moved the post-TGD footprint further away from Chongming Island. Additionally, the outward side footprint was formed during the flood season, when the average discharge was lower than that during the pre-TGD period, being 'pushed' to the northwest by the monsoon and Taiwan warm current, resulting in a narrowing of the overall extent. The TGD positively impacted the XLJ and BLG simulation sites, given their shrinking footprint range and the decreasing trajectories of intruding sensitive targets in Scenario 2, in contrast to SDK and ZY.
Key words: Yangtze Estuary; Mega Hydropower; Cu Footprint; Excursion; Quantification Method
Abbreviations

1. **Monitoring Section (Station):** Nantong (NT), (120° 50' 41" E, 31° 58' 55" N); Xuliujing (XLJ), (120° 57' 34" E, 31° 46' 17" N); Baimaokou (BMK), (121° 08’ 48” E, 31° 45’ 20” N); Qinglonggang (QLG), (121° 14’ 01” E, 31° 51’ 36” N); Qidonggang (QGD), (121° 40’ 12” E, 31° 43’ 12” N); Beigang (BG), (121° 37’ 00” E, 31° 30’ 34” N); Nangang (NG), (121° 33’ 06” E, 31° 23’ 00” N); Wusongkouxia (WSKX), (121° 43’ 42” E, 31° 17’ 00” N).

2. **Simulation Site:** Xuliujing (XLJ), (121° 05’ 42” E, 31° 43’ 44” N); Shidongkou (SDK), (121° 25’ 01” E, 31° 27’ 50” N); Zhuyuan (ZY), (121° 37’ 18” E, 31° 21’ 05” N); Bailonggang (BLG), (121° 45’ 01” E, 31° 15’ 25” N).

3. **Study Period:** Biological sensitive aggregation period of the Yangtze Estuary (BAPYE).

4. **Hydropower:** Three Gorges Dam (TGD); Gezhou Dam (GZD).

5. **Sensitive Target:** Shanghai Yangtze Estuary Chinese Sturgeon Conservation (SYECSC); Shanghai Chongming Dongtan National Nature Reserve (SCDNNR); Shanghai Jiuduansha Wetland National Nature Reserve (SJWNNR); Qingcaosha Reservoir (QCSR); Dongfengxisha Reservoir (DFXSR); Chenhang Reservoir (CHR).

6. **Simulation Scenario:** The year before the river closure of Three Gorges Dam (1996) (Scenario 1); the year after the completion of entire Three Gorges Project (2010) (Scenario 2); a post-TGD year after the adaptation of the Chinese Sturgeon (2017) (Scenario 3).

7. **Quantification Method:** Modified polar co-ordinated segmented quantification method (MPCSQM).

8. **Other:** suspended particulate matter (SPM); heavy metal (HM); Hydrology and Water Resources Survey Bureau of Yangtze Estuary (HWRSBYE); turbidity maximum zone (TMZ); East China Sea (ECS).
1. Introduction

Heavy metal (HM) risk has become a global environmental concern because of its toxic effects, persistence, and biomagnification (Eeva and Lehikoinen, 2000; Ofukany et al., 2014). The industrial clusters in the Yangtze River Delta, represented by the Yangtze Estuary, have occupied a significant share of the Chinese economy, accounting for 25% of the total economic output and 37% of the total import and export volume of this country (CPC Central Committee, 2019). However, the vigorous development of the Chinese industry has increased the risk of chemical spills (Jiang et al., 2012), the threat of floods to coastal megacities (Du et al., 2020), and nutrient emissions (Cloern et al., 2014; Wang et al., 2020), which put great pressure on local ecosystems. Among them, like many other countries in the world, such as Cuba (Olivares-Rieumont et al., 2005), India (Singh and Kumar, 2017) and Iran (Jafarabadi et al., 2021), heavy metal pollution is an unavoidable threat (Zhao et al., 2012). As conservative pollutants that are generally considered to lack biodegradability (Yi et al., 2011), approximately 90% of HMs in water are related to suspended particulate matter (SPM) (Zheng et al., 2008), and are easily deposited on the surface of sediments. Surface sediments are the main feeding source for benthic fauna; thus, HMs are easily transferred to fish (Yi et al., 2011), oysters (Rajeshkumar et al., 2018), and other organisms (Uluturhan and Kucuksezgin, 2007) through predation behaviour, and eventually transmitted to humans through the food chain with biological enrichment, posing a significant threat to health (Kumar et al., 2019; Llobet et al., 2003). Moreover, the harm of HMs to birds is evident in the thin and porous eggshells when laid in the vicinity of the pollution source (Eeva and Lehikoinen, 2015) along with the reduction of wing growth (Sanchez-Virosta et al., 2018); these are linked to large amounts of HMs consumed by parent birds from their invertebrate prey (Eeva and Lehikoinen, 2000).

With the economic development of China, the Yangtze River, the longest river in the Eurasian continent
(Wang et al., 2020), has also become one that is significantly affected by anthropogenic activities (Yang et al., 2002; Zhang et al., 2006). Since the 1960s, marked by the completion of the Danjiangkou Dam in 1968, more than 50,000 dams have been built on the main stream of the Yangtze River or its tributaries (Yang et al., 2018). In particular, the completion of the Three Gorges Dam (TGD), the largest hydropower station in the world, has significantly changed the inter-annual discharge distribution pattern of the Yangtze River combined with the Gezhouba Dam (GZD) completed in 1988 (Fig. 1). This change in peak discharge reduction during the flood season (from May to October) and discharge replenishment in the dry season (from November to April) can be intuitively reflected in the comparison between the pre-TGD and post-TGD periods (Wang et al., 2020).

When assessing the environmental impacts of dams on rivers, most studies have focused on the variation in water and sediment caused by dam construction, which indirectly affects the distribution of their pollutants (Dai and Liu, 2013; Liu et al., 2020; Liu et al., 2019). They provided valuable references for macro-control ideas, while people completed the establishment of corresponding hydrodynamic models (Hu et al., 2009). However, to date, there has been no systematic quantitative assessment of the estuarine variation in HM transport in response to changes in the TGD-induced discharge regulation. Given the need to protect the rare and unique species in the Yangtze Estuary region and the drinking water safety of 24 million residents in the Shanghai Municipality, it is essential to analyse the HM transport caused by chemical leakage or sewage discharge, and pollution prevention and control strategies should be periodically adjusted according to the patterns adapted to the post-TGD period.

For the aforementioned purposes, the Xuliujing national monitoring section (XLJ) and three main typical sewage outlets in the Yangtze Estuary, including Bailonggang (BLG), Zhuyuan (ZY), and Shidongkou (SDK) of the Shanghai Municipality, were selected as simulation sites (Fig. 1). Herein, to facilitate the analysis of migration, the term ‘footprint’ will continue to be employed, and is defined as ‘the motion trajectory of a particular contaminant
particle from a specific place as the starting point under the simultaneous influence of water flow and other external forces’ (Yichuan et al., 2021). Three representative years from 1996 (Scenario 1), 2010 (Scenario 2), and 2017 (Scenario 3) were selected to describe the process of the pre-TGD period, TGD completion period, and post-TGD period after the adaptation of rare organisms to the obstruction of mega hydropower. Moreover, considering that the discharge of the Yangtze River was the main source of HM copper (Cu) in the estuary (Yin et al., 2015) and that salinity considerably promoted the release of copper from SPM into the water body (Yao et al., 2016), the modified polar co-ordinated segmented quantification method (MPCSQM) was further adopted to characterise the dam-induced excursion on the particulate Cu footprint between Scenarios 1 and 2.

2. Methodology

2.1 Study area

Fig. 1. Distribution of monitoring sections and sensitive targets. (a) The location of TGD, GZD, and Yangtze
Estuary; (b) the distribution of the main sewage outlet and sensitive targets in the Yangtze Estuary; and (c) the box-plot of the average monthly discharge at the Xuliujing monitoring section since the first impoundment of the TGD at a water level of 175 m (2011-2018).

As the entrance of the Yangtze River into the East China Sea (ECS) is affected by both the discharge and tidal currents, the Yangtze Estuary has been vital as a transfer station for migratory birds (Zou et al., 2016), a nursery for rare species (Whitfield, 2017) and one of the world logistics centres. In 2020, According to a report from the Ministry of Transport of People's Republic of China, the annual container throughput of Shanghai Port reached 43.5 million twenty-feet equivalent units, ranking first in the world for 11 consecutive years (Ren, 2021). The equipment manufacturing industry in the Yangtze River Delta (Zhou et al., 2021) and the tertiary industry, accounting for more than 50% of the Shanghai economy (Zheng et al., 2016), has driven an increase in the logistics industry; but it also inevitably increases the risk of sudden pollution incidents listed in Appendix 1. As for hydrodynamic conditions, the Three Gorges Project, located approximately 1900 km upstream of the Yangtze Estuary (Sun et al., 2021), significantly shaped the annual discharge distribution at the river-sea transition from the completion of the closure in 1997 until the completion of all facilities in 2009. This is evidenced by the 24% discharge reduction at the end of the flood season and the increase from December to March due to its regulation (Chen et al., 2016).

Additionally, there are three drinking water reservoirs, the Chenhang Reservoir (CHR), Dongfengxisha Reservoir (DFXSR), Qingcaosha Reservoir (QCSR), and three national nature reserves, with a total of six major sensitive targets (Fig. 1). Among them, there are two overlapping nature reserves situated on the eastern edge of Chongming Island. One is the Shanghai Yangtze Estuary Chinese Sturgeon Conservation (SYECSC), which aims to provide a ‘nursery’ for the juveniles of Chinese sturgeons (Zhou et al., 2020). The Shanghai Chongming Dongtan National Nature Reserve (SCDNNR) is established to protect migratory birds such as Charadriidae, Anatidae,
Ardeidae, and Laridae, as well as the estuarine wetland ecosystem on which they live. There are also two precious and fragile species, which are resident birds observed in the SCDNNR. One is the Reed Parrotbill (Paradoxornis heudei) that mainly lives in the mudflat wetland reeds of the SCDNNR (Boulord et al., 2012), forming pairs every April, nesting, and breeding. The other is the scaly sided Merganser (Mergus squamatus), found only in East Asia, and its type locality is in China (Zeng et al., 2015). The third reserve is located at the end of the South Branch of the Yangtze Estuary, the Shanghai Jiuduansha Wetland National Nature Reserve (SJWNNR). Before the completion of the TGD, the migratory rare species (Chinese sturgeon), spawning upstream from mid-October to mid-November, arrived in the Yangtze River estuary the following year in mid-May (Zhang et al., 2010). However, since the completion of the TGD in 2009 and combined with the GZD, the water temperature increased by 2-3 °C during the spawning period, with an average annual decrease of about 0.4 °C (Wenxian et al., 2009). This changed the spawning time of the Chinese sturgeon and made the juveniles reach the Yangtze Estuary one month earlier, around mid-April (Zhuang et al., 2016).

2.2 Data collection

The diverse data sources provide a solid guarantee for calibrating models and cross-referencing. The first type of data is obtained from the integrated data platforms. The original terrain and bathymetry data involved in the model were provided by the products of Taile maps (http://www.arctiler.com/). The daily average wind, precipitation, and evaporation data for the three scenarios (1996, 2010, and 2017) were acquired from a series of ‘daily value dataset of China surface climatic data’ from the National Meteorological Science Centre (http://data.cma.cn/en). The water level of the sea surface boundary and the background salinity value of the study area were obtained from two channels. One was from the National Marine Data Centre, National Science & Technology Resource Sharing Service Platform of China (http://mds.nmdis.org.cn/). The section distribution of
the monitoring station is shown in Fig. 1(b).

Meanwhile, the hydrodynamic and water quality data of a specific monitoring station were obtained from the Hydrology and Water Resources Survey Bureau of Yangtze Estuary (HWRSBYE). They are Nantong (NT), Xuliujing (XLJ), Baimaokou (BMK), Qinglonggang (QLG), Qidonggang (QDG), Beigang (BG), Nangang (NG), and Wusongkouxia (WSKX), respectively. BG, NG, and WSKX were monitored twice every March, July, and November, with a total of six times each year. The monitoring frequency of NT, QLG, and QDG was once a month.

As a national key monitoring station, four buoys equipped with acoustic Doppler current profilers (ADCPs), GPS, OBS-3A turbidity meter, General Packet Radio Service (GPRS) terminal, and digital radio (VHF), were set up at the XLJ monitoring section. They work at regular intervals and send real-time data to the central control station every half hour to ensure the model accuracy of hydrodynamics, including the flow velocity, direction, turbidity, temperature and conductivity, tidal level, and flow. The water samples collected from the monitoring section were pre-treated and tested within 24 h. SPM is monitored by the gravimetric method, referring to the national standard GB/T 11901-1989. The HM content was determined by inductively coupled plasma Agilent 7700X ICP-MS in accordance with the water conservancy industry standard SL 394.1-2007, issued by the Ministry of Water Resources, PRC. Nitric acid (5 mL) was added per 100 mL of homogeneous water sample which was placed on a hotplate and heated slowly until nearly dry and then cooled. This process was repeated until the colour of the sample solution stabilised. After cooling, small amounts of nitric acid solution and deionised water were added, and the residue was dissolved by heating. The solution was then fixed with water to the original sample volume to maintain a 2% nitric acid concentration. The analytical procedure required the addition of quality control or duplicate test samples at a frequency of at least one out of every 10 tested samples, and the results were required to meet the quality control requirements. Otherwise, the instrument should be recalibrated with a calibration standard.
solution to proceed with the determination. For regions containing both types of data, the mean values were calculated.

Three typical sewage plants were selected as the simulation sites to represent urban pollution sources. The SDK Urban Wastewater Treatment Plant project, with a scale of 0.4 million m$^3$/d, is currently the largest integrated activated sludge process in China, as well as the largest secondary biological treatment of urban wastewater treatment plants in Shanghai with nitrogen and phosphorus removal functions. Wastewater treatment plants in BLG and ZY are both located in the Shanghai Pudong New Area, with a sewage treatment scale of 2.8 and 2.2 million m$^3$/d respectively. Detailed information on the major sewage treatment plants in Shanghai can be found at https://www.dowater.com/company/shanghai/Index.html.

2.3 Numerical simulation

2.3.1 Simulation periods

Fig. 2. Simulation periods diagram. (a) The timeline of TGD construction and the location of the three scenarios and (b) distribution of natural events in the monthly timeline.

Three representative years were selected as three comparison scenarios to reflect the TGD-induced changes in
the spatiotemporal discharge distribution of the Yangtze River, as well as the variation caused by blocking the migration of Chinese sturgeons, forcing them to adapt to new spawning sites, and exploring the variation of HM footprints under such changes., Scenario 1, simulated in 1996, mainly describes the HM footprint under the original hydrodynamic conditions before the closure of the Yangtze River in 1997. Scenario 2, simulated in 2010, is vital in estimating the impact on the HM footprint after the completion of the Three Gorges Project in 2009. Beginning in 2013, no spawning activity was detected during the monitoring of Chinese sturgeons downstream of the GZD until April 2015, when some juveniles were found in the Yangtze Estuary (Zhuang et al., 2016). Therefore, Scenario 3 in 2017 focused on simulating the intrusion threat to regionally sensitive targets from the HM footprint during the post-TGD period, when the population of Chinese sturgeons started to recover after adapting to the presence of the TGD and arrived at SYECSC in mid-April each year, as shown in Fig. 2(a). In the context of the previous study, based on the current situation of reproduction that involves seedling breeding of rare species in the Yangtze Estuary from March to June each year, we continue to pay attention to the migration regularity of HM footprints in the biological sensitive aggregation period of the Yangtze Estuary (BAPYE; Fig. 2(b)). Simultaneously, the simulation period for each scenario was chosen from 1 March to 30 September considering the reduction effect of TGD on flood peaks during the flood season (May to October). Comparison between Scenarios 1 and 2 allowed the quantification of the TGD-induced migration excursion of the HM footprint, thus providing a reference for the periodic adjustment of regional pollution control strategies.

2.3.2 Applicable model

The simulation process is described by a 2D estuarine hydrodynamic model, and the specific formulae of sediment transport and heavy metal simulation are obtained from previous studies (Wang et al., 2020; Yichuan et al., 2021). Herein, the water current and random walk particle tracking (Rwpt) model describing the HM footprint and
its formula are presented in detail.

- Water current simulation

The equations are as follows:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} &= 0 \\
\frac{\partial (hu)}{\partial t} + \frac{\partial \left(hu^2 + \frac{gh^2}{2}\right)}{\partial x} + \frac{\partial (huv)}{\partial y} &= gh(S_{ox} - S_{f_x}) + hf v + hF_x \\
\frac{\partial (hv)}{\partial t} + \frac{\partial \left(hv^2 + \frac{gh^2}{2}\right)}{\partial y} + \frac{\partial (huv)}{\partial x} &= gh(S_{oy} - S_{f_y}) - hf u + hF_y
\end{align*}
\]

where \(u\) and \(v\) are the velocities of the surface water flow in the \(x\) and \(y\) directions, respectively; \(t\) is time; \(S_{f_x}\) and \(S_{f_y}\) are the friction slopes in \(x\) and \(y\) directions, respectively; \(S_{ox}\) and \(S_{oy}\) are the slopes of the riverbed in the \(x\) and \(y\) directions, respectively; \(F_x\) and \(F_y\) are the components of friction in the \(x\) and \(y\) directions, respectively; \(h\) is the water depth; \(g\) is the acceleration of gravity; and \(f\) is the Coriolis force parameter (DHI, 2011a). The above parameters were calculated using the following formula:

\[
S_{f_x} = \frac{\rho u \sqrt{u^2 + v^2}}{hc^2} = \frac{\rho n^2 u \sqrt{u^2 + v^2}}{h^{4/3}}, \quad S_{f_y} = \frac{\rho u \sqrt{v^2 + u^2}}{hc^2} = \frac{\rho n^2 v \sqrt{u^2 + v^2}}{h^{4/3}}
\]

\[
S_{ox} = -\frac{\partial Z_b}{\partial x}, \quad S_{oy} = -\frac{\partial Z_b}{\partial y}
\]

\[
F_x = \frac{1}{\rho h} \rho_a C_D w_x \sqrt{w_x^2 + w_y^2}, \quad F_y = \frac{1}{\rho h} \rho_a C_D w_y \sqrt{w_x^2 + w_y^2}
\]

\[
f = 2\omega \sin \varphi
\]

where \(\rho\) and \(\rho_a\) are the water and air densities, respectively; \(w_x\) and \(w_y\) are the measured wind speeds in the \(x\) and \(y\) directions, respectively; \(\omega\) is the angular velocity of the earth’s rotation; \(\varphi\) is the latitude; \(c\) is the Chezy coefficient; \(n\) is the roughness coefficient; \(C_D\) is the empirical drag in the air, and the specific formula (Wu, 1980; 1988; 1994) is expressed as:

\[
C_D = \begin{cases} 
C_a & w < w_a \\
C_a + \frac{C_b - C_a}{w_b - w_a} (w - w_a) & w_a \leq w \leq w_b \\
C_b & w > w_b
\end{cases}
\]

The empirical values of the above parameters are \(C_a = 1.255 \times 10^{-3}\), \(C_b = 2.425 \times 10^{-3}\), \(w_a = 7 \text{ m/s}\),
and \( w_b = 25 \text{m/s}; \) \( w \) is the measured wind speed measured at 10 m height.

- **Particle Tracking**

  The particle path was calculated using the output velocity of the hydrodynamic model. The fourth-order accurate Runge-Kutta method was used to integrate the particle position equation (DHI, 2011b). Owing to the existence of current and random walk in the sub-grid scale diffusion process, the Rwpt model can be described as advection, and is reformulated as diffusion.

  \[
  X^{t+\Delta t} = X^t + U \Delta t + R(t)\sqrt{2K_h\Delta t}
  \]

  where \( X^t \) and \( X^{t+\Delta t} \) are the passive particle position vector times of \( t \) and \( t + \Delta t \), respectively; \( U \) is the velocity vector of the model flow field; \( \Delta t \) is the time step of the random walk; \( R(t) \) is a uniformly distributed random number in the interval \(-1–1\), which is given by the Fortran 90 random number generator; and \( K_h \) is the eddy diffusion coefficient of the horizontal random walk, which is derived from the hydrodynamic model.

2.4 Modified polar co-ordinated segmented quantification method (MPCSQM)

To embody the impact of the TGD on the Cu footprint in the Yangtze Estuary, a polar co-ordinate system was established with the easternmost end of Chongming Island (121° 59’ 20” E, 31° 29’ 38” N) as the origin, the eastward direction from the origin as the positive direction of the polar axis, and the clockwise direction as the positive direction of the angle. Sensitive targets are mostly concentrated in the southwestern part of the polar co-ordinate system, where the variation in the TGD-induced footprint for the extent of intrusion cannot be assessed by previous quantitative methods. To fill this gap, in the MPCSQM, the research area was divided into: Part 1 (0-90°), Part 2 (90-135°), Part 3 (135-180°), and Part 4 (>180°) according to the co-ordinates. The seaward side is regarded as the outward side, while the seaward excursion is positive (Table 1, Outward excursion). Similarly, the side facing Chongming Island is regarded as the inward side, using the same standard to judge the direction of...
deviation as the outside side (Table 1, Inward excursion). A ray rotated clockwise from the co-ordinate axis to the angle at which the footprints in Scenarios 1 and 2 have the longest overlap range with the ray in each part, and the angle between the ray and the co-ordinate axis is denoted as $\theta$. $(r_1, \theta)$ and $(r_2, \theta)$ represent the intersection point of the ray and footprint boundary in Scenarios 1 and 2, respectively, according to the above requirements. The change in radius was expressed as $\alpha$ using the formula $\alpha = \frac{r_2 - r_1}{r_1}$. Therefore, in this MPCSQM, the direction of the footprint excursion is according to the positive and negative values of $\alpha$. To distinguish between the outward and inward sides, $\alpha$ is labelled in the lower right corner. The symbols ‘o’ and ‘i’ represent the outside and the inside, respectively.

In addition to the excursion, the impact of the footprint on the six sensitive targets is also considered in the MPCSQM. The concept of sensitive target influence ($E_j$) is defined by the following formula:

$$E_j = 1 - \frac{L_{S2j}}{L_{S1j}}(j = 1, 2, 3, 4)$$

where $L_{S1j}$ and $L_{S2j}$ are the lengths of the footprints in Part $j$ $(j=1, 2, 3, 4)$ of Scenario 1 and Scenario 2 (the sum of the lengths of each footprint branch that enters the sensitive target area). The number of sensitive targets affected by the footprint was shown on the right side of the column ‘$E_j$’ (column ‘No.’). Further, the concept of the TGD footprint impact index ($I$) is established:

$$I = \frac{1}{4} \sum_{j=1}^{4} (\alpha_{ij} - \alpha_{oj} + E_j)$$

where $\alpha_{ij}$ and $\alpha_{oj}$ are the changes in the radius on the inward and outward sides in Part $j$ $(j=1, 2, 3, 4)$ of Scenarios 1 and 2, respectively. As both $\alpha$ and $E_j$ represent the percentage of the footprint range variation, their sum can comprehensively reflect the influence of the TGD on the entire region. $\alpha_{ij} - \alpha_{oj} > 0$ represents the reduction in the footprint range and $E_j > 0$ represents the reduction of footprint intrusion into sensitive targets. Therefore, if $I > 0$, TGD is considered to have a positive effect by assisting sensitive targets to reduce the threat of
15 footprints; $l < 0$ indicates a negative effect; and $l = 0$ implies no effect.

2.5 Model configuration

![Fig. 2. Range of simulation in the Yangtze Estuary. (a) The bathymetric map; and (b) the area covered by the computational grid and the location of mesh refinement.]

The simulation experiment ensured that the hydrodynamic simulation conformed to the actual conditions in the Yangtze Estuary, further ensuring the accuracy of the footprint simulation. Considering the surface area of the estuary with a simulation area of $4.08 \times 10^4$ km$^2$, the modelling area was covered by a total of 10864 quadrilateral elements and 6648 nodes as the simulation foundation, as shown in Fig. 3(a). Additionally, considering the construction of the waterway regulation project in the Yangtze Estuary, local mesh refinement was conducted in the area of the waterway regulation project between Jiuduansha and Changxing Island (Fig. 1), as shown in Fig. 3(b). The calculation time step of the model was dynamically adjusted to 60 s according to the model grid size and water depth condition, ensuring that the Courant-Friedrich Levy (CFL) number was less than 0.8 to meet the required
model stability. The model contains three inflow boundaries (Yangtze River, Huangpu River, and Qiantang River) and one outflow boundary (south of the Yellow Sea, ECS), which unifies the elevation by utilising the Wusong datum. According to the simulation scheme, the model was calculated thrice to adapt to the scenarios in 1996, 2010, and 2017. The three simulated HM particle tracking modules all began to release particles at XLJ, SDK, ZY, and BLG from 0:00 on March 1st to 24:00 on September 30th; HM particles are considered to be non-degradable, with a release intensity of 4 particles per 7 days. Spatially varying Manning numbers were used from $50 \frac{m^1}{s}$ in the channels to $30 \frac{m^1}{s}$ in the marshland and were obtained from the research results of (Attari and Hosseini, 2019). The horizontal eddy viscosity with a value of $0.5 \times 10^5 cm^2/s$ was determined by the Smagorinsky formulation (Chen et al., 1999; SMAGORINSKY, 1963). To verify the accuracy of the model to describe the characteristics of the three scenarios in the Yangtze Estuary as the representative index in this study, the mean relative error (ARE) of SPM, namely, particulate Cu, for the three scenarios was calculated. $ARE = \left| \frac{\text{Calculated} - \text{Measured}}{\text{Measured}} \right|$ in the calibration and validation periods was 8.31-24.57%, with an average of 17.13%. XLJ, a national water quality monitoring section with continuous monitoring data, was selected for the calibration and validation, as shown in Appendix 2.
3. Results

3.1 Footprint analysis across the entire process of TGD construction

3.1.1 The year before the river closure for TGD (Scenario 1, 1996)

From Fig. 4, footprint migration with different colours for each simulation site prior to the closure of the TGD was acquired, wherein we assumed that the hydrodynamic conditions of the Yangtze River had not yet been interfered with by the world's largest hydropower station. The abbreviations for sensitive targets subject to footprint intrusion are indicated on the right of Figs. 4-6. The general trend of the footprint reflected a narrower range in the middle of the South Branch, covering an area that began to expand as it departed from the SJWNNR. After reaching the southeastern area offshore of the Yangtze Estuary, it turned in a counter-clockwise direction at a specific location and headed northeast. As the two outlets are in close proximity, the trajectories of BLG and ZY are highly similar and do not impact other sensitive targets, except for ZY, which has a 2.4 km long footprint track that

Fig. 4. Footprint simulation before the Yangtze River closure for TGD in 1996
intrudes into the edge of SJWNNR. In the range of 122° 18' 18" E-122° 31' 26" E, the footprint originally expanded in a southeasterly direction, and subsequently began to turn northwest and converged after approaching the Shengsi archipelago. The turning locations of BLG and ZY appeared approximately 11 km northeast of the main island of Shengsi County, while ZY had a branch reaching the northern shoreline of Shengsi County. After crossing northward to the latitude of the easternmost point of Chongming Island, it narrowed to a minimum width outside the estuary, 6.5 km (BLG, formed between the 28th-36th day) and 7.1 km (ZY, formed between the 31th-41th day) wide, respectively. Immediately thereafter, the trajectory progressively began to extend its area of interference and reached the northern boundary in a dispersed state. Owing to the diversity in the location of the simulation site, a large proportion of particles released from the SDK were blocked by the Changxing Island and Jiuduansha Shoal, while relatively few particles migrated into the offshore waters. Nevertheless, among the sparser trajectories, a branch still reached the centre of Shengsi County and turned northward after crossing the islands.

The XLJ site undoubtedly occupied the largest number of affected sensitive targets, including DFXS, QCSR, SYECSC, and SJWNNR. Starting upstream from Chongming Island, the trajectory was divided into two branches after skimming but not invading DFXSR; one entered NG, where Changxing Island and one island of the SJWNNR blocked the way. The other branch entering BG first intruded the QCSR and subsequently reached the southern part of the SYECSC, leaving the reserve and shifting from the coastal sea of the northern Yangtze Estuary to the northern boundary. Prior to the closure of the TGD, Chinese sturgeons spawned between October and November each year, and the juveniles arrived at SYECSC the following year around May. Based on the simulation of Scenario 1, a sudden accident such as a shipwreck or chemical spill at XLJ would be fatal to the Chinese sturgeon juveniles; the release of HM particles at BLG and ZY can be regarded as having no significant impact on sensitive targets.
3.1.2 The first year after the completion of TGD (Scenario 2, 2010)

Fig. 5. Simulation after the completion of the entire Three Gorges Project in 2010.

Since the completion of the Three Gorges Project, the combined water discharge scheduling of the two dams has reshaped the water temperature distribution, negatively affecting the spawning locations of Chinese sturgeons, causing alterations in the hydrodynamic conditions of the Yangtze Estuary, and advancing the timing of the arrival of juveniles at SYECSC. For the SDK, the main body of the footprint moved partly to the northwest and did not enter the core area of the Shengsi archipelago in Scenario 2. The number of trajectories intruding into the area governed by the SJWNNR increased, but there was a clear narrowing of its overall interference range. Conversely, BLG showed the opposite trend in SDK in the post-TGD simulation period. Compared to Scenario 1, the BLG footprint drifted away from Chongming Island and narrowed near the northern boundary, while the southeastern portion expanded toward the Shengsi archipelago, forming an encircling pattern. In Scenario 2, the ZY footprint followed the BLG, contracting in the southeast and expanding in the north. Although there was an intuitive increase
in the track density within the interference, it can be considered less dangerous than that in Scenario 1 because it did not intrude into any additional islands after leaving SJWNNR. The XLJ footprint performed well in Scenario 2, as evidenced by the complete withdrawal from QCSR, reduced intrusion into SYECSC, and a significant reduction in the extent of branch influence south of Changxing Island. The widening of the southeastern part of the intervention could be considered as a change without much concern, as no sensitive targets would be additionally affected. Therefore, in combination with Figs. 4 and 5, we suggested that the hazards to the sensitive areas during the migration of the footprint decreased due to the accidental HM spill in the upstream section of the river represented by XLJ after the construction of the TGD.

3.1.3 Comparison in a normal Post-TGD Year (Scenario 3, 2017)

![Simulation after the Chinese sturgeon adapted to the TGD in a common water year (2017).](image)

Juvenile Chinese sturgeon populations have been gradually recovering from valley values since 2015. However, the migration of spawning grounds downstream from the blockage of the upstream TGD resulted in their
appearance in the SYECSC in mid-April each year, one month earlier than during the pre-TGD period (Zhuang et al., 2016), reflecting an earlier period of high aggregation of sensitive targets. According to the Office of Shanghai Chronicles, 2017 was a typical common water year with no extreme flooding. Thus, it was selected as a simulation scenario to analyse the negative effects of the footprint range on the spatio-temporal overlap in the range of biological activity of juvenile Chinese sturgeons arriving in the SYECSC, based on the objective conditions of altered biological rhythmic activity. The XLJ footprint completely blocked the juveniles' access to SYECSC in the South Branch on the 20th day. The SDK footprint enclosed the Jiuduansha Shoal and only the corridor between Changxing Island and Chongming Island and the North Branch was available for juveniles. By the 40th day, the river-sea transition area was largely surrounded by all the trajectories. As the juveniles of Chinese sturgeon stayed at SYECSC for about three months, they left the reserve around July-August and continued their seaward migration. Therefore, although the footprints of ZY and BLG did not negatively impact the entry of rare species into the reserve and the nursery process of the rare species, all trajectories blocked the marine passage. Intuitively, the hazard of the footprint at the four simulation sites were ranked in descending order according to the number of sensitive targets affected as follows: XLJ > SDK > ZY > BLG. If an accidental pollution event occurred in the SDK-XLJ river section, in addition to reducing the number of safe corridor routes for rare species to reach the SYECSC, it would also narrow out the safe feeding space for migratory birds. This would increase the pressure on the two overlapping nature reserves at the eastern end of Chongming Island to manage the foraging, breeding, and roosting of organisms in BAPYE. Hence, from late March onwards, safety checks on the XLJ-SDK river section should be strengthened to prevent the threat of accidental HM leakage on the migration corridor of sturgeon juveniles arriving in mid-April.
### 3.2 Assessment of the footprint by utilising MPCSQM

From the simulations in Scenarios 1 and 2, the impact of the TGD on the Cu footprint can be determined by considering the increase or decrease of two components: the width and length of the footprint into sensitive targets. The sum of these two variations should be the criterion for determining the greater footprint hazard between the two scenarios before and after the construction of the TGD. This enables a reasonable quantification of the impact of the presence of the TGD on the extent of the footprint hazard resulting from pollution events such as HM spills at the four simulation sites. Table 1 presents these specific relationships through the MPCSQM.

#### Table 1 Comparison and quantification of the Cu footprint excursion between Scenarios 1 and 2

<table>
<thead>
<tr>
<th>Simulation Site</th>
<th>Part Number</th>
<th>Inward Excursion</th>
<th>Outward Excursion</th>
<th>Sensitive Target</th>
<th>TGD impact Index (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>α&lt;sub&gt;i&lt;/sub&gt;(%)</td>
<td>θ&lt;sup&gt;i&lt;/sup&gt; (°)</td>
<td>α&lt;sub&gt;o&lt;/sub&gt;(%)</td>
<td>θ&lt;sup:o&lt;/sup&gt; (°)</td>
</tr>
<tr>
<td>1(0-90°)</td>
<td></td>
<td>-34.1</td>
<td>73.6</td>
<td>-29.0</td>
<td>36.7</td>
</tr>
<tr>
<td>2(90-135°)</td>
<td></td>
<td>8.4</td>
<td>119.5</td>
<td>-14.1</td>
<td>118.3</td>
</tr>
<tr>
<td>SDK</td>
<td>3(135-180°)</td>
<td>-9.6</td>
<td>155.3</td>
<td>-4.0</td>
<td>161.4</td>
</tr>
<tr>
<td></td>
<td>4(&gt;180°)</td>
<td>-21.2</td>
<td>286.5</td>
<td>-32.8</td>
<td>313.4</td>
</tr>
<tr>
<td>1(0-90°)</td>
<td></td>
<td>21.7</td>
<td>42.9</td>
<td>-20.1</td>
<td>36.0</td>
</tr>
<tr>
<td>ZY</td>
<td>2&amp;3(90-180°)</td>
<td>-1.4</td>
<td>91.3</td>
<td>-9.0</td>
<td>114.8</td>
</tr>
<tr>
<td></td>
<td>4(&gt;180°)</td>
<td>12.0</td>
<td>271.7</td>
<td>54.5</td>
<td>322.7</td>
</tr>
<tr>
<td></td>
<td>1(0-90°)</td>
<td>20.3</td>
<td>52.1</td>
<td>9.3</td>
<td>54.6</td>
</tr>
<tr>
<td>BLG</td>
<td>2&amp;3(90-180°)</td>
<td>0.5</td>
<td>97.6</td>
<td>-0.7</td>
<td>97.0</td>
</tr>
<tr>
<td></td>
<td>4(&gt;180°)</td>
<td>21.3</td>
<td>280.7</td>
<td>-17.1</td>
<td>289.4</td>
</tr>
</tbody>
</table>
Overall, the average value of the footprint inward excursion was $\alpha_i = 10.4\%$ and that of the outward excursion was $\alpha_o = -1.8\%$, indicating that the overall trend of the trajectory influenced by the TGD is moving away from Chongming Island while narrowing the interference range. However, the case of SDK was contrary to the overall trend, as shown by the overall shift closer to Chongming Island, the expansion of the interference range, and further intensification of the intrusion into the SJWNNR, resulting in a TGD impact factor of $I = -6.6\%$ in Scenario 2. Both the ZY and BLG footprints showed characteristics of contraction in the southeast and expansion in the north, which were evaluated by the MPCSQM and considered to have a reduced footprint interference compared to Scenario 1. This difference reflects that ZY further intruded into the SJWNNR in Part 2, while BLG did not pass through any sensitive targets; hence, TGD was considered to have an expanding impact on ZY ($I = -4.4\%$) and a narrowing impact on BLG ($I = 16.8\%$) through the quantification method. On a whole, the XLJ footprint moves toward the ECS, and the interference range expands somewhat ($\alpha_i - \alpha_o = -22.5\%$). In contrast, the sensitive targets were significantly less threatened by the footprint due to the complete withdrawal of the trajectory line from the QCSR, SJWNNR, and partially from SYECSC. Therefore, XLJ, as the simulation site affecting the largest number of sensitive targets, experienced the most obvious improvement induced by the TGD ($I = 35.2\%$).

### 4. Discussion

After the 1950s, the North Branch accounted for only 5% of the total pre-diversion discharge (Obodoefuna et
al., 2020), while 31 and 69% of the net discharges to the South Branch were allocated to NG and BG, respectively; thus, the XLJ footprint mainly entered the ECS through the BG (Figs. 4-6). For the SDK, located in the middle of the south bank of the South Branch, the Deep Waterway Project in the North Passage of the Yangtze Estuary stabilised the flow in the inlet branch between the SJWNNR and Changxing Island at more than 55% of the total flow entering the NG (Hu et al., 2007) into the ECS mainly through this channel. ZY and SDK, conversely, are located in the southern waterway of the SJWNNR and enter the ECS entirely from here. During the flood season (May to October), an average of 80% of the annual Yangtze sediment is deposited offshore in the Yangtze Estuary (Liu et al., 2006). Simultaneously, the prevailing south-easterly winds in summer intensify the northward movement of the Taiwan warm current (Li et al., 2019; Liu et al., 2007). This leads to the formation of river sediments deposited offshore of the Yangtze Estuary, contributing to the further development of the turbidity maximum zone (TMZ; Fig. 3) in the estuary (Wang et al., 2018). Additionally, the estuarine SPM is dominated by fine sediment particles, which have a significant adsorption effect on heavy metals such as Cu (Yao et al., 2016). The Cu footprint outside the estuary is largely influenced by the south-westerly monsoon and warm currents, changing its direction in the sea near the Shengsi archipelago and subsequently migrating northward mainly in the TMZ with fine sediment particles.

The TGD cut the flow peak around the late flood season (August to October) each year to compensate for the dry season (December to March) flow (Chen et al., 2016). The overall trend of the inward side footprint of Scenarios 2 and 3 in the post-TGD period moved further away from Chongming Island than that in Scenario 1, which can be attributed to a significant increase in discharge during the dry season. Alternatively, the outward part of their footprint was formed during the flood season, with lower average discharge than that in the pre-TGD period. Additionally, this could be regarded as being 'pushed' toward the TMZ by the monsoon and warm currents,
resulting in an overall narrowing trend. Notably, all footprints of the four simulation sites have varying degrees of negative impacts on sensitive regional targets, including intrusion into the water reservoirs, national nature reserves, or threats to rare biological migration passages. The presence of TGD can only partially ameliorate but never eliminate these negative effects. Therefore, it is necessary to manage the potential risk during the transportation of cargo ships in the Yangtze Estuary and conduct strict safety checks on ships sailing into the SDK-XLJ section. For ships carrying hazardous chemicals through XLJ, it is recommended to increase the frequency of traffic tracking and monitoring to minimise the probability of copper leakage in XLJ.

5. Conclusion

Four simulation sites were selected to assess the TGD-induced excursion of the particulate Cu footprint in the estuarine area under three representative scenarios, and further quantify their influence on six sensitive targets and the migratory behaviour of Chinese sturgeon through the MPCSQM. The results indicated that the TGD had an overall narrowing effect on the extent of the threat caused by the Cu footprint, with a mean TGD impact index of 10.3%. The hazard of the footprint at the four simulation sites can be ranked in descending order according to the TGD impact index (I) as follows: XLJ (35.2%) > BLG (16.8%) > ZY (-4.4%) > SDK (-6.6%). As the simulation site affected four sensitive targets, XLJ emerged as the simulation site most positively affected by the TGD under Scenario 2 because of the reduced intrusion into national reserves. The increased discharge in the dry season moved the post-TGD footprint further away from Chongming Island. The outward side footprint was formed during the flood season, when average discharge was lower than that during the pre-TGD period, and was 'pushed' toward the TMZ by the southeast oriented monsoon and Taiwan warm current, resulting in a narrowing of the overall extent. The XLJ and SDK footprints could threaten the corridor of juvenile Chinese sturgeon migrating to SYECSC. The footprints of all four simulation sites could pose a threat to the seaward migration of Chinese sturgeons in August.
This study did not address the toxicological threat of Cu concentration during the encounter between migrating Chinese sturgeons and Cu footprints, and subsequent research can further facilitate the optimisation of the ecological risk response.

**Declaration of interest**

None

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