The impacts of piers on oil spill transport in a typical reach of the Middle Yangtze River

Haibin Xiong, Li Chen and Zhaohua Sun

ABSTRACT

Oil spill, a frequent pollution in the utilization of rivers, is receiving increasing attention in the study of river ecosystems. Taking the Zhuankou–Yangluo Reach (ZYR) of the Middle Yangtze River as an example, the spatial and temporal behaviors of leaked oil in the river under uniformly arranged piers with varying densities were studied based on a MIKE21 hydrodynamic and oil drift model. The results show that the oil spill spread is less affected by the piers when the upstream oil spill point is located on the other side of the shoreline with piers. However, the influence of the piers on the same shoreline of the oil spill point on oil spill transportation cannot be ignored. The piers significantly reduce the oil spill drift speed in the engineering area, resulting in a significant increase in slick retention time and slick area, especially when the density of piers is greater than 1.25 units/km. These results will provide useful reference for river management, for example, in the upstream river of the water conservation area, especially on the same bank as the water intake, where a large number of piers should not be built.

Key words | MIke21FM model, oil spill transport, pier, water intakes, Yangtze River

HIGHLIGHTS

• The influences of river pier densities on hydrodynamic and oil spill transport were studied using MIKE21.
• When the piers are on the same side as the oil spill point, the influence on oil spill transportation is much greater than when on the other side.
• A pier density of more than 1.25 units/km will significantly reduce the oil spill drift speed and increase the slick retention time and slick area.

INTRODUCTION

Due to global economic growth, the demand for petroleum products is increasing rapidly, hence many more oil spill accidents can be expected because of extensive oil exploitation and frequent water transportation (Vethamony et al. 2007). Oil spills pollute the ecological environment and endanger aquatic organisms significantly, often leading to long-term adverse impacts on the environment, ecology and socioeconomic activity of an area (Burk 1977; Glémarec 1986; Literathy 1992). Oil spill simulation in different scenarios can not only provide emergency plans for the prevention and control of secondary disasters after an accident but also help to distinguish high pollution risk areas according to the spill trajectories.

The study of oil transport processes is mostly carried out through numerical simulation. Most of the past investigations on the behavior and movement of spilled oil have concentrated on open sea or coastal areas (Cheng et al. 2000; Ventikos & Psaraftis 2004; Verma et al. 2008).
example, Reed et al. (2004) predicted the probable distribution of oil in West Matagorda Bay for eight scenarios considering release points, wind directions and oil volumes. Verma et al. (2008) carried out simulation studies for oil spills in the Arabian Gulf, and two scenarios (e.g. instantaneous and continuous spill) were considered in the simulation. Yuan et al. (2014) simulated Daya Bay waters near Mangzhou Island using a spilling model to compare the difference between moving and fixed oil spilling sources. Various indicators such as spill trajectory, slick area, and residence time were proposed to present pollution characteristics. Although these studies can help to better understand the factors affecting oil transport in those marine environments, it should be noted that there have been relatively few studies on oil spill transport in inland rivers (Yapa & Shen 1994). Compared with sea areas, inland waterways are mostly narrow and curved, and the movement of the oil slick down the river is more easily affected by shorelines. Different from coastal waters, hydrodynamic factors such as velocity and flow direction are profoundly affected by the river boundary. The trajectory of a river oil spill is usually dominated by currents rather than winds. Despite some researchers having paid attention to the influence of flow rate, shoreline type and the characteristics of the spill (size, location, continuous or instantaneous spill) on spill trajectory, retention time, and slick area (Shen & Yapa 1988; Danchuk & Willson 2010; Liu et al. 2017), to date there has been no attempt to study the influences of artificial constructions along river banks. We aim to contribute to filling this gap by integrating pier structure in the hydrodynamic model. In particular, we focus on oil spill transport for multi-scenarios under different pier densities.

With the increase in the scale of shoreline utilization, the piers on both sides of the river in some port cities are dense. These piers increase traffic flow and further increase the hidden risks of navigation accidents. They also directly change the hydrodynamics near the shoreline. Changes in hydrodynamic factors such as water level and flow velocity after the construction of a pier are key issues of project demonstration on flood hazards (Wang et al. 2019). Many studies have confirmed that the cumulative impacts on the flow caused by the pier groups (pile piers or grouped piers) should not be ignored (Zhang & Stive 2019). The hydrodynamic changes caused by the construction of piers near the shoreline have significant spatial differences in the local river waters of the project area and its upstream and downstream (Ali & Karim 2002; Zhang et al. 2011; Ataie-Ashtiani & Aslani-Kordkandi 2013). Hence, the piers’ shoreline is bound to have a certain impact on oil spill transport, but what kind of impact is a question worth exploring.

As a section of ‘golden waterway′ in China and also a representative urban reach of the Middle Yangtze River, the ZYR flows through the famous port city of Wuhan and there are a great number of piers distributed along both sides of the river. Therefore, in this context, it is essential to understand the impacts of the piers on oil drift. The MIKE21 OS model was used to simulate the oil transport process. The objectives of this study were as follows: (i) to simulate hydrodynamics of the ZYR after arranging varying pier densities on the shoreline, (ii) to predict the spill trajectories for different scenarios under various pier densities, and (iii) to offer advice for shoreline utilization and plan suitable response strategies for port areas when spill episodes occur.

### STUDY AREA

The Yangtze River is the longest river in China, with a total length of 6,300 km, and it is usually divided into upper, middle, and lower reaches on the basis of different geographical and hydrological characteristics (Chai et al. 2019). The study reach in this work, i.e., the ZYR, is located in the Middle Yangtze River, which spans a total length of 50.6 km, as shown in Figure 1. The upper section of the ZYR, which extends from Zhuankou to Guishan (15.2 km), has a relatively straight channel pattern, whereas the lower ZYR is classified as a slightly curved and branched channel extending from Guishan to Yangluo. One considerable tributary is located in the left bank of this stretch: the Han River, which converges into the main river at Hankou (Han et al. 2017). The mainstream flow lies in the middle of the channel in the upper section of ZYR, and gradually shifts from the left side of the channel to the right branch at Guishan and gradually moves to the middle of the channel again after leaving the branch.

There are many piers on the ZYR’s left and right banks, and their distributions are relatively irregular. The left bank
mainly includes Zhuankou port, Hanyang port, Hankou port, and Yangluo port; the right bank port areas are mainly distributed in the middle and lower sections, such as Nianyutao port, Wuchang port, Qingshan port, etc. The Nianyutao–Xujiaipeng Shoreline (NXS) is adjacent to the Wuchang deep trough with adequate water depth. The shape of NXS is smooth and it is suitable for port construction. Moreover, the narrow width in this river section makes the flow easily interfered with after pier construction, which will affect material transport. Therefore, this paper selects the NXS as a typical shoreline. Through numerical experiments, we explore the effect of arranging piers with different densities in the NXS on hydrodynamics and oil spill transport within an idealized ZYR to give insight into river oil spill transport with and without piers.

METHODS

Numerical model

MIKE21 FM, developed by the Danish Hydraulic Institute (DHI), a two-dimensional model for free surface flows, has been chosen in this study. After more than 20 years of development, this model has become a robust and reliable tool for flow simulation studies (Vethamony et al. 2007; Verma et al. 2008; Zhen et al. 2020). We performed simulations using the MIKE21 FM coupled hydrodynamic module (HD) and oil spill module (OS). As a basic module, the HD module simulates water current distributions and surface water elevations by taking into account hydraulic characteristics governed by bed topography, surface wind and boundary conditions (DHI 2014a). The OS module simulates the spreading of crude oil or refined product after spillage into the aquatic environment. It implements a Lagrangian model, which means that the spilled oil is divided into discrete parcels and sets of spatial coordinates are assigned to each parcel. All of the critical phenomena, such as evaporation, dispersion in horizontal and vertical directions, dissolution, emulsification, and heat transport, are considered (DHI 2014b).

The model range of the computational domain covers the entire ZYR as well as the shoreline regions. Solid conditions and topographic data were extracted from a 1:10,000 measured map, which was obtained from Changjiang Waterway Bureau (CWB). The computational mesh was generated using the Mesh generator provided by the MIKE21 software. The model consists of 46,563 units and 23,254 nodes with local mesh refinement in the engineering

Figure 1 | Sketch maps of the study reach and oil spill locations.
area (i.e., NXS). The bottom elevation distribution and mesh generation of the model are shown in Figure 1. Discharges of the Zhuankou station and the Hanjiang River were specified as the upstream boundaries, and the water level of Yangluo station was used as the downstream boundary. Initial water levels were set to slightly larger than the downstream boundary, and initial velocities were set to 0 m/s. A computational time step of 30 s was chosen. The model was calibrated with hydrologic data observed at ten fixed sections (Figure 1) of the study reach in March 2009 and August 2011 (corresponding to Hankou station flow rates of 12,700 m$^3$/s, 31,600 m$^3$/s, respectively), which were collected from Changjiang Water Resources Commission (CWRC). The results show that the roughness coefficient is between 0.017 and 0.021 m$^{-1/3}$/s, and the values of the roughness for the verification and calculation of the flow level are 0.018–0.019 m$^{-1/3}$/s.

**Verification of hydrodynamic model**

Since the hydrodynamic module provides data such as water depth and flow field required to drive the oil spill module’s operation, accurate hydrodynamic simulation is essential. The model verification data adopts the water level and velocity data measured in July 2011. The incoming flow of the river during this period is 23,560 m$^3$/s. The water level verification results show (Table 1) that the absolute error (AE) of the water level is within 0.05 m. The root mean squared error (RMSE) is 0.031, and the Nash–Sutcliffe efficiency coefficient (NSE) is 0.99, which reflects the excellent performance (Ritter & Muñoz-Carpena 2013). Velocity verification shows that the calculated velocity distributions in each typical section match well with observational data and the AE of the velocity is within 0.2 m/s (Figure 2). Compared with the previous study (Zhang & Zhang 2009), the verification results also show a satisfactory agreement. Hence, the hydrodynamic model can be used as the dynamic condition for further prediction of oil spill movement in the study area.

**Numerical simulation scheme**

To reflect the average situation, the simulations for oil spill prediction select the average annual discharge and stage as the boundary condition, and the values of 22,600 m$^3$/s, 2,820 m$^3$/s, and 18.2 m were specified at Zhuankou, Hanjiang and Yangluo.

The piers’ size in the hydrodynamic module refers to the relevant parameters of the piers that exist in the study reach. The size of the platform is uniformly set to 100 m × 20 m, and 13 × 5 piles are evenly arranged below, with a pile diameter of 1 m. The approach bridge is set to 150 m × 15 m, and the number of pile foundations is ten with a diameter of 1 m. The piers are uniformly distributed along the shoreline of the NXS in a T-shape, and a single pier is generalized using the Pier structure in MIKE21. The effect on flow due to the piers is modeled by calculating the additional drag force of each individual pier, which has been widely used in practical engineering (García-Oliva et al. 2011; Ren et al. 2017). Wang (2008) found that when the pier groups’ density is greater than 1.33 units/km, the influences of the piers on the hydrodynamics will interfere with each other. Thus five densities of piers (0.31, 0.62, 1.25, 2.5, and 5 units/km) were implemented in this study, respectively (i.e. 3, 6, 12, 24, and 48 piers are evenly arranged along the NXS with the length of 9.6 km). Together with the condition without piers, it is composed of six densities, which have a specific generalization, but to some extent reflect the current sparse pier layout and the possible construction of dense pier groups in the future.

As we focus on exploring the impact of hydrodynamic changes caused by the pier shoreline on the spread of

| Section | 1# | 2# | 3# | 4# | 5# | 6# | 7# | 8# | 9# | 10# |
|---------|----|----|----|----|----|----|----|----|----|----|
| Obs.(m) | 19.23 | 19.06 | 18.98 | 18.88 | 18.84 | 18.76 | 18.68 | * | 18.33 | 18.19 |
| Cal.(m) | 19.26 | 19.08 | 18.99 | 18.89 | 18.79 | 18.75 | 18.69 | 18.58 | 18.38 | 18.24 |
| AE (m) | –0.03 | –0.02 | –0.01 | –0.01 | 0.05 | 0.01 | –0.01 | * | –0.05 | –0.05 |

*represents missing measurement.
slicks, the wind field of the oil spill module only considers the calm condition without wind. To reflect various situations as much as possible, this paper considers the possibility of oil spills upstream of the study reach, at the Hanyang port area on the left bank, and at the engineering area on the right bank. There are different scenarios of oil spill accidents at point A at the center of the river upstream of the pier group, point B at 400 m from the bank on the left, and point C at 350 m from the bank on the right (Figure 1), which are named as scenarios 1, 2, and 3 respectively. We calculate the spill spread of six different pier densities for each scenario, a total of 18 simulation conditions (Table 2). Referring to related research, the main input parameters selected in each scenario are shown in Table 3.

The statistics and analysis of the results follow the criterion from overall to partial thinking: first, analyze the change characteristics of the entire river section, and then focus on exploring the detailed hydrodynamics and changes of oil spill behavior in the waters near the engineering area.

**RESULTS**

**Changes in hydrodynamics**

According to the analysis, the flow conditions of different pier densities are similar. Taking the maximum density of 5 units/km as an example, Figure 3 shows differences in the water level and velocity distributions with and without piers. It can be seen that compared with the natural situation, the water level at the front and upstream of the engineering area is somewhat higher, and the maximum water level rise is about 0.05 m, whereas the water level at the tail edge of the engineering area decreases slightly. Due to the backwater effect of the pier groups, a narrow and long flow velocity reduction area is formed in the engineering area, with a maximum reduction of 0.95 m/s. In contrast, the front water area of the engineering area forms a large-scale flow velocity increase area. The maximum increase is 0.2 m/s.

Figure 4 further analyzes the maximum upstream water level and velocity changes under different pier densities. It
can be seen that when the density is 0.31 units/km, the water level and velocity change little. For example, the water level is lower than 0.01 m, and the increase and decrease of velocity are 0.03 m/s and 0.27 m/s, respectively. With the increase of the piers’ density, the changes in water level and flow velocity also increase considerably, and even the change amplitude increase by an order of magnitude, reflecting that the impact of the project group is much greater than that of a single project. However, when the density increases to a certain extent, the water wakes caused by the backwater effects of the piers interfere with

Table 3 | Input parameters

| Parameters                        | Value                     | Description                                                                 |
|-----------------------------------|---------------------------|-----------------------------------------------------------------------------|
| Time step                         | 30 s                      | Considering the drift time of oil spill from inlet to outlet boundary       |
| Simulation duration               | 20 h                      |                                                                             |
| Spill time                        | at 10 h                   | The HD module is stable at this moment                                      |
| Spill volume                      | 20 t, instantaneous spill | River oil spill generally does not exceed 20 t                              |
| Number of oil particles           | 2,000                     | Yuan et al. (2014)                                                          |
| Oil type                          | Crude oil                 | Light and heavy components account for 35% and 65% respectively             |
| Specific gravity                  | 875 kg/m³                 |                                                                             |
| Temperature                       | 10 °C                     | Wang & Shen (2010)                                                          |
| Kinematic viscosity of oil        | $2.5 \times 10^{-6}$ m²/s | Liu et al. (2017)                                                           |
| Kinematic viscosity of water      | $1.005 \times 10^{-6}$ m²/s | Liu et al. (2017)                                                           |
| Vertical dispersion coefficient   | 0.25 m²/s                 | Yuan et al. (2014)                                                          |
| Horizontal dispersion coefficient | 0.1 m²/s                  | Yuan et al. (2014)                                                          |
| Emulsification coefficient        | $10^{-6}$ 1/s             | Wang & Shen (2010)                                                          |
| Maximum water content             | 0.85                      | Yuan et al. (2014)                                                          |
| Beaching probability              | 0.5                       | Danchuk & Willson (2010); DHI (2014b)                                       |

Note: other parameters such as evaporation and emissivity coefficient adopt OS module default values.

Figure 3 | Differences in hydrodynamics with and without piers under typical discharge: (a) water levels; (b) velocities.

Figure 4 | The maximum variation of flow conditions under varying pier densities.
each other. The cumulative effect tends to weaken, and the increasing water level and flow velocity tend to slow down. This is similar to the law that the increase of river resistance gradually weakens with the increase of the density of river obstacles (Pagliara & Chiavaccini 2006; Pagliara et al. 2008).

Based on the above analysis, it can be seen that the changes in hydrodynamics mainly occur near the engineering area. Therefore, in the following oil spill analysis, the river section will be divided into Zhuankou to Nianyutao, Nianyutao to Xujiapeng, and Xujiapeng to Yangluo. In each section, the retention time of the slick is counted, and we focus on the analysis of the distribution of oil particles and the change of slick area at the beginning of the oil spill (0.5 h), the time when it spreads to Nianyutao, Hanjiang Estuary, Xujiapeng and Yangluo.

Changes in oil spill transport

Scenario 1

Figure 5(a) shows the spill trajectories at different times with or without piers after the oil is spilled at point A (like the hydrodynamics, taking the density of 5 units/km as an example). It can be seen that the spill trajectory is consistent with the position of the mainstream line. Compared with the case of no piers, the overall spill trajectory changes little after the piers’ construction, and it only shifts slightly to the left in the river section and downstream of the piers.

Comparing the changes of the spill patches at different times (Figure 5(b)–5(f)), it can be seen that the slick is roughly circular at the beginning, and its shape gradually elongates as it drifts downstream. The spill patches are more dispersed in a band-like shape over time. When the patches have not yet moved to the front of the engineering area, the distributions of the two spill patches with and without piers almost overlap. When the patches move to the reach of the engineering area, the distributions of patches with the piers are more downstream than those without piers. As the patches continue to drift downstream, the distance between the two patches tends to widen.

Figure 6 shows the instantaneous slick area at different moments. It can be seen that as spill patches drift downstream, the slick area generally increases first and then decreases. The reason is that the expansion and drift of patches dominate in the early stage, and the effects of evaporation, dissolution, and emulsification begin to appear in the later stage. The area decreases and then gradually dissipates over time (Shen & Yapa 1988; Yuan et al. 2014). Comparing the slick area at the same time with and without piers, it can be seen that the spill patches are less affected by the pier group.

Figure 7 shows the retention time of spill patches in each section under varying pier densities. It can be seen

![Figure 5](http://iwaponline.com/ws/article-pdf/21/6/3114/932655/ws021063114.pdf)

**Figure 5** | Comparison of spill trajectories and spill patches with and without piers in scenario 1: (a) spill trajectories, (b), (c), (d), (e), and (f) represent the spill patches at times of 0.5, 2.3, 3, 4, and 8.4 h, respectively. The positions of the spill patches are shown in (a). (The partial shoreline in the enlarged picture is ignored.)
that as the density of the piers increases, due to the backwater effect of the piers on the upstream (Figure 3(a)), the retention time of spill patches in the section from Zhuankou to Nianyutao increases slightly, with a maximum increase of 0.01 h. Benefiting from the influence of frontier mainstream acceleration caused by the piers, the residence time of spill patches in the sections from Nianyutao to Xujiapeng and Xujiapeng to Yangluo decreases slightly, with the largest decreases of 0.11 h and 0.02 h, respectively. In general, the impact of the piers on the retention time of spill patches is mainly distributed in the local section of the engineering area, and its impact is relatively small.

Scenario 2

Figure 8(a) shows the spill trajectories after the oil is spilled at point B. It can be seen that the spill moves downward along the left bank in the upper section and slowly shifts to the right after passing the Hanjiang Estuary. After adsorbing by the shallows, the rest of the patches enter the right branch and move downward. The spill trajectory does not change much, no matter with or without piers. Comparing the position of the spill patches and the slick area at different moments (Figure 8(b)–8(e)), it is found that the changes are similar to scenario 1 with smaller variation range. Obviously the spill moved along the left side of the mainstream line. However, the changes in hydrodynamics caused by the piers are mainly reflected in the middle and right sides of the river channel (Figure 3(b)), and thus they have little effect on the spill transport.

Scenario 3

Figure 9(a) shows the spill trajectories after the oil is spilled at point C. It can be seen that the piers have little influence on the spill trajectory, which is located on the right bank of the river, and gradually closer to the mainstream of the river near the outlet. Observing the changes in the position and area of spill patches at different times (Figure 9(b)–9(e)), it can be seen that the movements of the spill patches lag significantly when they enter the engineering area compared with the case of no pier (1.0–2.0 h). The distance between the two patches decreases after moving out of the engineering reach (after 2.0 h).

Figure 10 shows the instantaneous slick area under various pier densities at different times. It can be seen that in the early stage of the oil spill accident (t < 0.5 h), the slick area is small, and then it increases rapidly over time. Comparing 6.5 h with 0.5 h, the area of the slick expands 43–65 times. As shown in Figure 10, after the construction of the piers on the shoreline, the slick area has increased as a whole. The greater the density of the piers, the more significant the increase in the slick area. The slick area is twice as large as that without piers at 6.5 h under the pier density of 5 units/km. In combination with Figure 3(b), it
is evident that when the slick moves through the engineering area, its tail is affected by the area with reduced flow velocity, leading to the spill patches being continuously elongated. After 6.8 h, the spilled oil begins to spread to the export boundary, and the slick area rapidly decreases. By 8.4 h, the slick area has dropped to zero when the pier density is less than 1.25 units/km.

The statistics of the slick retention time in the sections from Nianyutao to Xujiapeng and from Xujiapeng to Yangluo under varying pier densities (Figure 11) show that there is little change in the retention time in the two sections.
when the pier density is small (0.62 units/km). With the increase of the pier density, the retention time in the two sections has an increasing trend. Especially when the pier density is greater than 1.25 units/km, the retention time is greatly extended. The maximum increase for the section from Nianyutao to Xujiapeng is 1.56 h. The maximum increase for the section from Xujiapeng to Yangluo is 1.3 h. This is obviously that due to the decrease in the drift velocity of the spill caused by the narrow and long flow velocity reduction zone on the right bank in Figure 3(b).

**DISCUSSION**

Advection is the dominant mechanism that governs oil slick transport in rivers. The advection of surface oil is driven by the effects of currents under the no-wind condition (Yapa & Shen 1994). Since the piers are arranged on the right bank, there are significant spatial differences in the impact on water flow conditions (Figure 3). With the same flow level and oil spill volume, the main difference between scenarios 1, 2, and 3 is that the oil spill location is different, which means that the slick is affected by different hydrodynamic conditions during the downward movement of the slick. The following compares the differences between the three scenarios in terms of the downward trajectory, slick area, and residence time.

From the perspective of the spill trajectory, all three scenarios all move downward along the stream zone where the initial oil spill location is located, and the lateral movement along the river is insignificant. Only near the outlet will it gradually approach the mainstream position of the middle of the river. The piers have little influence on the spill trajectory.

From the perspective of the slick area during the downward movement, it shows an increasing trend along the way within a certain period (Figure 6, Figure 10). After a certain time, the slick area begins to decrease. The slick areas in scenarios 1 and 2 are not affected much by the piers. In contrast, the area in scenario 3 increases sharply and the range increases with the increase of pier density.

From the perspective of the drift speed of the spill patches, the oil spill point is close to the mainstream line in scenario 1, and the slick drifts the fastest. After the construction of piers, the drift speed of the spill is not greatly affected by the piers in scenarios 1 and 2. However, the piers have significant impacts in scenario 3, which increase with the increase of the pier density. The average drift speed of the slick in the section from Nianyutao to the Xujiapeng is reduced from 1.01 to 0.63 m/s. Due to the change of the downward speed, the residence time is greatly extended (Figure 11).

Overall, the calculation results in this paper are consistent with the previous studies, which show a narrow belt shape with the spill patches moving down in the inland river (Shen & Yapa 1988; Liu et al. 2017). Because the spill patches move downward in a strip shape, and the velocity changes caused by the piers are mainly distributed on the right bank side, thus scenario 3 is most affected. This is consistent with the changes in hydrodynamic conditions in Figure 3(b). Since the vicinity of the pier operation area is a region with a higher risk of oil spills, the results of scenario 3 indicate that it is not advisable to arrange a considerable pier density (<1.25 units/km) when planning and utilizing the shoreline for piers.
For water source protection areas such as water intakes, two critical issues in the oil spill pollution emergency plan are the arrival time of pollutants and the duration of the impact on water intake. Based on the above calculation results, it can be seen that the increase in slick retention time in the engineering area and downstream waters in scenario 3 is most unfavorable. In this regard, it is not advisable to build wading buildings such as pier groups and port areas near the same bank upstream of the water intake. Water intakes should not be arranged on the same bank side downstream of these areas.

It needs to be pointed out that the understanding of this paper is calculated based on the Wuhan reach. In fact, the boundary shape and flow conditions of different river sections are different. There is a certain randomness in the volume and location of oil spills. The situation of other rivers will be different from the results of this paper. However, the ideas, methods, and qualitative lessons of this paper can also lead to a better understanding for similar rivers.

CONCLUSION

Using a depth-averaged two-dimensional hydrodynamic oil-spill-drift model, the changes of hydrodynamic and oil spill transport of ZYR under varying pier densities of the local shoreline were simulated. The response characteristics between pier densities and oil spill transport were analyzed. The main conclusions are as follows:

(1) The movement of slicks mainly depends on the currents where the spill episodes occur under the calm condition without piers. It drifts along the flow directions of the initial spill location at first and gradually shifts to the mainstream flow of the river over time.

(2) The shoreline of the piers has little effect on the spill trajectory. With hydrodynamic changes, when oil spill episodes occur different sides of the piers’ shoreline, the slick area and drift speed are not significantly affected by the piers. However, when the oil spill occurs on the same side as the piers’ shoreline, its movement is more affected by the piers. The oil slick retention time and slick oil area increase considerably when the piers’ density is greater than 1.25 units/km.

(3) Considering the impact of pier groups on oil spill transport, it is not suitable to build wading buildings such as piers and port areas on the same bank upstream of the water intake, and thus it is not advisable to arrange water intakes on the same bank side downstream of dense piers.

ACKNOWLEDGEMENTS

This research was funded by the National Key Research and Development Project of China (Grant No. 2018YFC0407802) and National Natural Science Foundation of China (Grant No. 51879198).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Ali, K. H. M. & Karim, O. 2002 Simulation of flow around piers. *Journal of Hydraulic Research* 40, 161–174. https://doi.org/10.1080/00221680209499859.

Ataie-Ashtiani, B. & Aslani-Kordkandi, A. 2013 Flow field around single and tandem piers. *Flow, Turbulence and Combustion* 90 (3), 471–490. https://doi.org/10.1007/s10494-012-9427-7.

Burk, C. J. 1977 A four-year analysis of vegetation following an oil spill in a freshwater marsh. *Journal of Applied Ecology* 14, 515–522. https://doi.org/10.2307/2402563.

Chai, Y. F., Li, Y. T., Yang, Y. P., Zhu, B. Y., Li, S. X., Xu, C. & Liu, C. C. 2019 Influence of climate variability and reservoir operation on streamflow in the Yangtze River. *Scientific Reports* 9 (1), 5060. https://doi.org/10.1038/s41598-019-41583-6.

Cheng, N. S., Law, A. W.-K. & Findikakis, A. N. 2000 Oil transport in surf zone. *Journal of Hydraulic Engineering* 126 (11), 803–809. https://doi.org/10.1061/(ASCE)0733-9429(2000)126:11(803).

Danchuk, S. & Willson, C. S. 2010 Effects of shoreline sensitivity on oil spill trajectory modeling of the Lower Mississippi River. *Environmental Science & Pollution Research* 17 (2), 331–340. https://doi.org/10.1136/009-0159-8.

DHI 2014a MIKE 21 & MIKE 3 Flow Model FM: Hydrodynamic and Transport Module – Scientific Documentation. Danish Hydraulic Institute, Horsholm, Denmark.
DHI 2014b DHI Oil Spill Module Oil Spill Template: Scientific Documentation. Danish Hydraulic Institute, Hørsholm, Denmark.

García-Oliva, M., Djordjević, S. & Tabor, G. R. 2017 The impacts of tidal turbines on water levels in a shallow estuary. International Journal of Marine Energy 19, 177–197. https://doi.org/10.1016/j.ijome.2017.07.006.

Glémarec, M. 1986 Ecological impact of an oil spill: utilization of biological indicators. Water Science & Technology 18 (4–5), 203–211. https://doi.org/10.1016/wst.1986.0196.

Han, J. Q., Sun, Z. H., Li, Y. T. & Yang, Y. P. 2017 Combined effects of multiple large-scale hydraulic engineering on water stages in the middle Yangtze River. Geomorphology 298, 31–40. https://doi.org/10.1016/j.geomorph.2017.09.034.

Literathy, P. 1992 Environmental consequences of the gulf war in Kuwait – impact on water-resources. Water Science & Technology 26 (1–2), 21–30. https://doi.org/10.2166/wst.1992.0382.

Liu, T., Li, T. & Lin, L. Q. 2017 Study on simulation of oil spills in Liyushan Channel of Middle Yangtze River. Environmental Science & Technology 40 (S2), 155–159 (in Chinese with English abstract).

Pagliara, S., Das, R. & Carnacina, I. 2008 Flow resistance in large-scale roughness condition. Canadian Journal of Civil Engineering 35 (11), 1285–1293. https://doi.org/10.1139/L08-068.

Pagliara, S. & Chiavaccini, P. 2006 Flow resistance of rock chutes with protruding boulders. Journal of Hydraulic Engineering 132 (6), 545–552. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:6(545).

Reed, M., Daling, P., Lewis, A., Ditlevsen, M. K., Brørs, B., Clark, J. & Aurand, D. 2004 Modelling of dispersant application to oil spills in shallow coastal waters. Environmental Modelling & Software 19 (7–8), 681–690. https://doi.org/10.1016/j.envsoft.2003.08.014.

Ren, Z. J., Wang, Z. A. & Lu, H. J. 2017 Application of pile group simulation method based on Mike21 in high-piled wharf. Port & Waterway Engineering 10, 118–124 (in Chinese with English abstract).

Ritter, A. & Muñoz-Carpena, R. 2013 Performance evaluation of hydrological models: statistical significance for reducing subjectivity in goodness-of-fit assessments. Journal of Hydrology 480, 33–45. https://doi.org/10.1016/j.jhydrol.2012.12.004.

Shen, H. T. & Yapa, P. D. 1988 Oil slick transport in rivers. Journal of Hydraulic Engineering 114 (5), 529–543. https://doi.org/10.1061/(ASCE)0733-9429(1988)114:5(529).

Ventikos, N. P. & Psaraftis, H. N. 2004 Spill accident modeling: a critical survey of the event-decision network in the context of IMO’s formal safety assessment. Journal of Hazardous Materials 107 (1/2), 59–66. https://doi.org/10.1016/j.jhazmat.2003.11.010.

Verma, P., Wate, S. R. & Devotta, S. 2008 Simulation of impact of oil spill in the ocean – a case study of Arabian Gulf. Environmental Monitoring and Assessment 146, 191–201. https://doi.org/10.1007/s10661-007-0071-y.

Vethamony, P., Sudheesh, K., Babu, M. T., Jayakumar, S., Manimurali, R., Saran, A. K., Sharma, L. H., Rajan, B. & Srivastava, M. 2007 Trajectory of an oil spill off Goa, eastern Arabian Sea: field observations and simulations. Environmental Pollution 148 (2), 438–444. https://doi.org/10.1016/j.envpol.2006.12.017.

Wang, P. 2008 Preliminary Study on the Influence of Shoreline Development and Utilization on River Flood Control. Changjiang River Scientific Research Institute, Wuhan, China (in Chinese with English abstract).

Wang, J. H. & Shen, Y. M. 2010 Development of an integrated model system to simulate transport and fate of oil spills in seas. Science China Technological Sciences 40 (11), 1367–1377 (in Chinese with English abstract).

Wang, W., Zhou, K. B., Jing, H., Zuo, J. L., Li, P. & Li, Z. B. 2019 Effects of bridge piers on flood hazards: a case study on the Jialing river in China. Water 11 (6), 1181. https://doi.org/10.3390/w11061181.

Yapa, P. D. & Shen, H. T. 1994 Modelling river oil spills: a review. Journal of Hydraulic Research 32 (5), 765–782. https://doi.org/10.1080/0022168940948713.

Yuan, C. G., Wang, Y. G., Huang, H. M., Yang, T. J. & Chen, C. 2004 Oil spill numerical simulation on the wharf engineering of Mangzhou Island in the Daya Bay. Marine Science Bulletin 33 (6), 659–667 (in Chinese with English abstract).

Zhang, Q. & Zhang, X. F. 2009 Analysis of effect of sand mining areas on braided channel. Engineering Journal of Wuhan University 42 (2), 153–157 (in Chinese with English abstract).

Zhang, R. & Stive, M. J. F. 2019 Numerical modelling of hydrodynamics of permeable pile groins using SWASH. Coastal Engineering 153, 103558. https://doi.org/10.1016/j.coastaleng.2019.103558.

Zhang, X. B., Lu, J. Y. & Lin, Q. S. 2011 Preliminary study on accumulated influence of the bankline use on flood control in the middle and lower reaches of the Yangtze River. Resources and Environment in the Yangtze Basin 20 (9), 1138–1142 (in Chinese with English abstract).

Zhen, Z., Li, D., Li, Y., Chen, S. & Bu, S. 2020 Trajectory and weathering of oil spill in Daya Bay, the South China Sea. Environmental Pollution 267, 115562. https://doi.org/10.1016/j.envpol.2020.115562.

First received 8 January 2021; accepted in revised form 11 March 2021. Available online 23 March 2021