Numerical Study on Influence of Water Exchange for Artificial Island Group

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Abstract. After the construction of artificial island group, the good water exchange ability is beneficial to improve the water environment quality and improve the landscape effect of the island group. In order to solve the water exchange in the island group, a numerical model based on solving the hydrodynamic and advection-diffusion equations was used to calculate the water exchange of artificial island group in Weifang, China. The water exchange rate was obtained by calculating the concentration variation of dissolved conservative tracer. Based on the analysis of water exchange and influence factors, the suggestion of optimization was proposed. First the narrow waterways should be avoided and the most effective way to enhance the hydrodynamics for weak flow region is increasing exchange of channel.

1. Introductions
Nowadays the artificial islands are widely constructed over the world, such as Dubai Lugger Hotel, Japan Osaka Kansai International Airport[1], Dalian artificial island[2], Longkou artificial island and Yangpu artificial island, etc. The influence of artificial island on the local water environment is uncertain, and the factors affecting water exchange are varied[3-6]. This uncertainty could be even more significant for the construction of island group. It may deteriorate the water environment and lead to serious environmental problem. The construction of artificial island group of Weifang in China is an example.

1.1. Background
Weifang artificial island is located at Laizhou Bay and is near the Weifang Sime Darby Port. There are two rivers namely Whitewater River and Yuhe River in this area. Laizhou Bay belongs to the storm surge prone region. Outside the artificial island group, a breakwater was built along the gates of Whitewater River and Yuhe River to resist the storm tide. The water inside the artificial island group has communication with the water of external sea through the gates. The island group consists of more than 20 islands, as shown in Figure 1.

1.2. Hydrodynamic Conditions
Tidal characteristics in the study area are irregular semidiurnal tide[7][8]. The average tidal range is 1.6m. According to the measured data, the average flow velocities of flood and ebb tide range from 0.07 to 0.18 m/s and 0.06 to 0.16 m/s during the spring tide and neap tide, respectively. Since the tidal power is weak, it has adverse effect on the water exchange. The layout of the island group is of importance.
2. Numerical Modelling

2.1. Mathematics

The MIKE21 FW module is employed in this study. The governing equations are based on the depth-averaged shallow water equations derived from the original three-dimensional ones and read as follows:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = 0
\]

\[
\frac{\partial v}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh^2}{\partial y} = -fu - g \frac{\partial \zeta}{\partial y} + \frac{\tau_{nx} - \tau_{ny}}{\rho h} + E_x \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{1}{\rho} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right)
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial uh^2}{\partial x} + \frac{\partial uhv}{\partial y} = fv - g \frac{\partial \zeta}{\partial x} + \frac{\tau_{nx} - \tau_{ny}}{\rho h} + E_y \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{1}{\rho} \left( \frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right)
\]

where \( x \) and \( y \) are horizontal coordinates respectively; \( t \) is time; \( h \) is total water depth; \( u \) and \( v \) are velocity components; \( g \) is gravity acceleration; \( f \) is the Coriolis force; \( \tau_{nx} \) and \( \tau_{ny} \) are bed shear stress components; \( E_x \) and \( E_y \) are horizontal eddy viscosity components; \( \rho \) is seawater density; \( S_{xx}, S_{xy}, S_{yx} \) and \( S_{yy} \) are wave radiation stress components.

The bed shear stress is calculated using the following equation.

\[
\tau_{b} = \rho \frac{g}{C^2} \left| U \right| \left[ U \right]
\]

where \( C \) is the Strickler coefficient. The eddy viscosity coefficient is calculated by Smagorinsky formula.

Based on the conservative substances dissolved in the water like the tracers, an advection-diffusion model is set up. The water exchange rate (WER) is calculated by observing the variation of tracer concentration. The governing equation is as follows:

\[
\frac{\partial C}{\partial t} + \frac{\partial uhC}{\partial x} + \frac{\partial vhC}{\partial y} = \frac{\partial}{\partial x} \left( D_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_y \frac{\partial C}{\partial y} \right) - FhC
\]

where \( C \) is the concentration of the tracer; \( F \) is the decaying factor, which can be set to zero for conservative matter; \( D_x \) and \( D_y \) are dispersion coefficients for \( x \) and \( y \) directions; \( D_x = D_y = 0.01 \text{m}^2/\text{s} \), respectively.

During the numerical simulation, the initial tracer concentration is set as 1.0 in the area of artificial island group and as 0.0 for other water areas (see Fig. 2). The simulation period is 30 days with continuous tide movement. The WER is defined as the percentage of the mass of tracer transporting out of the
artificial island group area over the mass of initial tracer in the seam area. The WER is calculated by
the following equation.

\[
WER(t) = 1 - \left\{ \frac{\sum_{i=1}^{N} C_i(t_j) h_i(t_j)}{\sum_{i=1}^{N} C_i(t_0) h_i(t_0)} \right\} \times 100\%
\]

where \(i\) is the index of a specific grid; \(N\) is the total number of grid inside the area of artificial island
group; \(j\) is the index of a specific time step.

**Figure 2.** Initial condition of concentration for simulation

2.2. **Model Set Up**
The range of model is the whole Laizhou Bay. Triangle mesh is used to divide the computational do-
main. The maximum grid size is 3000 m. The grid is refined in the area of island group, where the
minimum grid size is 10 m. The computational time step is 0.5 s. The tidal levels at the open bound-
daries are extracted from the Chinese sea tide model. Figure 3 shows the mesh arrangement for the study
area.
3. Results and Discussions

The present hydrodynamic model of the Laizhou Bay has been verified in the previous study, where the computed tidal level, current speed and current direction were validated against the field-measured data. Figure 4 shows the time history of the water exchange and velocity field for the original planning. Based on the analysis of numerical results, the main findings are summarized as follow.

The tidal current movement in the study area demonstrates typical reciprocating feature. The main flow direction during ebb tide is northeast. It is west southwest during flood tide. After the artificial island group and the breakwater are built, the tidal current becomes reciprocating along the waterways due to local topography and constructed structure. The average flow velocity changes from 0.01~0.25m/s to 0.01~0.93m/s. Increase of flow velocity can improve the capability of water exchange. The gates of Whitewater River and Yuhe River are the main flow channel, where the flow velocity significantly increases. During the flood tide, water from the external sea flows into the breakwater area and then dilutes the tracer concentration between island groups. During the ebb tide, the water carrying high concentration of tracer flows out. Exchange between the internal and external water continues under the action of tide. Therefore, the WER increases as time gradually increases. The WERs over 4, 15, 30 days are approximately 43%, 71% and 80%, approximately.

The change of tracer concentration shows that the WER is poor in the backwater area. Take the northwest and southeast sides of islands as examples, the flow velocity approaches zero. The WER is less than 10% over 30 days. The backwater will cause the deterioration of the water quality and then affect the whole water quality and landscape. The original planning needs to be modified.

To modify the layout of island group while avoiding large change of original planning, the feasible approach is to increase the hydrodynamic force in the weak flow region and prevent the forming of backwater. The proposed optimization planning is shown in Figure 5.

Figure 6 shows the time history of water exchange and velocity field for optimization planning. Figure 7 compares the time history of WERs over 30 days for the original and optimization planning. After the layout of island group is optimized, the hydrodynamic in the weak flow region is strengthened. The backwater disappears. The WER increases substantially. The WERs of the optimization planning over 4, 15 and 30 days are nearly 56%, 82% and 92%, respectively. Compared with the original planning, the water exchange capability increases 30% in the early stage and 15% after 30 days. Increase of tidal capacity has proved to be more effective measure for improving water exchange of island group.
Figure 4. Time history of water exchange and velocity field for original planning

Figure 5. Optimization planning
4. Conclusion
The artificial island group is a complex system. With the rational arrangement of islands, the flow velocity between island groups can be effectively improved to provide favorable conditions for the water exchange. The present study shows that:
From the aspect of improving water exchange, to avoid the backwaters is the most desirable; increase of tidal capacity has proved to be the effective measure for improving water exchange of island group. Increasing exchange of channel is the easiest and most effective way to enhance the hydrodynamics for weak flow region; narrow waterways can lead to siltation, so it should be avoided.
In addition, based on the study of Xu[9] and Yao[10][11] et al, the water exchange can be benefited from a reasonable design of water depth. Water depth of island group should be minimized under the condition of meeting planning requirements and security conditions.

5. References

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