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Modeling the impact of culture facilities on hydrodynamic and solute transport in marine aquaculture waters of the North Yellow Sea

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ABSTRACT: An increasing number of marine aquaculture facilities are being placed in shallow bays and open sea. In this study, we present a coupled hydrodynamic and solute transport model with high-resolution schemes in marine aquaculture waters based on depth-averaged shallow water equations. A new expression of drag force is incorporated into momentum equations to express the resistance of suspended culture cages. The coupled model is used to simulate the effect of suspended structures on the tidal current and the motion of a contaminant cloud in the marine aquaculture of the North Yellow Sea, China. Simulation results show a low-velocity area inside the aquaculture cage area, with a maximum reduction rate of velocity close to 45% under high-density culture. The results also show that the tidal currents are sensitive to the suspended cage densities, cage length and drag coefficients of cages. The transport processes of pollutants inside aquaculture facilities are inhibited away from the vicinity of the culture cage area because of the reduction in tidal currents; therefore, the suspended cages significantly affect the transport processes of pollutants in coastal aquaculture waters. Furthermore, the reduction in the horizontal velocity can significantly decrease the food supply for aquaculture areas from the outside sea. The results of this study provide new insight into the planning of high-density suspended facilities for coastal aquaculture activities.

Keywords: Marine aquaculture; Suspended cages; Numerical simulation; Current reduction; Solute transport

1 Introduction

The global demand for seafood continues to rise sharply because of population growth and increased per capita consumption; marine aquaculture has thus become one of the world's fastest-growing food sectors [1]. Although estuaries, bays and coastal waters occupy a small fraction of the Earth's surface, the large-scale expansion of marine aquaculture has been concentrated in these areas. The rapid growth in marine aquaculture over the last two decades has also been accompanied by the development of diversified culture systems ranging from ponds and floating rafts [2] to suspended cages in coastal waters [3-4]. These types of rafts or cages in estuaries offer many advantages, including high utilization rate of breezing space, low unit cost and reduced disease probability [5]. However, floating aquaculture structures significantly alter the water exchange ability and the food supply of plankton in the aquaculture structure; furthermore, high-density culture can directly affect the transport process of pollutants released during the production process [6] and thus may have consequences for the environment as well as for the productivity of aquaculture farms [7].

The detailed hydrodynamics induced by the aquaculture structures in estuaries and coastal waters need to be characterized to evaluate the efficacy of the design of marine aquaculture structures. Several field investigations have been conducted to examine the frictional effect of aquaculture on the tidal current in various types of culture areas [8-10]. However, the effect of existing marine aquaculture structures on tidal currents with and without aquaculture facilities is difficult to evaluate by field measurements, especially distinguishing the effects of aquaculture facilities from changes in shoreline and seabed topography [11]. Numerical modeling provides an alternative approach for predicting the interactions between floating aquaculture structures and the surrounding fluid. Several studies have been conducted to enhance our understanding of the effects of floating canopies on hydrodynamics at the scale of a farm block using

numerical simulations [12-13]. Most studies have used bulk drag forces in a two-dimensional model [11, 14], where the drag forces were assumed to be evenly distributed in the vertical direction with water depth. In addition, the effects of canopy installations have been examined by incorporating drag terms in both the momentum and turbulence-closure equations in 3D models [15]. Several high-resolution CFD models have been used to study the effect of block spacing and angle from the shellfish structures on the long-line vorticity production [16-17] and the hydrodynamic effects of a salmon farm in an idealized environment [18-19]. Moreover, some coupled dynamic models have been developed for a large-scale kelp raft culture system to describe the culture line deformation and force under the combined action of pure current, wave and current [20]; these results have indicated that these suspended aquaculture facilities can significantly reduce the current speed under a uniform current.

Large-scale interactions between a whole farm and its surrounding circulation have been investigated using numerical approaches in bays and larger-scale coastal waters [21-25]. The numerical results have indicated that current speeds passing through an aquaculture area might be significantly affected by farms; more generally, these studies have established an approach that can be used to provide insight into production, environmental effects and disease interactions. Recent developments in computational behavior of the fate and transport of contaminants have permitted the transient loading over the complicated geometry of the real estuarine systems in 2D models to be accurately described [26-27]. These studies have shown that the effect of suspended aquaculture facilities on coastal circulation is important for the efficiency of aquaculture management practices. Although much research has examined the hydrodynamic characteristics of coastal waters near aquaculture facilities, quantitative studies examining how marine aquaculture facilities can affect the hydrodynamic flow field and solute transport in large-scale coastal waters have been rarely conducted. Moreover, few studies have described the dispersal of aquaculture

wastes and the food supply under varying aquaculture facility conditions at the field scale.

In this study, a two-dimensional depth-integrated model with high-resolution schemes to predict hydrodynamics and waste material transport in coastal aquaculture waters is explored. The simulation results with and without the drag forces from the suspended cages are analyzed, and this model is then used to evaluate the potential effect of aquaculture facilities on the dispersion and transport of solute using a tracer released from aquaculture areas. The remainder of this paper is organized as follows. The basic equations of hydrodynamic and solute transport and the numerical discretization method of FVM are described in Section 1. Procedures for validating the numerical model are presented in Section 2. The hydrodynamic and mass transport characteristics in the water of suspended cages are analyzed and discussed in Section 3. Section 4 presents some of the main conclusions.

2 Methodology

2.1 Hydrodynamic Model

The depth-averaged shallow water equations are obtained by integrating the Navier–Stokes equations over the flow depth. These equations include the continuity equation and momentum equations for depth-averaged free surface flows [28]. They are written as:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial hv}{\partial y} = 0 \quad (1)$$

$$\frac{\partial hu}{\partial t} + \frac{\partial \left(huu + \frac{1}{2} gh^2 \right)}{\partial x} + \frac{\partial (huv)}{\partial y} - \frac{\partial}{\partial x} \left(v_t h \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial y} \left(v_t h \frac{\partial u}{\partial y} \right) = \frac{\tau_{wx} - \tau_{bx}}{\rho_w} - gh \frac{\partial z_b}{\partial x} + f_c hv - f_x \quad (2)$$

$$\frac{\partial hv}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial \left(hvv + \frac{1}{2} gh^2 \right)}{\partial y} - \frac{\partial}{\partial x} \left(v_t h \frac{\partial v}{\partial x} \right) - \frac{\partial}{\partial y} \left(v_t h \frac{\partial v}{\partial y} \right) = \frac{\tau_{wy} - \tau_{by}}{\rho_w} - gh \frac{\partial z_d}{\partial y} - f_c hu - f_y \quad (3)$$

where t is time; h indicates the flow depth $h = d + \eta$; d is the still water depth; η is the water surface elevation above the still water; u and v indicate the depth-averaged velocities in the x and y directions, respectively; v_t is the eddy viscosity coefficient; g is gravitational acceleration; f_c is the Coriolis parameter; f_x and f_y indicate

the drag force of suspended cages in the x and y directions, respectively; τ_{bx} and τ_{by} indicate the bed friction in the x and y directions, respectively; τ_{wx} and τ_{wy} are the surface wind stresses in the x and y directions, respectively; and z_b is the bed elevation.

When planning and assessing the aquaculture cages at larger-scale waters, the drag force imparted by the distributed structure on the fluid needs to be represented [29]. The loss of energy of the mean flow through cages is proportional to the drag force exerted by a single cage and the cage density within the marine aquaculture area [16, 26, 30, 31]. Therefore, the drag force caused by suspended cages (Fig. 1 (a)) in the ocean can be parameterized as:

$$f_x = \frac{1}{2} NC_d \phi L_c u \sqrt{u^2 + v^2}, \quad f_y = \frac{1}{2} NC_d \phi L_c v \sqrt{u^2 + v^2} \quad (4)$$

where C_d is the drag force coefficient of the suspended cages, N is the cage density defined as the number of cage elements per unit area, ϕ is the diameter of a cage element, and L_c is the length of the cage elements (see Fig. 1 (b)).

(a) Culture cages in the North Yellow Sea

(b) Sketch of solution variables

Fig.1 A schematic illustration of suspended cages in estuaries

A Godunov-type finite volume method with an unstructured triangular mesh is used for the numerical discretization and to solve the governing equations in this study. The study domain is first divided into a set of triangular control volumes with an unstructured computational mesh, and then an explicit time-marching scheme is used in the calculation model. The physical variables are the same in every triangular mesh element because of the average depth integration in the equation; a series of piecewise functions are developed in the solution domain. The approach of the Monotonic Upstream-Centered Scheme for Conservation Laws with a multi-dimensional limiter and the Roe's approximate Riemann solver were used to calculate the interface fluxes between triangular grid cells [32-33].

2.2 Solute Transport Model

The scalar's vertical distribution can be assumed to be uniform for shallow estuaries. The depth-averaged equation for solute transport subjected to advection and diffusion process can be derived as follows:

$$\frac{\partial hC}{\partial t} + \frac{\partial(huC)}{\partial x} + \frac{\partial(hvC)}{\partial y} = \frac{\partial}{\partial x} \left(K_{xx}h \frac{\partial C}{\partial x} + K_{xy}h \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial y} \left(K_{yx}h \frac{\partial C}{\partial x} + K_{yy}h \frac{\partial C}{\partial y} \right) + S_c - K_c hC \quad (5)$$

where C is the depth-averaged substance concentration; S_C represents the source contribution per unit area, which is obtained from external loading; and K is the decay rate of the substance.

$$K_{xx} = \frac{\sqrt{gh}(\varepsilon_l u^2 + \varepsilon_t v^2)}{c \sqrt{u^2 + v^2}}, \quad K_{xy} = K_{yx} = \frac{\sqrt{gh}(\varepsilon_l - \varepsilon_t)uv}{c \sqrt{u^2 + v^2}}, \quad K_{yy} = \frac{\sqrt{gh}(\varepsilon_t u^2 + \varepsilon_l v^2)}{c \sqrt{u^2 + v^2}} \quad (6)$$

where c is Chèzy's coefficient, and ε_l and ε_t are the dimensionless coefficients of longitudinal dispersion and turbulent diffusion, respectively. In the absence of field measurements, 13.0 and 1.2 are the typically recommended values for ε_l and ε_t , respectively [34].

The solute transport equation also applies the finite volume method to integrate the mass equation over a control volume. When convection is dominant in pollutant transport, the problems of numerical oscillation and high artificial diffusion are common in the first-order upwind scheme. A flux limiter function is used to reduce the numerical diffusion error because of the upwind approximation of the advection term. A central difference scheme with second-order accuracy for the diffusion term is adopted for the unstructured triangular grids; it involves the nearest neighboring points in the time advancement [35].

3 Model validation

3.1 Study Area

The study area is located in the northern Yellow Sea, China (Fig. 2 a); it is one of the major estuaries for marine aquaculture in China with approximately 60 years of maricultural activities. This water represents a typical coastal ecosystem of China that is influenced by the freshwater influx from the Yalujiang River, Biliu River and Zhuang River as well as saline water influx from the Yellow Sea. The mudflats along the coastline make the region highly productive and support several economically important shellfish species, especially *Patinopecten yessoensis* (Fig. 2 b). In addition to bottom-seeded culture, one of the most important aquaculture modes for *Patinopecten yessoensis* consists of suspended facilities (rafts or

cages) in coastal waters (Fig. 2 (c)). This structure is used to suspend spat-laden culture cages from the sea surface to 3 m deep, sometimes more, depending on the water depth. Generally, the suspended aquaculture facilities are in an area with a depth of 10–15 m northwest of Shicheng Island in the North Yellow Sea. The aquaculture density is represented through the projected area of suspended cages per unit area, which is the product of the diameter of cages and the number of cages per unit area. The hanging cages collectively form a canopy extending downward from the water surface. The computational area ranges from 122.06° E to 123.88° E and from 38.764° N to 39.645° N, and some islands occur in the computational domain including Shicheng island, Dachangshan island, Xiaochangshan island and others. The bathymetry of the study area is complicated, with a water depth range from 3 m to 20 m.

(a) Study domain

(b) Aquaculture types in study areas

(c) High-density aquaculture of *Patinopecten yessoensis*

Fig. 2 Sketch of the study domain and topography in the North Yellow Sea

3.2 Model Setting and Verification

In the simulation experiments, the computational area is discretized into 38257 unstructured triangular cells, which provides more flexibility in defining the fine spatial resolution across channel, island and aquaculture waters; a coarse grid is used in the open sea (Fig. 3). Where tides are primarily semi-diurnal, the amplitude of tidal elevation can reach more than 4 m. In the numerical calibration, the model is run with eight of the main harmonic constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) at the open boundary. The value of the constituents is imposed in the nodes of the open boundary by adjusting the coefficients (in amplitude and phase) for each harmonic constituent. The tidal process covers 144 hours from October 14th, 2016 to October 19th, 2016. Manning's n is set as 0.025, and the computational time step is 0.5 s. Because wind data are not available, the surface wind stress is neglected. Figure 4 shows the measured water level at Dachangshan tidal station and the simulated model results. The root mean square error between the modeled and observed data is about 5 cm. The high water levels during spring tide lead to unnoticeable deviation between observed and predicted values. The simulated tidal current speeds at four observation stations are approximately consistent with the field data (Fig. 5); furthermore, the simulated tidal directions closely match the measured values of the several observation stations. Figure 6 shows the distribution of

the tidal flow field in flood and ebb tide during the spring tide. During the flood tide, the general flow of tidal current in the study waters is northeast (Fig. 6). The main flow flooding into aquaculture waters in the North Yellow Sea is divided and goes around both sides of the islands. After that, the current directions are forced to change, and the current velocity becomes high in the channel area because of the obstruction of the islands; an obvious weak current area occurs behind the islands. Because of the effect of many islands during the ebb tide period, the current at the islands is divided into many branches; the main tide current flows south-north and then enters the outside sea. The results of the model are consistent with the field data collected at sites in these coastal waters. The results further indicate that the present model accurately predicts the magnitude and timing of the highest velocities of each tidal cycle. Based on the hydrodynamic verification results, this model can be used to predict flow phenomena and solute transport in marine aquaculture areas.

Fig. 3 Mesh, field gauges and marine aquaculture domain in the North Yellow Sea. The white domain is the island, and the orange domain is the suspended aquaculture cage area.

Fig. 4 Comparison of the measured and simulated water levels at Dachangshan tidal station.

(a) Tidal current

(b) Tidal direction

Fig. 5 Comparison of the measured data and simulated results in tidal currents and flow directions

(a) Fastest flood tide

(b) Fastest ebb tide

Fig. 6 Flow fields within a tidal period in which the effect of aquaculture facilities is not considered

4 Results and discussion

4.1 Effect of Suspended Cages on Tidal Currents

To investigate the effects of suspended culture structures on bay-scale circulation in coastal waters, this section considers the computation of tidal water flow in a real aquaculture estuary of North Yellow Sea. The aquaculture facilities in the study domain introduce an additional friction on tidal movement, and this resistance force is similar to the vegetation canopy in fluid and is related to flow condition, cage density, relative gap size, cage diameter and the drag coefficient [34,36]. In the aquaculture waters, the cage diameter is 0.35 m, the cage length is 2 m and the drag coefficient of cages is set to 1.0. Generally, the number of cages is 330 in an area of 4000 m², and the density per square meter is about 0.08. In this study, several experiments are conducted to investigate the sensitivity of reductions in mean water speed under conditions of variable densities of suspended culture cages (0, 0.04, 0.06, 0.08 and 0.1). Six gauge stations are used to compare the changes in the simulated velocities inside (P1, P2 and P3) and outside (P4, P5 and P6) the cage domain in the study area (Fig. 7), where the depth-averaged current speeds within the culture cages significantly decrease as the cage density increases. Compared with cases in which the culture cages

are not considered, the velocity reduction is larger in the culture cage area than outside the culture cage area. Figure 8 shows the simulated current directions with different culture cage densities. The tidal current direction both in and out of the cage domain shows that the effect of aquaculture facilities on the flow direction is limited. When the change of velocity amplitude in gauge 6 is small, the phase change is obvious; the main reason is that this gauge is close to the culture cage area, and the suspended cage affects the water flow movement during tidal flood and ebb. Figure 9 compares the current changes in the absence and presence of culture cages. Increasing cage densities leads to larger reductions in the average speed inside culture cages, and reductions in current speeds are typically 45% in areas inside the domain; however, reductions in water speed are smallest in areas outside the domain of suspended cages. The relationship between cage density and mean speed reduction is not linear; when the density of the suspension cage is 0.04, the attenuation rate of tidal current peaks in the culture cage area, the rate of change reduces gradually as the cage density increases.

Simulation experiments were also carried out to study the effects of variable cage lengths (2 m and 4 m) on tidal current speeds and current directions within embayments. The cage number per unit area is 0.08, the cage diameter is 0.35 m and the drag coefficient of floating cages is set to 1.0. As shown in Fig. 10, the simulated results indicate that increasing cage lengths reduces current speeds inside culture areas; no apparent change in velocity occurs in some parts outside culture areas. Three different drag coefficients (0.25, 0.5 and 1) are used to investigate the interaction mechanism between suspended aquaculture facilities and hydrodynamics (Fig. 11); increases in the drag coefficient result in greater reductions in the average tidal speed. Figure 12 shows the corresponding velocity fields in the presence of culture cages (cage density=0.08) during the periods of flood and ebb tide; the results are also compared with the absence of culture cages (Fig. 6). Generally speaking, flow patterns are similar whether or not the marine cages are

included in the simulations; however, reductions in water speed can be observed in areas inside culture cages. These areas outside of marine aquaculture facilities show a small change in depth-average velocity. The simulated results indicate that the culture cages in these coastal waters have a significant effect on the currents traveling through suspended cages. Higher densities of the suspended cage culture result in a weaker current area in the culture area.

Fig. 7 Comparison of the simulated tidal velocities with different culture cage densities

Fig. 8 Comparison of the simulated current directions with different culture cage densities

Fig. 9 Comparison of the simulated velocity change with different cage densities in a tidal cycle

Fig. 10 Changes in depth-averaged mean current speeds as a function of the ratio of the cage length.

Fig. 11 Changes in depth-averaged mean current speeds as a function of the drag force coefficients.

Fig. 12 Flow fields within a tidal period in which the effect of aquaculture facilities is considered

4.2 Effect of Marine Cages on the Waste Transport

Shell aquaculture (*Patinopecten yessoensis*) tends to release additional fecal material into the water column. To understand the effect of suspended cages on mass transport and dispersal in aquaculture waters, a hypothetical release scenario is considered using a tracer to represent the amount of fecal material, which is discharged into the water body at the P2 station from aquaculture areas. It can be thought of as a waste effluent. The emission intensity and duration are 100 g/s and 4.1 h, respectively. The pollutant concentration at the boundary of the sea area and the boundary of land was set to 0. The effects of cage densities on waste transport are illustrated in Fig. 13; the maximum concentration occurs inside cage areas in the presence of advection and diffusion. The pollutant concentrations are higher in the inner parts of cages at higher cage densities than in the absence of cage densities (see P1, P2 and P3 in Fig. 13). However, in the P4 gauge outside the culture area, the pollutant concentration is significantly higher in the absence of suspended cages than at high cage densities. In most of the culture area, cage densities reduced the dispersal of waste from advection because of the reduction in tidal current speeds. That is to say, the aquaculture facilities limit the water exchange rate inside the aquaculture ground with the outside cage

environment. A decreased water exchange rate means a lower supply of nutrients and food and vice versa. As a result, the food availability may be insufficient for high cage densities. Figure 14 shows a sequence of the concentration snapshots across the computational domain to highlight the differences in the plume behavior between these cases; the results show the movement of the pollutant cloud in the first tidal cycle after release. The pollutant plume oscillates back and forth with the tidal currents, and the plume undergoes a much stronger reversal as the tide changes direction. As time progresses, the material spreads over a broader area and becomes less concentrated. The simulated mixing and dispersion processes of pollutants in the presence of cages are obviously different from those in the absence of cages. The plume concentration growth is further inhibited in the presence of cages than in the absence of cages, which indicates that the reduction in the tidal current induced by the suspended facilities has an important effect on the spread and mixing of the waste material in the suspended cage area.

Zhuanghe City lies southeast of Liaodong Peninsula and is one of the most important cities in the northern Yellow Sea. There are three small rivers southeast of Zhuanghe that flow into the North Yellow Sea. Their runoff is controlled by the season, and runoff is highest in the flood season. There is a reservoir upstream with flood control and the urban water supply as its main mode of operation; it also features the comprehensive utilization of irrigation, fish farming and power generation. These rivers carry large amounts of suspended detritus into the North Yellow Sea, which supplies food to shell aquaculture. Here, a continuous food supply scenario is considered to test the impact of suspended aquaculture on the food supply following the expansion of high-density aquaculture facilities. The point source is located at the mouth of the rivers near Shicheng Island; the release rate is 100 g/s. The initial concentration of the computational domain is assumed to be 0 mg/L. Figure 15 shows the change in detritus concentration at several time points in the absence of aquaculture facilities and in the presence of aquaculture facilities.

After entering the bay at the mouth of the Zhuanghe River, the suspended debris mainly spreads to the southwest. When the suspended debris does not enter the culture sea area, there is no obvious effect of the culture facility on the debris concentration transport; however, the debris food enters the culture sea area associated with current circulation, and the attenuation of the flow field produced by the culture facilities has a great effect on the transportation of the debris. In our simulation, aquaculture facilities limit the water exchange rate inside the aquaculture ground; a decreased water exchange rate means a lower supply of food in suspended detritus. A relative food shortage for *Patinopecten yessoensis* in this study domain is more serious during neap tides, especially in areas with high densities of aquaculture. Generally, the food supply occurring in shallow coastal waters is closely tied to the tidal current; thus, the aquaculture density in marine aquaculture waters of the North Yellow Sea needs to be carefully designed.

Fig. 13 Time series of concentration profiles of fecal material at several different locations near the culture cage embayment

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(a) Waste transport in the presence of culture cages

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(b) Waste transport in the absence of culture cages

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Fig. 14 Development of the pollutant concentration field at several time points

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Fig. 15 The transport process of suspended detritus in the culture waters in absence of cages (left) and in the presence of cages (right)

5 Conclusions

This study presents results from highly resolved 2D depth-averaged numerical simulations of the hydrodynamic characteristics and current changes caused by suspended cages in marine aquaculture waters. The effect of suspended cages on the transport processes of pollutants is also discussed. The finite volume method is used to discretize the shallow water equations and solute transport equation. This model uses an unstructured grid to compute flow movement in the coastal ocean. The high-resolution scheme is evaluated to solve the advection and diffusion terms for pollutant transport in near-coastal environments. The resistance force caused by the suspended cages is modeled as a source term in momentum equations. The results highlight the hydrodynamic change and the complex and varying dispersion patterns that occur under tidal flow conditions with aquaculture activities. The main conclusions of this study are detailed below.

- (1) Tidal velocity is reduced within the aquaculture area because the presence of structures suspended in waters causes the partial blockage of the tidal flow, leading to the deceleration of the approaching flow and the formation of downstream wakes near aquaculture facilities during the flood and ebb tides.

(2) The related parameters of cage densities, cage lengths and the drag coefficients are significantly related to the reductions in tidal current speed in the aquaculture domain; thus, models must incorporate the resistance effect caused by culture facilities to calculate the suspended cage-induced changes on hydrodynamics in the design of the suitable densities, layouts and depth of the suspended cages.

(3) The mixing and dispersion of the pollutant field with additional resistance force from the suspended cages is obviously different from cases in which the effect of suspended cages is absent; the importance of the reduction in water speeds caused by marine culture cages is the fact that they affect the transport and dispersal of particulate matter and dissolved nutrients, which affect environmental quality and are sub-optimal for shellfish health in the aquaculture environment. Moreover, the cage-induced changes on hydrodynamic conditions in marine aquaculture waters directly affect the food supply of suspended detritus from the outside sea during the production process.

Shellfish aquaculture tends to release additional material into the water column, including fecal material and food wastes; there is thus a need to accurately characterize the hydrodynamic conditions using numerical models at particular shellfish farm sites because these conditions dramatically affect how far a waste plume from a shellfish farm site would spread. Such modeling requires the use of accurate parameters for reliable calculations of the water renewal rates and nutrient supplies. Future numerical modeling studies should be conducted to aid the selection of suitable locations for shellfish cages; a coupled ecological-hydrodynamic model should also be developed to improve predictions of nutrition transport and cage productivity.

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest.

Availability of data and material

All data included in this study are available upon request by contact with the corresponding author.

Code availability (software application or custom code)

Code that support the findings of this study is available from the corresponding author upon reasonable request.

Authors' contributions

H J performed the archive research, YJ and M Z analyzed flash flood data; M Z wrote the paper.

Ethics approval (include appropriate approvals or waivers)

Not applicable.

Consent to participate (include appropriate statements)

Not applicable.

Consent for publication (include appropriate statements)

Not applicable.

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Figure 1

(a) Study domain

(b) Aquaculture types in study areas

(c) High-density aquiculture of *Patinopecten yessoensis*

Figure 2

Sketch of the study domain and topography in the North Yellow Sea Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Mesh, field gauges and marine aquaculture domain in the North Yellow Sea. The white domain is the island, and the orange domain is the suspended aquaculture cage area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Comparison of the measured and simulated water levels at Dachangshan tidal station.

(a) Tidal current

(b) Tidal direction

Figure 5

Comparison of the measured data and simulated results in tidal currents and flow directions

(a) Fastest flood tide

(b) Fastest ebb tide

Figure 6

Flow fields within a tidal period in which the effect of aquaculture facilities is not considered Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Comparison of the simulated tidal velocities with different culture cage densities

Figure 8

Comparison of the simulated current directions with different culture cage densities

Figure 9

Comparison of the simulated velocity change with different cage densities in a tidal cycle

Figure 10

Changes in depth-averaged mean current speeds as a function of the ratio of the cage length.

Figure 11

Changes in depth-averaged mean current speeds as a function of the drag force coefficients.

Figure 12

Flow fields within a tidal period in which the effect of aquaculture facilities is considered Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 13

Time series of concentration profiles of fecal material at several different locations near the culture cage embayment

(a) Waste transport in the presence of culture cages

(b) Waste transport in the absence of culture cages

Figure 14

Development of the pollutant concentration field at several time points Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its

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Figure 15

The transport process of suspended detritus in the culture waters in absence of cages (left) and in the presence of cages (right) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.