

Article

Predicting Epipelic Algae Transport in Open Channels: A Flume Study to Quantify Transport Capacity and Guide Flow Management

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Abstract: The functionality of rivers and open diversion channels can be severely impacted when the epipelic algae group that grows on concrete inclined side walls, which are typical of urban rivers, joins the water flow. This study aims to increase the long-distance transport of epipelic algae groups in urban rivers and open diversion channels through flow scheduling and to anticipate their transport capacity with respect to water flow. Current research on contaminant movement is primarily based on mathematical models with limited data on flake epipelic algae types. A sidewall epipelic algae group in a flume was modeled using a generalized hydrodynamic experimental approach. Hydraulic experiments were conducted to study the physical movement form and transport capacity of the suspended epipelic algae group. This study suggests that the epipelic algae group will create transport movement without sedimentation when the velocity reaches 80–85% of the main flow velocity and settle to the bottom when it falls below 80%. This research can support the mathematical modelling of hydrodynamic transport, provide a research foundation for long-distance transport, and estimate potential gathering places and sediment amounts under different water flow conditions.

Keywords: side wall of open channel; epipelic algae group; suspension mechanism; critical conditions



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1. Introduction

With increasing awareness about human environmental protection and the importance of water resources, the eutrophication of water bodies has been effectively controlled worldwide. However, epipelic algae groups that grow on the concrete lining of open channels, such as urban rivers and diversion canals, enter these channels in the form of blocks, which are transported with the water flow and even settled. In the past, researchers paid more attention to how to avoid the growth of epipelic algae, but after investigation and research, it was found that the side walls of open channels inevitably grow epipelic algae. At the low flow rate of the channel, the epipelic algae will gradually sink to the bottom of the channel, decay, and emit a stench, which will affect the water quality and environment. However, at an appropriate flow rate, epipelic algae can gather after a certain distance of suspension with the water flow. Therefore, if the suspension mechanism and theoretical formula of epipelic algae groups can be clarified, it will help to achieve long-distance transportation through flow scheduling, improve water quality, and reduce environmental pollution.

However, the current research on algae mostly focuses on its growth-influencing factors and growth changes in different directions. Related research into the suspension movement of epipelic algae is relatively rare. We collected relevant research results regarding the diffusion and migration with the water flow of sediment, oil, and other pollutants

for reference and analysis to provide a basis for this research. Shang Xuemei et al. [1] used the pollutant transport–diffusion model coupled with a hydrodynamic module to numerically simulate the bearing rate of pollutants in Laizhou Bay, Bohai Bay, Liaodong Bay, and the central Bohai Sea (China) after oil diffusion. He Leping and Hu Qijun [2] used the Fluent (3D) software to establish a three-dimensional simulation model of buried oil pipeline leakage, including trenches, to simulate the leakage and diffusion processes under specific accident scenarios. Huang Hailong [3] adopted a two-dimensional mathematical model of suspended sediment transport to study the relationship between suspended sediment diffusion, water depth, and tidal patterns. When the water is shallow or there is a neap tide, suspended sediment is not easily diffused, and the increases in the sediment concentration and the area of turbid water with a high concentration of sediment (exceeding 10 mg/L) are larger. Yao Jian [4] established a two-dimensional free-surface-flow MIKE 21 FM model to simulate the pollutants in the confluence area of a Y-type river in southwest China. The results showed that a larger confluence ratio will lead to a wider distribution of pollution zones, a smaller vertical concentration gradient of pollutants, and a longer vertical diffusion distance. At the same time, the increase in the confluence ratio will increase the horizontal concentration gradient of pollutants and aggravate the diffusion trend of pollutants at the intersection. Based on the EFDC model, Li Yafeng [5] simulated the diffusion of pollutants that may occur in reservoir areas and the leakage of pollutants from sudden-risk accidents in the water. The results showed that the wet year had a great influence on the effluent quality, and the dry year had little effect on the effluent quality. Hou Jingming [6] simulated the pollutant transport process in sudden water pollution accidents based on the GPU-accelerated surface water flow and transport model (GAST model), which can quickly and accurately simulate the pollutant transport process in sudden water pollution accidents caused by rainstorm flash floods or dam-break floods. Based on the environmental fluid hydrodynamic model (EFDC), Tao Ya [7] numerically simulated and analyzed the influence range, time, and degree of sudden water pollution accidents in the Shenzhen Estuary (China) under different hydrological conditions from the perspective of hydrodynamics. Based on the hydrodynamic conditions of Barcelona Port in Spain, Manel et al. [8] simulated and analyzed the degree of influence of different waters under the influence of a near-shore tidal current in sudden oil spill pollution accidents, and they put forward control countermeasures to deal with the deterioration of water quality. Sun Sanxiang [9] studied the transport of pollutants by establishing a transport model of pollutants in runoff on the underlying surface covered by plants. The results showed that the concentration of pollutants in the runoff had an exponential relationship with the effective rainfall depth. Yang Zhonghua [10] used Lagrange's random displacement model to set different vegetation densities and measure the probability of riverbed pollutant absorption. The transport process of instantaneously released pollutants in wetlands with dense rigid submerged vegetation and riverbed absorption boundaries was simulated.

At present, the main research method for studying suspension is mathematical modeling. However, in view of the fact that mathematical models cannot fully simulate the biochemical characteristics of the main body of suspension, we directly used epipelagic algae, whose bulk density and thickness are close to the prototype used in previously described hydrodynamic test research [11]. By changing the flow level, algae thickness, and algae size, a generalized model test of the suspension of the epipelagic algae group was carried out. The aims of this study were to predict the transport capacity of the epipelagic algae group with the water flow and to increase the long-distance transport of the epipelagic algae group through flow scheduling. Based on the relationship between the transport velocity of the epipelagic algae group, the mainstream velocity, and the movement form, the transport capacity of the epipelagic algae group was analyzed, and the quantitative relationship of the transport of the epipelagic algae group was established. At the same time, the experimental data results were verified by the formula. This research provides a strong theoretical basis for the comprehensive analysis of later mathematical model calculation.

2. Materials and Methods

On the basis of the flume of a previous experimental study into the hydrodynamics of epipellic algae on the side wall of an open channel [11], the longitudinal slope in our model was 1:26,000, the slope of the side wall was 1:2.5, the maximum water flow was $420 \text{ m}^3/\text{s}$, and the generalization was carried out according to the scale of 1:30. According to the flow of the prototype channel, the size of the epipellic algae, the sediment, and algae content in the algae group were simulated (Figure 1). We selected 40 groups of epipellic algae sizes and 5 groups of different flow rates to carry out the test.



Figure 1. The epipellic algae with the same sediment and algae content as the prototype. (a) Flake epipellic algae groups. (b) The surface of epipellic algae group.

The flow stabilization measures were set up in the forebay of the flume (Figure 2). According to the gravity similarity, resistance similarity criterium, and water flow continuity, the Froude number similarity condition was used to calculate the scale of the flow velocity, flow rate, and time. The test instrument adopted a propeller current meter (accuracy 0.01 m/s) and an electromagnetic flowmeter (accuracy 0.01 L/s).

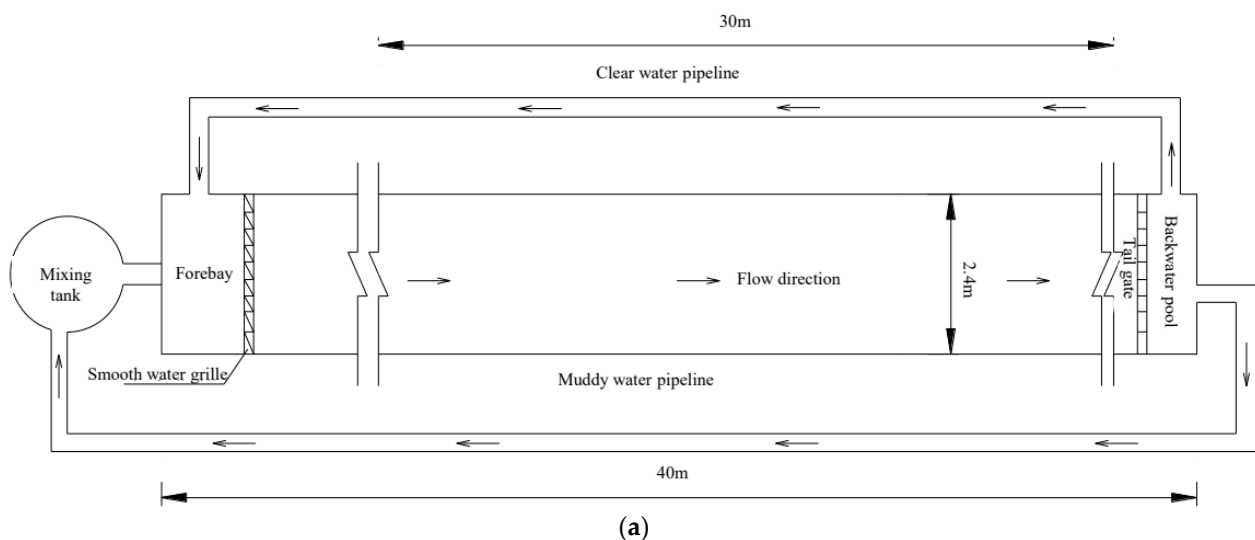


Figure 2. Cont.

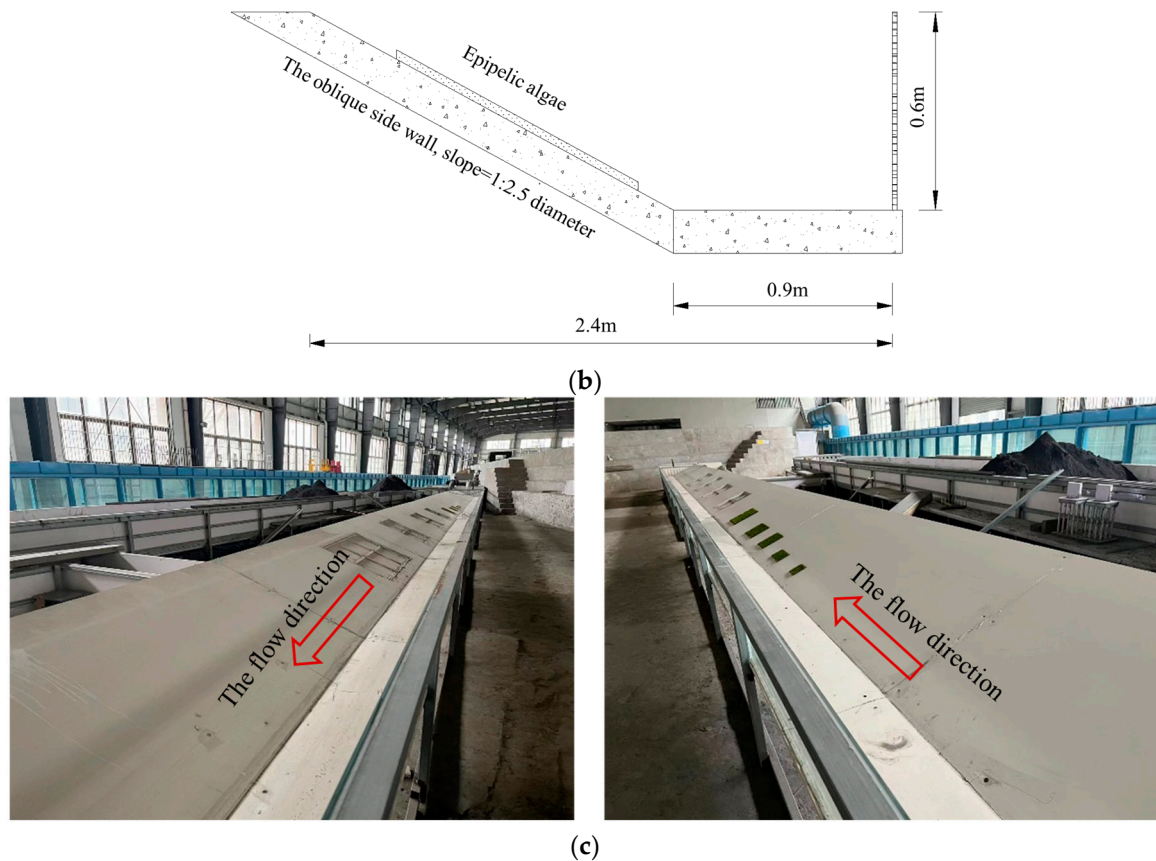


Figure 2. Design of generalized model test: (a) schematic diagram of model circulation system; (b) section shape of test flume; (c) photographs of test flume.

The results of previous research [11] show that the position of the maximum velocity on the vertical line of a channel flow appears at a relative water depth of 0.6 (the ratio of the distance from the measuring point to the bottom of the flume to the water depth). Therefore, the current meter was installed at a relative water depth of 0.6 in the center of the flume to measure the mainstream velocity of the flume.

3. Results

3.1. Physical Figure of Suspension of Epipellic Algae Group

Through multiple sets of test results, it was found that the epipellic algae group was taken away by the water flow at the moment of shedding, and the critical hydrodynamic state of suspension was the critical hydrodynamic state of shedding. However, due to the internal effects of physical and chemical properties such as the thickness, size, and growth cycle of the epipellic algae group, there may be a lag in suspension compared with the main stream of the channel. In general, the suspension state after the epipellic algae group enters the water flow was divided into flip suspension, no-flip suspension, aggregation transport, settlement transport, and other forms, and its suspension state was directly related to the main flow rate and the flow rate of the channel.

When the flow rate was $102.04 \text{ m}^3/\text{s}$, small-scale epipellic algae groups could be easily taken away by the water flow (Figure 3). Although the forms of the suspension of epipellic algae were different, they could flip, settle, or float on the water surface, but they could all be brought downstream with the water flow. The difference was the time taken to travel downstream. The transport form of flipping and settling took a long time and had obvious hysteresis compared with the suspension mode floating on the water surface.



Figure 3. The transport form of epipelagic algae group at $Q = 102.04 \text{ m}^3/\text{s}$: (a) the state of transport in the early time; (b) the state of transport in the late time.

When the flow rate was $220.84 \text{ m}^3/\text{s}$, the shed epipelagic algae were also transported downstream with the water flow in the form of flipping, settling, and floating on the water surface (Figure 4). With the increase in the flow rate, the time taken by flipping and floating on the water surface to travel downstream was almost the same. However, the form of re-transport after sedimentation took a long time to move downstream, and it still had obvious hysteresis.

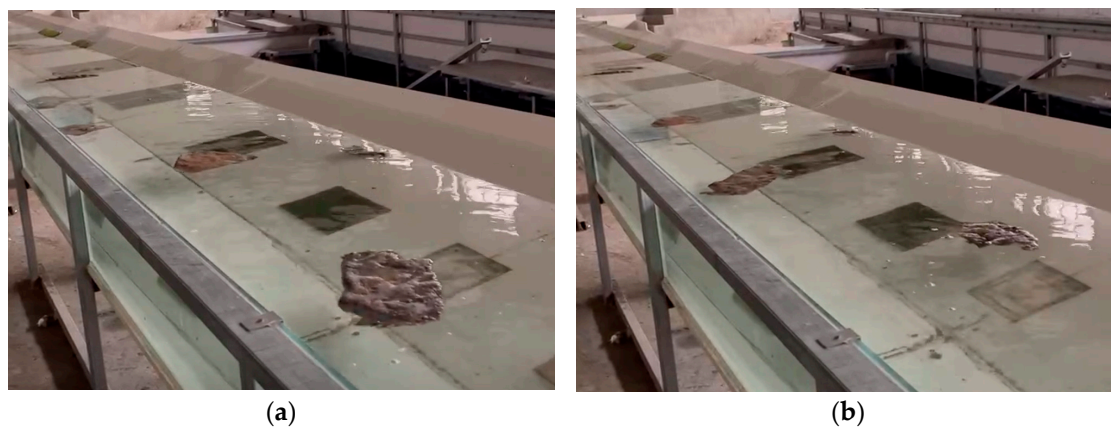


Figure 4. The transport form of epipelagic algae group at $Q = 220.84 \text{ m}^3/\text{s}$: (a) the state of transport in the early time; (b) the state of transport in the late time.

When the flow rate was $301.69 \text{ m}^3/\text{s}$, most of the shed epipelagic algae were transported downstream while being suspended on the water surface, and only a very small amount of epipelagic algae with a thickness of 8 mm first settled and then was transported downstream (Figure 5). Therefore, our research shows that as the flow rate increases, the flow velocity increases, and the main stream of the water flow has a stronger suspension effect on the epipelagic algae group.

According to the physical graphics describing the turnover, settlement, and floating of the epipelagic algae group on the water surface (Figure 6), in order to reduce the water pollution caused by the shedding and settlement of the epipelagic algae group, the law of easy suspension and less settlement should be followed when there is a large flow rate and a small scale of the epipelagic algae group. In the early stage of the growth of epipelagic algae, the flow rate should be increased to reduce settlement by the epipelagic algae group.



Figure 5. The transport form of epipelagic algae group at $Q = 301.69 \text{ m}^3/\text{s}$: (a) the state of transport in the early time; (b) the state of transport in the late time.

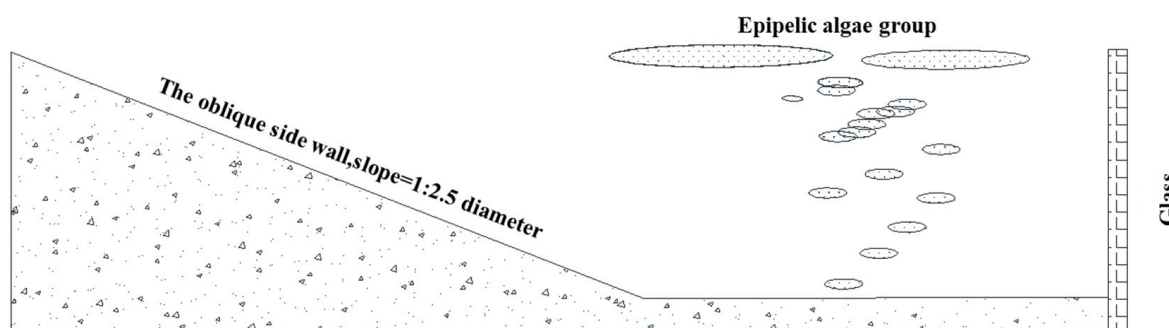


Figure 6. Physical figure of suspension of epipelagic algae group.

3.2. Establishment of a Critical Theoretical Formula for the Suspension of the Epipelagic Algae Group

3.2.1. Analysis of Transport Capacity of Epipelagic Algae Group

Epipelagic algae groups that enter channel flows after shedding are studied as relatively independent media in the water body. It is of great significance to study the mechanism of transport and the transport capacity of the water flow to improve the hydrodynamic conditions and control water pollution through main canal scheduling. Based on the pollutant migration theory of environmental hydraulics, the drifting of epipelagic algae into a water body with the water flow is regarded as the flow of the epipelagic algae into the water body. The resistance of the epipelagic algae to the water flow can be referred to the Stokes formula of viscous resistance. This viscous resistance is the basis for analyzing the capacity of a flow of water to transport epipelagic algae under different water flow conditions.

At present, most research has studied the resistance of algae groups in flows with a small Reynolds number. Scholars believe that the particle size of common algae groups and the relative velocity between the fluid and particles are very small. Therefore, the particle flow model is used to analyze the force of algae groups in the flow. The flow around the particles is a typical small-Reynolds-number flow, and the Stokes formula of viscous resistance is:

$$W = 6\pi\mu V'r \quad (1)$$

in which W is the viscous resistance; μ is the viscosity of water; V' is the relative velocity of algae in water; and r is the radius of the algae group.

Formula (1) is used to particlize the algae group and analyze it. In view of the fact that the scale of the epipelagic algae group is very small relative to the whole channel, there is a velocity difference between the fluid and the algal group related to the density of the algae group. Therefore, we introduce the velocity difference coefficient $f(\epsilon)$ related to the density of the algae to correct V' . At the same time, the lamellae of the algae group are quantified

as the size of the spherical particles. Because the algae group has a thickness, we convert its volume into the volume of the body sphere.

$$\frac{4}{3}\pi r^3 = l w \delta \quad (2)$$

in which l is the length of the algae group; w is the width of the algae group; and δ is the thickness of the algae group.

The parameter z is introduced to represent the radius of the epipelagic algae ball:

$$z = \sqrt[3]{\frac{3 l w \delta}{4 \pi}} \quad (3)$$

Then, the Stokes formula of viscous resistance is transformed as follows:

$$W = 6 \pi \mu f(\varepsilon) V' z \quad (4)$$

Formula (4) shows that the viscous resistance of the water body is directly related to the relative velocity in the water body and the size of the epipelagic algae group, but it is not directly proportional to the relationship, and the specific quantitative relationship still needs further study.

When the epipelagic algae group is washed off from the side wall by the water flow, whether the water flow has an effective transport effect on the epipelagic algae group can be determined by analyzing the followability of the algae group in the water body. The density of common algae groups in rivers and lakes is basically the same as that of water bodies. Therefore, it can be considered that the buoyancy and gravity of algae groups offset each other, and the biological resistance of algae groups is ignored. It is considered that algae groups are mainly affected by the viscous resistance of the fluid in water flow. However, due to the biochemical effect of the sediment and algae on the side wall of the channel, it cannot be ignored. Some epipelagic algae float on the water surface and are transported at the same speed as the water flow, while some algae enter the water body and continue to be transported under the longitudinal action of the water flow. The density of the water and algae is recorded as ρ . If the main flow velocity of the water is V_0 and the instantaneous velocity of an isolated algae group in the water is V , then the relative velocity of the algae group and the water flow is $V' = V_0 - V$. According to Formula (4) of the viscous resistance of the algae group, the acceleration of the algae group is:

$$a = \frac{W}{m} = \frac{6 \pi \mu f(\varepsilon) (V_0 - V) z}{l w \delta \rho} = \frac{162 f(\varepsilon) v^2 \pi^2 (V_0 - V)^2}{(l w \delta)^2} \quad (5)$$

where

$$v = \mu / \rho \quad (6)$$

in which a is the acceleration of the algae group; v is the kinematic viscosity coefficient of water; and m is the mass of the algae group.

The instantaneous velocity V of the algae group satisfies the following equation:

$$dV = \frac{162 f(\varepsilon) v^2 \pi^2 (V_0 - V)^2}{(l w \delta)^2} dt \quad (7)$$

Formula (7) shows that under the action of viscous resistance to the water flow, the instantaneous velocity of the epipelagic algae group approaches the mainstream velocity V_0 with the increase in time t .

The smaller the size of the epipelagic algae group, the shorter the time it takes to catch up with the mainstream velocity, the better the followability of the epipelagic algae group, and the more obvious the effect of the water flow on the algae group. Through experimental research, the following conclusions can be obtained (Table 1): When the velocity V of the

algae group reaches more than 95% of the main flow velocity V_0 , it can be considered that the algae group has all moved forward with the water flow without relative lag, that is, it is suspended on the water surface. If it reaches 95~85% of the main flow velocity, it is considered that the algae group is lagging behind, that is, it is transported with the water flow below the water surface. If it reaches 85~80% of the main flow velocity, it is first settled and then transported with the water flow. If it is lower than 80% of the main flow rate, with the increase in time, the epipellic algae group is likely to stop moving after a certain distance, which will cause the epipellic algae group to accumulate at the bottom of the channel and cause water metamorphism.

Table 1. The transport velocity of the epipellic algae group as a percentage of the mainstream velocity.

Flow rate (m^3/s)		36.53	68.03	102.04	220.84	301.69
The mainstream velocity (m/s)		1.25	1.36	1.48	1.75	1.89
Length $\times$ width of algae group	Thickness of algae group	The percentage of the transport velocity of the epipellic algae group to the mainstream velocity (%)				
3 m $\times$ 3 m	3 mm	98.25	99.89	100.00	100.00	98.24
	6 mm	99.44	99.39	100.02	100.00	98.13
	8 mm	99.51	96.01	97.97	92.42	95.12
6 m $\times$ 3 m	3 mm	100.35	100.12	97.82	100.10	98.94
	6 mm	92.97	100.12	97.13	98.73	97.80
	8 mm	95.05	97.18	97.97	97.71	97.36
6 m $\times$ 6 m	3 mm	99.20	97.63	96.54	99.26	96.71
	6 mm	92.00	85.13	97.39	96.20	90.56
	8 mm	88.00	83.31	94.17	95.91	94.30
9 m $\times$ 6 m	3 mm	96.00	99.39	99.32	93.80	90.66
	6 mm	92.00	85.40	94.01	91.78	96.39
	8 mm	88.00	80.98	92.06	94.56	98.68
9 m $\times$ 9 m	3 mm	93.60	95.70	98.86	86.94	96.28
	6 mm	88.00	85.40	92.21	85.20	95.24
	8 mm	88.00	82.45	88.51	86.78	96.49
15 m $\times$ 15 m	3 mm	92.80	94.23	94.59	92.24	86.51
	6 mm	88.00	88.34	88.51	82.65	85.66
	8 mm	81.60	89.08	87.84	95.13	83.28
21 m $\times$ 15 m	3 mm	88.00	92.02	94.59	94.75	84.66
	6 mm	72.00	80.98	86.49	87.92	80.43
	8 mm	48.00	80.98	81.08	94.27	79.37
18 m $\times$ 18 m	3 mm	72.00	88.34	94.59	91.43	83.60
	6 mm	72.00	73.62	81.08	77.14	82.96
	8 mm	56.00	66.26	81.08	74.29	78.89
30 m $\times$ 18 m	3 mm	40.00	80.98	91.22	91.43	85.82
	6 mm	32.00	58.89	67.57	74.29	87.91
	8 mm	32.00	58.89	67.57	68.57	80.06

3.2.2. Analysis of Influencing Factors on the Transport Velocity of Epipellic Algae Groups and Verification of Model Test

The transport velocity of epipellic algae groups is mainly related to the average flow velocity of the main stream (flow rate), the thickness of the algae, the size of the algae (area), and the shape. The various factors are analyzed below.

- (1) The effect of the average flow velocity of the main stream on the transport velocity of epipellic algae groups.

This experiment mainly considered the effects of five main stream average flow velocities of 1.25 m/s, 1.36 m/s, 1.48 m/s, 1.75 m/s, and 1.89 m/s on the transport velocity of an epipellic algae group. The smaller the average flow velocity of the main stream, the smaller the transport velocity of the epipellic algae group. When the average flow velocity of the main stream is 0 m/s, the transport speed of the epipellic algae group should also be 0 m/s; the larger the average flow rate of the main stream, the greater the transport speed

of the epipelagic algae group, and the transport velocity of the epipelagic algae group generally does not exceed the average flow velocity of the main stream. The transport velocity of the epipelagic algae group was basically linearly correlated with the average flow velocity of the main stream (Figure 7). Therefore, the following can be obtained:

$$V \propto a_1 V_0 \quad (8)$$

in which V is the transport velocity of the epipelagic algae group; a_1 is a parameter, which should be in $(0, 1)$; and V_0 is the average flow velocity of the main stream.

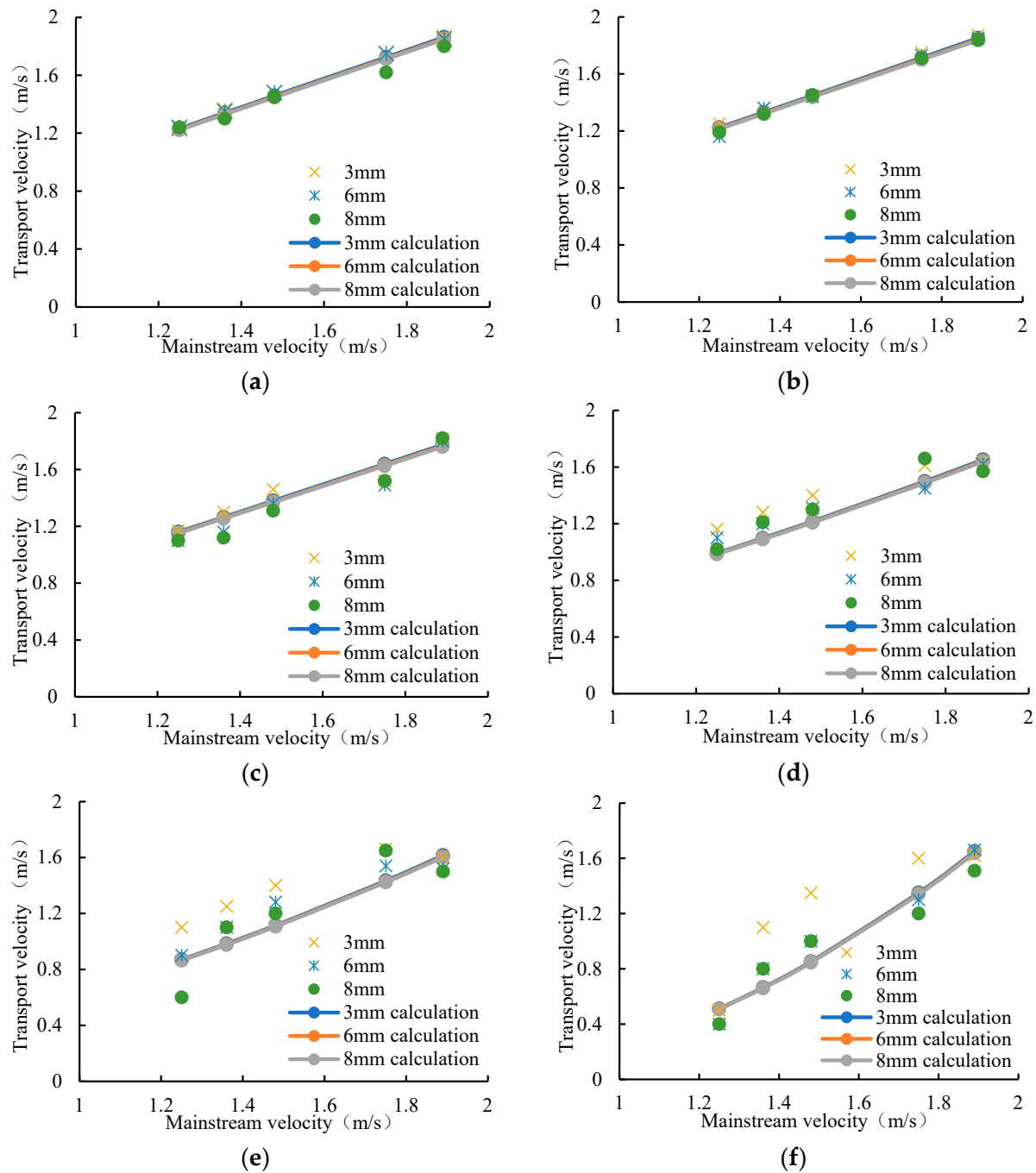


Figure 7. Transportation of different sizes of epipelagic algae group: (a) $a \times b = 3 \text{ m} \times 3 \text{ m}$; (b) $a \times b = 6 \text{ m} \times 3 \text{ m}$; (c) $a \times b = 9 \text{ m} \times 9 \text{ m}$; (d) $a \times b = 15 \text{ m} \times 15 \text{ m}$; (e) $a \times b = 21 \text{ m} \times 15 \text{ m}$; (f) $a \times b = 30 \text{ m} \times 18 \text{ m}$.

(2) The effect of algae thickness on the transport velocity of epipellic algae group.

This experiment mainly considered the influence of thicknesses of 3 mm, 6 mm, and 8 mm on the transport velocity of epipellic algae groups. The smaller the thickness of the algae, the greater the transport velocity of the epipellic algae group, and the transport velocity of the epipellic algae group was inversely related to the thickness of the algae. The transport velocity of the epipellic algae group was basically linearly correlated with the thickness of the algae (Figure 8). Therefore, the following can be obtained:

$$V \propto -a_2\delta + a_3 \quad (9)$$

in which V is the transport velocity of the epipellic algae group; a_2 and a_3 are parameters greater than 0; and δ is the thickness of the algae group.

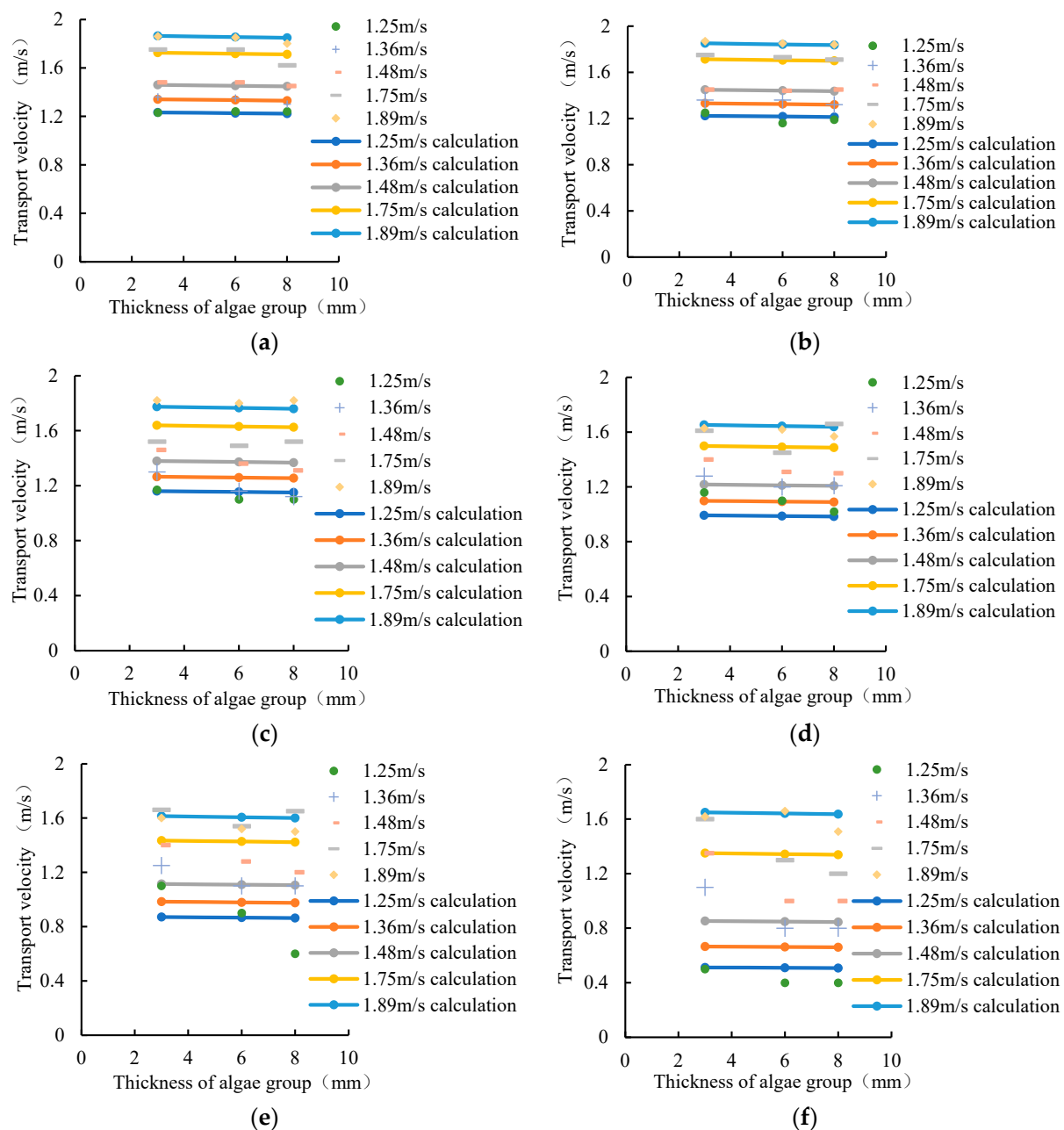


Figure 8. Transportation of epipellic algae groups with different thickness: (a) $a \times b = 3 \text{ m} \times 3 \text{ m}$; (b) $a \times b = 6 \text{ m} \times 3 \text{ m}$; (c) $a \times b = 9 \text{ m} \times 9 \text{ m}$; (d) $a \times b = 15 \text{ m} \times 15 \text{ m}$; (e) $a \times b = 21 \text{ m} \times 15 \text{ m}$; (f) $a \times b = 30 \text{ m} \times 18 \text{ m}$.

(3) The effect of algae area on the transport velocity of epipelagic algae groups.

The influence of the shape and area of nine kinds of algae groups ($3\text{ m} \times 3\text{ m}$, $6\text{ m} \times 3\text{ m}$, $6\text{ m} \times 6\text{ m}$, $9\text{ m} \times 6\text{ m}$, $9\text{ m} \times 9\text{ m}$, $15\text{ m} \times 15\text{ m}$, $21\text{ m} \times 15\text{ m}$, $18\text{ m} \times 18\text{ m}$, $30\text{ m} \times 18\text{ m}$) on the transport velocity of the epipelagic algae groups was mainly considered in this experiment.

The smaller the area of the algae, the greater the transport velocity of the epipelagic algae group, and the transport velocity of the epipelagic algae group was inversely related to the area of the algae group. The transport velocity of the epipelagic algae group was basically linearly correlated with the area of the algae (Figure 9). However, there was also a quadratic relationship. When the mainstream flow velocity was below 1.48 m/s , with an increase in area, the transport velocity of the epipelagic algae group had an accelerated downward trend. When the mainstream flow velocity was greater than 1.75 m/s , with an increase in area, the downward trend of the transport velocity of epipelagic algae group could slow down and rise. Therefore, the following was obtained:

$$V \propto a_4(V_0 - a_5)A^2 - a_6A + a_7 \quad (10)$$

in which V is the transport velocity of the epipelagic algae group; a_4 , a_5 , a_6 , and a_7 are parameters greater than 0, where a_4 is a very small number, and a_5 should be in $(1.48, 1.75)$; V_0 is the average flow velocity of the main stream; and A is the area of the algae group.

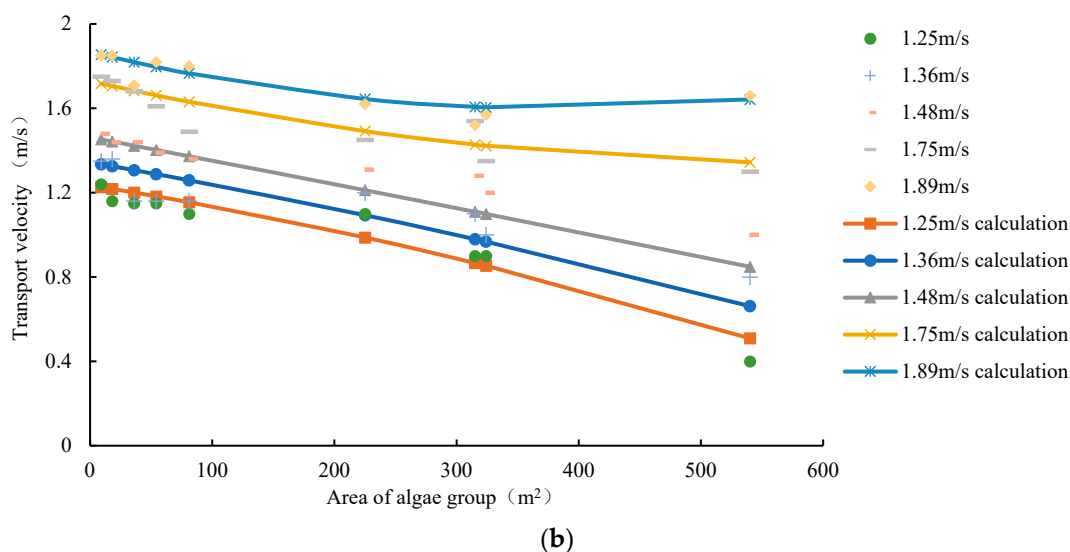
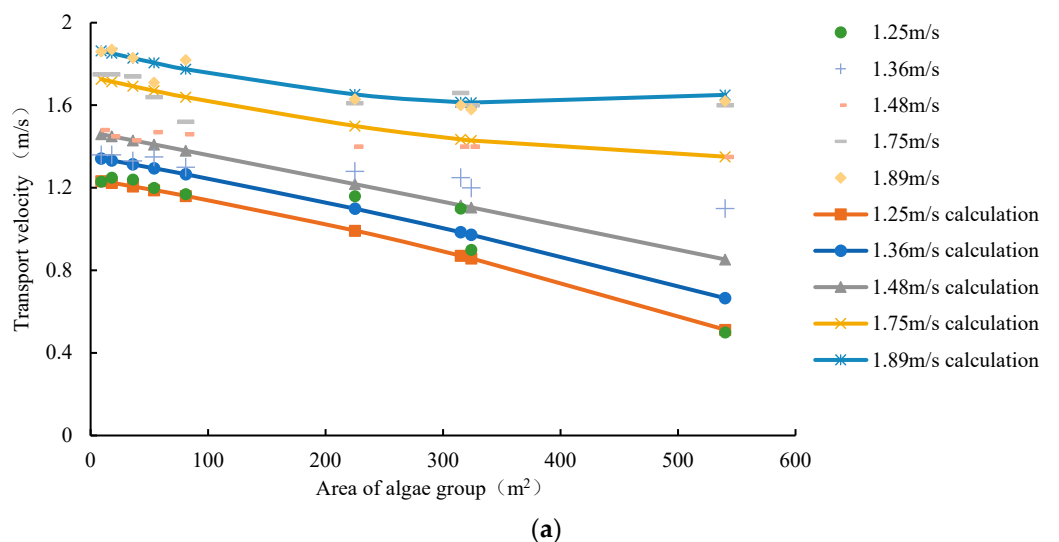


Figure 9. Cont.

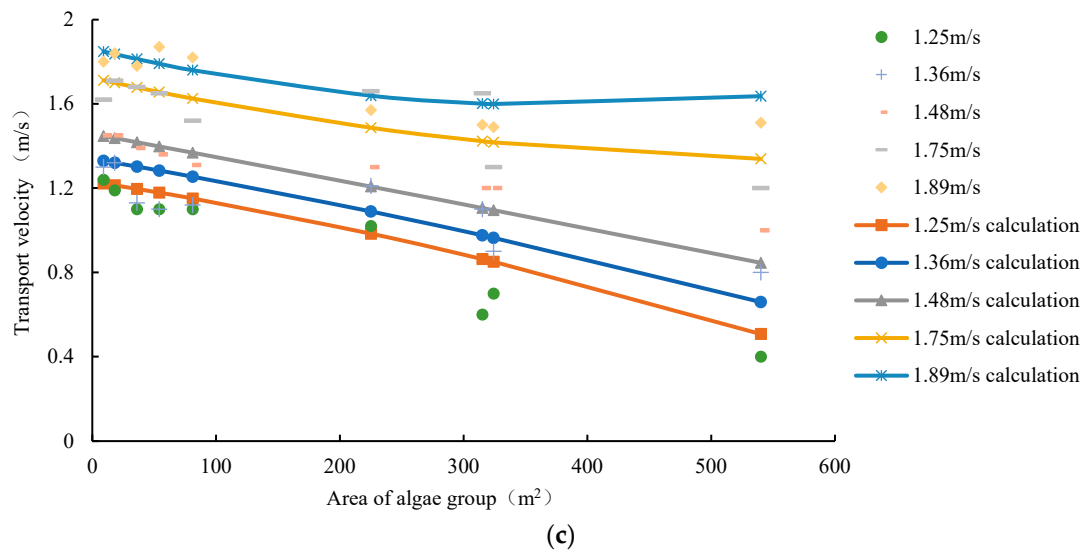


Figure 9. Transportation of epipellic algae groups of different areas: (a) thickness of epipellic algae groups of 3 mm; (b) thickness of epipellic algae groups of 6 mm; (c) thickness of epipellic algae groups of 8 mm.

From the above, we can conclude that:

$$V = a_1 V_0 \times (-a_2 \delta + a_3) \times [a_4 (V_0 - a_5) A^2 - a_6 A + a_7] \quad (11)$$

The values of a_1 , a_2 , a_3 , a_4 , a_5 , a_6 , and a_7 were obtained by fitting, and the formula for calculating the transport velocity of the epipellic algae group was obtained by bringing them into the following relationship:

$$V = 0.693 V_0 \times (-0.002 \delta + 1.2) \times [0.000003 (V_0 - 1.5) A^2 - 0.0009 A + 1.2] \quad (12)$$

4. Discussion

4.1. Research Results of Longitudinal Transport Velocity along the Sidewall

Based on the Mike21 model, Sun Zhaohua [12] established a two-dimensional hydrodynamic water quality model to study the changes in the water level, flow velocity, and self-purification ability after sudden nearby water pollution accidents caused by the arrangement of different-density wharf groups. The differences among the three changes were compared from the perspectives of the spatial difference and maximum amplitude, and the relationship between the wharf density, hydrodynamic conditions, and pollutant concentration amplitude was summarized. The results showed that the concentration of the mainstream area in the project area increased, the concentration of the near-shore zone decreased, and the overall retention time of the high concentration increased. Ren Chun-ping [13] studied the horizontal two-dimensional transport and diffusion characteristics of pollutants through physical model tests. The results showed that pollutants were mainly transported along the sidewall direction, and the transport speed in the vertical sidewall direction was less than that along the sidewall direction. The results of this study show that the transport of epipellic algae had a certain lag relative to the main stream of the channel. This was because the longitudinal transport along the sidewall was the main trend of the transport of the epipellic algae when the epipellic algae group entered the water flow in the early stage. After a short period of lateral transport and sidewall transport, it was transformed into the longitudinal transport of the main stream. The epipellic algae group was mainly transported by the influence of the main stream. There was no effect of the concentration and water dilution in this study, but the results were consistent with the research results of other scholars.

4.2. Study on the Influence of Wind on Transport

Shu Yehua [14] established a high-precision three-dimensional wind-induced current numerical model and wind-induced current–pollutant coupling numerical model for Taihu Lake (China). The study analyzed the characteristics of a wind-induced current in Taihu Lake under the action of prevailing winds and the characteristics of pollutant transport in Taihu Lake driven by wind-induced currents. The results showed that the surface velocity of the stable wind-induced flow field in Taihu Lake was greater than the bottom velocity, and the surface flow direction was basically the same as the wind direction, while the bottom flow direction was roughly opposite to the surface, with the characteristics of compensation flow. The wind direction can significantly affect the morphology and structure of wind-driven currents in Taihu Lake. Huilin Wang and Wenxin Huai [15] considered that both surface wind and bed absorption have an important influence on the pollutant diffusion process. Considering these two factors, a multi-scale method was used to describe the environmental diffusion process in wetland flow. The results of the proposed multi-scale method were in good agreement with the data set generated by the numerical method. Zhao Guixia and Gao Xueping [16] studied the influence of wind-induced lateral disturbance on the horizontal migration and aggregation of algae in a lake. There were significant differences in the influence of different wind directions on the horizontal transport of algae. Overall, the wind field changed the spatial distribution of the algae residence time in the lake area. From the perspective of spatial distribution, the influence of the wind field on the algae residence time was the most significant in the middle and lower reaches, but it was not significant in the middle and upper reaches. In addition, the wind field effectively enhanced the migration connectivity of algae in the lake. The migration connectivity between the algae in the lake and upstream of the source area increased with the increase in the wind field, and the migration connectivity with the downstream of the source area increased with the increase in wind field intensity; the distribution was also more uniform. Scholars [14–16] have studied the influence of wind on transport from different angles. However, in this study, because it was an indoor generalized model test, combined with the results of a field investigation, the effect of wind on the transport of the epipelagic algae groups was attributed to the effect of wind on the water flow, and the water flow then formed the transport of the epipelagic algae group. In addition, the scale of epipelagic algae groups is larger than that of pollutants, so the effect of wind was no longer considered separately. Secondly, due to the complicated formation process of epipelagic algae groups, through the analysis of their prototype characteristics, it can be seen that epipelagic algae groups have a strong adhesion force inside and are a result of biochemical comprehensive action. The role of wind makes it difficult to lead to its decomposition. Therefore, the role of wind was no longer considered in this study.

4.3. Study on the Influence of Water Flow Characteristics on Transport

Zhu Jingge [17] studied the varying characteristics of pollutant transport rates in western Taihu Lake (China). The results showed that the input rates of nitrogen and phosphorus in Chengdong Port were controlled by the concentration, and the transport rates of other rivers were controlled by the flow rate. Zhang Yinghao and Lai Xijun [18] used the energy spectrum distribution of instantaneous velocity to separate the wave velocity from the turbulent velocity, and they analyzed the effects of aquatic plants on the time-averaged velocity, wave velocity, and turbulent kinetic energy, respectively. In order to study the capacity of a water flow to transport algal blooms, Ji Daobin [19] generalized algal blooms into material particles in water bodies. Studies have shown that water flow can produce significant push flow transport effects on algal blooms. Scholars regard the water flow velocity, kinetic energy, and density flow as the main factors affecting transport, which is consistent with the results of this study. In this study, through a large number of transport experiments, it was found that under the same flow conditions, the transport velocity of different scales and different thicknesses were significantly different. The larger the scale, the greater the possibility of sedimentation of the epipelagic algae groups, that is, the transport

capacity of the water flow could not carry large-scale material particles. According to the results, in order to reduce the water pollution caused by the shedding and sedimentation of the epipellic algae groups, the law of easy suspension and less sedimentation should be followed when the flow rate is large and the epipellic algae groups are small. In the early stage of the growth of epipellic algae, the flow rate should be increased to reduce the sedimentation of epipellic algae.

4.4. Research Results of Gathering Place Prediction

Magdalena Musielak et al. [20] used the immersed boundary method to simulate the interaction of rigid and flexible diatom chains with surrounding fluids and nutrients. Galabov et al. [21] took an oil tanker accident in the Gulf of Burgas as an example, used a numerical simulation method to analyze the pollutants drifting on the sea surface, evaluated the impact of the oil spill accident on the risk to the water environment of the Port of Burgas, and determined the potential dangerous area and its occurrence conditions. Due to the great environmental impact of pollutants and epipellic algae on rivers, lakes, and oceans, if pollutant accumulation prediction can be carried out according to its transport characteristics, active measures will be taken to effectively reduce the impact on the environment. Scholars have predicted potential dangerous areas by mathematically simulating the interaction of pollutants with water flow and by conducting water environmental risk assessments, but they have not established a quantitative relationship. In this study, a large number of hydraulic tests were carried out to analyze the relationship between the average flow velocity, the thickness of algae, and the size (area) of algae groups. The data from the results of the model tests were used to verify the transport formula. The results showed that the fit of the formula was good, which increases the possibility of predicting the accumulation area of epipellic algae groups in the future. Although this study is different from other scholars' research methods, the fundamental purpose is to predict the accumulation area and reduce the impact on the environment. This physical model will provide a research basis for the continuous optimization of mathematical models in the future.

5. Conclusions

This experimental study on the suspension of epipellic algae groups on the side wall of open channels in a water flow has shown the following:

- (1) Epipellic algae have many forms, including flip suspension, no-flip suspension, aggregation transport, and settlement transport, and its suspension state is directly related to the main flow velocity and flow rate of the channel.
- (2) When the velocity V of the algae group reaches more than 95% of the main flow velocity V_0 , it can be considered that the algae group has all moved forward with the water flow without relative lag, that is, it is suspended on the water surface. If it reaches 95~85% of the main flow velocity, it is considered that the algae group is lagging behind, that is, it is transported with the water flow below the water surface. If it reaches 85~80% of the main flow velocity, it is first settled and then transported with the water flow. If it is lower than 80% of the main flow rate, with the increase in time, the epipellic algae group is likely to stop moving after a certain distance.
- (3) The hydrodynamic formula of an epipellic algae suspension was established, and the formula was verified using experimental data. The results showed that the formula calculation and the data were in good agreement.

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