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Experimental Study on the Impact of Pulsed Flow Velocity on the Scouring of Benthic Algae from a Mountainous River

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Abstract: The decrease in periodic scouring of pulsed flows in regulated rivers can result in algal communities dominated by filamentous algae, not available as food sources for fish and macroinvertebrates. To study the pulsed flow velocity required to scour benthic algae from natural river beds, the removal effects on the algal biomass and resistances of different species were tested in a laboratory flume at different velocities of 0.8, 1.1, 1.4, 1.7, and 2.0 m/s. The removal of total algal biomass showed a significant positive relationship with increasing velocities, which reached 22% at 2.0 m/s. The biomass removal of green algae and diatoms was higher than that of blue–green algae. The flow velocity at 1.4 m/s had a clear removal effect on filamentous algae. The velocity higher than 1.7 m/s caused a significant increase in the removal percentage of total biomass dominated by diatoms and blue–green algae. To reduce the filamentous algae and retain the diatoms and blue–green algae, a range of near bed flow velocity was suggested to be 1.4–1.7 m/s. This range could serve as a reference for required pulsed flow velocity to reduce the growth of excessive or nuisance periphyton.

Keywords: benthic algae; pulsed flow; flow velocity; environmental flow; Nanxi River; experiment

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1. Introduction

Benthic algae are dominant primary producers and energy sources in mountainous river ecosystems. Their biomass and species composition are important for the aquatic food web and bioenergy [1–4]. They can affect the food sources of fish and benthic invertebrates [5]. Fishes prefer diatoms as food, whereas digest less filamentous green and blue–green algae, which are less palatable or physically difficult to consume [6]. The growth of excessive or nuisance periphyton might also block or slow the flow of an otherwise fast-flowing water body at shallow locations, thereby deteriorating the water quality and aquatic habitat [7–9].

The pulsed flow of a flood could fundamentally alter the biomass and species composition of benthic algae [2,10]. The significant short-term increase in flow velocity can reduce benthic algal biomass by scouring through shear stress and sediment abrasion [11,12]. In regulated rivers, the magnitude and frequency of high-flow events are diminished [6,13]. Compared with the conditions before dam construction, the algae are under less influence of pulsed flows. Regulation can alter benthic algal assemblages from natural conditions, dominated by diatoms, to late-succession states often dominated by filamentous green algae [1,6,14]. Hydrological factors for the habitat requirements, such as the flow velocity, require more attention to determine the environmental flow for freshwater ecosystems.

To study the scouring impact of pulsed floods on benthic algae, experimental studies were performed with the algae exposed to elevated flow velocities for a short period of several hours. By scouring benthic algal communities on artificial substrates with altered flow velocities in flow tanks [15] or channels [7], researchers have compared the differences in the biomass and species compositions of these algae before and after the scouring by the flow at different velocities. Biggs and Thomsen [15] examined the various factors that could affect the detachment of filamentous benthic algae, including the flow velocity, scouring duration, and resistance of different algal species to the flow velocity. Their results showed that non-filamentous diatom communities were more resilient to scouring than filamentous algae. Flinders and Hart [7] observed that flow velocities above 1.5 m/s had a significant removal effect on benthic algae through an experimental study with velocities ranging from 0.2 to 2.4 m/s. Using field observations, Davie and Mitrovic [16] compared the different effects of dam flow release and tributary natural flooding on the benthic algae of the Severn River, Australia, and found that flow velocities above 1.2 m/s effectively removed filamentous green algae during a natural flood event.

The Nanxi River is located in the coastal region of the southeastern Zhejiang Province, China, at the geographical coordinates of 120°19′–120°59′ E and 28°00′–28°34′ N. With a drainage area of 2436 km^2, the river is the second largest tributary of the Oujiang River (Figure 1). The middle and upper reaches of the river were feeding grounds for fishes with most of the river beds covered by cobbles and high-quality water, suitable for the growth of benthic algae. There are 87 fish species including the Ayu (*Plecoglossus altivelis*), an endangered and commercially important species. The Ayu is anadromous. Its larvae spend January and February in the estuary and coastal seawater. From March to May, the juveniles migrate upstream from their wintering ground to their feeding ground in the middle and upper reaches of the river. During the maturation and spawning stages, the Ayu feeds primarily on diatoms and blue green algae [17]. Ayu has been endangered since the 1990s because of over fishing, river bed dredging, and water pollution in the tidal reaches. The Shatou Gates was a water storage project with sluice gates, built in the middle reaches in 2010 to separate the tidal reaches and provide fresh water supply. Although fishing and dredging were prohibited in the river in recent decades, there are still artificial barriers such as Shatou Gates and a series of weirs in the upstream reaches.

The Nan'an Reservoir is being planned to be constructed in the upstream reaches, aiming at flood control and water supply. It would have a catchment area of 311.9 km^2 and a total storage capacity of 366.76 million m^3. The regulation of the Nan'an Reservoir and Shatou Gates should be optimized and coordinated to provide environmental flow in the feeding ground and for the migration requirement of Ayu. To achieve the eco-friendly operation of the reservoir and avoid the excessive growth of filamentous algae as a result of the constant flow, it is necessary to study the pulsed flow velocity needed for the scouring and regeneration of benthic algae.

Most experimental studies focusing on the scouring of benthic algae were conducted with excessive grown algae colonizing on artificial substrates. The natural substrates have different roughness, higher heterogeneity in species composition and biofilm structure. Rough substrata were found to protect organisms during high-flow events [18], and were more species-rich than smooth substrata [19]. The algae communities on natural substrates may have different resistance to scouring. Few studies have examined the quantitative influence of the flow velocity on the biomass and species composition of benthic algae growing on natural riverbed substrates. Moreover, the main finding of the previous studies was the lower limit of flow velocity to achieve removal effects on the excessive grown algae, with less reports on the upper limit to retain the algal community dominated by non-filamentous algae.

We performed experiments with benthic algae from riverbed cobbles of the Nanxi River scoured by different flow velocities to: (1) test the hypothesis that there are increasing scouring impacts of elevated flow velocities on algal biomass on natural substrates and differences in the resistance of algae species, (2) test flow velocity for the significant detach-

ment of filamentous algae, and the velocity to avoid a large amount of losses of diatoms as food sources for fishes. The results could support the regulation of eco-friendly flow velocities based on habitat requirements.

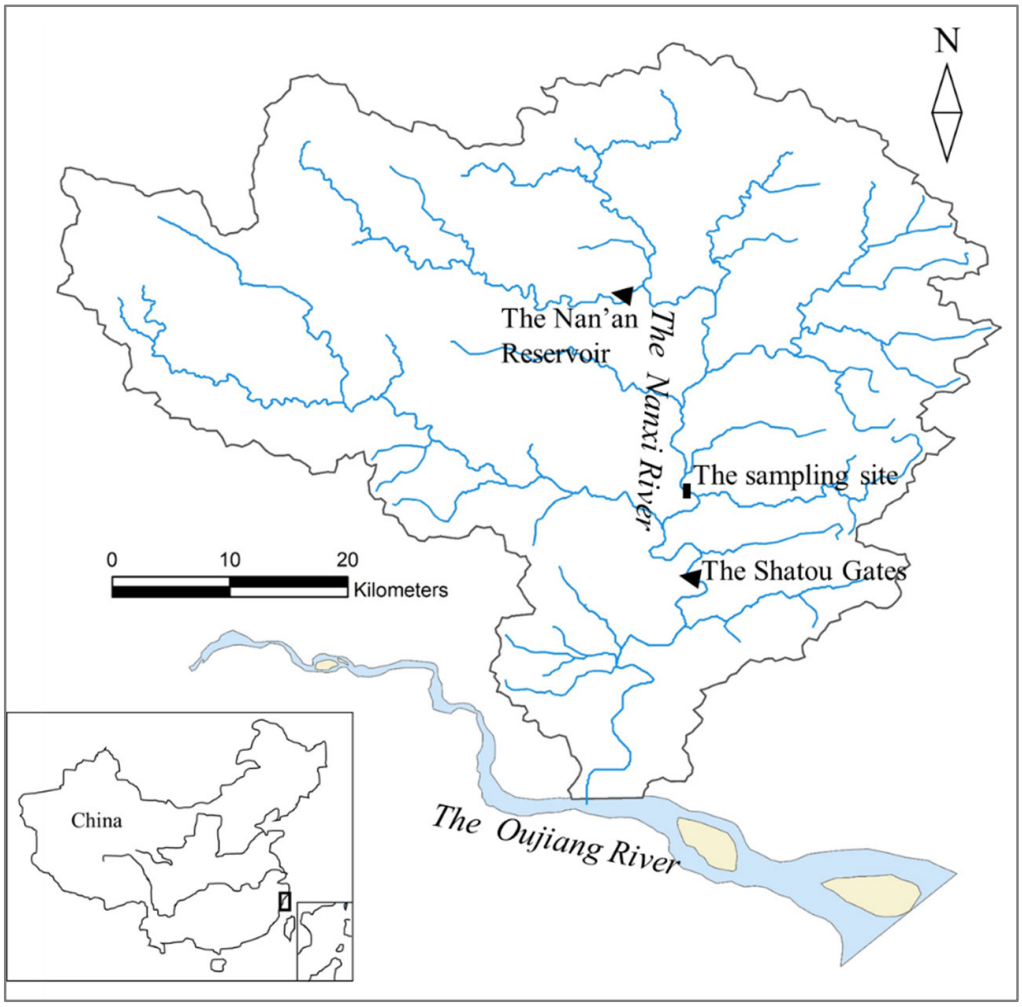


Figure 1. The Nanxi River and the sampling site of cobbles for tests.

2. Materials and Methods

2.1. Experimental Apparatus and Flow Velocity Calibration

2.1.1. Experimental Apparatus

A laboratory flow tank system was designed to test the short-term impact of different flow velocities on the scouring of algae. It was a modified version similar in size to the tanks used by Biggs and Thomsen [15], and Lacoursiere and Craig [20]. The entire system consisted of a servo motor, a water tank, flow diversion grids, a flow rectifier, a test section, and a water outlet, as shown in Figure 2. A servo motor is a device with a controllable motor rotation speed and high accuracy that can deliver a stable conversion of electrical signals into rotational motion. A 1.5-kW servo motor was selected for these experiments. The frequency and rotational speed of the motor were adjusted to drive the propeller blades and regulate the flow velocity in the flow tank. The flow diversion grid was used for diversion and adjusting function to prevent turbulent flow. The test section was at the bottom of the flume for the placement of the cobbles for souring.

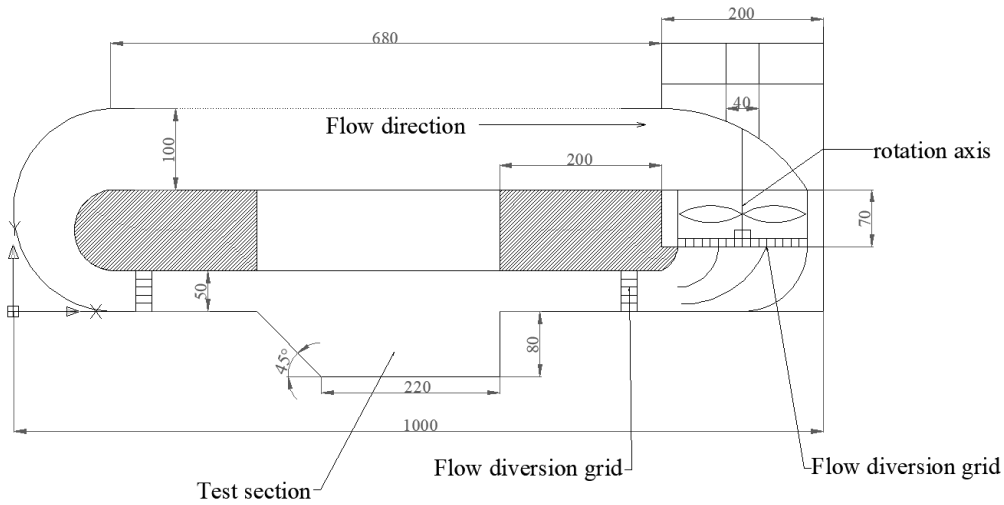


Figure 2. Front view of experimental tank (unit: mm).

2.1.2. Velocity Measurement and Calibration

Pitot tubes were used to measure the flow velocity 2 cm above the test section. The relationship between the flow velocity and the rotational speed of the servo motor was determined in advance. The measured data of the rotational speeds and the flow velocities were analyzed to obtain the linear regression line, which was used to relate the flow velocity and the rotational speed (Appendix A: velocity measurement and calibration). The servo motor was set to a certain rotational speed corresponding to a required flow velocity before each test. During the test, the flow tank system was fixed to avoid any effects of its movement on the calibration of the flow velocity in the testing section.

2.2. Experimental Conditions

To test the scouring impact of the flow velocity on algae, the experiments were performed focusing on elevated flow velocities, which were comparable to the near bed flow velocity of natural pulsed flows. Other environmental conditions, such as the water temperature, were recorded during the test. Past studies on the influence of the flow velocity on the detachment of benthic algae [7,15,16] indicated that the flow velocity had a limited influence on the algal biomass at a short-term scouring velocity below 1.0 m/s. Based on these findings and stability considerations of the flow tank system at high flow velocities, the velocity range in this study was set at 0.8–2.0 m/s.

Three parallel experiments were conducted at each flow velocity of 0.8, 1.1, 1.4, 1.7, and 2.0 m/s. The motor rotation speed was adjusted to deliver the required flow velocities. The pitot tube was also used to verify the flow velocity prior to the start of each test run. Based on previous results [7,15] and our pilot experiment, algae removal tended to stabilize within 2 h of exposure to scouring.

2.3. Experimental Procedure

2.3.1. Collection of Benthic Algae Samples

The experiments were implemented from 18–27 September 2017. The sampling site was at the Ayu feeding ground in the mountainous river reaches of the Nanxi River, close to the hydrological station of Shizhu (Figure 1). The sampled cobbles were embedded in an unshaded shallow pool, with water depth of 30–50 cm. It is apart from the main stream, only have flow scouring when storm flow happens. The cobbles for scouring were randomly selected in this area. To facilitate transportation and placement of the samples in the flow tank system, the maximum length of these cobbles was 10 cm. The collected cobbles were placed in the sampling bucket and capped. A small amount of river water was maintained in the bucket to keep the samples wet during transportation.

2.3.2. Scouring Experiment

The tests were performed immediately after the cobbles with benthic algae being sampled and transported to the laboratory. The detached algal biomass in the water body during the scouring process and the remaining biomass on the cobbles after scouring were sampled and analyzed. The experimental steps were as follows.

1. The removable cover above the test section of the flow tank was opened and the cobble sample was placed inside. The side of the cobble with algal growth was faced upward. The cover was placed back on the test section. Tap water maintained at room temperature was slowly added to the tank;
2. The motor was turned on to its pre-set rotational speed. The experiment was run at each speed for 2 h. The water body was mixed uniformly during the running process of the motor. Water samples, each 500 mL, were collected every 0.5 h (a total of four bottles) and stored at 4 °C in darkness. To avoid error in suspended biomass calculations in later samplings, this volume was replaced with fresh water after each sampling. For each test, the water volume filled in the tank was 38.16 L, which was multiplied by the biomass concentration of the water samples to calculate the suspended biomass sloughed from the cobbles;
3. After 2 h, the motor was turned off and the water in the tank was drained. The cobble sample was removed with the algae-covered side facing up to avoid scratching. The remaining algae still attached after scouring were scraped and washed into a beaker with a stiff nylon brush. Each cobble was scrubbed clean and rinsed with distilled water to wash dislodged algae into a clean beaker. Both the brush and beaker were rinsed thoroughly with distilled water between samples to avoid cross contamination of samples. This treatment technique can remove more than 95% of biomass on the cobbles [6]. The biofilm suspension was then stored refrigerated in darkness. The algae-covered surface area was measured by the technique of covering and weighing the aluminum-foil [21]; and
4. The chlorophyll a concentrations were tested for the five bottles with algae samples (four from the water body, one from the cobble after scouring). The algae species were then identified. The samples were preserved with Lugol's iodine solution and sitting for at least 48 h. After that, each sample was concentrated by siphon to a volume of 20 mL, and a 0.1 mL subsample was extracted for microscopic examination.
5. The above steps were repeated for each flow velocity (three replicates for each flow velocity). The flow tank was cleaned after each experiment to avoid contaminating the subsequent tests.

2.3.3. Quantification of Chlorophyll a and Species Identification

The total chlorophyll a concentration for each sample was tested using a Phyto-PAM chlorophyll fluorometer. The results were verified using a spectrophotometer, which provided a measurement of the algal biomass. Chlorophyll a was collected by filtering the water sample through a Whatman GF/C filter (47-mm-diameter and 1.2-μm-pore-size) and the filter was then extracted overnight in the dark with absolute methanol at 4 °C. After centrifugation at 5000× *g* for 5 min, the absorption spectra of the supernatants were measured with a spectrophotometer (UV 530; Beckman Coulter, Pasadena, CA, USA). The concentration of chlorophyll a was calculated according to equation of Porra [22].

The algae taxa were identified using a microscope at 400× magnification to analyze the effect of the scouring on different species. The algae were counted by cells, with colony broken by ultrasonic waves. The algae taxa were typically determined at the species level or genus level. Identification and quantification of algae species were performed under a Zeiss Axiolab 5 phase contrast microscopes (Carl Zeiss, Jena, Germany). Algae cells were identified and counted using Groove-type 0.1-mL counting slide with a mold-type grid on its bottom under a working magnification of 400×. For each sample, a minimum of 400–500 cells were counted from randomly selected transects at multiple magnifications; and all the samples were counted 2–3 times to improve the accuracy and reproducibility.

Through microscopic identification of the algae species, the cell counts of green algae, blue–green algae, and diatoms were calculated. The blue–green algae are a group of photosynthetic prokaryotes. The species composition of the benthic algae on the cobbles before scouring was shown in Figure 3. The benthic algae grown on the cobbles were mainly composed of diatoms and blue–green algae, making up 57% and 41% of the total number of algae cells, on average respectively. Green algae accounted for 2%.

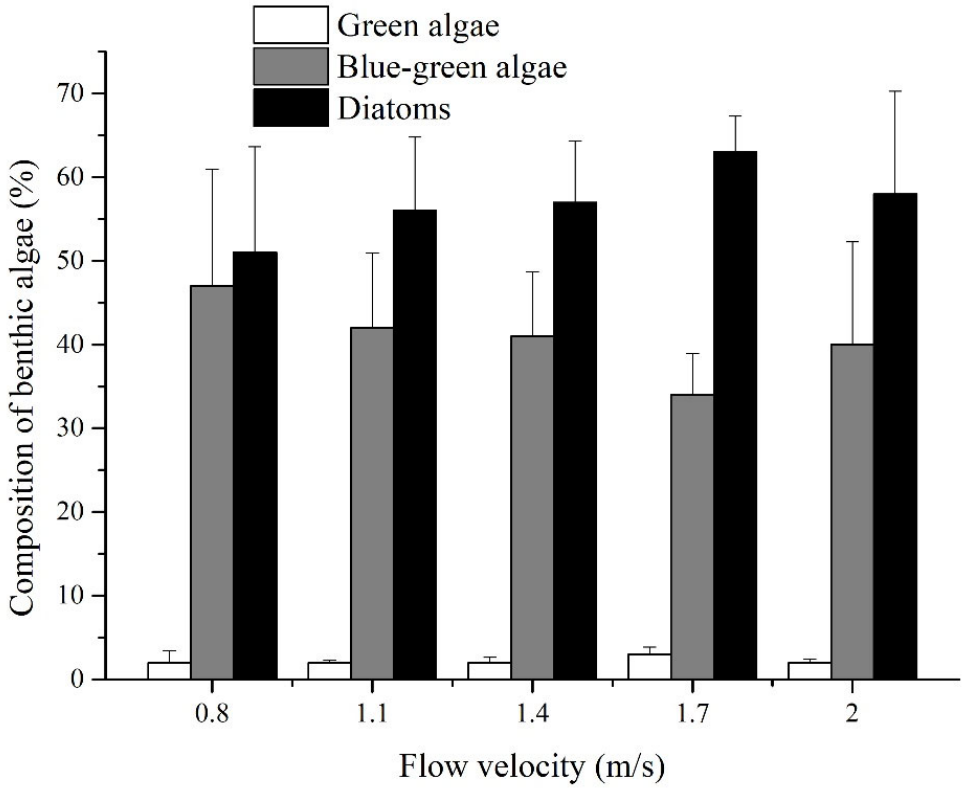


Figure 3. The composition of benthic algae on cobbles before treated (in cell counts, %), which was the average of the 3 replicates at each flow velocity of 0.8, 1.1, 1.4, 1.7, and 2.0 m/s.

2.4. Analysis of Results

The removal proportion of algae by the scouring was quantified based on the data of algal biomass detached by scouring and the remaining biomass on the scoured cobble. The algal biomass on the cobbles before scouring could be calculated by summing up the sloughed and remaining algal biomass. Although the plexiglass tank is smooth enough, the rotation axis and the flow diversion grid could also keep some suspended biomass. So, it would result in underestimation of the removed and the initial biomass. Based on the experiments in similar tank system of scouring artificial cobble substratum by Biggs and Thomsen [15], the difference between material remaining on the substrata after the scouring and initial mass produced a value comparable to the sloughed chlorophyll a obtained from sampling the water, which meant redeposition of sloughed organic matter was not significant. Due to the large heterogeneity in the biomass distribution of the algae on the cobbles before scouring (Coefficient of Variation being 0.35 for chlorophyll a), it was not feasible to estimate the removal proportion by comparing the sampled biomass in the water and the biomass on the substrata without scouring.

The percentage of the removed algae was calculated with the algal biomass detached by scouring relative to the algal biomass before scouring. The algal biomass was analyzed both in chlorophyll a and in cell counts. The effects of scour duration and flow velocity on biomass removal percentage were assessed using linear regression respectively. The t test was conducted for the significance, with the threshold value set at $p = 0.05$. The one-way

ANOVA was used to analyze the differences in impacts by taxa of green algae, blue–green algae and diatoms on removal percentages.

3. Results and Discussions

3.1. Effect of Scouring Duration and Flow Velocity on Algal Biomass

At the same flow velocity, the removal percentages of algae biomass did not increase significantly with the scouring durations of 0.5, 1.0, 1.5, and 2.0 h (Table 1, Figure 4). According to the study of Francoeur and Biggs [23], most biomass losses (83–100% of maximum observed removal) occurred within the first 5 min of disturbance.

Table 1. Summary of linear regression results for the effect of scouring duration on biomass removal percentage under a certain flow velocity.

Velocity (m/s)	Slope	R^2	*p*
0.8	0.39	0.89	0.055
1.1	−0.76	0.34	0.415
1.4	−0.14	0.05	0.770
1.7	0.78	0.42	0.350
2.0	−0.76	0.70	0.163

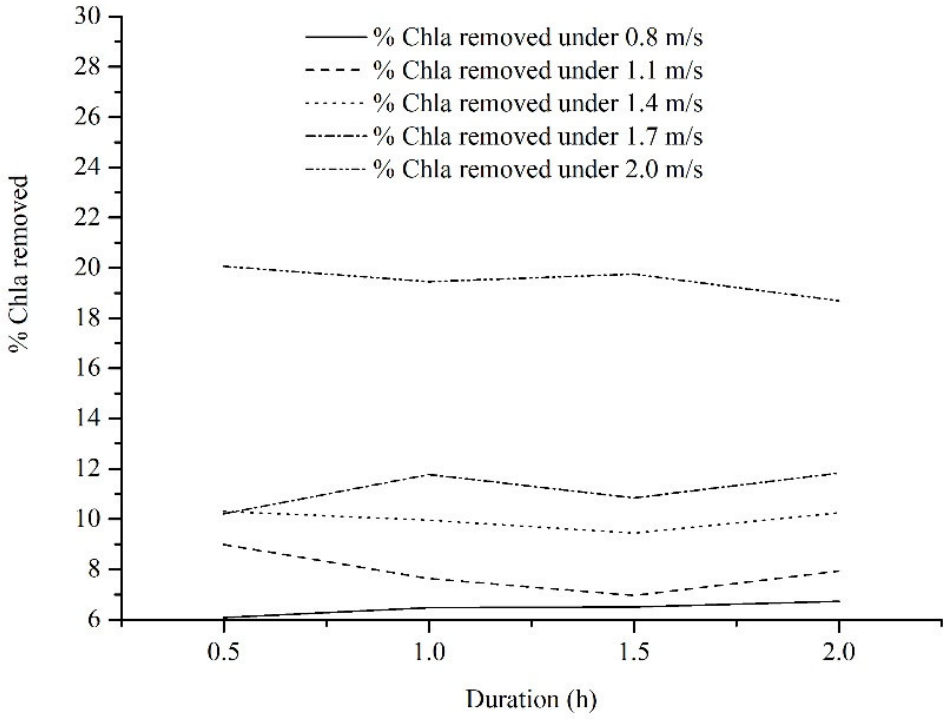


Figure 4. Variation of the biomass removal percentage of benthic algae (% chlorophyll a, mean + SD) as a function of the scouring duration, 0.5, 1.0, 1.5, 2.0 h. The removal percentages show no significant increase with duration.

The removal proportions of benthic algae in the three parallel tests were averaged to obtain the removal proportion for the corresponding flow velocity. At flow velocities of 0.8, 1.1, 1.4, 1.7, and 2.0 m/s, after 2.0 h of scouring, the removal of algae was 7.04%, 9.24%, 11.37%, 12.88%, and 22.73%, respectively (Figure 5). From the result of liner regression, the removal percentage (calculated in biomass of Chlorophyll a) showed a significant positive relationship with increasing flow velocities (slope = 11.67, R^2 = 0.84, p = 0.029). These results clearly demonstrate that elevated flow velocities can reduce biomass of benthic algae. The significant positive relationship between algal removal and flow velocities was

also witnessed by researchers [6,7,14–17]. From the experimental data, algae removal by scouring was significantly greater at flow velocities over 1.7 m/s.

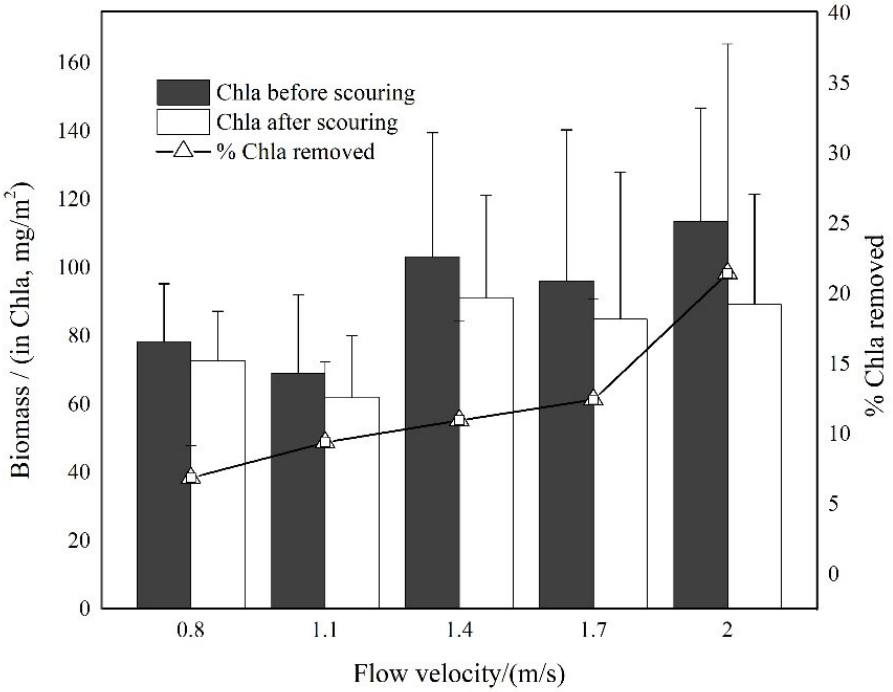


Figure 5. Variation of the biomass of benthic algae (in chlorophyll a per unit area, mean + SD) before and after scouring by different flow velocities, 0.8, 1.1, 1.4, 1.7, and 2.0 m/s.

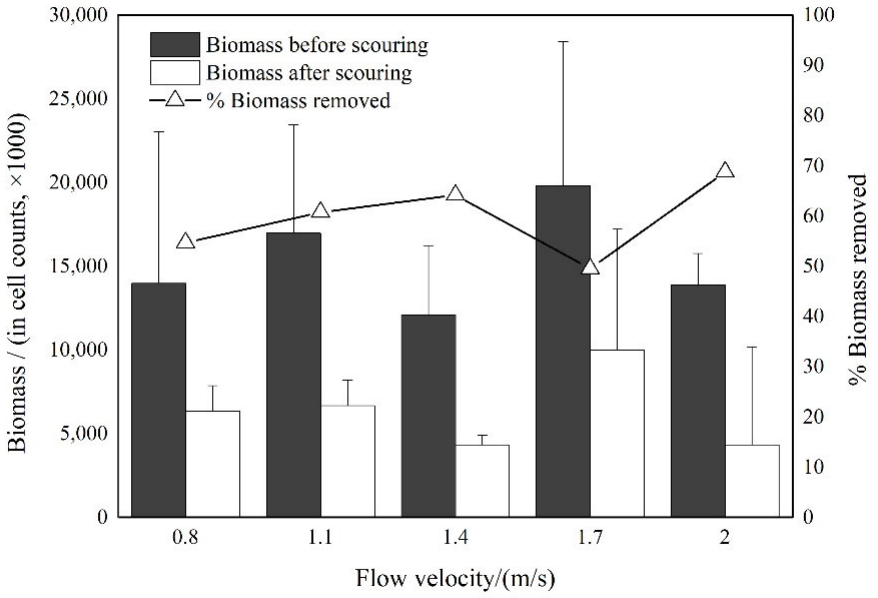
According to related studies, the resistance of algae to the river flow was affected by factors such as the flow velocity, sediment concentration, initial assemblage composition, growth form, and abrasion by transported bedload particles [23–26]. There is considerable variability in the velocities required to reduce algal biomass, and the effectiveness of biomass removal differs. The flow velocity (1.7 m/s) for significant scouring of total biomass in this study was higher than the values of 1.5 m/s identified by Flinders and Hart [7], and the velocity (1.2 m/s) identified by Davie and Mitrovic [16].

These differences resulted from the factors of initial density, species composition, substrates, and suspended sediment. (1) Higher initial density would result in lower resistance. The algal biomass exceeding 150 mg/m^2 is considered to be the growth of excessive or nuisance periphyton [27] associated with river regulation. The algae growing on artificial substrates with an initial density of >600 mg/m^2, in the test by Flinders and Hart [7], was less resistant to scouring. The average initial algal biomass before testing in our study was 92 $\pm$ 32 mg/m^2 (mean $\pm$ SD), and the average value after removal was 80 $\pm$ 27 mg/m^2. (2) Different algae species have various resistance capacities to scouring. (3) Algae assemblages on natural substrata with higher roughness were reported to be more resistant to disturbances than artificial substrates [18,28,29]. (4) The scouring effect would be enhanced by suspended sediment. The suspended sediment concentration from dam releases is commonly lower than the natural flood, so the flow velocity from dam releases required for scouring benthic algae should be higher than that from a natural flood which has an added effect of the sediment [16].

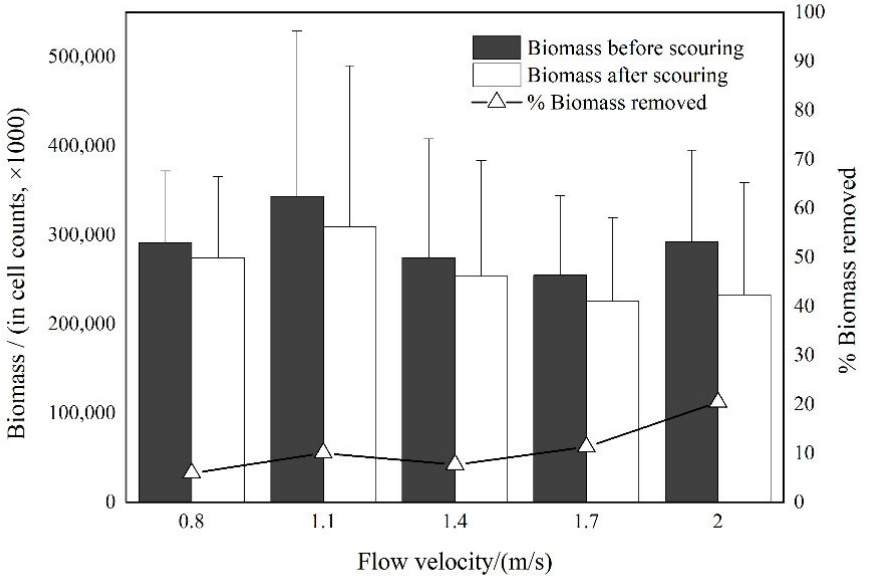
Under the conditions of this study, with lower initial density on natural substrata, and scouring flow with no suspended sediment, the velocity (1.7 m/s) for significant scouring was relatively higher than other studies. Nevertheless, this relative higher velocity might result in the detachment of diatoms and blue–green algae which are feeding sources of Ayu (*Plecoglossus altivelis*). More analysis should be conducted to understand the responses of different algae taxa to scouring and required velocity for reducing filamentous algal biomass.

3.2. Effect of Scouring on Removal of Different Benthic Algae Taxa

The proportions of removed green algae, blue–green algae, and diatoms increased with the flow velocity. The removal percentages of different algae taxa at different flow velocities were calculated using the cell counts of green algae, blue–green algae, and diatoms before and after scouring (Figure 6). At flow velocity of 2.0 m/s, the removal of all the algae species increased significantly. Based on the cell counting before and after scouring, removed proportions of green algae, blue–green algae, and diatoms at 2.0 m/s were 69%, 20%, and 64% respectively, increasing by 14%, 14%, and 19% compared to the values at 0.8 m/s (55%, 6%, and 46%).

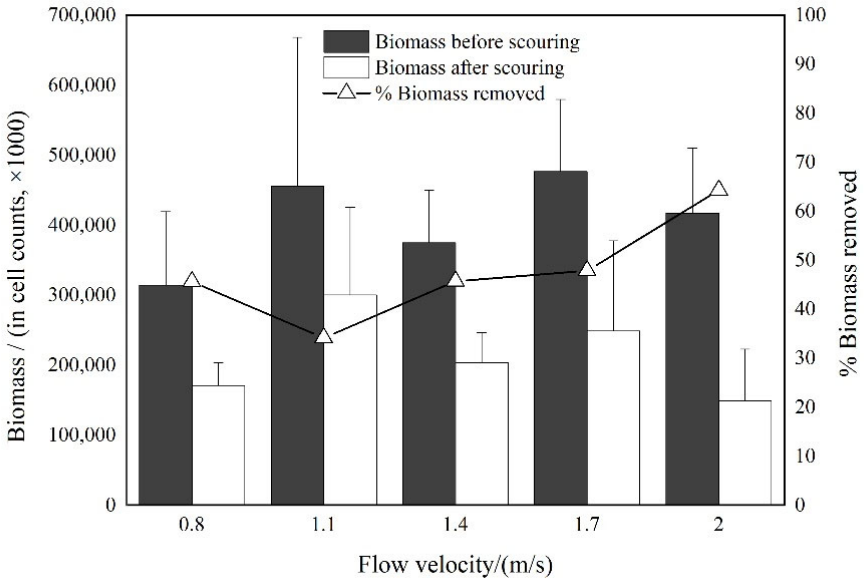


(**a**)



(**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. Variation of the biomass of benthic algae (in cell counts, mean + SD) before and after scouring by different flow velocities, 0.8, 1.1, 1.4, 1.7, and 2.0 m/s. (**a**) Variation of the biomass of green algae. (**b**) Variation of the biomass of blue–green algae. (**c**) Variation of the biomass of diatoms.

The removed proportions of green algae and diatoms were significantly higher than that of blue–green algae. Through the one-way ANOVA to analyze the different impacts by taxa on removal percentages, the results showed that the impacts of green algae, blue–green algae and diatoms on the means of removal percentages are significantly different ($p = 4.77 \times 10^{-7} < 0.01$). According to the pairwise comparison by Fisher test, the different impacts between green algae and blue–green algae on removal percentages is significant ($p = 1.96 \times 10^{-7} < 0.01$), and also significant in the different impacts between diatoms and blue–green algae ($p = 2.77 \times 10^{-5} < 0.01$), but not significant between diatoms and green algae ($p = 0.14$). The differences in resiliencies of the species were consistent with those obtained by Davie and Mitrovic [16], who discovered that the blue–green algae had stronger resistance than diatoms under the scouring velocity of 1.2 m/s, and filamentous green algae had the lowest resistance.

The resistance of benthic algae toward scouring is closely related to the morphology and structure of the algae [30,31]. The common morphologies of algae include close attachment to the substrate, interwoven structures, stem-like structures, and filamentous structures. Of these, benthic algae closely attached to the substrate or with interwoven structures were the most resilient toward scouring, while the filamentous type was the least resilient. The filamentous types have different mechanisms of biomass loss, either from the canopy layer, or through breakage or sloughing. Some filamentous, and other mucilaginous or prostate types, might release from the substrate at their holdfast structures or through classic biofilm sloughing models. Blue–green algae could tolerate higher velocities than do filamentous green algal taxa under the flow velocity higher than 1.0 m/s [32].

The diatoms and blue–green algae as the feeding sources of the endangered fish species, Ayu (*Plecoglossus altivelis*), include *Navicula, Fragilaria, Gomphonema, Synedra, Cymbella, Phormidium*, etc. [17], mainly non-filamentous algae. Based on the data from microscope inspection, the filamentous green algae genera, *Spirogyra* sp., was removed 100% under the velocity of 0.8 m/s, and *Stigeoclonium* was removed 53% under the velocity of 1.4 m/s. This difference is related to multiple mechanisms of species of the effect of velocity on scour. *Spirogyra* has sticky extracellular polymeric substance (EPS) and forms attached mats, whereas *Stigeoclonium* forms holdfast structures. *Spirogyra* has

large cell diameter and comparatively weak mucilaginous sheaths, whereas *Stigeoclonium* is the opposite. The filamentous blue–green algae, *Pseudoanabaena* sp., was removed from 28% (at 0.8 m/s) to 100% (at 1.4 m/s) with the increasing velocities. Some non-filamentous diatoms were also washed off, including *Melosira granulate, Navicula* sp., *Cymbella* sp., and *Eunotia* sp. In the tests run at different flow velocities from 0.8 to 2.0 m/s, *Navicula* sp. and *Cymbella* sp. were removed at proportions of 49–100% and 12–58%, respectively. The *Cymbella* sp. possessed relatively stronger resistance toward scouring (Figure 7). The figure shows non-significant increasing trends of removal with flow velocity. A uni-algal experiment for each algae taxa scoured at different velocities is needed for further studies to have a significant results.

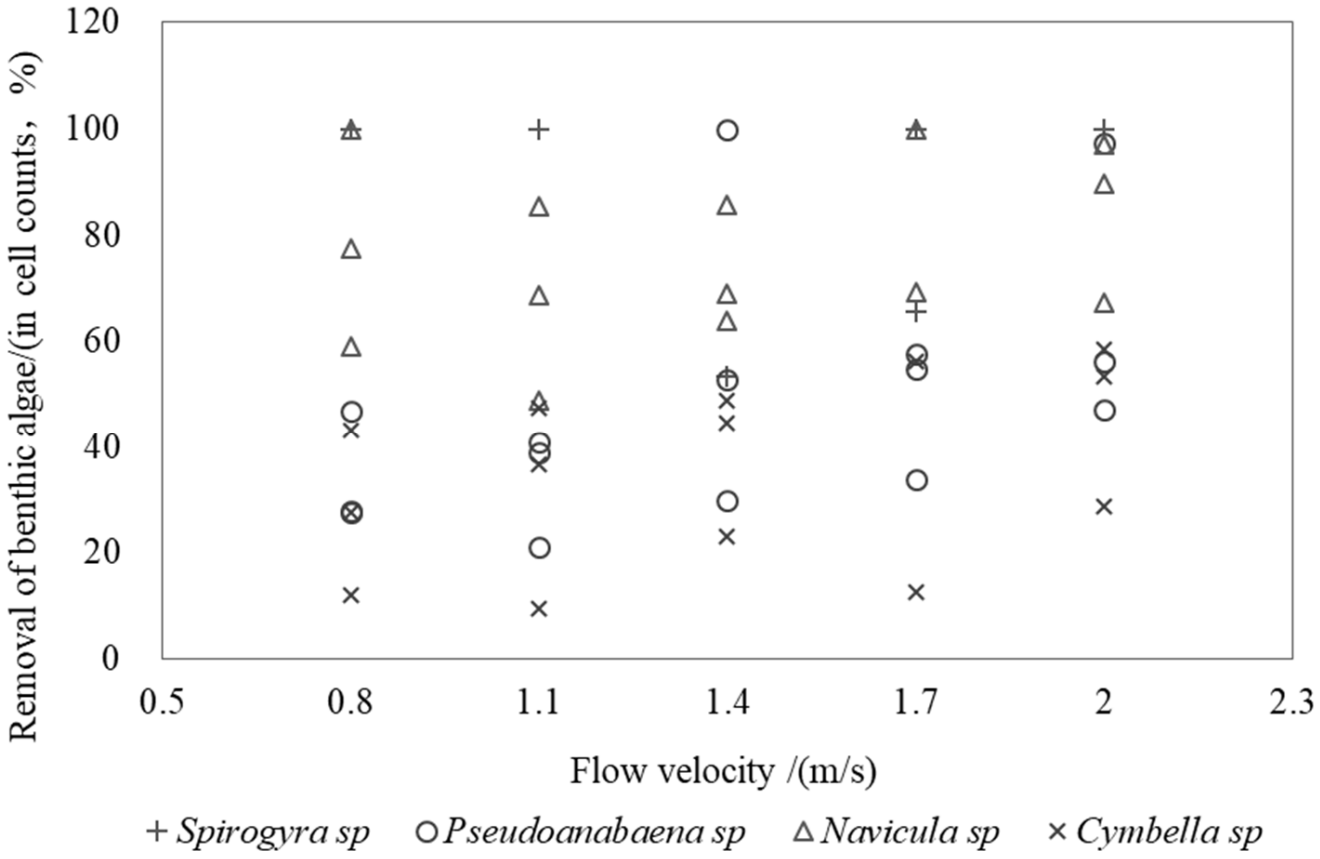


Figure 7. Proportion of removed algae taxa under different flow velocities, 0.8, 1.1, 1.4, 1.7, and 2.0 m/s.

Due to the diversity of resistance of different algae species on the cobbles, there is a range of flow velocity that causes significant increase in removal of algae community. To reduce the filamentous algae, it is suggested to have a lower limit for the near bed flow velocity to be 1.4 m/s. From the results on scouring of total biomass dominated by diatoms, to retain the diatoms and blue–green algae from removal in large quantities for feeding sources of Ayu (*Plecoglossus altivelis*), it is suggested to have an upper limit for the near bed flow velocity to be 1.7 m/s. This range of 1.4–1.7 m/s should be converted from near bed velocity to mean velocity through hydraulic modeling. Given the large diversity in river bed structure, flow regime, and algae species, further studies on uni-algal populations from different taxa groups are needed to provide references for the regulation of environmental flow.

4. Conclusions

The scouring effects on the natural benthic algae were studied quantitatively by experiments with different flow velocities. For the same flow velocity, the removal of algae does not change significantly with the increasing scouring duration from 0.5 to 2 h. At flow velocities of 0.8, 1.1, 1.4, 1.7, and 2.0 m/s, the proportion of removed algae attached to the natural riverbed cobbles increased significantly with the increase in the flow velocity. A removal percentage of 22.73% was achieved at the flow velocity of 2.0 m/s.

A pulsed flow release from dam could potentially be used to reduce nuisance periphyton growths. Based on the data from microscope inspection, the proportion of removed green algae and diatoms was significantly greater than that of blue–green algae. The flow velocity at 1.4 m/s had a clear removal effect on filamentous algae, e.g., *Stigeoclonium* and *Pseudoanabaena* sp. To reduce the filamentous algae and to retain the diatoms and blue–green algae as feeding sources of Ayu (*Plecoglossus altivelis*), it is suggested to have a range of the near bed flow velocity of 1.4–1.7 m/s. This range could be taken as reference for determination of a required pulsed flow velocity to regulate the algal biomass and composition in fish feeding reaches. Further studies should be conducted to consider the impact of heterogeneity in river bed structure and the added scouring effects of sediment in the natural flow conditions.

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Appendix A

Velocity measurement and calibration

Pitot tubes were used to measure the flow velocity in the testing section. The two narrow openings of the pitot tubes were perpendicular to each other. The hydraulic head difference between them provided the velocity head h_v. The flow velocity v was calculated using the pitot tube equation:

$$v = \sqrt{2gh_v} \quad \text{(A1)}$$

where h_v is the velocity head, g is the gravitational acceleration, and v is the flow velocity.

Three evenly-positioned measuring points were set 2 cm above the test section perpendicular to the flow direction. The inlet of the pitot tube was parallel to the flow direction, and both openings were connected to piezometric tubes to measure and calibrate the flow velocity. The servo motor was set to a certain rotational speed. The corresponding flow velocity at this motor rotation speed was calculated from the average flow velocity heads measured at the three measuring points with Equation (A1).

In the rotational speed range of 500–1500 r/min, the corresponding flow velocity was measured at rotational speed increments of 200 r/min. The measured data of the rotational speeds and the flow velocities were analyzed by a one-dimensional linear regression to obtain the regression line and an equation, which were used to relate the flow velocity and the rotational speed (Figure A1).

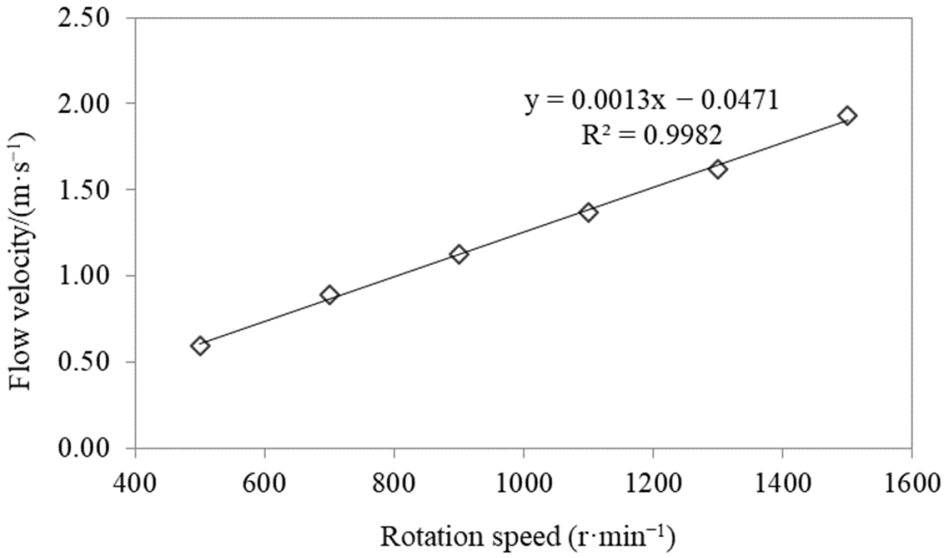


Figure A1. Relationship between the flow velocity and motor speed.

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