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Effect of cutter type on sediment pollutants release in channel dredging

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Abstract. Dredging activities are often used to maintain existing navigation channels. However, traditional dredging equipment inevitably leads to sediment resuspension and nutrient loading in water. In this work, the existing cutter used for dredging was transformed environmentally to reduce the release amount of sediment pollutants, and to avoid the formation of secondary pollution to water bodies. Simulated tests with a general cutter, a spiral cutter, along with a general and spiral cutter equipped with the anti-diffusion device were conducted respectively in this study. The change of pollutants concentration in overlying water was examined. The environmental performance of each different structure cutter was comparatively analysed as well. The result revealed that in channel dredging with a spiral cutter, the release amount of sediment pollutants was less than with a general cutter, and that a general/spiral cutter equipped with the anti-diffusion device could effectively reduce the release amount of sediment contaminants, particularly the release of the nitrogen nutrient during the 1h after the dredging treatment. The best transformation scheme for a cutter suction dredger (CSD) in its environmental-protection function may be: a spiral cutter equipped with the anti-diffusion device.

1. Introduction

Scientific research has characterized the effects of dredging as an underwater excavation process for navigational purposes or material extraction [1]. Dredging activities are necessary for the maintenance of existing navigation channels [2,3], which are important for supporting trade and economic sustainability [4]. The Yangtze River, with first-ranking freight volume among all inland waterways in the globe, plays a pivotal role in the global river economic belt. In accordance with the Chinese issued document (NO.[2014]39), the guidance of the State Council on promoting the development of the Yangtze River economic belt, the Yangtze River will be transformed into a smooth golden waterway to meet the navigation requirements of million-ton class cargo ships. Accordingly, treatments of the Yangtze River channel system must be promoted to achieve this objective, especially enforcing shoal dredging, reef dredging and backwater section dredging. In general, dredging starts with the excavation of sediments at a site with a hydraulic and/or mechanical cutter [5-8]. However, traditional dredging equipment inevitably incurs sediments retaining nutrients, heavy metals, and permanent organic pollutants [1, 9-11], to suspend again in dredging. Sediments can therefore also release



contaminants into the environment, as contaminants bound on sediment particle surfaces and interior matrices can be released when sediments are disturbed [12-15], causing secondary pollution to water environment. Therefore, existent dredging equipment in channel dredging will result in adverse effects on the aquatic ecosystems of Yangtze River. So far, there are a significant amount of technologies about sediment dredging applied in the treatment of polluted lakes [9,16,17], while there is still a lack of essential study about whether sediment in channel dredging will cause secondary pollution to water bodies. Most studies nowadays mainly focus on the diffusion of suspended matters [18,19], instead of pollutants release resulting from sediment resuspension.

Consequently, based on the mostly-employed CSD in channel dredging, this work will investigate the effect of a different structured cutter on the release of sediment pollutants, as well as comparatively analyze the environmental performance of each structure-different cutter, so as to provide theoretical and technical support for inventing environmental dredging equipment.

2. Materials and methods

2.1. Materials

The cutter-suction dredging device we constructed in this work consisted of a suction/drainage system and power systems which were comprised of the cutter power system and the mud pump power system as shown in figure 1. In addition to fully considering the working conditions of CSD in real practice, we set up a metering device for measuring the weight/volume of dredged sediments, a rack for the cutter-suction dredging device motion, and mud sumps for forming aquatic environment and placing dredged sediments (a main sump and a vice one, whose sizes are 60×30×50cm and 30×10×5cm respectively) in order to be as close as possible to operating in real engineering. Based on common sense and specific calculation, the main geometrical and moving parameters of the initial environmental cutter were as following: 2.5m of length, 2.0m of diameter, 7.5° of helical angle, 16° of conical angle, 40 r/min of rotation rate and 10 m/min of transverse movement speed. According to the geometric and dynamic similarity theories, those main parameters of the environmental protection cutter in this study were determined as following: 25mm of length, 20mm of diameter, 7.5° of helical angle, 16° of conical angle, 40 r/min of rotation rate and 0.1 m/min of transverse movement speed. Moreover, the main parameters of the general lab-scale cutter are 25mm of length, 20mm of diameter, 0° of helical angle, 16° of conical angle, 40 r/min of rotation rate and 0.1 m/min of transverse movement speed. Detailed parameters of the initial and the lab-scale environmental cutter are listed in table 1. Lab-scale cutters in this study are shown in figure 2.

According to the Surface Water Environment Quality Standard of the People's Republic of China (GB3838-2002), which sets the maximum limits for basic contaminants in water bodies, in order to protect aquatic life and ensure agricultural irrigation use, the water quality of the Yangtze River should meet the standard as described in table 2. Sediment samples in the study were collected from the Zhongxien County region (Chongqing, China) of the Yangtze River, the place with the most serious deposition in the perennial backwater area of the Three Gorges. To measure the maximum release amount of sediment pollutants, 25g sediments were placed in the conical flask, which was added to 500mL potable water, and shaken in a constant temperature (18.2 °C, the annual average water temperature in the Three Gorges reservoir area) for 24h. Samples were taken at 1, 2, 4, 6, 8, 12 and 24h for pollutant concentration measurement after centrifugation (4000 r/min of rotation rate, 20min of durational time). The maximum release amount of sediment pollutants attained is shown in Table 3, where total nitrogen (TN), ammonia nitrogen (NH₃-N) and chemical oxygen demand (COD) were 77.8, 45.2 and 2484.8 mg/kg respectively. Potable water was used as the overlying water in this work, so as to make the release performance of sediment pollutants more remarkable.



Figure 1. Cutter-suction dredging device in the study.

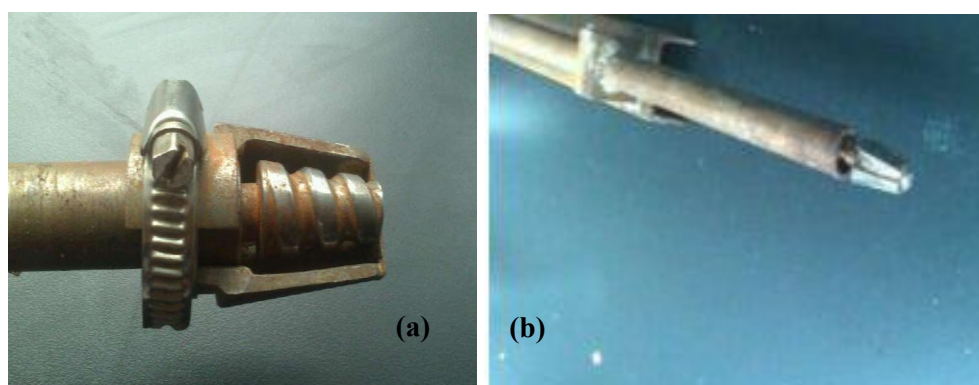


Figure 2. Lab-scale cutters in the study: (a) spiral cutter equipped with the anti-diffusion device; (b) general cutter.

Table 1. Detailed parameters of the initial and lab-scale environmental cutter.

Item	Length (m)	Diameter (m)	Helical angle (°)	Conical angle (°)	Rotation rate (r/min)	Transverse movement speed (m/min)
Initial cutter	2.5	2	7.5	16	40	10
Lab-scale cutter	0.025	0.02	7.5	16	40	0.1

Table 2. The maximum limits for basic contaminants in water bodies.

Pollutants index	TN	NH ₃ -N	COD
Maximum limit (mg/L)	2.0	2.0	40.0

Table 3. The maximum release amount of sediment pollutants.

Sediment pollutants index	TN	NH ₃ -N	COD
Maximum release amount (mg/kg)	77.8	45.2	2484.8

2.2. Methods

Simulated dredging experiments with a general cutter, spiral cutter and general/spiral cutter equipped with the anti-diffusion device, were carried out respectively in this study. The change of pollutant concentration in overlying water, including NH₃-N, TN and COD, was monitored at 0.25, 0.5, 1, 3, 5, 7, 12 and 24h, after the finishing of dredging. Corresponding analysis methods used for determining each of these items are described in more detail in table 4. The environmental performance of each different structure cutter was analysed comparatively. Based on the cumulative release amount of nutrient nitrogen, the release rate, M ($\text{g}/\text{m}^3 \cdot \text{h}$), was calculated by the following equation to analyse the release of sediment pollutants: $M = (R_i - R_{i-1}) / n$, where R_{i-1} and R_i refer to the cumulative release amount, taken at the $i-1$ and i times sample respectively.

Table 4. The schedule of analysis items and methods

Item	Analysis method
NH ₃ -N	Salicylic acid spectrophotometric method
TN	Alkaline potassium persulfate digestion-uv spectrophotometer
COD	Fast digestion spectrophotometric method

3. Results and discussion

3.1. Effect of cutter type on the release of sediment pollutants

Cumulative release performance of sediment pollutants surrounding dredging sites, when dredging with a general cutter and with a spiral cutter, was monitored as displayed in figure 3. More significantly, figure 3 clearly shows that the release of sediment pollutants can be substantially reduced by dredging with a spiral cutter. The maximum cumulative release amount of NH₃-N, TN and COD, when dredging with a spiral cutter, were 0.64, 1.28 and 40 g/m^3 respectively, whereas the maximum cumulative release amount of NH₃-N, TN and COD, when dredging with a general cutter, reached to 0.69, 1.48 and 47 g/m^3 respectively.

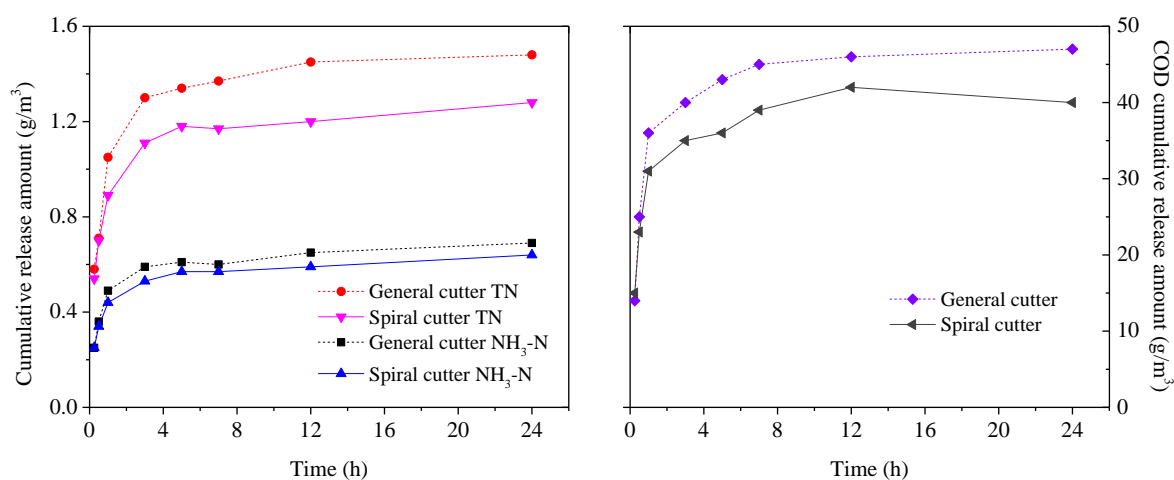


Figure 3. Release performance of pollutants contained in sediment under dredging with a spiral/general cutter: nutrient nitrogen (left); COD (right).

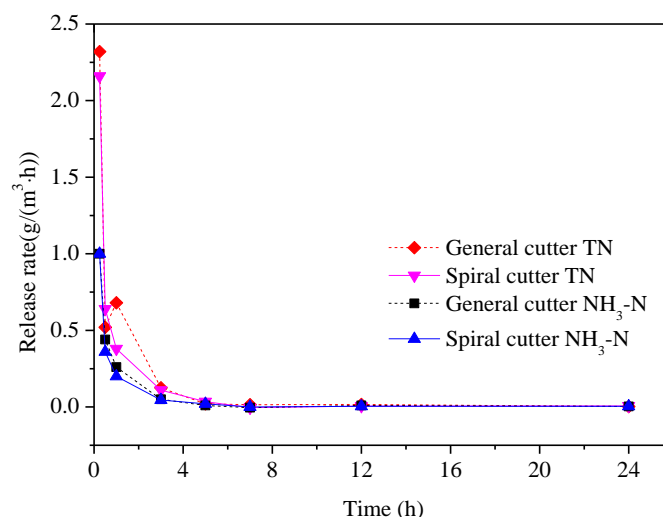


Figure 4. Nitrogen nutrient release rate under dredging with a different-structure cutter.

The nutrient nitrogen release rate under a different cutter is illustrated in figure 4. It shows that the release rate of nutrient nitrogen, after dredging, was fading over time. The difference of the nutrient nitrogen release rate between the two different-structure cutters was distinctive during the first 1h of dredging treatment, and the nutrient nitrogen release rate under dredging with spiral cutter was less than with the general one. However, there was no difference between different structure cutters after 1h of the dredging treatment. Subsequently, the declining trend of the nutrient nitrogen release rate became progressively smooth over time, approaching 0 g/(m³·h) after 7h. Results indicated that a spiral cutter, compared with a general cutter, has many advantages when it comes to governing nutrient nitrogen release amount. For different contaminants in sediments, after overlying water became smooth, dredging with a spiral cutter could effectively abate the release resulting from the dredging operation, wherein COD, TN and NH₃-N release amount diminished approximately 14.9%, 13.5% and 7.2% respectively, compared with a general cutter.

Engineering dredging is mainly applied in channel dredging and harbor construction in order to increase the capability of channel, while environmental protection dredging aims at removing polluted sediments and providing a good condition for the advancement of the aquatic ecosystem [20]. In effect, polluted sediments cleared by environmental dredging are softer than by engineering dredging. Not only can this characteristic make sediments easy to be cut, it may also facilitate sediment suspension and diffusion. The edge of a spiral cutter is serial, which makes it stable to cut sediment and makes only small disruptions on the surface of sediment. While a general cutter, driven by the pursuit of sediment-broken and adapting abilities, abandons the serial performance. Consequently, a general cutter used in dredging would create a great shock on sediments, and disruption would rapidly foment the suspension of sediments. The shock can also release pollutants into water bodies, as pollutants bound on sediment particle surfaces and interior matrices can be released when sediments are disturbed [1,12,15].

3.2. Effect of a general cutter equipped with the anti-diffusion device on the release of sediment pollutants

The cumulative release feature of pollutants around disposal sites in the dredging experiment with a general cutter, equipped with the anti-diffusion device, is illustrated in figure 5. As shown, dredging with a housing general cutter has a great impact on diminishing the release of sediment contaminants, with the maximum cumulative release of 0.57g/m^3 for $\text{NH}_3\text{-N}$, 1.16 g/m^3 for TN and 34 g/m^3 for COD. The variations of the nutrient nitrogen release rate with time under dredging with a cutter that is equipped with the anti-diffusion device, is described in figure 6. As expected, the release rate of nutrient nitrogen — $\text{NH}_3\text{-N}$ and TN — gradually declined after dredging. Meanwhile, dredging with a housing general cutter has a significant influence on the nutrient nitrogen release rate during the first hour of dredging, in which the release rate of nutrient nitrogen was less than a general cutter not equipped with the anti-diffusion device. The difference disappeared after 1h, and the decreasing trend of nutrient nitrogen release rate became increasingly smooth over time, approaching $0\text{ g}/(\text{m}^3\cdot\text{h})$ after 7h.

Results indicated that a housing general cutter used in dredging can substantially constrain the release of pollutants. Dredging by a general cutter equipped with the anti-diffusion device could reduce the release of each pollutant, which had the most significant effects on the release of COD among all, whose release rate was lighter than with a general cutter without the anti-diffusion device, decreasing around 27.7%. Moreover, it also had impacts on regulating the release of TN, of which the decreasing amount was about 21.6%. Its restriction on $\text{NH}_3\text{-N}$ release amount was weaker than on COD and TN. Specifically, the release amount of $\text{NH}_3\text{-N}$ decreased around 17.4%, compared to a cutter without the anti-diffusion device. Overall, this result revealed that dredging with a housing general cutter has a distinctive effect on reducing the release of sediment pollutants, and this regulating function was stronger than a spiral cutter.

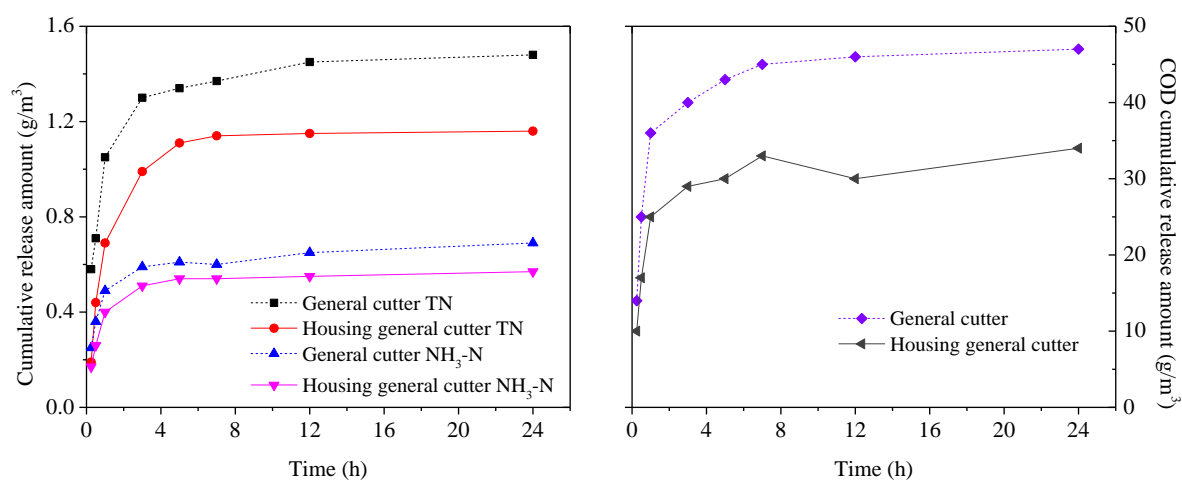


Figure 5. Release performance of pollutants contained in sediment under dredging with a housing-general/general cutter: nutrient nitrogen (left); COD (right).

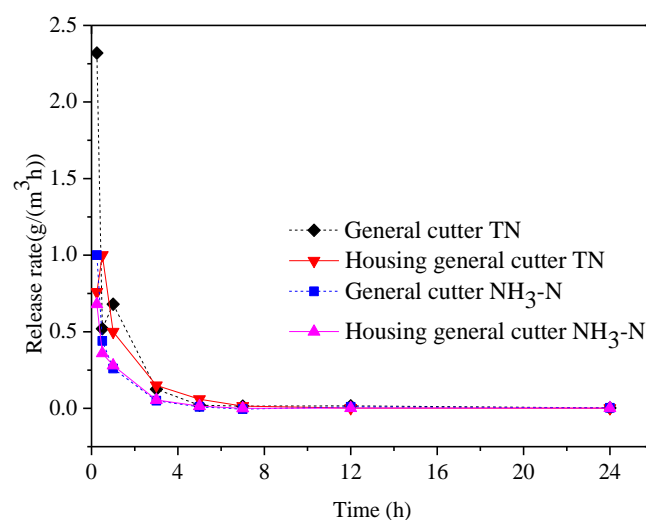


Figure 6. Nitrogen nutrient release rate under dredging with different-type cutter.

It could thus be speculated that when the cutter cuts sediments in channel dredging, water around the cutter would move as the movement of cutters, hence causing a unique flow distraction that mixes water and granulated sediment during cutting. As a result, slurry mixture will break away from the suction field of the mud pump and will diffuse in all directions. The diffusing slurry mixture therefore becomes a new source of pollution and releases contaminants contained in sediments to aquatic ecosystems, thus forming a secondary pollution in water bodies. Accordingly, when the cutter is equipped with the anti-diffusion device, the diffusion of sediments could be effectively controlled, avoiding slurry mixture to break away from the suction field of the mud pump and the formation of secondary pollution in water bodies.

3.3. Effect of a spiral cutter equipped with the anti-diffusion device on the release of sediment pollutants

When dredging with a spiral cutter equipped with the anti-diffusion device, the cumulative release characteristics of contaminants surrounding dredging points is portrayed in figure 7. It should be pointed out that dredging with a housing spiral cutter could abate the release amount of pollutants in sediment as described in figure 7. When pollutants concentration in overlying water became stable, the maximum release amount of $\text{NH}_3\text{-N}$, TN and COD, under dredging with a housing spiral cutter, were 0.54, 1.07 and 30 g/m^3 respectively, reducing about 11.8%, 7.8% and 5.3% compared with a housing general cutter.

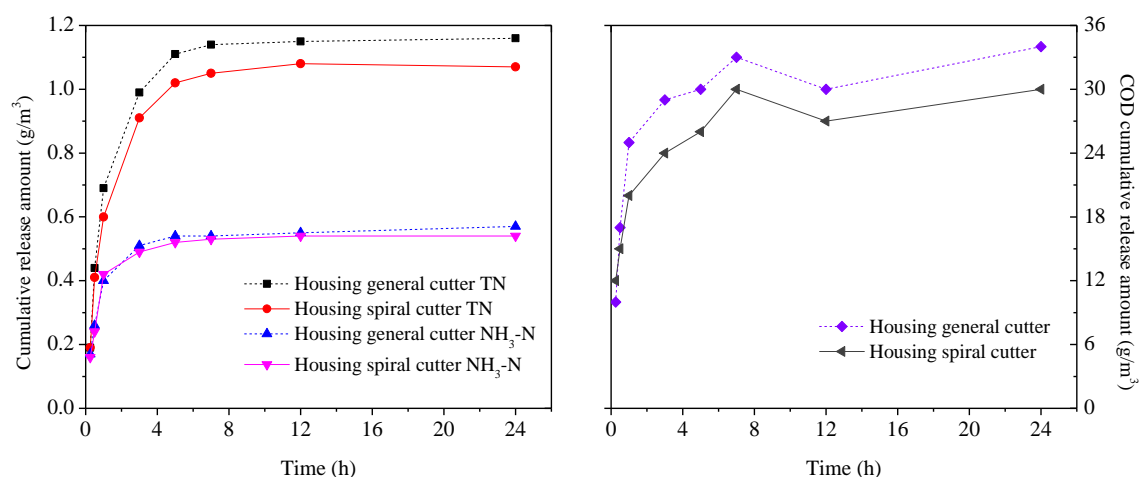


Figure 7. Release performance of pollutants contained in sediment under dredging with a housing-general/ housing-spiral cutter: nutrient nitrogen (left); COD (right).

The changes of the nutrient nitrogen release rate with time, when dredging with a housing spiral cutter, and the housing general one are shown in figure 8, from which it could be observed that the release rate of sediment nutrient nitrogen became increasingly slow over time. While dredging with a housing spiral cutter could significantly affect nutrient nitrogen release rate during the first hour of dredging. The nutrient nitrogen release rate under dredging with a spiral cutter equipped with the anti-diffusion device was relatively low compared with the housing general one. After 1h, the difference became small, and the nutrient nitrogen release rate became slow over time, approaching 0 $\text{g}/(\text{m}^3\cdot\text{h})$ after 7h (figure 8).

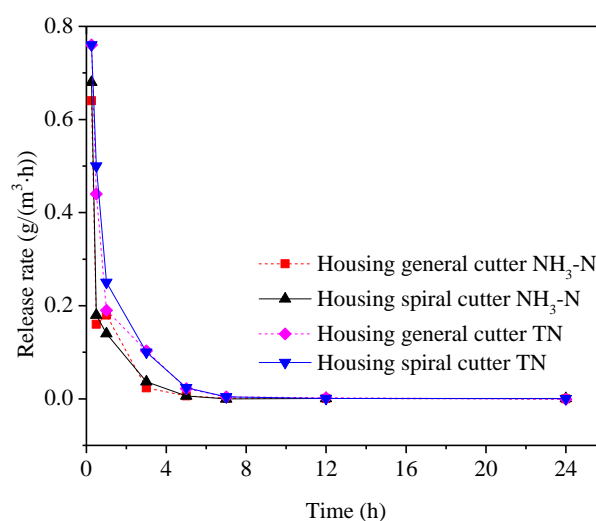


Figure 8. Nitrogen nutrient release rate under dredging with different-type cutter.

Results suggested that dredging with a housing spiral cutter could substantially restrain the release of sediment pollutants to some degree, with cumulative release of COD, TN and NH₃-N in sediments reducing around 36.2%, 27.7% and 21.7% respectively, compared with a general cutter. Therefore, given the restriction of sediment pollutant release, the most ideal transformation scheme for CSD in its environmental-protection function could be dredging with a spiral cutter that is equipped with the anti-diffusion device. In this research, for dredging with each environment-friendly cutter (the spiral and general/spiral equipped with the anti-diffusion device), the restriction on sediment NH₃-N release was less than on COD and TN. We hypothesise that each environment-friendly cutter can effectively abate disturbance to sediments and particle re-suspension, more or less in dredging practice. It can hence be speculated that COD and TN release would be diminished dramatically due to their contents in overlying water being in close relation to suspended particles derived from channel sediments. However, NH₃-N exists as ionic-form easily dissolved in water, and thus has a weaker association with suspended particles compared to other contaminants, which could explain why its release restraint from environment-friendly cutters is relatively light.

4. Conclusions

This paper describes the outcomes of a research study undertaken to investigate the release performance of sediment contaminants in dredging with a different structure cutter, and the results obtained can be summarized as following: (1) when dredging with a spiral cutter, the cumulative release of NH₃-N, TN and COD in sediments, compared with the general one, reduced about 7.2%, 13.5% and 14.9% respectively; (2) when dredging with a general cutter equipped with the anti-diffusion device, the sediment NH₃-N, TN and COD cumulative release amount, compared with the general one, decreased around 17.4%, 21.6% and 27.7% respectively, and (3) when dredging with a spiral cutter that is equipped with the anti-diffusion device, the cumulative release of NH₃-N, TN and COD from sediments, compared with the housing general one, diminished approximately 5.3%, 7.8% and 11.8% respectively.

The study revealed that both dredging with each of the two cutters — general and spiral — equipped with the anti-diffusion device, and dredging with the spiral cutter, can effectively restrain the release of sediment pollutants, but the former is superior to the latter. Dredging by a spiral cutter equipped with the anti-diffusion device, compared with other different type cutters, has the best environmental performance, which may be the optimal advancing method for CSD in its

environmental performance. Nevertheless, further study, especially the consideration of stream turbulence in real engineering which is relevant to sediment pollutant diffusion, is highly desirable.

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