Water–sediment separation efficiency prediction of gill-piece separation device
Hongfei Tao, Yang Zhou, Mahemujiang Aihemaiti, Qiao Li, Wenxin Yang, Youwei Jiang and Zijing Wu

ABSTRACT
As the key piece of equipment of a micro-irrigation system, the filter can prevent clogging of the emitter and ensure normal operation of the micro-irrigation system. A gill-piece separation device is used for the removal of viscous sediment, which helps to reduce the sediment concentration and decrease the burden on the filter. In this study, using the water–sediment separation efficiency as an evaluation index, a uniform orthogonal experiment was conducted to study the flow rate, sediment concentration, and gill-piece spacing using a physical model. Based on the experimental results of the physical model, multiple linear regression and projection pursuit regression were used for analysis. The results showed that the order of the factors affecting the water–sediment separation efficiency was as follows: flow rate at muddy water inlet > gill-piece spacing > sediment concentration. The correlation coefficients of the water–sediment separation efficiency models established using multiple linear regression and projection pursuit regression were 0.93 and 0.98, respectively. Both models could predict the water–sediment separation efficiency and determine the optimal working conditions of the gill-piece separation device.

Key words | filter, gill-piece separation device, model, multiple linear regression, projection pursuit regression, water–sediment separation efficiency

HIGHLIGHTS
- A prediction model for water–sediment separation efficiency of the gill-piece separation device was established under the conditions of sediment concentration of 2–12 kg/m³, flow rate of 0.3–1.1 m³/h, and gill-piece spacing of 5–11 cm.
- The order of influence of each factor on the water–sediment separation efficiency is as follows: flow rate at muddy water inlet > gill-piece spacing > sediment concentration.

INTRODUCTION
China is one of many countries with a severe sediment problem. In sediment-laden rivers, cascade treatment methods are mainly used to achieve efficient water diversion and sand removal. Common first-level sediment treatment engineering measures are sluice-type, bend-type, bottom-stockade-type, and layered water diversion projects. However, the treated water flow often cannot meet the requirements on sediment concentration or particle size. Therefore, secondary sediment treatment engineering measures must be built on the intake gate or downstream channel to further treat the sediment, such as a vortex tube sediment extractor, sand funnel, and circular-ring
desilting and sediment ejection basin (Zhang 2013). To prevent the clogging of emitters in micro-irrigation systems with surface water as the water source, a settling basin is usually set up to allow the sediment to settle, and then a single or combined filter is installed to further purify the water. Next, the treated purified water is transported to the emitter via a pipeline system to meet the water requirements for crop growth.

Extensive studies have been carried out on filters, which have yielded fruitful results. Sand filters exhibit the best filtration performance, especially when the water source contains algae and organic impurities, and daily backwash is conducive to maintaining the good performance of the sand filter (Duran-Ros et al. 2009a; Elbana et al. 2012). Disc filters have the advantages of low costs and convenient management. With a reasonable and high-quality design, a disc filter can achieve a filtering effect similar to a sand filter (Capra & Scicolone 2005; Capra & Scicolone 2007). Screen filters have simple structures and easy operation, and they are mainly used for the removal of inorganic impurity particles (Adin & Alon 1986). Many experimental studies have been conducted on the filtration mechanisms of different types of filters and the performances of filters and drippers (Zeier & Hills 1987; Capra & Scicolone 2005; Puig-Bargués et al. 2005a; Capra & Scicolone 2007; Demir et al. 2009; Duran-Ros et al. 2009a, 2009b; Elbana et al. 2012; Bové et al. 2015; Wen-Yong et al. 2015), which provides a basis for the structural optimization of filters. The performance parameters of filters include filter head loss, treatment capacity (treatment speed and treated water quality), cost, and ease of maintenance. Researchers have adopted physical model tests, theoretical analysis, and numerical simulation to study different types of filters, tested the head loss and treatment capacity of different filters under different test conditions, given the applicable conditions for each type of filter, and pointed out the direction of structural optimization. Using theoretical analysis, they have studied the filtration mechanism of filters and the formation of filter cake. The computational flow dynamics (CFD) technique was used to study the flow field distribution of different filters under different test conditions, which laid the foundation for an in-depth understanding of the filtering process and the internal flow field of the filter (Puig-Bargués et al. 2005a; Yurdem et al. 2008; Duran-Ros et al. 2010; Yurdem et al. 2010; Elbana et al. 2012; Wu et al. 2014; Yurdem et al. 2015; Zong et al. 2015).

In Northwest China and North China, the sediment in most rivers has high concentrations and small particle sizes, which increases the difficulty of sediment treatment. As the key equipment of a micro-irrigation system, the filter can remove most of the impurities in the water. However, when the filter is used to treat muddy water with a high sediment concentration, problems such as easy clogging and frequent flushing occur. Although increasing the area of the settling basin in front of the filter can reduce the sediment concentration, it will increase the system investment and occupy more floor area, and it cannot effectively process viscous fine sediment. Studies have shown that the sediment concentration and particle size are the main factors that cause the clogging of emitters. When the particle size is less than 0.1 mm, the sediment concentration has a significant impact on clogging. When the sediment concentration is greater than 1.25 kg/m$^3$, the risk of clogging will increase (Niu et al. 2015). Therefore, determining how to effectively purify fine sediment with a high sediment concentration is very important for delaying the clogging of emitters and ensuring the safe operation of micro-irrigation systems. To meet the demands of agricultural water, high turbidity water must be purified, and the addition of flocculants plays an important role. However, inorganic salt and organic polymer flocculants have problems such as requiring large dosages, being harmful to the human body, and creating environmental pollution. Separating fine sediment, reducing the sediment concentration in water resources, and improving the separation efficiency have been the subjects of sediment studies. Qiu improved the traditional inclined-plate settling basin and developed a new water–sediment separation device called the gill-piece separation device. The gill-piece separation device could accelerate the sedimentation of sediment particles, with sedimentation velocities that were 1.9–3.7 times faster than those under static conditions. A series of subsequent studies was carried out on the gill-piece separation device under static water conditions. In terms of structural optimization, Zhu et al. (2008, 2009a, 2009b) carried out sediment deposition experiments on different sandy water flows and studied the effects of the gill-piece type, inclination, and spacing on the efficiency of the water–sediment separation. The results
showed that the gill-piece in the gill-piece separation device should be arranged in a single row of gill-pieces, and the optimal arrangement for the gill-piece inclination angle was $\alpha = 60^\circ$ and $\beta = 45^\circ$. The gill-piece spacing had a great influence on the efficiency of the water–sediment separation. The smaller the gill-piece spacing was, the higher the separation efficiency became. Yan et al. (2011) studied the influence of the sediment settling channel width on water–sediment separation. Experiments showed that the critical width for silting in the sediment settling channel in the gill-piece separation device was 1 mm, and the channel width should be greater than or equal to 5 mm. In terms of the acceleration mechanism, Zhu et al. (2009c) pointed out that the reason the gill-piece separation device accelerated sediment settling was that gill-pieces destroyed the rigid spatial structure network formed during sediment settling. Tao (2014) summarized the separation mechanism of the gill-piece separation device by combining physical model experiments and numerical calculation results and pointed out that the structure of the gill-piece separation device was conducive to water–sediment separation. The addition of gill-pieces improved the hydraulic conditions, reduced the flow turbulence, increased the settling area, and improved the separation efficiency. The transverse density current formed between the gill-pieces and the entrainment effect of the local eddy current on the flow and sediment accelerated the process of water–sediment separation. The settling velocities on the upper surfaces of the gill-pieces and sediment channel were larger, which was conducive to the rapid separation of water and sediment. Yan et al. (2011b) obtained images of the sediment movement in the gill-piece separation device using high-speed camera technology, which proved that vertical density and transverse density current phenomena occurred in the gill-piece separation device. In addition, Yan et al. carried out a mechanical analysis on the sediment in the gill-piece separation device and described the movement trajectories of the sediment. Zhao et al. (2012) measured the velocity field of the gill-piece separation device using particle image velocimetry. The experimental results showed that a vertical density current appeared in the gill-piece separation device, in which the sediment moved downward along the upper surface of the gill-piece and the clean water moved upward along the lower surface of the gill-piece. The analysis results were consistent with the theoretical analysis and the observed phenomena.

In terms of flow field studies, Tao et al. (2013b), (2014a), (2015) carried out numerical simulations on the flow field of the gill-piece separation device with different sediment particle sizes and sediment concentration conditions and determined that the Euler model in the Fluent software could well simulate the flow field of the water–sediment two-phase flow in the gill-piece separation device. The average sediment concentration on the upper surfaces of the gill-pieces was far greater than that on the lower surface of the gill-pieces. The larger the sediment particle size was, the higher the water–sediment separation efficiency became. The smaller the sediment concentration was, the higher the water–sediment separation efficiency became. These studies laid a foundation for the practical application and structural optimization of gill-piece separation devices.

Many studies have been carried out on the gill-piece separation device using physical experiments and numerical simulations. However, the relationships between the water–sediment separation efficiency of the gill-piece separation device and the key structural (gill-piece spacing) and operating (sediment concentration and inlet flow) parameters have not yet been established. In this study, based on previous study results, a uniform orthogonal experiment was designed. The results were analyzed using multiple linear regression and projection pursuit regression (PPR) to obtain the order of the factors that affected the water–sediment separation efficiency of gill-piece separation devices and to construct a water–sediment separation efficiency prediction model.

**MATERIALS AND METHODS**

**Device**

The experiments were conducted in the hydraulic engineering laboratory of the College of Hydraulic and Civil Engineering of Xinjiang Agricultural University. The gill-piece separation device was a new water–sediment separation device, which is mainly used for the treatment of viscous fine sediment. It was composed of gill-pieces and a gill-duct. The gill-piece separation device used in this
experiment was made of polymethyl methacrylate with a uniform texture and no bubbles. The circulation system is shown in Figure 1. It was composed of a water tank, mixing pump, water pump, gill-piece separation device, and gate valve, and it was provided with a clean water outlet, sediment outlet, and diversion port. Before the experiment, the prepared water and sediment were added into the water tank and fully mixed using the mixing pump. The pump was turned on to pump the well-mixed sandy water into the gill-piece separation device for the water–sediment separation experiments. After settling due to the gill-piece separation device, the sediment particles were discharged into the water tank from the bottom sediment outlet, and the clean water flowed from the upper overflow port back to the water tank. The water and sediment in the water tank were then remixed evenly, and the experiment entered the next cycle. The structure of the gill-piece separation device is shown in Figure 2. The device had a length of 200 mm, width of 100 mm, and height of 1,000 mm. The gill-piece spacing was d. The gill-pieces were fixed on the two side walls in the length direction of the ordinary tube at an inclination angle of $\alpha = 60^\circ$, forming an inclination angle of $\beta = 45^\circ$ with the two side walls in the width direction. A clean water ascending channel was set between the gill-piece and the ordinary tube, with a width of 10 mm, and the sediment descending channel had a width of 10 mm. The diameter of the sediment outlet at the bottom of the gill-piece separation device was 2.5 mm. There were sandy water inlet and clean water outlet channels with diameters of 20 mm on both sides in the width direction, and the clean water outlet was 950 mm away from the bottom of the gill-piece separation device.

**Working principle of gill-piece separation device**

The experiments were carried out under static and dynamic water conditions. The static water conditions were as follows. The gill-piece separation device was only open at the top, with a free surface, closed periphery, and bottom, and it did not discharge sand. The dynamic water conditions were as follows. The top and bottom of the gill-piece separation device were open. Water was introduced through the water inlet, and the water and sand outlets facilitated the discharge of clean water and sand, respectively. Figure 3 shows the working principle of the gill-piece separation device. The sediment particles settled freely under the action of gravity. When the particles reached the upper surfaces of the gill-pieces, they slid from the top to the bottom along the upper surfaces of the gill-pieces due to gravity. During the sliding process, the particles encountered other particles and gathered under the action of particle contact, friction, collision, and adhesion to form sediment flow.
stream flowed vertically downward into the triangle sediment channel, while the clean water flowed from bottom to top along the lower surface of the gill-pieces and moved vertically upward in the clean water channel, thus achieving the separation of water and sediment. The movement of the sediment flow on the upper surfaces of the gill-pieces and the movement of the clean water flow on the lower surfaces of the gill-pieces formed an anticlockwise transverse density current between the gill-pieces, marked by the dotted line with an arrow in Figure 1. The sediment at the lower end of the gill-pieces slid down to the sediment channel and moved vertically downward, while the clean water at the upper end of the gill-pieces moved vertically upward when it flowed into the clean water channel, thus forming a clockwise vertical density current along the side wall of the gill-piece separation device, marked by a solid line with an arrow in Figure 3.

**Sediment**

The gill-piece separation device was mainly used for the treatment of viscous fine sediment. In this experiment, the natural loess from Xishan Mountain, Urumqi City, Xinjiang Uygur Autonomous Region was selected as the experimental sediment, and the sediment density was \( \rho_s = 2650 \text{ kg/m}^3 \). The particle size distribution was as follows: 100% of the particles were smaller than 0.075 mm, 80.4% were smaller than 0.048 mm, 47.8% were smaller than 0.023 mm, 26.0% were smaller than 0.01 mm, 13.5% were smaller than 0.005 mm, and 6.6% were smaller than 0.0015 mm. The median diameter \( D_{50} \) was 0.025 mm. Figure 4 shows the particle size distribution.

**Steps**

Before the experiment, the viscous sediment and water were mixed evenly in various proportions to prepare sediment-
laden water with specified concentrations. The experiment was started after the viscous sediment was fully mixed. During the experiment, the water samples were collected from the inlet of the muddy water, the outlet of the clean water, and the desilting outlet, and the parameters such as the flow rate and sediment concentration were measured and calculated. The experimental phenomena in the gill-piece separation device with different filtration times were observed, and the water–sediment separation efficiency of the gill-piece separation device under different conditions was analyzed.

Based on the results of the physical experiment and the numerical simulation under static and dynamic water conditions (Tao et al. 2013a, 2014b, 2015; Zhang et al. 2019), a three-factor, three-level, uniform orthogonal table UL0 (3^4) was selected for this experiment, as shown in Table 1. The experiments were designed mainly to investigate the influence of the flow rate of muddy water at the inlet, the sediment concentration, and the gill-piece spacing on the water–sediment separation efficiency of gill-piece separation device.

### Flow rate measurements

The flow rate was determined by measuring the volume. Glass beakers were used to take water samples with certain volumes at the clean water outlet and the desilting outlet. The corresponding time \( T \) was recorded with a stopwatch. The water sample volume \( V \) was measured using a graduated cylinder. Sampling was performed three times at each position, and average value was taken as the volume of the water sample. The corresponding flow rate could be calculated using the following equations:

\[
Q = \frac{V}{T} \quad (1)
\]
\[
Q_c + Q_d = Q_m \quad (2)
\]

where \( Q \) is the flow rate (m^3/h), \( V \) is the volume of the water sample (m^3), \( T \) is the sampling time (h), \( Q_c \) is the flow rate at the clean water outlet (m^3/h), \( Q_d \) is the flow rate at the desilting outlet (m^3/h), and \( Q_m \) is the flow rate at the muddy water inlet (m^3/h). The flow rate \( Q_m \) at the muddy water inlet could be calculated by substituting the flow rate \( Q_c \) at the outlet of the clean water and the flow rate \( Q_d \) at the desilting outlet into Equation (2).

### Measurement of sediment concentration

The principle of the replacement method was used to measure the sediment concentration quickly and accurately. The volume of the conical flask was calculated using Equation (3), where the sample was weighed using an electronic balance with an accuracy of 0.01 g, and the sediment concentration of the sample was calculated using Equation (4):

\[
V_f = \frac{M_{f+c} - M_f}{\rho_w} \quad (3)
\]
\[
S_m = \frac{(M_{f+m} - M_f - \rho_w V_f)\rho_s}{(\rho_s - \rho_w)\rho_s} \quad (4)
\]

where \( S_m \) is the sediment concentration of the muddy water (kg/m^3), \( M_{f,m} \) is the mass of the conical flask and the muddy water (kg), \( M_{f+c} \) is the mass of the conical flask and the clean water (kg), \( M_f \) is the mass of the conical flask (kg), and \( V_f \) is the volume of the conical flask (m^3).

### Experimental index

The water–sediment separation efficiency was used to evaluate the filtration performance of the gill-piece separation device. The water–sediment separation efficiency refers to the ratio of the difference between the sediment

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Inlet flow Q (m^3/h)</th>
<th>Sediment concentration S (kg/m^3)</th>
<th>Gill-piece spacing d (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (0.3)</td>
<td>1 (2)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>2</td>
<td>1 (0.3)</td>
<td>2 (7)</td>
<td>3 (11)</td>
</tr>
<tr>
<td>3</td>
<td>1 (0.3)</td>
<td>3 (12)</td>
<td>2 (8)</td>
</tr>
<tr>
<td>4</td>
<td>2 (0.7)</td>
<td>1 (2)</td>
<td>3 (11)</td>
</tr>
<tr>
<td>5</td>
<td>2 (0.7)</td>
<td>2 (7)</td>
<td>2 (8)</td>
</tr>
<tr>
<td>6</td>
<td>2 (0.7)</td>
<td>3 (12)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>7</td>
<td>3 (1.1)</td>
<td>1 (2)</td>
<td>2 (8)</td>
</tr>
<tr>
<td>8</td>
<td>3 (1.1)</td>
<td>2 (7)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>9</td>
<td>3 (1.1)</td>
<td>3 (12)</td>
<td>3 (11)</td>
</tr>
</tbody>
</table>
concentration at the inlet of the muddy water and that at the outlet of the clean water to the sediment concentration of the muddy water. The equation is:

\[ \eta = \frac{S_m - S_c}{S_m} \times 100\% \] (5)

where \( \eta \) is the water–sediment separation efficiency (%), \( S_m \) is the sediment concentration at the inlet of the muddy water (kg/m³), and \( S_c \) is the sediment concentration at the outlet of the clean water (kg/m³).

**RESULTS AND DISCUSSION**

**Uniform orthogonal experiment results**

In the uniform orthogonal experiment, the water–sediment separation efficiency was the index, and the results are shown in Table 2. R is the range of factors, which reflects the variation range of the indices when the levels of the factors change. The larger the range is, the greater the influence of this factor on the index becomes. According to the results of the range analysis, the order of influence of each factor on water–sediment separation efficiency was as follows: flow rate at muddy water inlet > gill-piece spacing > sediment concentration. The optimum conditions were a flow rate of 0.3 m³/h at the muddy water inlet, a gill-piece spacing of 11 cm, and a sediment concentration of 2 kg/m³.

**Establishment of multiple linear regression model for water–sediment separation efficiency**

A multiple linear regression is mainly used to study the linear relationship between a dependent variable and multiple independent variables. Its objective is to use the values of multiple independent variables \((x_1, x_2, x_3, \ldots, x_k)\) to estimate the dependent variable \(y\).

In this study, SPSS 25.0 software was used to analyze the experimental results, and the statistical significance threshold was set to \(P < 0.1\). Non-significant parameters were excluded from the model. The observed values in the study were independent of each other. The Durbin–Watson experiment value was 2.016. The regression tolerances were all greater than 0.1, and there was no multicollinearity. The chart of the regression standardized residuals shows that the data were distributed on and near the diagonal line (Figure 5). The regression model met the normality assumption and could be used for regression analysis.
The regression model was statistically significant. $R^2 = 0.874$, suggesting that the fit was good. Table 5 shows that among the independent variables, the flow rate at the muddy water inlet, sediment concentration, and gill-piece spacing had a significant impact on the water-sediment separation efficiency ($P < 0.1$). According to the standardized coefficient of the regression model, the level of influence of each factor on the water-sediment separation efficiency was in the following order: flow rate at muddy water inlet > gill-piece spacing > sediment concentration, which was consistent with the results of the range analysis.

According to the results of the SPSS regression analysis, the obtained prediction model of the water-sediment separation efficiency was as follows:

$$\eta = 32.79 - 19.537Q - 0.775S + 1.789d$$

where $\eta$ is the water-sediment separation efficiency (%), $Q$ is the flow rate (m$^3$/h), $S$ is the sediment concentration (kg/m$^3$), and $d$ is the gill-piece spacing (cm).

According to Equation (6), when the minimum flow rate was 0.3 m$^3$/h, the minimum sediment concentration was 2 kg/m$^3$, and the maximum gill-piece spacing was 11 cm. The water-sediment separation efficiency of the gill-piece separation device reached a maximum of 45.06%, which was consistent with the results of the range analysis.

The water-sediment separation efficiency predicted using Equation (6) was compared with the measured value, as shown in Figure 6. Under the same conditions, the predicted water-sediment separation efficiency was close to the measured value. The mean relative error between the measured value and the predicted value was 8.44%, and the $R$ was 0.93. Therefore, this model could be used to predict the water-sediment separation efficiency of gill-piece separation device.

**Establishment of PPR water-sediment separation efficiency model**

Projection pursuit regression (PPR) (Zheng et al. 1995) is a method for processing and analyzing high-dimensional data, and the model of PPR, a new multivariate statistical analysis technique, can be expressed as follows:

$$\hat{y} = E[y|x_1, x_2, \ldots, x_p] = \hat{y} + \sum_{i=1}^{M} \beta_i f_i \left( \sum_{n=1}^{p} a_{in}x_n \right)$$

where $f_i$ is the $i$th ridge function, $E_{f1} = 0$, $E_{f2} = 1$, and $\sum_{n=1}^{p} a_{in}^2 = 1$. The solution steps have been published previously (Jiang et al. 2019).

The PPR was used to analyze the experimental data of nine groups of physical gill-piece separation device models. The model projection parameters were: $N_m = 9$, $p = 3$, $Q = 1$, $M = 5$, $Mu = 3$, and Span = 0.5, where $N_m$ is the number of modeling data, $p$ is the number of influencing factors, $Q$ is the number of dependent variables, $Mu$ is the number of the optimum of ridge function, $M$ is the number of the upper limit of the ridge function. $Mu$ and $M$ determine the fineness of the internal structure of the data that the model is looking for, while Span is the smooth coefficient, whose value depends on the accuracy of the experimental data and determines the sensitivity of the model. The range of Span is $0 < Span < 1$. The smaller the value, the more sensitive the model is.

In the process of establishing the water-sediment separation efficiency model using PPR, the calculated contribution weight coefficient $\beta$ and projection direction

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**Table 3 | Results of multiple linear regression analysis**

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Regression coefficient $R^2$</th>
<th>Independent variable</th>
<th>Non-standardized coefficient $B$</th>
<th>Standard error</th>
<th>Standardized coefficient $\beta$</th>
<th>Significance level $P$</th>
<th>Root mean square error RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-sediment separation efficiency</td>
<td>0.874</td>
<td>Intercept</td>
<td>32.790</td>
<td>6.229</td>
<td>-0.713</td>
<td>&lt;0.05</td>
<td>4.265</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q$</td>
<td>-19.537</td>
<td>4.353</td>
<td></td>
<td>&lt;0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S$</td>
<td>-0.775</td>
<td>0.348</td>
<td>-0.354</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d$</td>
<td>1.789</td>
<td>0.580</td>
<td>0.490</td>
<td>&lt;0.05</td>
<td></td>
</tr>
</tbody>
</table>
$\alpha$ of the ridge function are as follows:

$$\beta = (1.099768, 0.276116, 0.285926)$$  

$$\begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \\ \hat{\beta}_3 \end{pmatrix} = \begin{pmatrix} -0.99605 \\ -0.71178 \\ 0.991148 \end{pmatrix}, \begin{pmatrix} -0.02558 \\ -0.53415 \\ -0.12661 \end{pmatrix}, \begin{pmatrix} 0.085002 \\ 0.456119 \\ -0.03994 \end{pmatrix}$$  

The weight coefficients of the influence of the flow rate at the muddy water inlet, sediment concentration, and gill-piece spacing on the water–sediment separation efficiency of the gill-piece separation device are shown in Table 4. The flow rate at the muddy water inlet had the greatest effect on the water–sediment separation efficiency, followed by the gill-piece spacing, and the sediment concentration had the least effect, which is consistent with the conclusions of the range analysis.

**Comparison of measured and predicted values of water–sediment separation efficiency model based on PPR**

The above PPR model was used to predict the water–sediment separation efficiency of the gill-piece separation device under different working conditions, and the measured value was compared with the predicted value of the model, as shown in Figure 7. $R$ reached 0.98. The mean relative error between the measured and predicted values was 5.11%. Compared with the multiple linear regression model, the mean relative error was reduced by 3.33%, indicating that the PPR model had a higher prediction accuracy.
Prediction of water–sediment separation efficiency based on the PPR model

The established PPR prediction model was used to predict the water–sediment separation efficiency of the gill-piece separation device when the flow rate at the muddy water inlet was 0.3–1.1 m$^3$/h, the gill-piece spacing was 5–11 cm, and the sediment concentration was 2–12 kg/m$^3$. The results showed that when the flow rate at the muddy water inlet was 0.3 m$^3$/h, the gill-piece spacing was 11 cm, and the sediment concentration was 2 kg/m$^3$, the water–sediment separation efficiency reached the maximum value. The optimal working conditions predicted using PPR model were consistent with those obtained using range analysis and multiple linear regression analysis, which validated the reliability of the PPR model prediction. Therefore, the PPR model could be used to predict the water–sediment separation efficiency of the gill-piece separation device under different working conditions.

The use of multiple linear regression analysis requires some conditions to be met, such as correlation, independence, variance homogeneity, and normality. These conditions will increase the difficulty of data processing, and human judgment will also affect the experimental results to a certain extent. To avoid the artificial assumptions and transformations of the original data and seek the real inherent dependencies of the data itself, the PPR method was applied for the material selection and concrete performance optimization, which validated the advantages of the PPR modeling method (Sheng & Wen 1997; Zhu et al. 2014; Jiang et al. 2019). In this study, a uniform orthogonal experiment was carried out on a gill-piece separation device under muddy water conditions. Multiple linear regression and the PPR method were used to establish the prediction model of the water–sediment separation efficiency. R of the water–sediment separation efficiency prediction model established using the multiple linear regression method was 0.93, and that of the PPR model was 0.98. The model established using these two methods could predict the water–sediment separation efficiency, and the prediction accuracy of the PPR model was higher, indicating that PPR method could also be used for modeling and analysis of normal data. In a
practical application, the multiple linear regression and PPR model can well predict the water–sediment separation efficiency. When the experimental data are not normally distributed, the PPR method can be used to establish the prediction model. The advantage of PPR modeling is its assumption-free modeling characteristics, that is, there is no need to assume the distribution type of the experimental data, thus avoiding the unreasonable constraints of human factors on the regression model. PPR can make full use of the information and real dependencies of the data itself and solve the optimization problem by exploring the internal structure of the data, giving it a higher degree of fitting.

It was found that, although the gill-piece separation device could treat the viscous sediment, its water–sediment separation efficiency was not high. To further improve the water–sediment separation capacity of the gill-piece separation device, the structural optimization requires further study. In previous studies, the water inlets were all arranged on the side of the device, and the size of the device was relatively small. Therefore, further improvement measures can be performed. The size of the gill-piece separation device could be increased to increase its sediment treatment capacity. The position of the water inlet could be changed, e.g., the water inlet could be moved to the bottom. The material or the structural form of the gill-pieces could be changed to increase the speed and efficiency of sediment treatment. Considering the influence of drainage solid flux may make the efficiency prediction more accurate. We will study this factor in further.

CONCLUSION

In this study, the effects of the flow rate at the muddy water inlet, sediment concentration, and gill-piece spacing on the water–sediment separation efficiency were investigated using a uniform orthogonal experimental design. The order of influence of each factor on the water–sediment separation efficiency was as follows: flow rate at muddy water inlet > gill-piece spacing > sediment concentration. Multiple linear regression and the PPR method were used to establish a prediction model of the water–sediment separation efficiency. The models established using the above two methods could well predict the water–sediment separation efficiency of the gill-piece separation device. The prediction results of the PPR model were more accurate than those of the multiple linear regression, and its R reached 0.98. The established PPR model was used to predict the optimal working conditions. When the gill-piece spacing was 11 cm, the sediment concentration was 2 kg/m³, and the flow rate at the muddy water inlet was 0.3 m³/h, the water–sediment separation efficiency reached the maximum value. The models in this study were both established under a sediment concentration of 2–12 kg/m³, a flow rate of 0.3–1.1 m³/h, and a gill-piece spacing of 5–11 cm. Whether these models are applicable under other conditions should be studied in the future.

ACKNOWLEDGEMENTS

This study is financially supported by National Natural Science Foundation of China (50969009), Xinjiang Uygur Autonomous Region Innovation Environment (Talents, Bases) Construction Special Project-Natural Science Foundation Project (2017D01B18), Xinjiang Uygur Autonomous Region University Scientific Research Program General Project (XJEDU2017M011).

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 2 December 2020; accepted in revised form 8 March 2021. Available online 22 March 2021.