Evaluation of flushing efficiency at a sand trap: A case study of Pengasih Weir, Special Region of Yogyakarta

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Abstract. Sand trap is a part of the main building of irrigation system. Its function is to settle the sediment that is carried away from a river stream. Sand trap needs to be flushed periodically with an optimal and efficient mechanism. This research aimed to evaluate the flushing efficiency of the sand trap of the Pengasih Weir. The data consisted the bedload samples along the channel and the sand trap's existing flushing mechanism data. The results showed that the most dominant grain of the bedload trap in Pengasih Weir was fine sand with a diameter between 0.075 and 0.425 mm of 77.2%. The bedload includes uniform and well-graded sediment because the Cu and Cc values were 2.751 (less than 5) and 1.027 (in the range 1 - 3), respectively. The flushing mechanism was divided into two stages. The first stage was the combination of 1.06 m/s flow velocity and 1.1 m flow depth, and the second stage was the combination of 1.59 m/s flow velocity and 0.35 m flow depth. Both two stages were efficient in flushing the sand trap of the Pengasih Weir, which apparent from all the bedload grains that were moved based on the concept of Shields.

1. Introduction

The Serang Watershed is administratively located in Kulon Progo Regency. This watershed area is 279.69 km², with the length of the main river about 28 km. The condition of the watershed and the water availability of this watershed directly affects the Kulon Progo society. In general, land use in Kulon Progo is for rice fields (wetlands) and drylands such as yards, public forests, ponds, buildings, and industry. The utilization of rice fields is 21.57% of the district's total land area. Most of the water used for rice fields in Kulon Progo comes from the Serang watershed and the Sermo Reservoir, which dams up the Ngrancah River. Meanwhile, dry land is known to be increasing, especially due to the addition of buildings by converting rice fields which can decline the condition of the Serang watershed.

Directorate General of Water Resources in 2010 explained that most of the watersheds in the Progo-Opak-Serang River Basin are included in the Priority I condition, a critical watershed and needs to be addressed immediately [1]. The sedimentation rate in the Serang Watershed was 0.03 mm/year, which indicated in a good category [2]. However, the management of the Serang Watershed is still not optimal [3]. It is shown from many disasters that have occurred in this watershed, such as landslides, floods, and drought. Moreover, based on the Indonesian Disaster Information Data released by the National Disaster Management Agency in 2020, there were 29 landslide incidents in Kulon Progo.
Regency during the last ten years. Soil layers due to erosion and landslides will automatically enter the river flow, which will then be detained in the weirs along the river.

There are two weirs in the Serang River as the main river in this watershed, one of them is the Pengasih Weir. There is a sand trap in the Pengasih Weir which functions to settle the sediment fraction greater than and equal to the fraction of fine sand (0.06 - 0.07 mm) and is usually located downstream of the intake [4]. Sediments of that size will be restrained in the weir and will be flushed periodically, while those with a smaller size has the potential to escape and enter irrigation intake. Before the water flow is streamed into the irrigation network, the flow's sediment is deposited in the sand trap. The sand trap has a specific capacity and can be filled over time, so it is needed to flush the sediment that has settled. Therefore, this study aimed to evaluate the flushing efficiency in the Pengasih Weir sand trap.

2. Methods

2.1. Location
This research was conducted in the Pengasih Weir sand trap located in Kulon Progo Regency, Special Region of Yogyakarta, Indonesia. This weir receives the water supply from the Serang River.

2.2. Data collection
The data collected is in the form of a bedload at several Pengasih Weir sand trap points. The sampling points are in the longitudinal and transverse path of the sand trap, which is considered to represent the physical characteristics of the bedload in the channel. There are 12 sampling points, each on the left, right, and center of the channel with a direction extending 10 meters, 30 meters, 50 meters, and 70 meters from the upstream of the sand trap (irrigation intake). Figure 1 showed the layout for bedload sampling.

![Figure 1. The layout for bedload sampling in the Pengasih Weir sand trap](image)

2.3. Initial of sediment movement
The initial sediment movement concept was closely related to sediment transport, river bed degradation, and stable channel design. It considers the channel's slope and dimensions so that the bed or channel walls do not experience erosion due to flow. There are several approaches to expressing the initial motion of the grains, namely when flow occurs: 1) one particle is known to have moved, 2) several particles are already moving, and 3) the condition for the amount of sediment transport is equal to zero. There is a theoretical approach to determine the initial sediment motion using the flow velocity approach, the lift force approach, and the critical shear stress approach [2]. The critical shear stress approach focuses on the forces acting on the sediment grains due to water flow. These forces cause the sediment grains to move. The force to move coarse sediment, namely sand and rock, is influenced by the weight of the sediment grains itself, while to move the silt and clay fractions, the cohesion of the sediment affects the force required. The shear force of flow on the sediment grains surface causes the motion of the sediment grains. The critical condition is the boundary force acting on the sediment grains. If the force is added a little, the sediment will move, and if the force does not
reach the force limit, the sediment grains will not move. In this condition, the flow parameters are the boundary shear stress ($\tau_o$) and the shear velocity ($U^*$), which reaches its critical condition. Equation 1 is the shear stress formula at the channel bed, and Equation 2 is the shear velocity equation [5,6].

\[ \tau_o = \rho g h I \]  
\[ U^* = \sqrt{ghI} \]  

where:
- $\tau_o$ = boundary shear stress (N/m$^2$)
- $U^*$ = shear velocity (m/s)
- $\rho$ = specific gravity of sediment grains (kg/m$^3$)
- $h$ = flow depth (m)
- $I$ = slope of channel bed

Shear stress ($\tau_o$) is dimensionless, and Reynolds number ($Re^*$) is a factor that influences the initial sediment motion [7]. The Reynolds number equation is shown in Equation 3.

\[ Re^* = \frac{U^* d_{50}}{v} \]  

Where $d_{50}$ is the representative diameter (m), and $v$ is the average velocity (m/s)

3. Results and discussion

The sand trap's flushing efficiency analysis requires two main parameters, namely bedload and flow during the flushing. The bedload parameter includes specific gravity and a representative diameter of sediment grains. Flow parameters consisted of depth and flow velocity during the flushing and the slope of the channel bed. To obtain the bedload parameters, sediment density test and sieve test are needed to get sediment grain size distribution.

3.1. Distribution of bedload grain size

Bedload sampling utilized a grab sampler. There was no bedload deposition on the right side of the channel at the sampling time, thus, samples were taken only on the sand trap's left and center. Table 1 showed the sediment specific gravity test results on the Pengasih Weir sand trap. Based on Table 1, it was known that from upstream to downstream, the specific gravity of sediment varies, with an average of 2.664 grams/cm$^3$. The highest specific gravity of sediment was at a point 10 m on the left side, and there was a tendency to decrease the downstream's value. It indicates that sediments with higher specific gravity tend to settle more quickly at the beginning of the sand trap. The absence of bottom sediment on the right side was due to the inclination of higher flow rates on the channel's right side. It happens because the floor of the right channel was relatively smoother than the middle and left sides. Besides, there was also a leakage at the right intake gate.

| Sampling location (m) | Specific gravity (g/cm$^3$) |
|-----------------------|-----------------------------|
| Left | Middle | Right |
| 10 | 3.313 | 2.508 | - |
| 30 | 2.627 | 2.728 | - |
| 50 | 2.589 | 2.511 | - |
| 70 | 2.475 | 2.497 | - |
| Average | 2.664 | | |
Figure 2. The grain size distribution of bedload on Pengasih Weir’s sand trap.

Figure 2 shows the grain size distribution of bedload on Pengasih Weir’s sand trap, including coarse sand to silt. Sediments with a steeper curve showed the more uniform grain, while the sediment with a more gentle curve showed more grain variations, or less uniform. The degree of uniformity in sediment was measured by the coefficient of uniformity ($Cu$). The most dominant grains were fine sand with a diameter between 0.075 - 0.425 mm as much as 77.2%, then medium sand in the value of 19.7%, and coarse sand and silt less than 2%. This percentage stated that the bedload includes coarse-grained soil, where the gravel and sand fraction were more than 50%. It could be seen from Figure 2 that there was a steep line in the fine sand classification column; this showed that each sampling point contains more fine sand than other types. To determine the characteristics of the sediment, $Cu$ and $Cc$ were calculated. $Cu$ is a coefficient of uniformity of grain size distribution, which is defined as the particle diameters $D_{50}$ and $D_{10}$, as shown in equation 4 [8]. $Cc$ is a curvature coefficient defined as the particle diameters $D_{50}$, $D_{30}$, and $D_{10}$, as shown in equation 5 [8]. Where $D_{50}$, $D_{30}$, and $D_{10}$ are particle size at 60%, 30%, and 10% finer, respectively.

$$Cu = \frac{D_{50}}{D_{10}}$$  \hspace{1cm} (4)

$$Cc = \frac{D_{50}^2}{D_{10} \times D_{60}}$$  \hspace{1cm} (5)

$Cu$ less than 5 is categorized as a uniform grade [9], while the grain size distribution is classified as a good grade when $Cc$ in the range of 1 – 3 [10]. Table 2 shows $Cu$ and $Cc$ of bedload on Pengasih Weir’s sand trap. It could be seen that $Cu$ and $Cc$ values were 2.751 and 1.027, respectively. It means that sediment includes uniformly and also well graded.
Table 2. Cu and Cc of bedload on Pengasih Weir's sand trap

| Sample code | Cu  | Cc  |
|-------------|-----|-----|
| 10Middle    | 2.340 | 1.146  |
| 10Left      | 2.686 | 1.050  |
| 30Middle    | 2.256 | 0.960  |
| 30Left      | 2.416 | 0.953  |
| Average     | 2.751 | 1.027  |

3.2 Flushing process of sand trap

The analysis of flushing efficiency was based on the initial sediment motion. The initial grain motion was based on the critical condition that occurs, namely the condition in which the sediment grain’s position begins to shake from an equilibrium or resting state. It happens because the factors that affect the critical condition have started to be exceeded. One of them is the critical discharge, which is the maximum discharge that the grains can hold to remain in an equilibrium state.

The data used was the flow depth data during the sand trap flushing carried out on July 31, 2019. Flushing was carried out in two stages because the sediment left behind from the first flushing, where the sand trap was not completely clean from the sediment. In the second flushing, the flow depth was lower than that in the first flushing, while the flow velocity was higher. In addition to the depth data, the initial movement of the sediment grains was determined by using the bedload and sand trap characteristics.

The flushing process was begun with the opening of the sand trap's flushing gate. There is one flushing gate with a width and a full opening of 1.5 m. In this process, the flushing gate was only opened as high as 0.4 m because the gate was difficult to operate and cannot be fully opened (Figure 3). After the flushing gate was opened, the three main intake gates were also opened. The three main intake gates have the same dimensions: the gates width of 1.2 m and the full opening of 4.8 m. All three gates could still be appropriately operated and could be fully opened. The discharge that entered the sand trap was more significant than the discharge that comes out, so that the water level in the sand trap was relatively high, namely 1.1 m, and the flow velocity was 1.06 m/s.

After 34 minutes of the first flushing, the three main intake gates were closed, but the flushing gate remains open. The flushing results could be seen after the water in the sand trap had receded, and there was the sediment left at specific points. The second flushing was carried out to clean all the remaining deposits. The flushing gate remains open 0.4 m high, and the three main intake gates re-open with a full opening of 4.8 m. With this operation, the measured flow velocity was 1.59 m/s, while the flow depth was 0.4 m. The second flushing results were relatively clean; the sediment left from the first flushing had been thoroughly carried away by the flushing stream. After the sand trap's flow was
receding, it was known that the bottom of the sand trap did not have the same shape and roughness. In the middle of the sand trap, there were also boulders of rock that obstruct the process of sediment flushing. Figure 4 showed a comparison of the sand trap conditions after the first and second flushing.

![Figure 4](a) (b)

**Figure 4.** A comparison of the sand trap condition (a) after the first flushing, there was a pile of sediment left behind (b) after the second flushing; it was known that there were boulders of rock in the middle part that obstruct the flushing process.

### 3.2 Flushing efficiency of sand trap

Flushing efficiency was determined from the initial sediment motion in the flushing process. The parameters used in the first flushing stage were flow depth \( h \) of 1.1 m, kinematic viscosity \( \nu \) of \( 8.7 \times 10^{-7} \) m/s, channel bed slope \( i \) of 0.00097, bedload average density \( \rho_s \) of 2,664 kg/m\(^3\), water density \( \rho \) of 1,000 kg/m\(^3\), gravitational acceleration constant \( g \) of 9.81 m/s\(^2\). It also uses other parameters that could be seen in Table 3. Table 3 and Figure 5 showed the initial sediment motion analysis in the first stage of flushing, with a depth of 1.1 m. Figure 5 showed that all sediment particles move because they were above the critical limit when plotted on the Shields Graph. It indicates that the flushing carried out with a flow depth of 1.1 m and a flow rate of 1.06 m/s, theoretically efficient in flushing the sand trap with an average sediment density of 2,664 kg/m\(^3\).

Table 4 and Figure 6 showed the initial sediment motion analysis in the second flushing process with a flow depth of 0.35 m. Figure 6 showed that all sediment particles move because they were above the critical limit when plotted on the Shields Graph. It indicates that the flushing carried out with a flow depth of 0.35 m and a flow rate of 1.59 m/s, theoretically efficient in flushing the sand trap with an average density of sediment of 2,664 kg/m\(^3\).

**Table 3.** Calculation of non-dimensional grain-size specific Shield Number in the first flushing stage

| Grain size distribution | Grain diameter \( d \) (m) | Shear velocity \( U^* \) (m/s) | Reynolds number \( Re^* \) | Boundary shear stress \( \tau_\sigma \) (N/m\(^2\)) | \( (\rho_s - \rho) g d \) |
|-------------------------|---------------------------|-------------------------------|---------------------------|-----------------------------|------------------|
| d10                     | 0.00014                   | 0.3235                        | 50.9364                   | 278.8481                    | 124.2852         |
| d20                     | 0.00018                   | 0.3235                        | 66.0408                   | 278.8481                    | 95.8595          |
| d30                     | 0.00022                   | 0.3235                        | 80.8699                   | 278.8481                    | 78.2818          |
| d40                     | 0.00026                   | 0.3235                        | 94.7996                   | 278.8481                    | 66.7792          |
| d50                     | 0.00029                   | 0.3235                        | 108.952                   | 278.8481                    | 58.1049          |
| d60                     | 0.00034                   | 0.3235                        | 124.605                   | 278.8481                    | 50.8056          |
| d70                     | 0.00038                   | 0.3235                        | 141.668                   | 278.8481                    | 44.6865          |
| d80                     | 0.00048                   | 0.3235                        | 178.574                   | 278.8481                    | 35.4512          |
| d90                     | 0.00063                   | 0.3235                        | 233.471                   | 278.8481                    | 27.1153          |
| d100                    | 0.00475                   | 0.3235                        | 1760.34                   | 278.8481                    | 3.5963           |
Theoretically, two variations of the flushing flow depths and flow rates derived from two different flushing process mechanisms give the same results. All the bedload grains in the sand trap could be lifted, and the flushing process can be said to be efficient. However, the field observations indicate sediment left in the sand trap after the first flushing. The sediment left behind was due to boulder's presence at the bottom of the sand trap, causing turbulence to flow and hinder the flushing process. The recommendation is to clean the sand trap mechanically to transport the rocks at the sand trap's bottom. It is also necessary to repair or replace the sand trap's flushing gate (as shown in Figure 3) to be fully opened during the flushing process. It can increase the flushing efficiency and improve the sand trap's performance, which primarily functions as the main barrier to sediment before entering the irrigation network [11]. In further research, hydraulic modeling is necessary to determine the optimal flow rate used in the flushing process.

**Figure 5.** Initial sediment motion in the first flushing stage, with a flow depth of 1.1 m and a flow rate of 1.06 m/s, based on the Shield concept.

**Table 4.** Calculation of non-dimensional grain-size specific Shield Number in the second flushing stage

| Grain size distribution | Grain diameter D (m) | Shear velocity $U^*$ (m/s) | Reynolds number $Re_e$ | Boundary shear stress $\tau_o$ (N/m$^2$) | $\tau_o$ | $\rho_d - \rho g d$ |
|-------------------------|----------------------|-----------------------------|------------------------|----------------------------------------|----------|------------------|
| d10                     | 0.00014              | 0.1825                      | 28.732                 | 88.7244                                | 39.5453  |                  |
| d20                     | 0.00018              | 0.1825                      | 37.2521                | 88.7244                                | 30.5008  |                  |
| d30                     | 0.00022              | 0.1825                      | 45.6168                | 88.7244                                | 24.9078  |                  |
| d40                     | 0.00026              | 0.1825                      | 53.4742                | 88.7244                                | 21.2479  |                  |
| d50                     | 0.00029              | 0.1825                      | 61.4572                | 88.7244                                | 18.4879  |                  |
| d60                     | 0.00034              | 0.1825                      | 70.2868                | 88.7244                                | 16.1654  |                  |
| d70                     | 0.00038              | 0.1825                      | 79.9115                | 88.7244                                | 14.2184  |                  |
| d80                     | 0.00048              | 0.1825                      | 100.729                | 88.7244                                | 11.2799  |                  |
| d90                     | 0.00063              | 0.1825                      | 131.696                | 88.7244                                | 8.6276   |                  |
| d100                    | 0.00475              | 0.1825                      | 992.965                | 88.7244                                | 1.14427  |                  |
4. Conclusion
The most dominant of the Pengasih Weir’s sand trap bedload grains was fine sand with a diameter between 0.075 and 0.425 mm as much as 77.2%. The average density of bedload was 2664 kg/m$^3$, including in uniformly and well-graded sediment due to the $Cu$ and $Cc$ values were 2.751 (less than 5) and 1.027 (in the range of 1 – 3), respectively. There were two stages of the flushing process, with the combination of a flow depth of 1.1 m and a flow rate of 1.06 m/s in the first stage and the combination of a flow depth of 0.35 m and a flow rate of 1.59 m/s in the second stage. The initial sediment motion concept was used to determine the flushing efficiency. Results showed that all sediment particles move because they were above the critical limit when plotted on the Shields Graph, both in the two flushing process. It indicates that the two flushing processes theoretically efficient in flushing the sand trap. However, the field observations indicate sediment left in the sand trap after the first flushing due to boulders rock at the channel bed that causes turbulence to flow and hinder the flushing process. It is recommended to clean the sand trap mechanically to transport the stones, repair or replace the flushing gate to be fully opened during the flushing process, and conduct hydraulic modeling to determine the optimal flow rate used during the flushing process.

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