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Original Article

On the Total Load Calculation in Combined Urban Sewer Conduits

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Abstract

Background: Particle size of sediment is necessary to design and operation of sewer systems. In this regard, calculation of the equivalent particle diameter (EPD) is of important to determine the particle Reynolds number (Re_t) as well as total load calculation.

Methods: In this research work, 5 different particle diameters (i.e. d_{35}, d_{50}, d_{65}, d_m and d_{eff}) have been used in three famous total load calculation methods for calculating the best EPD. For this goal, a field experimental data has been collected at the entrance grit chamber of wastewater treatment plant (WWTP) of Khomein city, Iran. The total load of the sediments has been measured and the results compared with the total loads calculated by the three famous total load computation methods (i.e. Graf & Acaroglu method, Laursen method and Yang & Lim method) by using the particle diameters.

Results: The results show that the methods estimate the total load of sediments with the relative errors of 4.25, 10.80 and 1.26 by using d_m, d_{35} and d_{65} as the EPDs, respectively. Also, a simplified and improved correction factor has been developed and the results show that by applying the correction factor the relative errors of the methods decrease and they are equal to 10.34, 3.45 and 496.5, respectively. The improvement of the mentioned total load methods is equal to are 82.70%, 93.10% and 34.80%, respectively.

Conclusion: The proposed correction factor can be applied for the standard deviation between 2.5-4.7 and the median particle diameter between 0.84-2.90 mm.

Keywords: Sediment characteristics, Sewer conduits, Total load, Graf & Acaroglu method, Laursen method, Yang & Lim method

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Introduction

The accumulation of sediment in sewer systems gives rise to a range of issues, including hydraulic section reductions and premature overflows, as well as concerns related to unpleasant odors and corrosion.[1] Operators expend significant financial and human resources in cleaning sewers, especially in areas where self-cleaning is ineffective, and sediment accumulation is likely. To optimize resource utilization and enhance sewer operation and maintenance, a deeper comprehension of sediment accumulation, erosion, and transport is imperative.[2-4] Understanding the characteristics of sewer sediments serves three primary objectives: (1) enhancing scientific knowledge of sediments and developing sediment transport models, (2) optimizing the allotment of resources in cleansing sewers by decision models on the basis of sedimentation rates and subsequently evaluating the effectiveness of cleaning efforts (3) estimating optimal locations of flushing gates for sediment scouring.[4-6] The characterization of sediments has been addressed in numerous research studies over the past decades, and various examples can be found in the existing literature.[1,7-14] Furthermore, new studies have focused on the bed strength variances depending on the consolidation time and aeration conditions.[15-19] From these studies, it was determined that the deposit strength is influenced by microbiological activity, which is in turn impacted by the organic matter and oxygen content. Furthermore, the attributes of sediments are closely related to the rates of suspended or bed load transport in sewer systems.[1] Customary sediment transport models are established on river sand equations while other parameters, like non cohesive sediment, are not taken into account.[20] Laboratory and field studies have been reported to validate sediment transport equations in sewer systems. However, the suggested models only incorporate the physical characteristics of sediments.[21,22] Studies in some laboratories have examined the presence of organic particles, and they have found that small organic fragments influence both bed shear stress and sediment transport rates.[23,24] In combined sewer systems, smaller-diameter upstream secondary pipes (diameters < 400 mm) are likely to contribute to solid output due to the particle sedimentation, particularly during dry-weather flow situations.[25] In the recent years, the study conducted by Wu et al[13] has been instrumental in determining the correction factor. They proposed a relationship for calculating this correction factor. Sewer sediment management is a significant issue in urban areas with substantial associated maintenance costs. To understand the sediment transport process in sewers, it is essential to include particle size in the models. Given the high variability in wastewater flows' particle size distribution (PSD), determining this distribution is crucial. Previous research has mainly focused on modeling sediment transport in sewer conduits while giving less attention to determining sediment characteristics and calculating the total load. This study aimed to determine sediment characteristics and calculate the total sediment load in combined urban sewer conduits using various methods, with a high level of accuracy based on a real case study. Therefore, an experimental study was conducted in a concrete rectangular channel at the entrance of the Khomein city wastewater treatment plant (WWTP), using real urban wastewater flow.

Material and Methods

Experimental Setup and Test Procedure

In this research, a rectangular concrete channel at the entrance of the Khomein city WWTP in Iran served as the conduit for wastewater flow. It has a length of 25 m, a width and depth of 0.5 m, and a longitudinal slope of 0.1% (Figure 1). A circular hole with the diameter of 7.5 cm was placed at the end of the channel to pour the flow at each test. At the start of each test, the circular hole was blocked, and it took 420 s to fill the channel. After that, the hole was opened, and because the flow discharge at the inlet and outlet was equal, the flow through the channel became uniform. Hence, each test had a duration of 840 s. The weight of the measured sediment rate was divided by 2 because during the first 420 s, the channel acted as a tank. In the subsequent 420 s, the channel functioned as a conduit, and all calculations were based on this flow period.

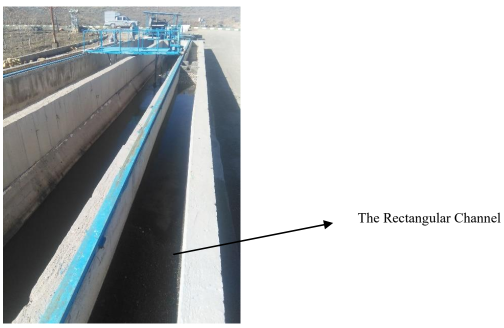

Figure 1. Experimental Setup of the Rectangular Concrete Channel (Upstream View)

The locations of the city, WWTP, and the catchment characteristics have been depicted in Figure 2. The objective of this setup was to collect and measure sediment deposition from the wastewater flow. A pumping system was installed at the entrance of the grit chamber to direct the wastewater to the rectangular channel (see Figure 3). The pump had the following specifications: Q = 18 L/s, H = 10 m, Power = 8 Kw, and an outlet diameter of 7.50 cm. Details of the individual WWTP have been listed in Table 1. A long period accumulation test was planned to determine the deposited sediment characteristics during 10 days. For this goal, continuous hydraulic conditions were set up with the flow rate (Q) of 14.7 L/s.

The duration of flow pumping for each test was 840 s, followed by allowing the sediments to settle for a complete 24 hours. Subsequently, the channel outlet was reopened to discharge the wastewater flow. The deposited sediments were then left to dry for a minimum of 72 hours (Figure 4). Next, the collected sediments were transported and delivered to the soil mechanics laboratory of Khomein for the purpose of determining their weights. The PSD of these sediments was assessed through a gradation test. In this grading test, a set of 26 samples was prepared, with each sample extracted at intervals of 1 m along the channel every 10 days, and these samples were then forwarded to the laboratory. The sampling procedure was done according to the ASHHTO T88-70 standard. Subsequently, the samples were collected in a plastic container and thoroughly mixed completely. Finally, a 2-kg sample, based on weight, was prepared and dispatched to the soil mechanics laboratory in Khomein to undergo a gradation test. For each test, the sample was subjected to a 24-hour drying process within an oven set at a temperature of 110 °C (the accuracy of 0.1 gr). A range of sieves was employed, with the following sieve sizes: 1 ¼", 1", 3/4", 1/2", 1/4", 4, 5, 8, 10, 14, 18, 25, 35, 50, 70, 100, and 200. For a comprehensive overview of the direct tests, along with the corresponding timeframes and sampling locations (Table 2).

Results and Discussion

Based on the examination of the test site, it was observed that the PSDs in the flow exhibited multiple modes, as illustrated in Figures 5 and 6. These figures provide a visual representation of the PSD in the flow. As indicated in these figures, the distribution of sediment particles exhibits variations in response to changes in weather conditions. Specifically, during wet weather conditions, the mean particle diameter (d_{50}) was larger compared to dry weather conditions. This phenomenon can be attributed to the presence of larger particles entering the sewer conduit during wet weather. Figure 7 provides a bar diagram displaying the average values of PSDs for both dry and wet weather conditions. The significant variability in PSDs was primarily a result of the flow transport process to the WWTP. However, it is important to note that, based on the findings obtained through this guided research, the authors were unable to draw definitive

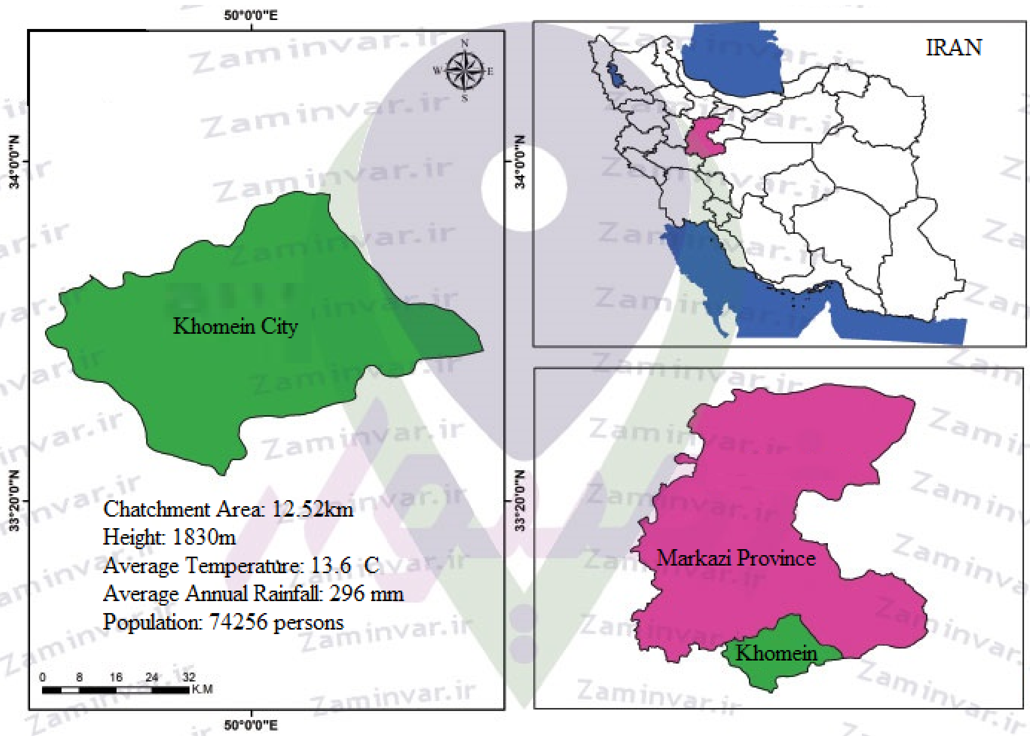

Figure 2. The Location of the Catchment and its Characteristics

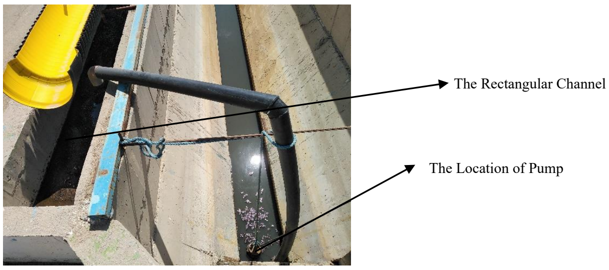

Figure 3. The Pumping Supply System

Figure 4. Deposited Sediments in the Channel in One Test to Determine the Weight of Deposition

conclusions regarding the impact of the sewer system on the particle distribution in the flow. The predominant fraction in the wastewater flow comprised particles ranging from 0.30 to 2 mm in size. The smallest particles detected in the flow had a size of 0.075 mm, constituting approximately 2.6% of the total weight. Conversely, the largest particles identified in the untreated sewage had an average size of about 31 mm, accounting for an average weight percentage of 0.75%, primarily observed during

Table 1. Specification of the Analyzed Wastewater Treatment Plant

WWTP	Location	WWTP Capacity, [m^3/d]	Volume of treated wastewater per annum [1000* m^3/year]
WWTP of Khomein	X=423085 Y=3723663	6600	2286

Table 2. Characteristics of the Number of Conducted Tests and the Period of the Experimental Works

Sample	Symbol	Number of Conducted Tests	Period of The Experimental Work (Day)	Sampling Point
Wastewater Flow	R	14	04.25.2020-12.10.2020	WWTP inlet (after screens)

wet weather conditions. Table 3 provides an overview of the particle size domains observed in the selected flow samples. Analysis of the obtained PSDs for the wastewater flow indicated that particles within the size range of 0.075 mm to 31 mm had the potential to be deposited within the sewer conduit. Notably, the analysis of the samples revealed that a significant portion of particles larger than 0.075 mm tended to be deposited in the grit chamber.

The analysis of d_{50} displayed that the d_{50} of deposit particles in the flow was within the range of 0.80 to 2.90 mm (see Table 4). According to Table 4 and Figure 8, the average sizes of d_{35}, d_{50}, d_{65} and d_{eff}, for the wastewater flow were about 0.98, 1.45, 2.21 and 2.9 mm, respectively.

Effective Particle Diameter (EPD)

The effective or average hydraulic EPD d_{eff} was based on the applied sieve method in which particles were divided over the slides of sieves and calculated according to the

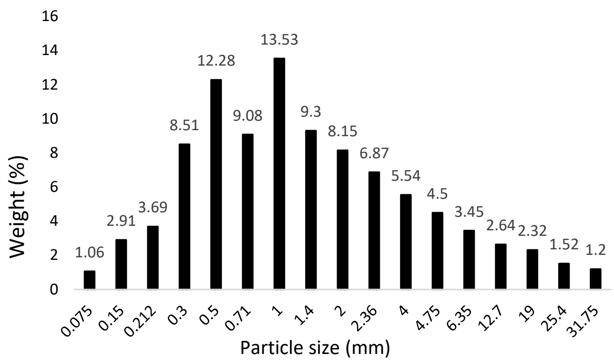

Figure 5. The Measured PSD in Dry Weather Condition

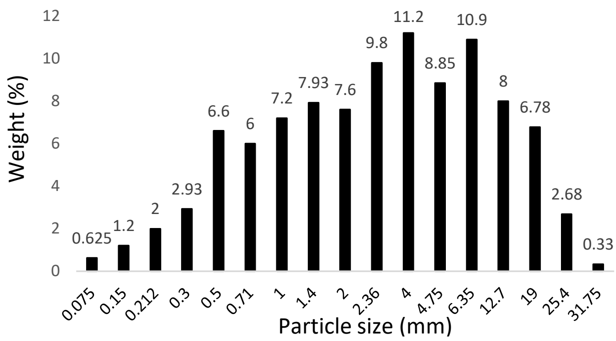

Figure 6. The Measured PSD in Wet Weather Condition

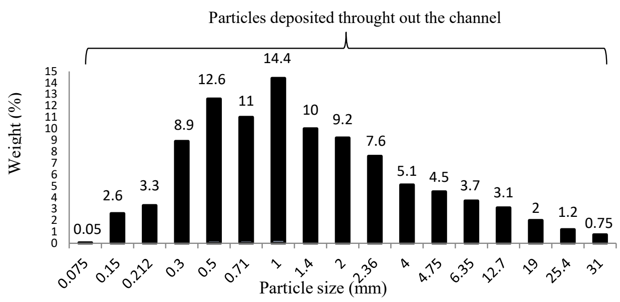

Figure 7. The Measured PSD in All Weather Conditions

appropriate geometric mean for the sieves as equation 1:

$$d_{eff} = 1/(\sum_{i=1}^{n} \frac{w_i}{d_{s.i}}) \quad (1)$$

where, d_s is particle size, w is the weight of each particle in percent and superscript n is the number of sieves that in this study is equal to 17. Thus, it is possible to calculate the EPD by using Equation 1 and Figure 8, which it gives 0.73 mm.

Mean Particle Diameter

The mean particle diameter of the sediments, as defined by Meyer-Peter and Müller in 1948, is expressed by equation 2.

$$d_m = \sum_{i=1}^{n} d_{s.i} w_i \quad (2)$$

where, d_s is the particle size, w is the weight of each particle in percent and superscript n represents number of each particle and n is the number of sieves. which was equal to 17 in this study. Therefore, it is possible to calculate the EPD by using equation 2 and Figure 8, which yields a value of 2.80 mm.

Table 3. Borderline Particle Sizes (in mm) Verified in Selected Samples of the Wastewater Flow

Date	WWTP of Khomein		Date	WWTP of Khomein	
	Min	Max		Min	Max
07.05.2020	0.15	6.35	10.21.2020	0.15	19
07.21.2020	0.15	12.7	11.05.2020	0.15	19
08.05.2020	0.15	12.7	11.20.2020	0.15	12.7
08.21.2020	0.15	12.7	12.05.2020	0.15	12.7
09.05.2020	0.15	12.7	12.20.2020	0.15	25.4
09.21.2020	0.15	12.7	01.04.2021	0.15	31
10.06.2020	0.15	12.7	01.15.2021	0.15	31

Table 4. Median Diameters of the Sediment (d_{50}) in the Wastewater Flow Collected From the WWTP

Date	WWTP of Khomein	Date	WWTP of Khomein
	d_{50} (mm)		d_{50} (mm)
07.05.2020	0.90	10.21.2020	1.30
07.21.2020	0.88	11.05.2020	1.60
08.05.2020	1.10	11.20.2020	1.50
08.21.2020	0.84	12.05.2020	1.90
09.05.2020	0.80	12.20.2020	1.80
09.21.2020	1.30	01.04.2021	2.90
10.06.2020	1.40	01.15.2021	2.20

Standard Deviation

In this study, the dimensionless standard deviation, σ_d, of particle distribution was calculated using equation 3.

$$\sigma_d = \sqrt{\frac{d_{84}}{d_{16}}} \quad (3)$$

where, σ_d is dimensionless standard deviation of particle distribution, the diater of sediments, d_{84}, for which 84% is finer and the diameter of sediments, d_{16}, for which 16% is finer. Based on the data in Table 5, the average standard deviation is calculated to be 3.18, falling within the range of 2.5 to 4.7.

Correction Factor

Correction factor can be employed to accurately estimate sediment combinations that are nonuniform, in contrast to sediment transport equations primarily designed for uniform sediments. In this research, the equation originally introduced by Wu et al[3] in the form of equation (4) has been refined and simplified through mathematical analysis based on the measured and computed total sediment load. Our calculations have determined the value of parameter "b" to be 0.79. Therefore, the modified version of equation (4) is represented as equation (5).

$$CF_d = e^{0.5(b \ln \sigma_d)^2} \quad (4)$$

Table 5. Dimensionless Standard Deviations of All the Samples

Sample no.	Σ_d	Sample no.	Σ_d	Sample no.	Σ_d	Sample no.	Σ_d	Sample no.	Σ_d
1	2.5	4	3.16	7	3	10	3.43	13	4.7
2	3.15	5	3.55	8	3	11	2.83	14	3.16
3	2.7	6	2.97	9	3.22	12	3.24		

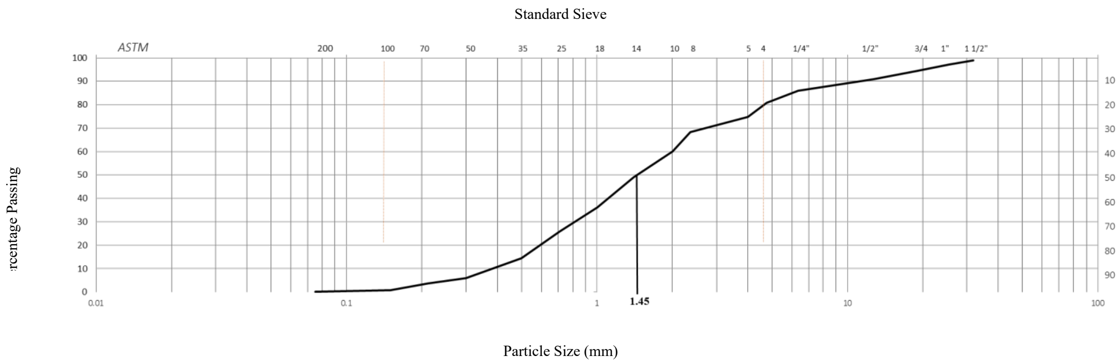

Figure 8. Gradation Curve for the Average PSDs of All the Samples

$$CF_d^{'} = e^{0.312(ln\sigma_d)^2} \quad (5)$$

Particle Size Distribution

The standard gradation test shows a high changeability of the PSDs in the wastewater flow. This discrepancy can be attributed to the fact that the flow samples were collected at the same location over extended intervals, leading to variations in the particle distribution obsd in the deposited sediments. This fluctuation suggests the presence of seasonal alterations in the distribution of particle sizes within the flow. Notably, particles measuring 1 mm in size constitute the highest percentage of the flow. As outlined in Table 4, the d_{50} size varies among all the samples, with values during wet weather conditions surpassing those in dry weather. Specifically, the average d_{50} value was approximately 0.98 mm in dry conditions and increases to 2.32 mm during wet weather conditions, underscoring the influence of weather patterns on PSD.

Particles Reynolds Number

One of the most popular and frequently used models for describing homogeneous liquid-solid fluidized suspensions is the model developed by Richardson and Zaki[26] as equation 6.

$$Re_t = \frac{\rho_l d_p v_t}{\eta} \quad (6)$$

where, Re_t is the Reynolds number of particle, ρ_l is the density of liquid phase, d_p is EPD, v_t is the terminal velocity and η is the dynamic viscosity of fluid.

As can be seen from equation 6, the value of EPD is very important to calculate Re_t. In addition, the determination of the EPD in urban wastewater flow is a crucial because of the existence of a wide range of solid particle diameters. Therefore, in this study using a sieve analysis the EPD of the urban wastewater flow was determined with a high accuracy and it can be used in equation 6.

Comparison the measured sediment rate with three famous total load methods

In this study, the unit weight per second of the sediments were measured in the flow according to equations 7 and 8. The results have been listed in Table 6. According to Table 6, the average weight of the sediment can be calculated using equation 7 as follows:

$$\overline{m} = \frac{1}{14}\sum_{i=1}^{14} m_i = \frac{1}{14} \times (13.02) = 0.93\,kg \quad (7)$$

where, $\overline{m}$ is the average weight of sediments in *kg* and m_i is the weight of each sample in *kg*.

Subsequently, by dividing the average weight of sediment by the duration of the experiment, the average sediment weight per second can be calculated using Equation 8 as follows:

$$\overline{M_t} = \frac{\overline{m}(kg)}{t(s)} = \frac{0.93\,kg}{420\,s} = 0.002\frac{kg}{s} \quad (8)$$

where, $\overline{M_t}$ is the average weight of sediment in *kg/s*, and *t* is time in *s*.

According to Equation 8, the measured average weight of sediment in the wastewater flow was equal to 0.002 *kg/s*. The relationship of the Graf and Acaroglu method,[27] the Laursen method[28] and the Yang and Lim method [29] are as equations 9 to 11, respectively:

$$q_t = \Phi_t \left(\Delta g d_i^3\right)^{0.50} \quad (9)$$

$$\overline{C}_t = 0.01\left(\frac{d_i}{h}\right)^{\frac{7}{6}} \left|\frac{\tau_0^{'}}{\tau_{0c}} - 1\right| f\left(\frac{u^*}{w_s}\right) \quad (10)$$

$$g_t = k\frac{s_0}{\Delta w_s}\left(u_*^2 - u_{*c}^2\right) \quad (11)$$

For more details about the above equations see Dey.[30] Table 6 gives a comparison of the measured and calculated weights of sediment in the flow. As can be seen in Table 6, without applying any correction factor the smallest relative error of the Graf and Acaroglu method, Laursen method and Yang and Lim method were 4.25, 10.80 and 1.60%, respectively. Therefore, the Yang and Lim method by using d_{65} as the EPD was the best method for calculating the total load of sediment in the flow. Hence, it can be asserted that d_m is appropriate for utilization in the Graf and Acaroglu method, d_{eff} suits the Laursen method, and d_{65} aligns with the Yang and Lim method. Furthermore, the application of the enhanced correction factor leads to a substantial reduction in the relative errors for all three methods. Table 7 reveals significant enhancements in the Graf and Acaroglu, Laursen, and Yang and Lim methods, with improvements of 82.70%, 93.10%, and 34.80%, respectively. It is important to note that the negative sign in Table 7 indicates that these methods tend to underestimate the total load in comparison to the measured total load of the flow.

Conclusion

- In this study, a significant effort has been made to meticulously measure and analyze the PSD of sediments in urban wastewater flows. The gradation curve of these particles and the EPDs of urban wastewater sediment have been accurately determined. These findings can serve as a valuable resource for other researchers aiming to calculate the Re_t and the total sediment load in sewer conduits. Furthermore, the sediment rate in the wastewater flow was quantified and compared with the results of three well-established total load calculation methods. The test results conclusively demonstrate that: There is a high changeability of the *PSDs* in wastewater flows. The *PSDs* were included sand and gravel particles in a diameter range from 0.075 to 31 mm.
- The average values of d_{35}, d_{50}, d_{65} d_m and d_{eff} in the wastewater flow were equal to 0.98, 1.45, 2.21, 2.80 and 0.73 mm, respectively.
- The mean values of d_{50} were about 0.98, 2.32 and 1.45 mm in dry, wet and all weather conditions, respectively.
- The total load of the sediments was measured and it was equal to 0.002 kg/s.
- The application of the enhanced correction factor significantly reduces the relative errors in all three methods. Notably, there is a substantial improvement in the Graf & Acaroglu method, with a reduction in relative error by 82.70%. The Laursen method also exhibits a noteworthy decrease in relative error by 93.10%, while the Yang & Lim method sees a moderate reduction by 34.80%.

Table 6. The Measured Weight of the Deposited Sediments

Date	Weight of Sediment (kg)	Date	Weight of Sediment (kg)
07.05.2020	0.84	10.21.2020	0.74
07.21.2020	0.80	11.05.2020	0.97
08.05.2020	0.88	11.20.2020	0.94
08.21.2020	0.92	12.05.2020	1.08
09.05.2020	0.77	12.20.2020	1.14
09.21.2020	0.81	01.04.2021	1.17
10.06.2020	0.85	01.15.2021	1.12

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Conceptualization: Mohsen Monadi, Mirali Mohammadi.
Data curation: Mohsen Monadi, Mirali Mohammadi.
Formal analysis: Mohsen Monadi, Mirali Mohammadi.
Funding acquisition: Mohsen Monadi, Mirali Mohammadi.
Investigation: Mohsen Monadi, Mirali Mohammadi.
Methodology: Mohsen Monadi, Mirali Mohammadi.
Project administration: Mohsen Monadi, Mirali Mohammadi.
Resources: Mohsen Monadi, Mirali Mohammadi.
Software: Mohsen Monadi, Mirali Mohammadi.
Supervision: Mohsen Monadi, Mirali Mohammadi.
Validation: Mohsen Monadi, Mirali Mohammadi.
Visualization: Mohsen Monadi, Mirali Mohammadi.
Writing–original draft: Mohsen Monadi, Mirali Mohammadi.

Table 7. Comparison of the Measured and Calculated Sediment Rate

Total Load Method	Relationship	Relative Error (%)					
		d_{35}	d_{50}	d_{65}	d_m	d_m	After applying CF_d Using d_{50}
Graf & Acaroglu Method (1968) [27]	$q_t = \Phi_t \left(\Delta g d_i^3\right)^{0.50}$	185	60	25	-4.25	-4.25	10.34
Laursen's Method (1958)[28]	$\overline{C_t} = 0.01\left(\frac{d_i}{h}\right)^{\frac{7}{6}} \left\lvert \frac{\tau_0^{'}}{\tau_{0c}} - 1 \right\rvert f\left(\frac{u*}{w_s}\right)$	19	50	140	215	215	3.45
Yang & Lim's Method (2003)[29]	$g_t = k\frac{s_0}{\Delta w_s}\left(u_*^2 - u_{*c}^2\right)$	1795	761	-1.6	285	285	496.5

Writing–review & editing: Mohsen Monadi, Mirali Mohammadi.

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