International Journal of GEOMATE, May., 2021, Vol.20, Issue 81, pp.35-43
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.81.j2072
Geotechnique, Construction Materials and Environment

# THE INFLUENCE OF SEMBAYAT WEIR ON SEDIMENT TRANSPORT RATE IN THE ESTUARY OF BENGAWAN SOLO RIVER, INDONESIA

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*Corresponding Author, Received: 31 Dec. 2020, Revised: 30 Jan. 2021, Accepted: 13 Feb. 2021

**ABSTRACT:** This research is aimed to assess the sediment transport rate under different conditions of estuary geometry by comparing the situations before and after the construction of Sembayat Weir. Sediment concentration, flow velocity, and temperature were obtained via field investigation from October 2016 to September 2017. River discharge and tidal discharge phenomenon are analyzed in the estuary, which affect hydraulic head changes. The HEC-RAS model was used for numerical modelling simulation of the hydrodynamics. The results revealed that the sediment transport rate increased under the influence of erosion in the river branches. BH2 and BH3 were the observation sites located before and after the tributary junction. Those location present the sediment transport rates decreased by 30% and 26%, respectively, in the rainy season because after weir construction. The results agree with previous research results in that sediments were deposited around the estuary weir. Meanwhile, in the river branches, a higher sediment transport rate was observed because of the tidal current that provided sediment transport over a longer term in the dry season. The findings extend the knowledge on the influence of Sembayat Weir on sediment transport rate characteristics with respect to seasonal changes.

*Keywords: Bengawan Solo River, Sediment Transport Rate,Seasonal Changing, HEC-RAS, Field Investigation.*

## 1. INTRODUCTION

The rate of sediment transport to an estuary is one of the important factors for assessing the rate of deposition. Deposition results in the geometry of alluvial deposits and reduces the flow discharge capacity of the river. Modification of geometry is also termed as morphological changes. Most studies on modelling morphological changes in an estuary have adopted numerical approaches. The prediction accuracy with two-source hydrodynamic sediment transport, including mixed sand-mud material (bedload and suspended load transport), was improved using a two-dimensional (2D) depth-averaged model [1]. Long-term simulation of fine sediments, which are affect by a three-regime hydrodynamic model (tidal flow, discharge, and wave condition) was performed [2]. In addition to hydrodynamic factors, physical factors too influence the sediment transport rate via morphological changes, such as the changes resulting from the presence of a weir, meandering of the river [3], and branching of the river; these physical factors have been explored in this study.

The effect of weir construction on sediment transport rate was studied and discussed based on the characteristics of suspended sediment concentration (SSC) in the estuary by statistical analysis and spectrum analysis for the conditions before and after construction [4]. Carroll, B., Li, M., Pan, S., Wolf, J., and Burrows, R. [5] examined a weir-imposed scenario created by the operation of two sluice gates and a turbine generator on the middle section. The effect of a weir on sediment control depends on the flow discharge. Generally, a weir in an estuary depletes the discharge via opening and closing operations through an upward (rubber weir) or downward (sluice weir) construction. Sluice weirs have the disadvantage that the sediment which induced on the upper weir [6]. This sediment has to be flushed indirectly (Fig. 1), resulting in morphological changes. This situation arises immediately after the gate is opened and the water level decreases. Furthermore, the case studies of river branches or tributaries are lacking. Cardot, R., Moradi, G., Mettra, F., Rennie, C., and Lane, S. [7] stated that river bed geometries at the junction of a tributary likely reflects the erosion and deposition patterns linked to the specific hydrodynamic circulation.

The sedimentation has not given negative impact in the estuary at all times. According to the locally fisherman, forming feature sedimentation in the estuary has given an advantage for farming mangrove area, it was also stated by Rosalina H. [8] at Citanduy River and Sutopo [9]. A previous work on Bengawan Solo River, a meandering river, examined the process of morphological changes and focused on the SSC resulting from erosion and the effect sediment grain size [3,8,11]. The rate of sediment transport before and after meandering was also observed, in particular, at the inner and outer riverbank. Soil properties related to sediment deposition were also assessed for selecting the dredging method to reduce excessive sedimentation

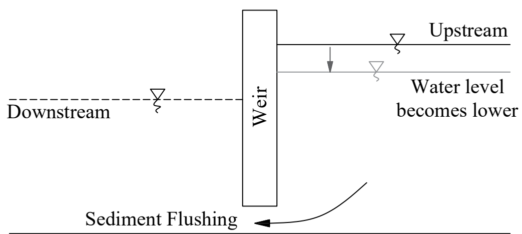


Fig. 1 Gate operation system at a weir

[12]; this study focused on the sediment transport rate influenced by the discharge variety affected by Sembayat Weir, a sluice weir, in the upstream region and river branches in the estuary. Its main function is to support industrial and irrigation water requirements in Gresik and Lamongan Regencies by providing long-term storage capacity; it also inhibits sea-water intrusion. The weir also plays an important role in controlling the discharge outflow, thereby greatly affecting the society—for example, by preventing flooding during the highest rainfall event in a season. The estuaries of Bengawan Solo River located in Ujung Pangkah in Gresik were chosen in this study because of the morphological changes observed here (Fig. 2). Considerable changes were observed every 20 years. In the period 1972–1994, the estuary had tributaries, namely, Lewean and Lebakan Rivers. In this period, the area of deposition had increased by about 10 km$^2$. Meanwhile, in 2015, the main channel of Bengawan Solo River projecting to north–northwest (NNW)

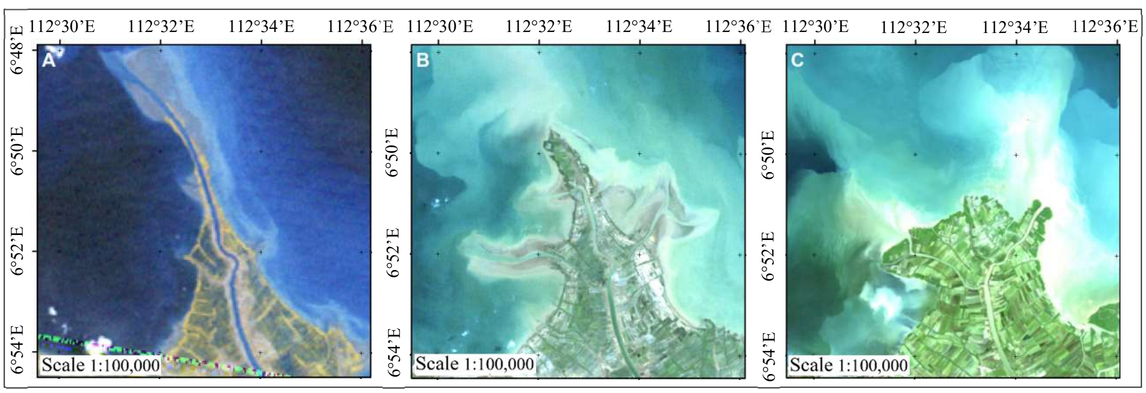


Fig. 2 Morphological changing history (A. 1972; B. 1994; C. 2015). The picture was taken from historical imagery of Google Earth.

began to disappear and the name of main channel from junction A to the river mouth changed to be Turi River by the locally fisherman. The sedimentation area resembled that of the 1994 dissemination period that was caused by the hydrodynamic behaviour of current flow and wave energy. The periodic repetition of the hydrodynamic behaviour led to the spreading out of the sedimentation region, forming a funnel-shaped area where the entry of flow water is unrestricted [12]. Further, regions upstream the river had high sediment concentration; for instance, the Kanor area was reported to have a sediment concentration between 500 and 1700 mg/l and a flow discharge between 20 and 445 m$^3$/s [10]. Those results indicate that extremely high sediment transport rate influences morphological changes. Furthermore, the morphological changes were manifested not only in the longitudinal shifting of the riverbank, but also in changes in the riverbed. Fig. 3 shows the study site. BH2 and BH3 were chosen as the observation sites. BH 3 was chosen owing to its shallow geometry as compared to Turi and Lewean Rivers (Fig. 3). BH 2 chosen was chosen to consider the control on the sediment transport rate before the river branches. Originally, Turi River was the main channel originating from Bengawan Solo River, but as the geometry of the region narrowed, it changed into a tributary. Currently, Lebakan River exhibits the constancy of the main channel. The water depth at the lowest tide was 0.5 m, 3 m, 1.5 m, and 3–3.5 m at the mouths of Lebakan, Turi, Lewean River, and Junction A–B, respectively. This case indicates that because of the slope of Lebakan River, the estuary is at a higher elevation than the upstream of Junction A or Bengawan Solo River (Fig. 4). On the other hand, the width of the Bengawan Solo River downstream Lebakan River did not vary

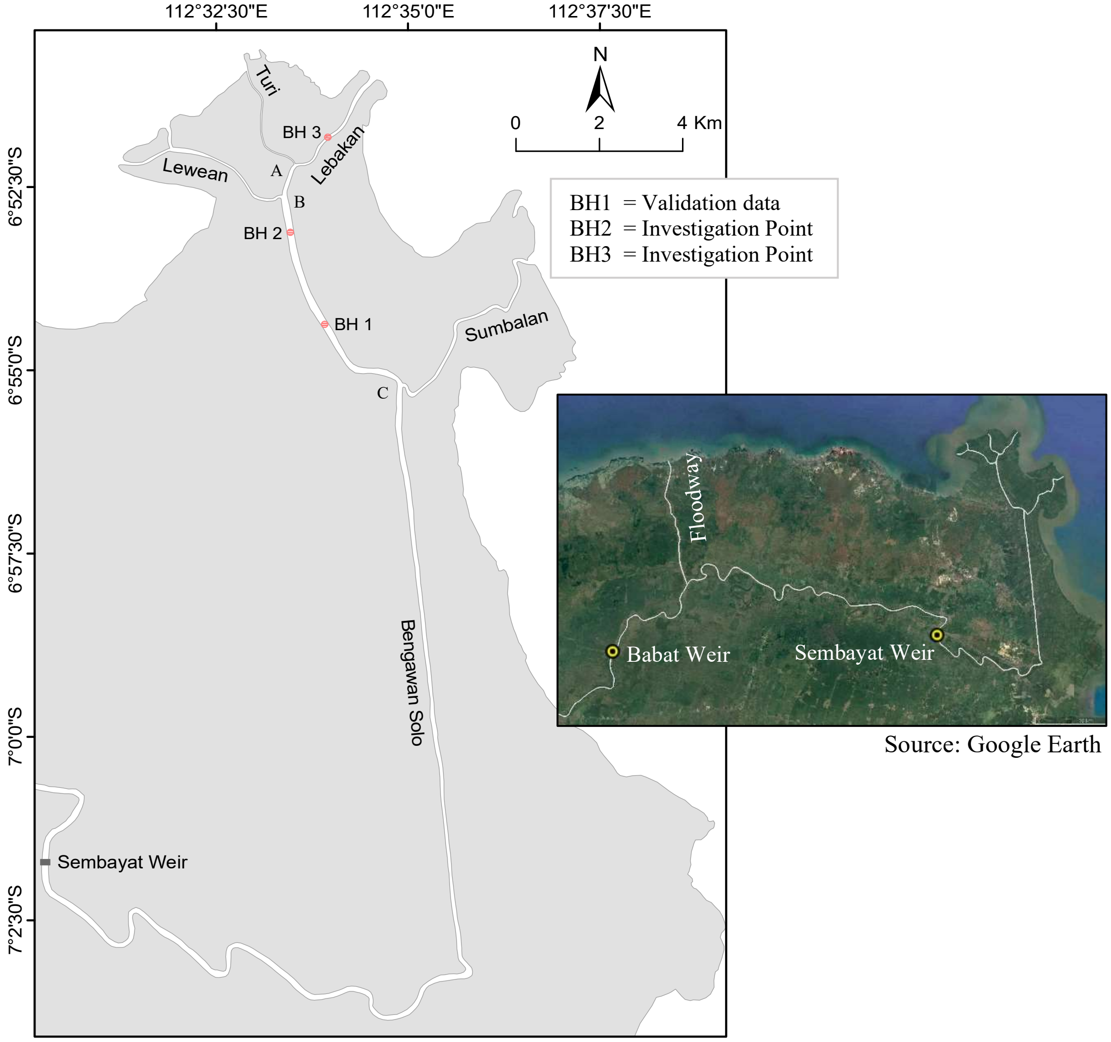


Fig. 3 Study site locations (BH1 was selected as a control for water level for 15 days; BH2 and BH3 were selected to observe the conditions before and after the river branches, respectively)

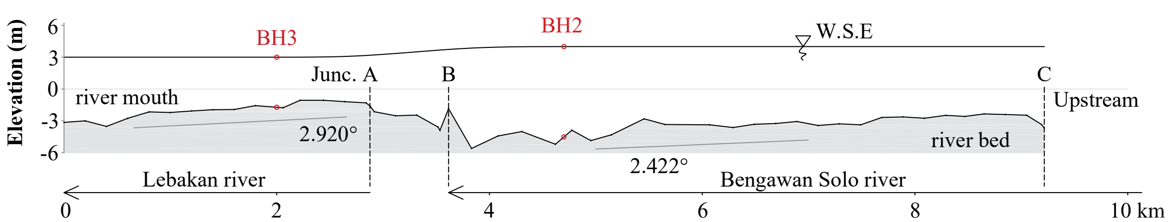


Fig. 4 Slope of the riverbed from Junction C to the mouth of Lebakan River

significantly; it was 120–180 m. BH3, BH2, and Sembayat Weir are located 2 km, 4.7 km, and 39 km away, respectively, from the mouth of Lebakan River.

Sembayat Weir is a relatively new construction, and its operation commenced in October 2016. The width of this weir is 161 m, and it has seven gates. As shown in Fig. 5 and based on the information obtained from residents surveyed by the authors, the middle gate was always opened first when the water level at the upstream weir reached the maximum. The picture shown in Fig. 5 was obtained on 20 September 2019. For three years of operation from 2016 to 2019, no maintenance was conducted to counter sedimentation upstream of the weir. The authors guessed that sediment transport to the estuary had reduced the deposition downstream the weir. Fig. 9A and 9B illustrate the deposition and erosion, respectively, before and after the construction of Sembayat Weir. The longitudinal deposition area at Junction A was higher in 2012–2013 (7.6 m) than in 2017–2018 (2.7 m). Nevertheless, at Junction B, the deposition area changed by only 1 m during the same period; in other words, there was no significant change. The objective of the present study was to assess the sediment transport rate under two cross-section geometric conditions (i.e., at BH2 and BH3) as influence of Sembayat Weir. This research was divided into three phases. The first result will be used for the next study as a load for self – weight sediment consolidation that deposited in the estuary. Furthermore, the hydrodynamic behaviour of hydraulic head is also discussed in this study.


Fig. 5 Sediment deposition after Sembayat Weir construction (on 20 September 2019)

## 2. METHODOLOGY

This research was conducted in three phases—field investigation, laboratory observation, and numerical modelling. Field investigation was undertaken to get the bathymetry data, flow velocity, sediment concentration, sampling water and temperature. The bathymetry data were measured by using a fishing boat to conduct echosounder mapping along ±36 km from Sembayat Weir up to downstream the Bengawan Solo River (Junction B). Measurements were also made for all the river branches (Turi, Lebakan, Lewean, and Sumbalan Rivers). The bathymetry data were processed to obtain contour depth data, and some cross sections were obtained as geometric input data for the numerical model. Bathymetry data were recorded on June 2017. Flow velocity, sediment concentration, and temperature were obtained at the same time in each month, from October 2016 to September 2017. The measurements were made by dividing every cross section into a five- and four-part column at BH2 and BH3, respectively. Each column consisted of three sampling materials based on the water depth (h), i.e., 0.2h, 0.6h, and 0.8h. Sediment concentration was obtained using a bottle water sampler. At the same location, the temperatures were obtained using a water quality tester (Constant WT61), and the flow velocity was tested using an electromagnetic current meter (Marsh Mc Birney Model 21, with ±0.5% accuracy). To obtain the average flow velocity in the wide cross section, for each water column, the following equation was applied:

$$\bar{U} = 0.25U_{0.2} + 0.5U_{0.6} + 0.25U_{0.8} \tag{1}$$

where $\bar{U}$ is the average flow velocity (m/s), and $U_{0.2}$, $U_{0.6}$ and $U_{0.8}$ are the flow velocities at 0.2, 0.6 and 0.8 m of water depth, respectively [13]. Further, Sediment concentration was observed in the Laboratory of Soil Mechanics and Rocks (ITS Surabaya) following the ASTM D 3977-96. Examining to reach the sediment transport rate of a mud deposit ($q_b$) was obtained using the following equation:

$$q_b = \frac{C_M\left(\rho_B - \rho\right) g \cdot d_m^3 \sin\beta}{3\mu} \tag{2}$$

where $C_M$ is the mass concentration (dry density) of mud at height $z$ or 0.8h (kg/m$^3$); $g$ is the acceleration due to gravity (m/s$^2$); $d_m$ is the thickness of the mud layer (assumed as 0.1 m following the dimension of the grab sampler); $\beta$ is the angle of slope of the riverbed (Fig. 4); and $\mu$ is the dynamic viscosity of mud (Ns/m$^2$). Dynamic viscosity was obtained from the graph of the parameter relationship between temperature and kinematic viscosity [14]. As the temperature average was 29°C, the dynamic viscosity was set as 0.82 Ns/m$^2$. The wet density of the mud layer $\rho_B$ (kg/m$^3$) was calculated as follows:

$$\rho_B = \rho + C_M\left(\frac{\rho_s - \rho}{\rho_s}\right) \tag{3}$$

The density of water sources was obtained from the average of sampling water density $\rho$ which ranged 996–1003 kg/m$^3$ (Table 1). Therefore, the density was assumed as 1000 kg/m$^3$. Further, $\rho_s$, the sediment grain density, was 2650 kg/m$^3$. Equation (2) and (3) are based on the consideration of dynamics of mud deposition in an estuary [15], and the data were organized separately to identify the sites from where the data were obtained (Appendix).

The numerical model was used to obtain the sediment transport rate for two years. Modelling was based on the conceptual framework of HEC-RAS 5.0.3 1D module (*www.hec.usace.army.mil*). In this study, simulation was performed for data for the period January 2017 to December 2018 under assumption of absence of the weir (which was under construction) in 2017.

Table 1. Data measurement of water physics and mechanics (October 2016–September 2017)

| | BH2 | | | BH3 | | |
|---|---|---|---|---|---|---|
| Sampling Time | ρ (kg/m³) | Temp (˚C) | Ū (m/s) | ρ (kg/m³) | Temp (˚C) | Ū (m/s) |
| Oct, 2016 | 996.09 | 28.84 | 0.56 | 996.11 | 29.05 | 0.57 |
| Nov, 2016 | 996.57 | 28.17 | 0.99 | 996.57 | 28.18 | 1.09 |
| Dec, 2016 | 996.14 | 28.72 | 0.83 | 995.98 | 29.28 | 0.84 |
| Jan, 2017 | 996.03 | 29.22 | 0.57 | 995.46 | 31.10 | 0.44 |
| Feb, 2017 | 996.21 | 28.62 | 0.97 | 996.28 | 28.40 | 0.79 |
| Mar, 2017 | 995.79 | 30.22 | 0.60 | 995.96 | 29.65 | 0.43 |
| Apr, 2017 | 996.23 | 28.48 | 0.97 | 996.08 | 28.95 | 0.93 |
| May, 2017 | 996.18 | 30.22 | 0.22 | 1001.84 | 30.53 | 0.23 |
| Jun, 2017 | 996.51 | 28.68 | 0.12 | 1000.71 | 28.95 | 0.09 |
| Jul, 2017 | 1001.77 | 28.74 | 0.20 | 1001.42 | 29.15 | 0.21 |
| Aug, 2017 | 1002.46 | 28.36 | 0.13 | 1002.64 | 28.85 | 0.08 |
| Sep, 2017 | 1002.49 | 29.30 | 0.11 | 1002.21 | 30.33 | 0.08 |

### 2.1 Boundary Condition

Flow discharges and water levels were used as the boundary conditions upstream and downstream the river, respectively. Discharge data of 2018 were obtained from public corporation of river basin agency (Perum Jasa Tirta 1), as shown in Fig. 6a. The data for 2017 supported from Babat Weir. The sources were different because Sembayat Weir was newly constructed. There is no valid information for the initial period of weir operation, but reporting of data commenced in January 2018. Babat Weir is located 12.4 km upstream of Sembayat Weir (Fig. 3), and there is floodway which shortcut the discharge to the sea partially. Therefore, the secondary data was used to reach the outflows discharge in 2017. It was based on the return-period of flood flows as follows $Q_{1.5}$, $Q_2$, $Q_5$, $Q_{10}$, $Q_{25}$, and $Q_{50}$ [16]. $Q_{1.5}$ until $Q_{50}$ are return-period in a year. The data was analyzed by using a linear function as shown below:

$$Q_{sembayat} = 0.7142Q_{babat} + 118.16 \quad (4)$$

where $Q_{babat}$ is the discharge outflow from Babat Weir, and $Q_{sembayat}$ is the discharge inflow to Sembayat Weir. The downstream boundary condition is a water level based on *tides.big.go.id* (Fig. 6b).

### 2.2 Validation

The simulation results were calibrated with the in-situ water level at BH1; the water level was recorded by a digital video camera for 15 days (6–20 November 2018) and indicated a diurnal tide (Fig. 7). From a comparison of the numerical model and field measurements, the root mean square error (RMSE) was 0.9; in other words, the simulation was close to the actual condition. Thus, this model was capable of predicting the dynamics of the water level.

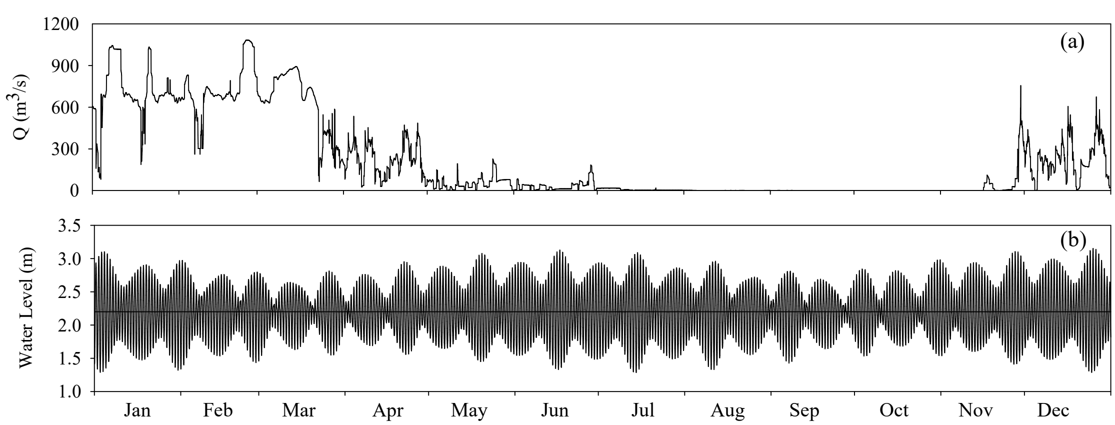


Fig. 6 Upstream boundary condition at Sembayat Weir in 2018 (a), and downstream of the mouth of Lebakan River (b)

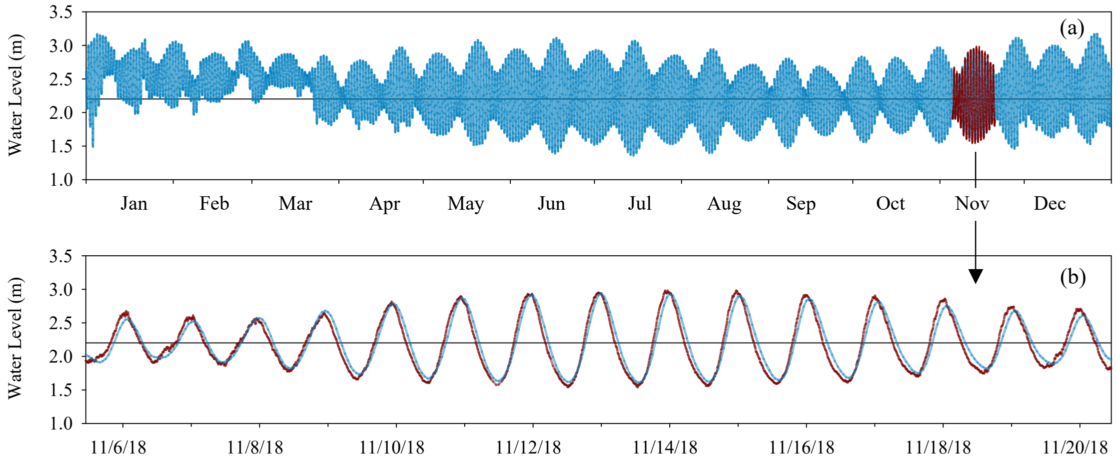


Fig. 7 Validation of the simulation results at BH 1 (red colour represents field measurement data, whereas blue colour represents simulation data)

There is gap in time sampling for bedload sediment and boundary condition data. Therefore, the analysis was carried out using different methods. Prediction of the sediment transport rate $q_b$ (kg/m$^3$) followed the power-function curve shown in the equation below:

$$q_b = aQ^b \quad (5)$$

where $Q$ is the discharge (m$^3$/s), and a and b are fitted parameters [17]. The equilibrium of flow discharge through the river branches can be separated as shown in the equation below:

$$Q_1 = Q_2 + Q_3 \quad (6)$$

where $Q_1$ is the flow discharge from the main river or Bengawan Solo River, $Q_2$ and $Q_3$ are flow discharge distribution to two river branches, i.e. Lewean and Turi River, respectively.

## 3. RESULTS AND DISCUSSION

### 3.1 Effect of River Branches on Sediment Transport Rate

Fig. 8 shows a comparison of the results obtained from observation data of the flow discharge and sediment transport rate at BH2 and BH3 and the results reported by Warrick [18]. BH2 and BH3 present the lower R-Square than Warrick. It seems possible that these results are due to Warrick site observation did not focus in the estuary, and the presence weir also obstructs the sediment transport rate. The R-square and sediment transport equation based on the graphs were used to predict the sediment transport rate described in sub-chapter 3.2. Based on the concept of flow discharge balance shown in Eq. (6), BH2 is supposed to have

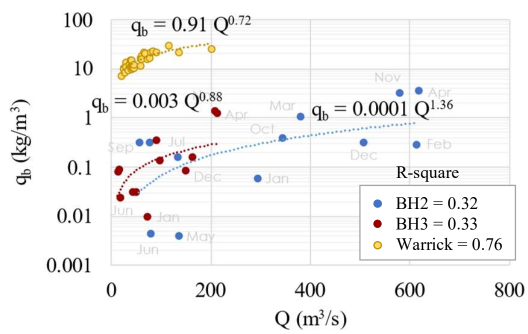


Fig 8. Correlation between flow discharge and sediment transport rate (October 2016–September 2017)

higher sediment transport rate than at BH3, which is located after the point where the river branches. The flow discharge conditions in range 13–210 m$^3$/s are illustrated (Fig. 8). The river width at BH2 and BH3 are 180 and 80 m, respectively. Because of erosion susceptibility, the sediment transport rate at BH3 was higher than that from downstream of Sembayat Weir. Nonetheless, BH2 still has more discharge flow capacity. Therefore, increase in the flow discharge also increases the sediment transport rate progressively. For BH2, the material sediment brought was 3.61 kg/m$^3$ with the maximum flow discharge of 617 m$^3$/s, whereas for BH3, 1.35 kg/m$^3$ of material sediment was transported under the maximum flow discharge condition of 210 m$^3$/s. Inconsistencies between the discharge flow and the sediment transport rates, as observed for the months of April and February for BH2 were due to the differences in the average flow velocity (Table 1).

With regard to transport rate, the observed behaviour of the sediment transport rate is similar to that in the Eel River, California [18]. The annual sediment rating curves are observed for higher sediment concentrations because of vulnerability to erosion [19]. These results provide important insights into the behaviour of sediment transport rate under the influence of physical objects. In this research, it was found that the use of water and sediment balance as applied for converging flows [17] is also valid for branch flows; this finding is consistent with the literature. Thus, it was concluded that the river discharge along BH2 to BH3 results in high erosion.

The impact of a higher river discharge is presumed to be larger because of the high sediment influx and high erosion potential [13,14]. From Fig. 9B, it is seen that an alluvial deposit on the left side after Junction B could be more easily eroded than that on the right side, which suffered little erosion. The embankment was eroded by 1 m per year; deposits tend to accumulate on the inner left side of Lewean River. This feature was also observed at Junction A (Fig. 9A); the volume of deposition was greater on the right side than the eroded volume on the left side. This finding agrees with findings of other studies on Medjerda River in which channel morphology changes and flow discharge were linked [20]. Although that study reported high deposition and narrowed meandering section of the river, these changes was due to the weir as explained in the next subsection. The source of the deposited sediment was not merely the river; the amount of marine sediments in the estuary also increase because of relatively strong tidal currents that result in changes in the suspended sediment delivery in the estuaries [21]. However, the sediment source classification is beyond the scope of this study, and will be discussed separately. The shape and radius of the river branches also influence the distribution of flow discharge [22] and sediment transport rate. The sediment distribution rates for transport to Turi River and Lebakan River show a unique behaviour. The rates for the Turi River and Lebakan River increased and resulted in narrow and shallow morphologies, respectively. Taken together, these results suggest that there is an association between the river branch and sediment transport rate.

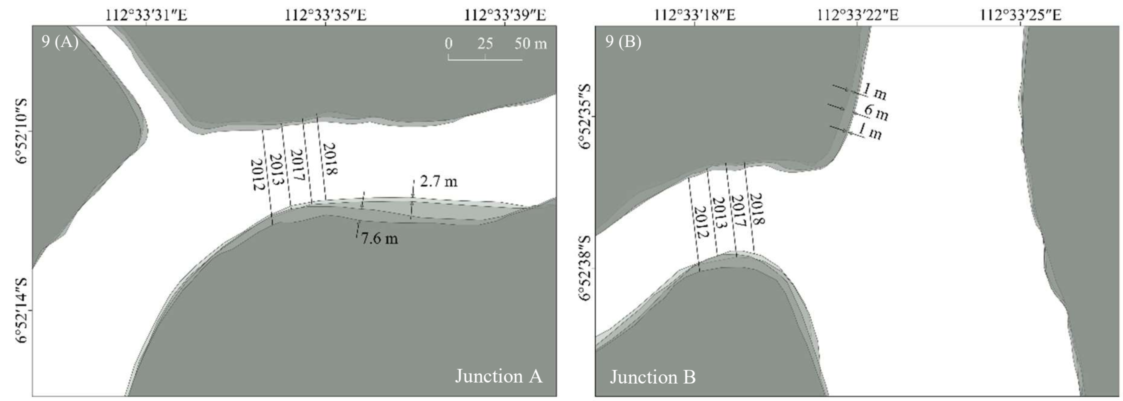


Fig. 9 Morphological changes at Junction A (9A) and Junction B (9B). The map was digitised based on historical imagery from Google Earth (18 August 2012; 9 August 2013; 21 April 2017; and 16 June 2018)

## 3.2 Effect of Sembayat Weir on Sediment Transport Rate

Now, the hydraulic head and sediment transport rate correlation are considered; in this case, the behaviour of sediment rate was very strongly influenced by seasonal changes. Please note that the hydrodynamics of the hydraulic head was influenced by the flow discharges and tides. Fig. 10 shows the diversity of hydraulic head (grey line), and the correlation with the sediment transport rate (blue and red lines represent BH2 and BH3, respectively). The results of the sediment transport rate were obtained from the equations for BH2 and BH3 (Fig. 8). In other words, the relation between flow discharges obtained from the HEC-RAS model was substituted for the equation. A high sediment transport rate was observed in the five months of the rainy season every year.

Before Sembayat Weir was built in 2017, for the sediment transport rate for BH2 in the rainy season, the highest mean frequency was 0.4–0.6 kg/m$^3$. Meanwhile, in 2018, after the construction of Sembayat Weir, the mean highest sediment transported was ranged 0.2–0.4 kg/m$^3$. Compared with the cumulative sediment transport in 2017, the value decreased by 30% in 2018 (Fig. 11A).

The sedimentation at the inflow of the gate was one factor reducing the sediment transport rate to estuary (Fig. 5). Zahar, Y., Ghorbel, A., and Albergel, J. [20] reported weirs result in the rapid narrowing of the downstream channels, and one part of the cross section of Medjerda River studied by them had shrunk by 20% in 15 years. A similar scenario model was obtained by simulation for Mersey River [5]. The results of these studies

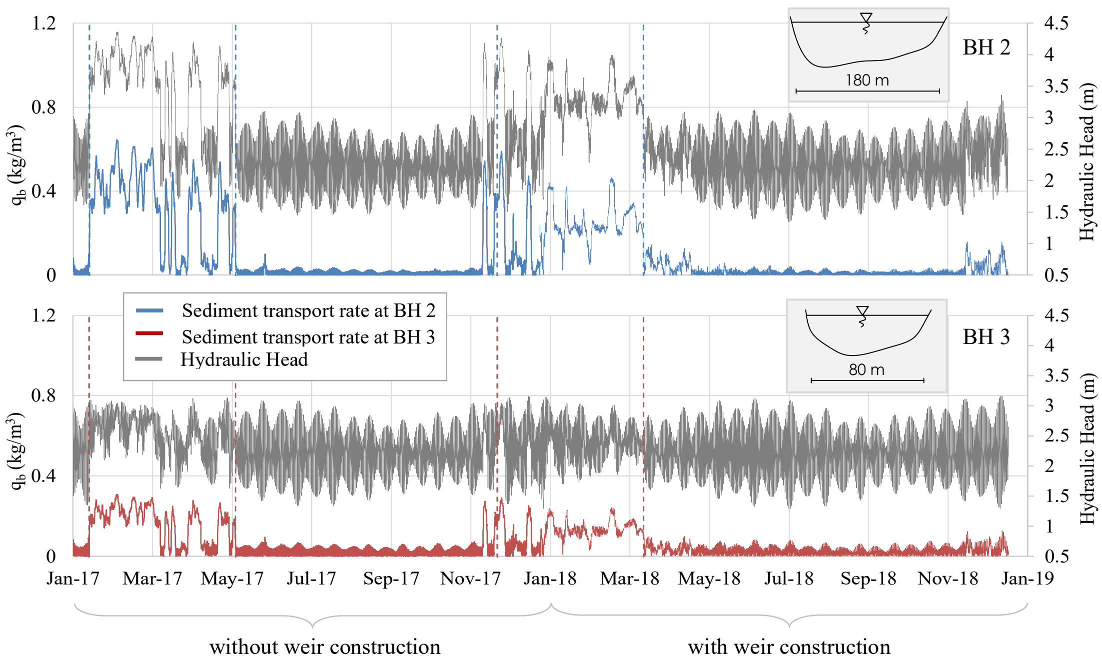


Fig. 10 Changes in sediment transport rate because of Sembayat Weir

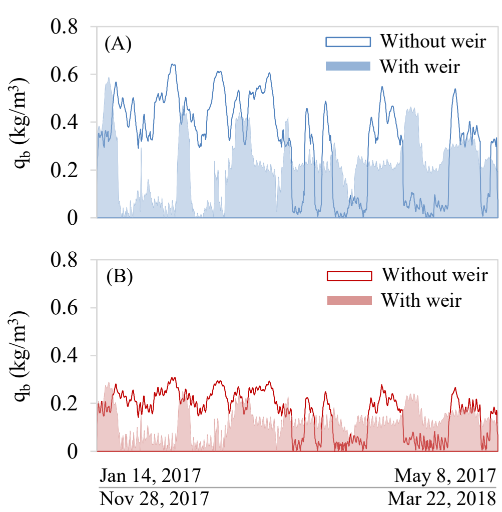


Fig. 11 Comparison of sediment transport rates at BH2 (A) and BH3 (B) before and after Sembayat Weir was built in the rainy season

imply that sedimentation occurs around a weir itself, leading to a decrease in sedimentation in the estuary. With regard to the sediment transport rate in 2017 (without weir), though the total sediment distributions of Lewean and Turi Rivers can be estimated, the specific transport rates of these rivers could not calculate because there were no measurements. The sediment transport in the main channel contributed 51.43% to Lebakan River in the rainy season; however, during the dry season, Lebakan River transported 75.92% higher sediment than the main channel, and this has occurred within longer period than on rainy season. The reason for this behaviour was the dominant role of tidal current phenomenon [23]. The impact of Sembayat Weir on BH3 does not show a significant increase; the sediment transport was reduced by 26% in the rainy season (Fig. 11B). In summary, because of the effect of the weir, the sediment transport rate at BH2 was largely reduced, but the effect was less at BH3. From another viewpoint, the weir led to an advantage for agriculture by controlling discharge irrigation can be overtaking. Unfortunately, the weir affected sedimentation in the upstream region.

## 4. CONCLUSION

This study revealed that generally, the sediment transport rate increases because of the influence of erosion at the tributary junction or river branches. The hydrodynamic model was validated using in situ water level fluctuations at BH1, with RMSE of 0.9. Thus, the sediment transport rate may change more rapidly at BH3 than at BH2 during the dry season because sediment was transported over a longer term by the tidal current. Likewise, geometry changes are also occurred in the surrounding area simultaneously. The influence of Sembayat Weir led to a reduction of 26–30% in the sediment transport rate at BH2 and BH3 after construction; these conditions were observed during the whole rainy season. This study contributes to the existing knowledge on sediment transport rate characteristics with respect to seasonal changing in the estuary under the influence of a physical object. If maintenance of the back of the weir is conducted periodically, the sediment transport rate from the river attributed to the weir will not change the morphology of the estuary significantly.

## 5. ACKNOWLEDGMENTS

This research was funded by National Academy of Science and Research Grant for Master Program of Education Leading to Doctoral Degree for Excellent Graduates 2015–2019 from Directorate General of Higher Education–Ministry of Education and Culture. We thank Partnerships for Enhanced Engagement in Research (PEER) program for inviting to apply for funds to support research and capacity-building activities, and also Japan Student Services Organization program for supporting the research collaboration.

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