Suspended Sediment Distribution Corresponds to Erosion and Deposition Processes at Bengawan Solo River, Indonesia

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Abstract*—Bengawan Solo River is one of the longest natural channels in Indonesia which functioned as irrigation, fresh water supply and flood control. This river covers up to 1.6x10^{6} ha of area from the mountainous region in the Central of Java to the North Sea of Java with approximately 600 km of river reach length. Bengawan Solo River is an alluvial river indicated by Holocene formation along the river flow. Since alluvial soils were easy to transport, the river morphology changing becomes main problem. The river morphology changing causes local river channel alteration such as degradation, aggradation, river channel enlargement, and equilibrium of river profile. During this work, the suspended sediment concentration (SSC), flow discharge (Q) and flow velocity (u) were investigated as primary data through field work. The SSC provides the maximum and minimum value with 1496.868 mg/l and 294.308 mg/l respectively correspond to the climate succession in Bengawan Solo River basin area. The suspended sediment value shows the promising sediment equilibrium correlation with the river profile transformation tendency. Inequality between input and output sediment concentration in this study explains the mechanism of river channel alteration including deposition and erosion processes. Further, the correlation between flow regime which expressed by Reynold number (R_e) and SSC was presented to evaluate river channel changes.

***Keywords*—sediment, erosion, deposition, morphology, Bengawan Solo River**

I. Introduction

An alluvial river, the most active natural channel is always fascinating to be studied since it's developed continuously. Fine material which composed river bed allows the channel altering easier than another river type. The study of river geomorphology changing involves some aspects such as hydrological conditions, hydraulic parameters, sediment transport, and geological formation. The precipitation as a hydrological aspect in basin area provides flow discharge in the channel which transported the sediment materials along river stream. In a large river, the sediment transport can be a significant issue in river morphology changing [1]. A massive sediment quantity comes along with large flow discharge especially in alluvial river [2]. This indicates that the alluvial river is quite sensitive to response the changes of hydrology condition in accordance to the sediment transport dynamic leads to river morphology alteration. In order to evaluate river morphology changes, the sediment budget is proposed as easiest way to predict the channel changes along observed section [3]. By observing sediment quantities, the erosion and sedimentation that may occur in the river segment can be determined. Moreover, the river morphology changing can be considered according to the erosion and sedimentation since these forms are the fundamental processes in river dynamic development.

The correlation between river flow and suspended sediment concentration (SSC) was indicated at Sukhaya Elizovskaya River, Rusia [4]. The study related with SSC has also conducted according to average flow and suspended sediment discharge between 1959 and 1969 in the Wuding River, China [5]. The detail new sediment concentration measurement associated with some turbulence characterization was performed in the undular tidal area of the Garonne River, France [6]. Another study resulted that the SSC at the bottom of riverbed was 280% of the total concentration at the water surface and the depth-averaged SSC was 180% of the total SSC at the water surface [7]. In other hand, the research of relation between SSC and bed shear stress shows that the suspended sediment concentration has a strong influence on the bed shear stress [8].

Commonly, Indonesian rivers classified into alluvial rivers as they are normally situated in residual soil [9, 10]. River conditions are varied during the dry and wet season. Water level river fluctuations, sedimentation rate, scouring and river water current are greatly varied due to the great difference of rainfall rate and temperature during the dry and rainy season. Curvaceous river morphology, deforestation and illegal sand

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river mining are triggered sedimentation and degradation phenomenon likely to be occurred [11].

II. Site Study

Bengawan Solo River is one of the most important river streams in Java Island. The stream length is approximately 600 km and it becomes the longest river in Java Island. Many problems occurred in this river due to the complexity of it river network, such as: flood, river morphology changing, illegally river sand mining, infrastructures failure, etc. Bengawan Solo River is one of a typical monsoon river that has been studied in detail to obtain more information on the interrelations between flow, sediment transport and depositional processes [12]. Mainly, the sediment transport problem is dominated in this river as erosion and sedimentation occurs in many sections. Deforestation resulted in soil erosion for the river basin and brings the soil material into the river stream. On the other hand, illegally sand mining in the river stream is causing river bed degradation. In a large scale, this phenomenon triggered excessive sediment load and lead the river morphology changing. Furthermore, the river capacity decreases as sediment transport result causes flood and inundation along river stream. One of the areas that most affected by the dynamic of Bengawan Solo River is Bojonegoro which experiences flood almost in every year. Therefore, the study location is proposed at Kanor, Bojonegoro, East Java. At this location, the river section is characterized by curvaceous channel and riverbank failure as river erosion indication. The field measurements were conducted at three cross sections as shown in the Fig. 1 [13].

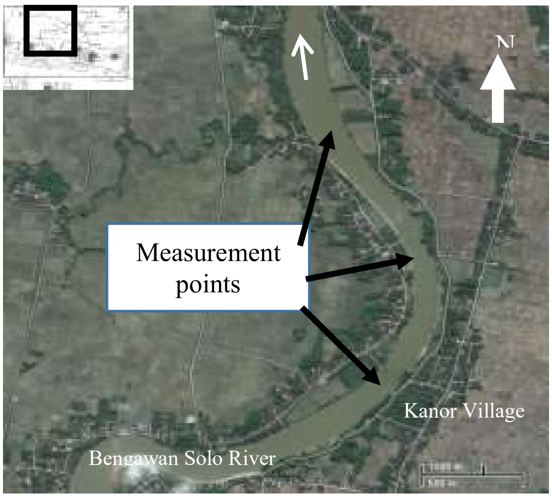

Fig. 1. Meandering segment of Bengawan Solo River as site study

III. Methodology

The field investigations, laboratory investigations and data analysis were conducted to obtain the sediment rate under several extreme and severe conditions (high river water current, river water level fluctuations and various sediment load). Flow velocity data was measured using current meter magnetic based on three points methods of measurement. The average flow velocity represents the flow condition of cross section. According to the flow velocity point measurements, average flow velocity can be analyzed using the equation as follows:

$$U = 0.25u_{0.2} + 0.50u_{0.6} + 0.25u_{0.8} \quad (1)$$

where U is mean flow velocity; $u_{0.2}$, $u_{0.6}$ and $u_{0.8}$ are the point velocity at 0.2, 0.6 and 0.8 of water depth respectively

The sediment samples of suspended load were taken by bottle sampler on various river depths. Meanwhile, the bed loads were collected from river bed using bottom grab. The analysis of water sample was resulting sediment concentration data on various conditions. Meanwhile, the bed material analysis provides grain size distribution of each cross section which representing the bed sediment condition. In advance, water level and current velocity have been analyzed to get the river flow condition during dry and rainy season. According to the field data, the sediment behavior at several river depths and during various climate conditions could be seen. Furthermore, the correlation between sediment and river flow parameters could be explained more detail. Finally, the sediment characteristics could be defined more accurately using the field data.

IV. Result and Discussion

A. Flow Velocity

This study provides the flow conditions in two different seasons, dry and rainy circumstances. The highest flow velocity was occured on January with 0.84 m/s, while the minimum was occurred on November with 0.1 m/s of flow current. Based on the climate information, from January to February is the peak of rainy season. Its represented by the flow velocity trend which increase significantly from December to January. High intensity of rainfall may contribute to the flow discharge which increasing during that period.

An extreme condition which represented by flow velocity condition is relevant with water level condition. The flow velocity is constantly speeding up with 0.2 m/s or 200% enhancement per month from October to January implicates an enormous river flow condition in Bengawan Solo River. The fluctuation data occured at every observation points may affected by flow condition. Related to the accumulation of sediment concentration which shows several occurrence of sediment flux blasting that generated by turbulent flow close to the riverbed [6].

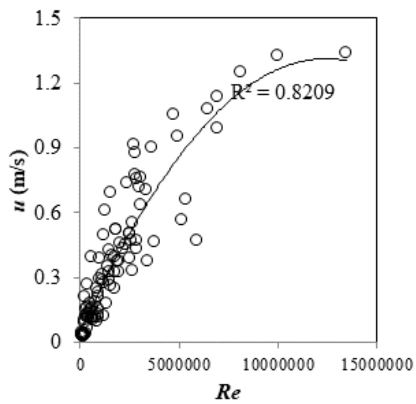

Fig. 2. Reynold number as turbulent indicator

According to the Fig. 2, low Reynold number occurs almost in all water column points. Meanwhile, high Reynold number relatively occurs in deeper water column. It could be due to the high flow velocity which generates high turbulent arises when the water layer free from bed friction effect. Hence, only deep-water column allows high turbulent flow developed. Graphic correlation between flow velocity and Reynold number explains the turbulent flow conditions along water column. Turbulent flow that influenced by flow velocity is reaching an asymptotic state around 1.3 m/s of flow velocity. An optimum condition of turbulence flow will develop erosion which influence the river profile change around the eroded segment. In case of sediment load, it might explain the segregation of sediment concentration on sub layers water column and determines the sediment distribution.

B. Flow Discharge and Sediment Concentration

Flow discharge as implication of hydrological condition on river system can be determined as flow area (*A*) multiplied by average flow velocity (*U*). From January to August period, the average flow discharge was around 230.64 m^3/s with the minimum and maximum values are 24.74 m^3/s and 445.83 m^3/s respectively. In general, the flow pattern is similar with previous data presented by Hoekstra et al in 1988. The peak season occurred between January until March. The flow decreases significantly on February, but back to positive trend on March indicates that the rainy season still on progress. After March, the flow continuously decreases until August implicates that there is no more water supply from upstream. The variation of flow discharge effected to the suspended sediment concentration (SSC) since the flow magnitude is establishing the quantity of sediment material.

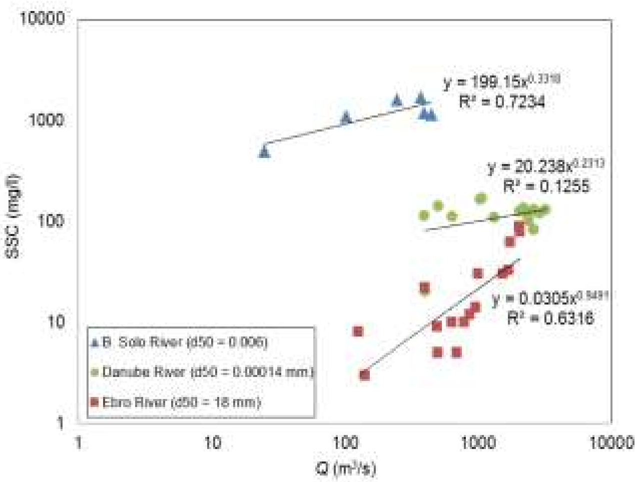

Fig. 3. Flow discharge and suspended sediment correlation of Bengawan Solo River comparing to Danube and Ebro River

The SSC that contained in the flow discharge signifies the erosion rate on river stream. To recognize the SSC quantity in Bengawan Solo River, the data is comparing to Danube River in Romania and Ebro River in Spain [14]. Fig. 3 shows the correlation between SSC and flow discharge in three different rivers. Danube River and Ebro River have great range in flow discharge, between 140 and 3200 m^3/s, but the SSC was confirmed in short variety, 3 to 166 mg/l. Bengawan Solo River shows the opposite condition with European River. The flow discharge between 20 and 445 m^3/s, while the SSC was affirmed between 500 and 1700 mg/l. Correspond to the river bed material, Ebro River has 18 mm while Danube River has 0.000135 mm of mean grain size (d_{50}). Low SSC explains that the sediment transport is firmly. In the meantime, aggressive behavior of SSC in Bengawan Solo River is implicating massive erosion which leads high sediment rate.

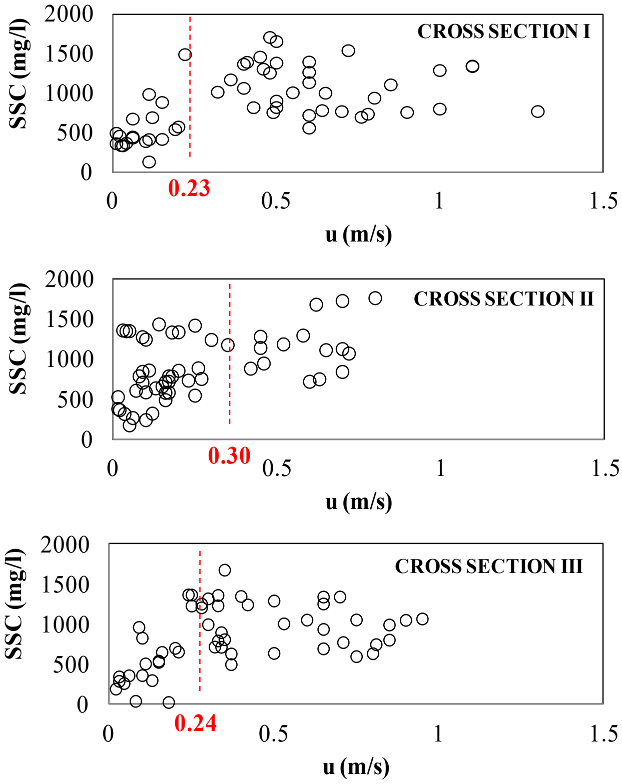

Fig. 4. The distribution of suspended sediment concentration at three measurement points

The correlation between SSC and flow velocity is rarely used to figure out the sediment transport conditions. Figure 4 shows the correlation that involved SSC and flow velocity in study location for three measurement points. Critical shear velocity implicates the initial motion of bed sediment material movement due to flow intervention. Critical shear flow velocity for cross section I, II and III are 0.23 m/s, 0.30 m/s, and 0.24 m/s respectively. In cross section II, around 70% out of total sediment concentration accumulates below critical shear velocity. It implies that cross section II which located in the center of curved channel is potentially to be eroded easier than cross section I and III. The conditions above could be generated by two possibilities, the concentrated sediment might be on deposited process due to material settling velocity is larger than flow velocity, or the sediment load could be generated by low flow velocity because of cross section II contains fine materials in majority.

The variation of SSC number at three measurement points indicates that cross section II was experiencing significant morphological changes according to the number of sediment concentration below critical shear flow velocity. This condition is supported by outer bank measurement that shows 0.20 m/year movement due to erosion.

V. Conclusion

Since the erosion and sedimentation are greatly affecting morphological changes in alluvial river, it is necessary to understand both flow and sediment parameters. According to this work, the number of SSC can be considered as an initial indicator of morphological changes that represents the potential erosion at the curved channel. Further field and laboratory works are required to better understand of river morphology changes in order to provides more information for mitigation purposes.

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