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SUSPENDED SEDIMENT CONCENTRATION ASSESSMENT AS A PRECURSOR TO RIVER CHANNEL SHIFTING IN THE BENGAWAN SOLO RIVER, INDONESIA

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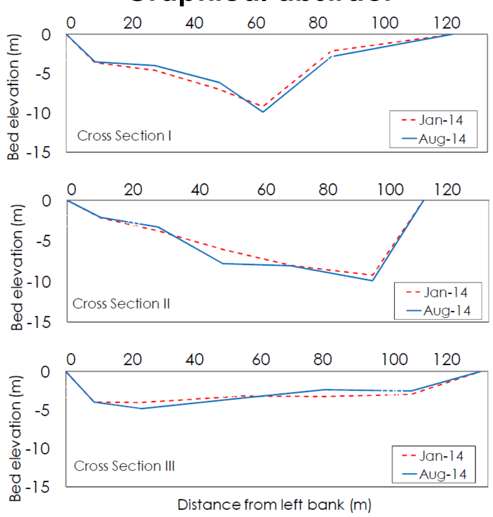
Graphical abstract



Abstract

This study attempts to recognize the fundamental issues in river morphology by examining suspended sediment concentration (SSC) and flow velocity at the curved channel in an alluvial river. To capture the entire set of the afore mentioned conditions, a field investigation was conducted at the inner and outer banks of the flow path of a curved channel, which is considered as the critical section in river change development. The field observations were conducted over a 1-year period, from January to December 2014, in which both dry and rainy seasons occurred. Because the curved channel is subject to severe erosion, especially around the outer bank, lateral migration of the channel might regularly occur. The field investigation showed that the outer side of the curved section migrated approximately 0.0625 m/month during the study period. The SSC, which peaked at 25% and 43% of the maximal flow velocity in the upstream and downstream sections, respectively, showed the rapid erosion of the curved section leading to lateral channel shifting. A channel resistance evaluation confirmed the potential capability of the riverbed material at the curved section was 20% lower than that in the upstream and downstream sections. According to the SSC and flow features, a new understanding of changing river morphology with respect to a curved channel of the Bengawan Solo River was developed.

Keywords: Bengawan Solo River, suspended sediment concentration, flow velocity, curved channel, erosion, channel shifting

1.0 INTRODUCTION

Sediment concentration is used as an indicator of the sediment delivery process in natural channels because it has a major effect on the entire river system. It has been found that a high sediment concentration, which reflects erosion and sedimentation processes could lead to the shifting of river channels [1, 2, 3]. The link between sediment concentration and variation in river channel elevation explains the mechanism by which sediment quantity controls a river system [4]. Generally, sediment concentration is linked to flow discharge rather than flow velocity [5, 6, 7, 8, 9, 4]. The correlation between flow discharge and sediment concentration indicates that the latter is also likely to affect flow variations [10, 8]. In advanced studies, the correlation between flow discharge and sediment concentration is practically used in the analysis of river morphology alterations [11]. Thus, these studies have led to the general understanding that sediment concentration is emerging as a flow discharge outcome.

According to preliminary assessments of river morphology alterations, flow velocity is the fundamental parameter controlling the sediment delivery process, especially in alluvial rivers [12, 13]. It includes erosion and sedimentation responses to flow velocity magnitude at a specific time and location. During floods, the increased flow velocity enables the removal of a higher quantity of sediment material from the banks and the riverbed, implying that there is a close relationship between flow velocity and sediment transport quantity [14, 15]. Some studies have shown that erosion tends to decrease during low flow and increases significantly during floods as indicated by sediment concentrations [16, 17]. Furthermore, erosion and sedimentation processes can be identified based on the relationship between flow velocity and sediment concentration, because they provide a greater justification of the sediment transport process. In essence, the sediment transport process consists of erosion and deposition. Both erosion and deposition are controlled by flow velocity. Sediments begin to move when the critical shear velocity exceeds the critical shear stress of the sediment particles [18]. Conversely, deposition occurs when the sediment particles attain the settling velocity; this process is supported by the flocculation process and a diminishing flow velocity [19]. Therefore, flow velocity as a parameter in understanding sediment transport should not be neglected.

The part of the river that is most affected by flow is the curved section as channel shifting occurs regularly in this section [20]. Massive erosion leads to frequent embankment failures around such sections, as stated by Uddin and Rahman [12]. Moreover, the outer bank of the curved segment suffers severe erosion because of the impact of flow on the river bank [21, 22]. It is believed that in the curved section, massive sediment transport occurs in accordance with the flow diversion process. The collision between the flow and river bank generates erosion produces sediment. Flow exerts dynamic forces on the sedimentary material and can generate massive sediment transport. Because sediment transport process is partly responsible for river morphology development, flow velocity and sediment concentration have a noticeable relationship [23]. Furthermore, a river bank collapse at a curved section demonstrates the extreme effects of flow impacts.

From a geological point of view, the soil type of the river basin has been confirmed as a substantial factor affecting sediment transport processes [24, 25, 25]. A river that flows over rock formations has relatively lower sediment transport than that of an alluvial river. Soft soil types provide large sediment transport volumes because of the interaction between soil particles and flow. Furthermore, some alluvial rivers present significant changes in sediment transport because of the significant effects of flow, especially during floods [2, 27, 3]. As a final consequence of the sediment transport process, severe damage occurs mainly on the river bank [22]. In case a river is situated near residential areas, sediment transport should be of serious consideration because it can endanger human lives.

The Bengawan Solo River is 600 km in length in total and 150 m in width on average. It is classified as an alluvial river because silt and clay materials dominate along the river course. The catchment area covers an approximately 16,000 km^2 of zone. On the other hand, only 24% of its catchment is conserved indicating land erosion in the study area. The average rainfall is approximately 2100 mm/year, with the minimum and maximum values of 1500 and 3000 mm/year, respectively, which potentially generate high flow discharge in the Bengawan Solo River.

The objective of this study was to identify the relationship between sediment concentration and flow at a curved section of the Bengawan Solo River. The curved channel was selected because it is an area of severe erosion, causing the river bank to collapse, as shown in Figure 1. Figure 1a shows that the outer river bank has a steep slope, indicative of the significant erosion occurring along this side. It also can be seen that clay and silt dominate the outer bank. In contrast, the inner river bank, as shown in Figure 1b, features a mild slope and shows the accumulation of sand, which has occurred as part of the sedimentary deposition process.

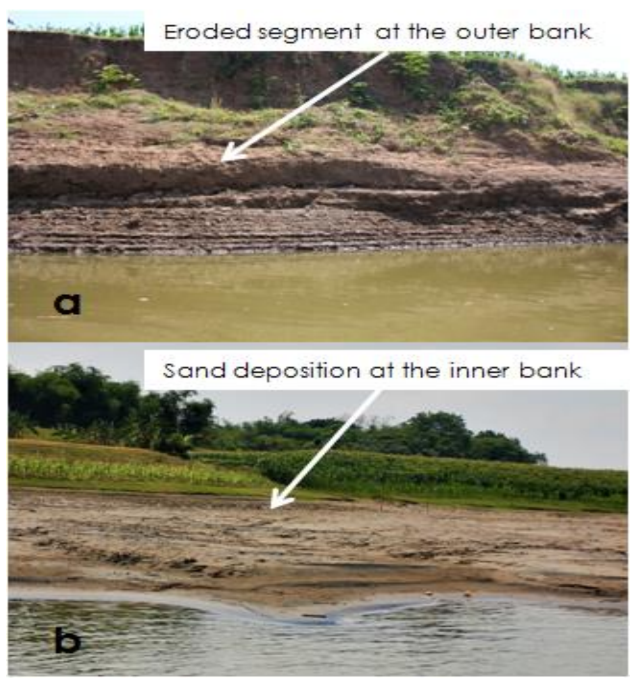


Figure 1 Outer bank (a) and inner bank (b) conditions at the curved channel

Because sediment concentration has always been linked to flow discharge, flow velocity as primary flow data is expected to provide a more realistic correlation with sediment concentration. The erosion process in alluvial rivers can be practically examined based on this study. Field data were collected from three different cross sections along curved segments to study flow velocity and sediment concentration behavior. Detailed field investigations were also conducted at the inner and outer banks of the curved section of the river to better understand sediment concentration and flow-velocity distributions as a precursor of river channel shifting. In this study, flow velocities and sediment concentrations along the curved section are presented meticulously to better understand the mechanism of river morphology change in an alluvial river. This study is focused on the change in river geometry of the Bengawan Solo River because a shift in many channels could endanger residential areas and potentially cause land losses mostly at curved sections. Therefore, this study was completed in order to capture both the hydraulic and sediment conditions, which play an important role in channel-shifting processes.

2.0 METHODOLOGY

Field investigations were conducted to collect primary data from the study site. Several data were collected from the Bengawan Solo River at Kanor Village, Bojonegoro, along a curved section of the river. This location was selected because it represents the general condition of Bengawan Solo River morphology. As there is 1037 m of curve radius and severe erosion along the outer side of channel, a river channel shifting mechanism was expected in this study. Simultaneous measurements were performed using a boat. The observations were obtained between 11:00 and 15:00 during all days of the investigation. Three measurement points (Cross sections I, II, and III) were established within a total length of approximately 1 km. Each cross section was separated by approximately 500 m. As shown in Figure 2, the investigation was focused at three cross sections to better understand the channel migration process by observing the erosional evidence around the outer river bank. Cross sections I and III as the upper and lower channels in this study, respectively, were chosen to obtain the flow conditions as a boundary for Cross section II. It can be seen that these sections have a relatively straight flow path in which it is possible to generate a high flow velocity magnitude. In term of erosional power, this can result in higher river bank erosion as seen in Figure 1a. The river banks were exposed to erosion mainly in the outer bank, producing an extremely steep bank. Cross section II as a main object is situated at the center of the curved channel. It apparently shows unique characteristics of the river bank including severe erosion at the outer bank. This section might migrate freely because the river bank material, which is composed of alluvial soil, allows the flow to readily transport the soil material.

Bed river materials were determined from both the inner and outer banks to obtain the grain size of the sediment material. A surface bottom grab was used as a simple method during field work. Sieve analysis was also conducted in the laboratory to determine the composition of sand, clay, and silt.

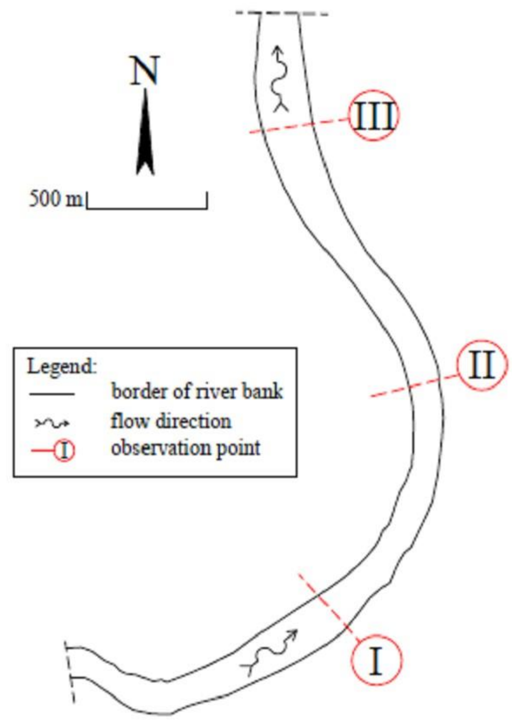


Figure 2 Curved channel in Bengawan Solo River

Based on d_{50}, the critical shear stress can be analyzed to determine the potential sediment material movement. Dingman [28] proposed a formula to express the correlation between critical shear stress and d_{50} as follows:

$$\tau^* = 0.0742\, d_{50} \qquad (1)$$

Where, τ^* is critical shear stress (kg/m^2) and d_{50} is mean grain size (mm). This equation was developed based on the mean bed material diameter, d_{50}, and the critical depth-slope at which sediment material begins to be transported.

The magnitude of flow velocity was measured using an electromagnetic current meter (Marsh Mc Birney Model 21, with ± 0.5% accuracy). The average velocity of the water column was calculated using the following equation:

$$U = 0.25U_{0.2} + 0.5U_{0.6} + 0.25U_{0.8} \qquad (2)$$

Where, 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 water depth, respectively [29].

Water samples were collected to measure suspended sediment concentration (SSC). Both flow velocity and SSC were taken at three points, 0.2, 0.6, and 0.8 m water depth as measured from the water surface [29]. Subsequently, the water samples were analyzed in the laboratory to obtain the SSC values based on ASTM D 3977-97. The water sample, which contained the sediment, was dried to obtain the dissolved-solids concentration. Furthermore, the SSC can be obtained using a formula as follows:

$$C_{ff} = F \times 10^6/W \quad (3)$$

Where, C_{ff} is the fine-fraction concentration (*mg/l*), *F* is the mass of sediment (*g*), and *W* is the mass of the entire sample (*g*).

3.0 RESULTS AND DISCUSSION

3.1 Bed Material Distribution Effect on River Channel Shifting

Figure 3 shows the river bed grain size distribution of the inner and outer river cross sections at the three observation points. The d_{50} at the outer bend was 0.025 mm, 0.006 mm, and 0.12 mm for Cross sections I, II, and III, respectively. On the other hand, the d_{50} at the inner path was 0.20 mm, 0.083 mm, and 0.60 mm for cross sections I, II, and III, respectively. These results imply that sediment particles at the outer bend have a relatively smaller size than those at the inner bend. The profile of mean grain size on the outer and inner river bank illustrates the sedimentary material heterogeneity in the study area. The finer grain size at the outer bank indicates that channel migration could potentially occur in this area. The investigation also confirmed the condition of the outer river bank which had a steep slope of 59°, 70°, and 65° for cross sections I, II and III, respectively. The flow exerts pressure on the river bed and bank and erodes material rapidly, hence the scouring establishes a deep pool and steep river bank along the outer section. However, the development of riverbed erosion of fine material occurs faster than that of coarse sediment.

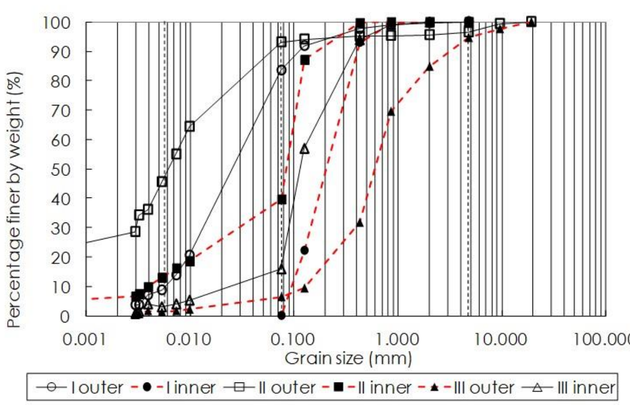


Figure 3 Grain size distribution of bed material at inner and outer sections of study area

Concerning the erosion process, the initial sediment particle movement is determined by the critical shear stress [30]. According to the d_{50}, the critical shear stress can be evaluated. The critical shear stress at the outer bank ranged between 0.0004–0.0089 kg/m^2. Meanwhile, the inner bank had a value between 0.0062–0.0445 kg/m^2 of critical shear stress. The contrasting values of critical shear stress represent the differences in potential sediment transport quantity between the inner and outer banks. It can be seen that the outer bank provides a lower critical shear stress number than that of the inner bank. A low critical shear stress value indicates weak bed resistance to flow disruption. As a consequence, erosion might occur more severely along the outer bend rather than along the inner bend. To support this statement, Figure 4 shows the tendency of outer bank erosion which leads to river channel alteration. The data is based on the river geometry during January and August 2014. It can be seen that the outer banks of cross sections I, II, and III decreased approximately 0.50 m, 0.70 m, and 0.45 m, respectively. Furthermore, based on river geometry measurements it was also found that there was a slight difference between the outer and inner banks' shape between cross sections I and III, while in cross section II there was a significant contrast. The river channel form in cross section I provides high flow velocity leading to high erosive power entering into cross section II. In advance, the heterogeneity of the sediment transport which is generated by various flow velocities might produce different SSC allowing for an imbalance in the river geometry.

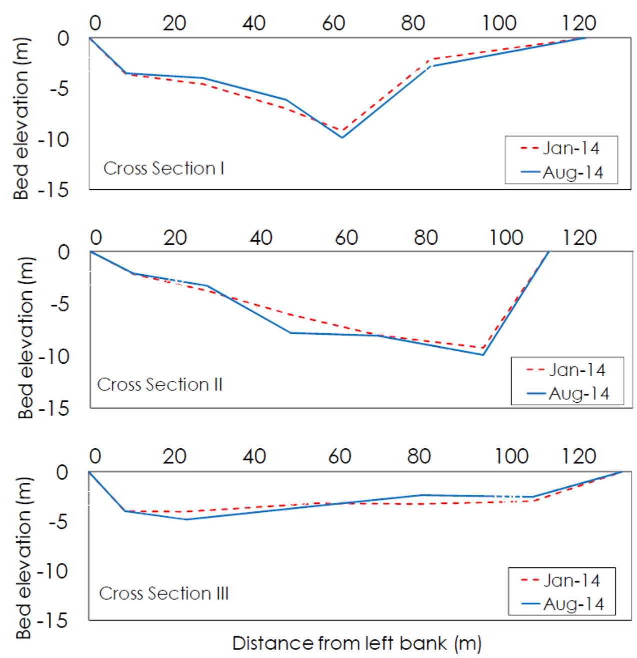


Figure 4 Channel geometry changing at three cross sections between January and August 2014

3.2 Flow Velocity and Suspended Sediment Concentration Correlation at the Curved Channel

Figure 5 presents the evaluation of SSC and flow velocity at the outer banks of cross sections I, II, and III. Please note that both cross sections I and III are the straight channels upstream and downstream of the curved channel, respectively, while cross section II is at the center of the curved channel. This study focused on the outer bank rather than the inner bank as the previous evaluation provides a significant precursor for the outer bank. It can be seen that the SSC at cross sections I and III are distributed evenly, indicated by the 0.668 and 0.555 of R-square value, respectively.

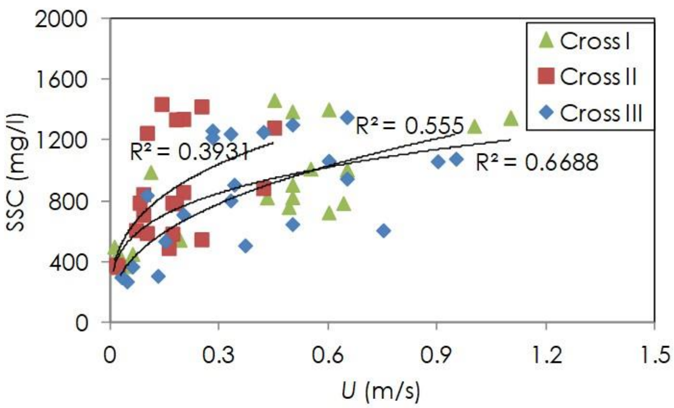


Figure 5 SSC and flow velocity behavior at the outer bank of cross section I, II and III

As seen in Figure 4, both cross sections I and III have relatively balanced river geometry as the flow and sediment transport are only slightly different on the outer and inner sections. Moreover, the aforementioned condition can be considered as a channel alteration indicator because the SSC distribution reflects the real situation in the curved channel. It confirms that the shape between the left and right sides of the river channel are not much different as sediment material transport is nearly equal on both sides of cross sections I and III. Meanwhile, cross section II provides a different condition to that of the other sections. It can be seen that the flow velocity and SSC graphic in Figure 4 presents the steepest pattern. This implies that the sediment material at the outer bank of Cross section II has a rapid response even under a low flow velocity magnitude that was below 0.30 m/s when the maximum SSC occurred. This is 27% and 31% of the maximum flow velocity of cross sections I and III, respectively. Considering the mean grain size (d_{50}) of the outer bank, it was found that cross section II had the smallest d_{50}, verifying the SSC behavior against flow velocity. The flow apparently suspended the sedimentary material more readily than at cross sections I and III. Parallel to the critical shear stress condition, cross section II also had the lowest value compared to the other cross sections. These results show that the sediment material transport process in cross section II is much more pronounced than that of the upper and lower sections, and that there is a close correlation between SSC, flow velocity, and sedimentary material size in river channel evolution. It can be seen noticeably that the size of the bed material sediment determines the SSC distribution during flow velocity intervention. In advance, the severe outer bank condition of cross section II can be explained by the SSC distribution against flow velocity.

3.3 Flow Regime Effect on the Suspended Sediment Concentration Distribution

According to the correlation between SSC and flow velocity at the three cross sections described in the previous sub chapter, it can be concluded that cross section II has a unique feature of SSC distribution which supports the severe condition in this section. To explain the flow disturbance of the river bank, the Reynolds number was analyzed for the open channel flow. The Reynolds number is determined by depth, flow velocity, and viscosity. It clarifies that the water particle inertia movement in a flow causes viscous damping, hence turbulent flow will develop [28]. In the case of a curved channel, the Reynolds number was calculated around the outer bank at the three cross sections to compare the turbulence conditions. Hence, the severe condition at cross section II can be further analyzed. Figure 6a, 6b and 6c shows the set of SSC, Reynolds number, and Froude number at the outer bank of cross sections I, II, and III respectively. It shows that the SSC and Reynolds number correlation provides an R-square value of 0.628, 0.433, and 0.543, respectively. It clarifies that the Reynolds number at cross section II has a relatively similar distribution compared to that of cross sections I and III, but note that the flow velocities are the lowest. It can be seen that the Reynolds number at the outer bank of cross section II reaches an optimal value of 0.30 m/s of flow velocity, which is more rapid than the other sections which have a higher flow velocity up to 1.07 m/s. This condition is parallel to the SSC distribution implying that the Reynolds number has importance in the SSC delivery process particularly in a curved channel.

Moreover, to evaluate the flow regime effect on SSC distribution, the Froude number was used. The Froude number is defined as a flow velocity and water depth function. When the Froud number approaches 1, this indicates the riverbed transforms to a dune or antidune. Generally, a dune or antidune is formed as sediment material moves under turbulent flow conditions. The results show that an R-square of 0.588, 0.261, and 0.425 for cross sections I, II, and III respectively. The result shows that the lowest number of R-square is in cross section II and that the SSC distribution is between 0 and 0.1 in terms of Froude number. Meanwhile, the other sections show a higher Froude number close to 0.3. Though the distribution of SSC is nearly identical at the three cross sections based on the Reynolds and Froude number evaluations, cross section II is able to produce an equal amount of sediment quantity with a lower flow velocity compared to that of cross sections I and III. In fact, the flow velocity at cross section II is possibly of a higher value than the observational data. Surely, a higher flow velocity is probable in generating a higher SSC as well. Therefore, severe erosion would be occurring and the channel geometry would be significantly changing as shown in Figure 4. These features enlighten the sensitivity of the curved channel to flow intervention which has the ability to control river channel shifting mainly around the outer bank. In advance, the turbulent flow regime generates the secondary flow which leads to further stress on the river bank and river bed; hence, the silt and clay particles that dominate the sedimentary material of curved section are more readily transported. However, SSC as an erosion indicator explains high dynamic behavior in the curved channel wherein a higher sediment concentration is produced at the outer bank, even under a low flow velocity magnitude.

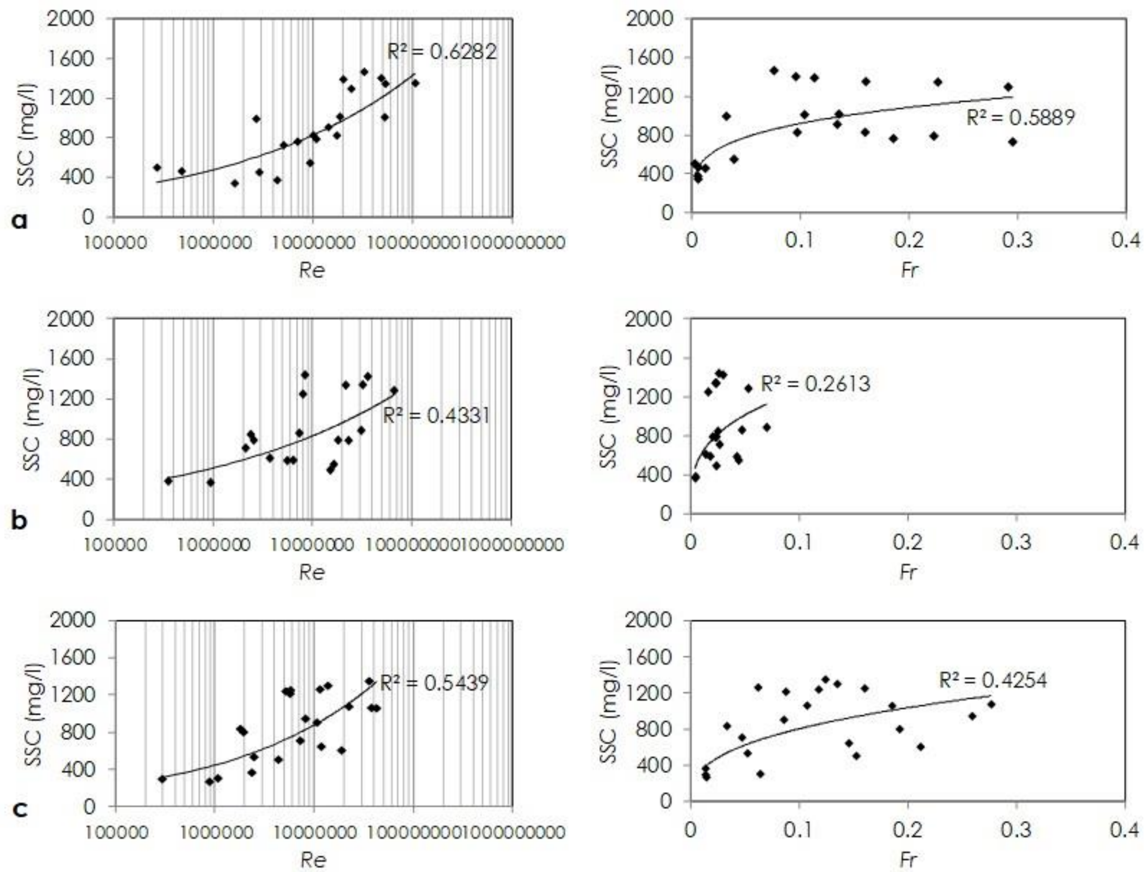


Figure 6 SSC and flow parameter correlation at the outer banks of Cross section I (a), Cross section II (b) and Cross section III (c)

3.4 Channel Resistance Evaluation

According to the Reynolds number evaluation described in the previous section, it was found that the potential sediment material transport is obviously subject to turbulence around the outer bank. This explains the more dynamic behavior at the outer bank because of the effect of turbulence flow on the river bank or bed contact at the curved channel. Simultaneously, this interaction might result in lateral channel migration as silt and clay soils exist on the outer bank. To provide a better understanding of the turbulence effect on channel resistance, the correlation between Reynolds number and channel resistance was used. The channel resistance is determined by the channel shape factor and denoted by Ω [28].

The correlation between Reynolds number and channel resistance at the outer bend of Cross sections I, II, and III is shown in Figure 7. The R-square indicates values of 0.927, 0.935, and 0.969 for Cross sections I, II, and III, respectively. Compared to that of Cross sections I and III, the correlation between Reynolds number and channel resistance in cross section II has a relatively lower trend line. Low channel resistance indicates channel material weakness in resisting flow interruption which contributes to the SSC number in the flow. As a consequence, there is a high possibility that sediment particles will be eroded from Cross section II, hence the severe channel geometry as shown in Figure 4.

In all sections, the Reynolds number tends to have an opposite correlation with channel resistance. These results show that the Reynolds number decreases as channel resistance increases. A similar trend was found based on experimental study on a smooth flume [31]. These results imply that the sediment material in a river bank or riverbed has decreased resistance due to massive turbulence interference.

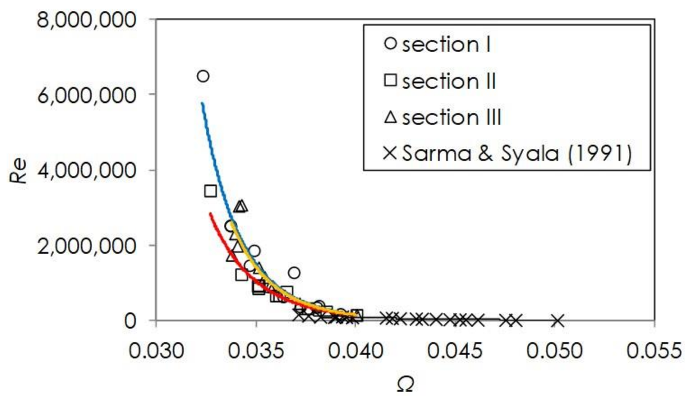


Figure 7 Relationship between Reynold number and channel resistance at the outer bank comparing to the experimental result

4.0 CONCLUSION

Significant variations in flow velocity can cause a high rate of erosion. The critical shear stress, which is an indicator of bed material resistance against flow, was confirmed to have a lower value at the outer bend in this study. The severe condition of Cross section II confirmed that a deep riverbed was formed at the outer bank, followed by massive river embankment failure. The SSC and flow velocity behavior explain the channel geometry distinction via SSC responses to flow velocity. The contrasting behavior among Cross sections I, II, and III shows the channel changing mechanism at the curved section. Furthermore, the development of sedimentary material erosion around the outer banks was confirmed based on the Reynolds number and the channel resistance correlation. Because of the complexity and the number of factors involved, further study is required to better explain the sediment transport process at curved sections because these sections are substantially affected during river morphological change.

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