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Sediment Transport Dynamic in a Meandering Fluvial System: Case Study of Chini River

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Abstract. Sedimentation in river reduces the flood carrying capacity which lead to the increasing of inundation area in the river basin. Basic sediment transport can predict the fluvial processes in natural rivers and stream through modeling approaches. However, the sediment transport dynamic in a small meandering and low-lying fluvial system is considered scarce in Malaysia. The aim of this study was to analyze the current riverbed erosion and sedimentation scenarios along the Chini River, Pekan, Pahang. The present study revealed that silt and clay has potentially been eroded several parts of the river. Sinuosity index (1.98) indicates that Chini River is very unstable and continuous erosion process in waterways has increase the riverbank instability due to the meandering factors. The riverbed erosional and depositional process in the Chini River is a sluggish process since the lake reduces the flow velocity and causes the deposited particles into the silt and clay soil at the bed of the lake. Besides, the bed layer of the lake comprised of cohesive silt and clayey composition that tend to attach the larger grain size of sediment. The present study estimated the total sediment accumulated along the Chini River is 1.72 ton. The HEC-RAS was employed in the simulations and in general the model performed well, once all parameters were set within their effective ranges.

Keywords: Sediment transport, meandering fluvial system.

1. Introduction

Chini River catchment has unique features as it was represented by a low lying lake as a detention area for a large flood event during the monsoon season. With seven mains feeder-rivers as its tributaries that allowing water coming from uncontrolled man-induced land development, sedimentation problem becomes vulnerable to more severe impact such as eutrophication and flood carrying capacity reduction [1].

Sediment transport dynamic within a catchment is reliant on its physical and hydrological characteristics [2,3] while these factors are intensely inter-related [4]. In describing the physical factors, a term of “meandering” of a river channel play a vital role in sedimentation dynamic [5,6,7,8,9], hydrological and ecological processes [10,11].



Meandering is a primary property of many natural rivers and meander bends are among the most recognizable and common features of the alluvial landscape. River meanders are of fundamental interest to many branches of pure and applied science, including geomorphology, geology, physical geography, and engineering. Meanders form across a variety of spatial scales produce characteristic depositional sequences within modern and ancient alluvium and recognition of these deposits lies at the heart of the development of predictive alluvial facies models. The movement of meandering rivers through lateral migration can be an important societal concern because such movement often threatens adjacent property and infrastructure.

Even with an lavishness of previous effort on sinuous waterways, our acquaintance of the fluid and sediment dynamics of complex meander curves in small low-lying undulating rivers, such as extended composite meander loops, is surprisingly sparse. As a consequence, our capacity to model and predict accurately the evolution behavior of complex bends in this type of rivers is still far from complete.

The present study attempts a step-change in our understanding of the sediment transport dynamic of a small meander river by exploring the interactions between one-dimensional flow structure, sediment transport and riverbed morphology within several complex meander loops along the low-lying catchment of Chini River.

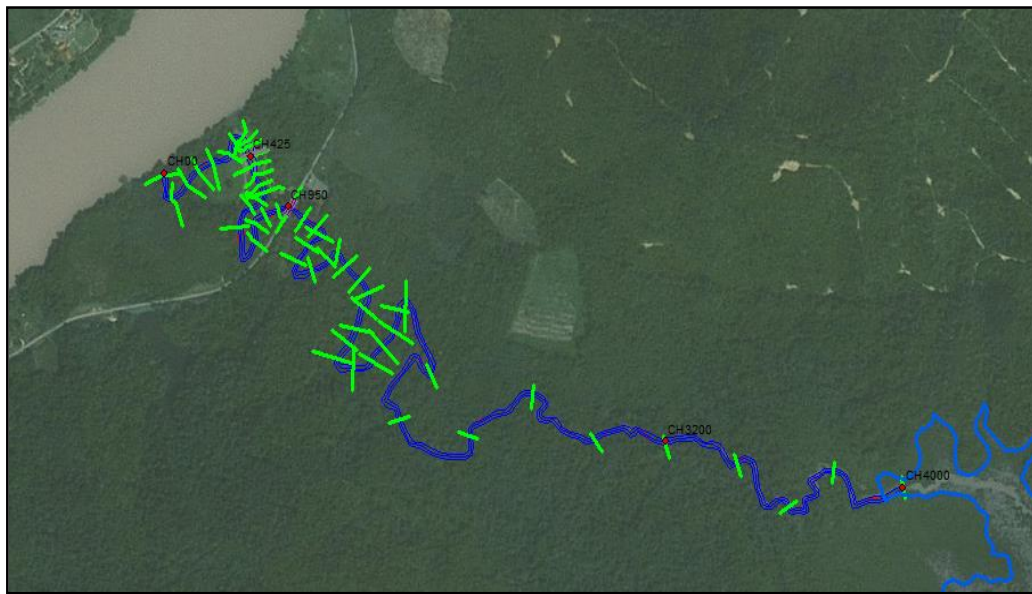


Figure 1. The reach of Chini River and established sampling locations.

2. Methodology

The meandering characteristics of Chini River was analyzed according to an equation derived by [12].

$$K = L_c / L_v \quad (1)$$

where K = Sinuosity Index, L_c = length of the valley axis, L_v = straight line distance between the two extreme points of the valley

Collection of sediment transport data and hydraulic data were made according to [13]. Analysis of particle size distribution of bed material (**Table 1**) was carried out using sieve analysis and hydrometry according to BS 1377-2:1990 (Methods of test for soils for civil engineering purposes:

Classification test. Analysis of sediment size is the measurement and information of size and particles range for a set of material. These collected dataset were later used as input for HEC RAS Sediment transport modelling. The Laursen-Copeland equation was chosen for the sediment transport modeling since it is the most suitable for silt and clay particles [14].

$$C_m = 0.01\gamma \left(\frac{d_s}{D} \right)^{7/6} \left(\frac{\tau_o'}{\tau_c} - 1 \right) f \left(\frac{u_*}{\omega} \right) \quad (2)$$

where C_m = sediment discharge concentration (lb ft³),

γ = specific weight of water (lb ft³),

d_s = mean grain size (ft),

D = effective flow depth (ft),

τ_c = critical shear stress (lb ft⁻²),

τ_o' = bed stress acting on bed grains (lb ft⁻²), u_* = shear velocity (ft s⁻¹),

ω = fall velocity (ft s⁻¹), and

f = function of the ratio of the latter two variables as defined by a figure in that has been incorporated into HEC-RAS.

Table 1. Bed material sediment results.

Locations	Coarse Sand (%)	Fine sand (%)	Total non-cohesive (%)	Silt (%)	Clay (%)	Total cohesive (%)	D ₅₀ (mm)
Lake confluence CH4000	3	22	25	58	17	75	0.0175
CH3200	0	3	3	61	36	97	0.018
Bridge CH950	5	43	48	35	17	52	0.08
Weir CH425	1	24	25	62	13	75	0.018
Confluence Chini River	2	4	6	69	25	94	0.0075

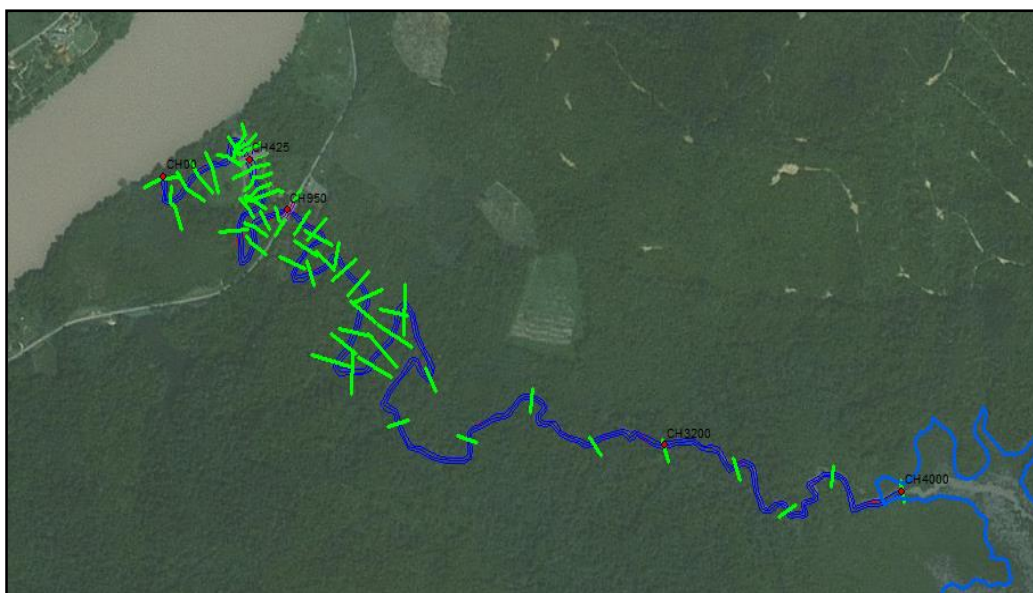


Figure 2. Particle size distribution curve for analysed bed material sediment samples at 5 established locations.

HEC-RAS is applied to develop one-dimensional Chini River sediment transport model. The model was calibrated by obtaining high goodness of fit between observed and predicted water level of hydraulic simulation run. With having the high accuracy of hydraulic model, sediment transport analysis then simulated for the current discharge and sediment supply. [15] produced a curve diagram plotting the tractive velocity flow between the incipient movement of grains and grain size. Thus, it was found that there was a correlation which clearly indicates that the coarse grain size is proportional to the velocity of the moving water. Hjulstrom curve gives a details interpretation about the flow velocity required to move and transport the various grain sizes in the composition of the deposit.

3. Results and discussion

3.1 Morphological - Meandering characteristics of Sg Chini

The sinuosity index, (K) for Chini River is 1.98 and categorized as a very unstable condition [16]. Chini River has greater percentage of suspended load with finer grained sediments dominated at all river sections. The range from flow discharge was between 1.30 m³/s to 1.97 m³/s. Most part of the riverbanks are found to be cohesive with little coarse sediment is observed.

3.2 Particle size distribution analysis

Analysis of sediment size is the measurement and information of size and particles range for a set of material. The analysis conducted through two types of laboratory analysis known as sieve analysis and hydrometer test. The size of bed material is the most important physical characteristics affecting the process of sediment transportation [17,18,19].

From the bed material sediment sampling analysis as shown in Table-1 and Figure-2, it was found that the silt particles dominates 35-69% of bed particles within the Chini River compared to sand particles. Sediment mixtures with a fraction of clay particles ($D_{50} < 0.063$ mm) which about 13-36% have cohesive properties because electro-statistical forces are higher than the gravity force acting between the particles.

Consequently, the sediment particles do not behave as individual particles but then to stick together forming a floc whose size and settling velocity are much larger than those of the individual particles. The D_{50} for bed particles and suspended particles has been interpolated to yield the spatial distribution within the Chini River water body.

Consolidation rate is an important factor in determining the level of soil erodibility. Fresh mud has a very loose texture in which the mud flocs has a low density. The wet bulk density of such cohesive deposit is within the range of 1050 to 1100 kg/m³ with estimated of 95% or more consists of water and in this phase, the cohesive forces be present in the deposits are still very low and tend to have effortless erosional effect [20].

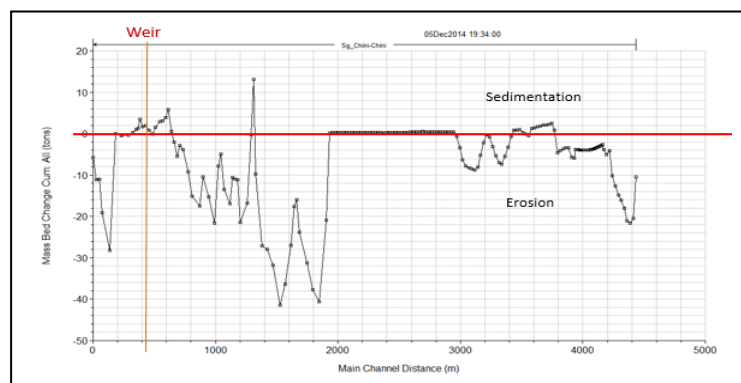


Figure 3. Cumulative weight of the sediments in the end of simulation period (5 Dec 2014) at all cross section for the current condition.

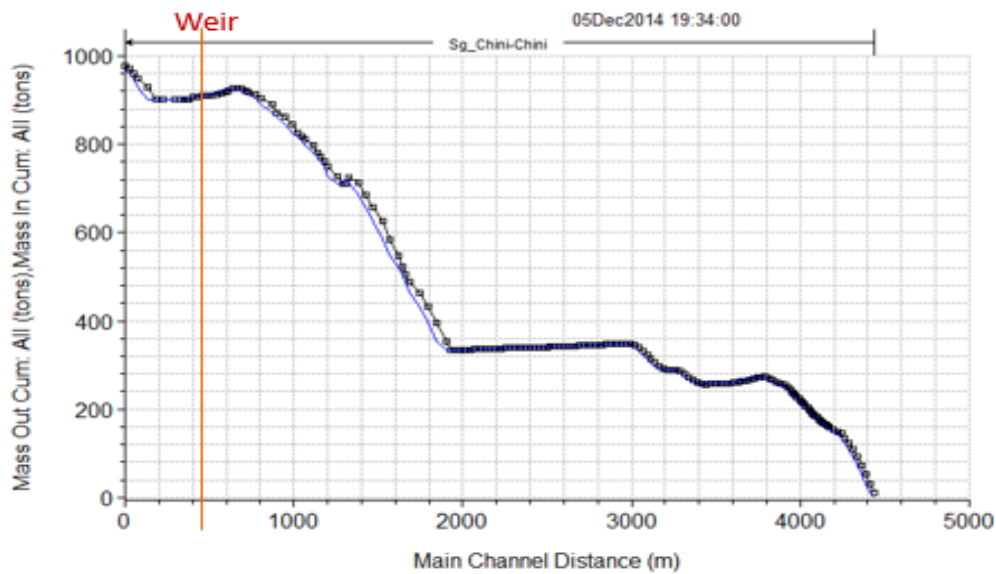


Figure 4. The accumulative weight of inflow and outflow sediments in all cross sections at the end of simulation period (5 Dec 2014).

3.3 Riverbed erosion and sedimentation dynamic of Chini River with the current condition

The simulation of flow sedimentation are presented as the transverse and longitudinal profile variation of the river, shear stress variation, sediment transport capacity and the volume of outflow sediment that were studied at different locations. The change in riverbed geometry during the model run can also be evaluated by comparing the longitudinal cumulative mass change in tons of sediment. Starting at the upstream boundary, this output sums to the mass change through every cross-section (Figure-3). At a steep slope sections, the observation indicated that is is an aggradation (positive slope) or degradation condition(negative slope).

Figure-4 gives the cumulative weight of inflow and outflow sediments values based on Laursen-Copeland sediment transport equation. As shown by the interpolation of the HEC-RAS model, the erosional activities along the river occurred at the upstream and middle stream of the river and at the downstream.

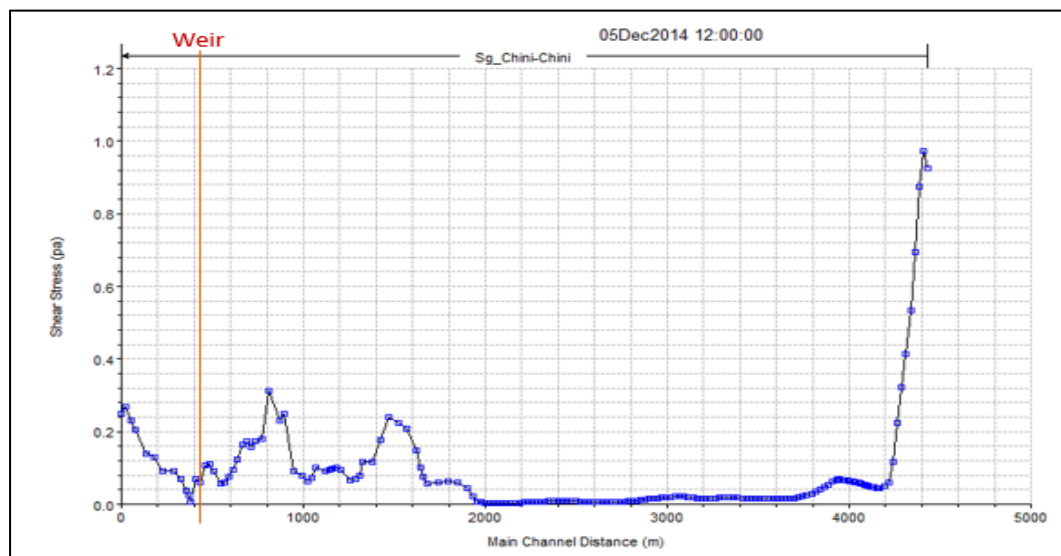


Figure 5. The shear stress variation during the simulation period (5 Dec 2014) at all river sections.

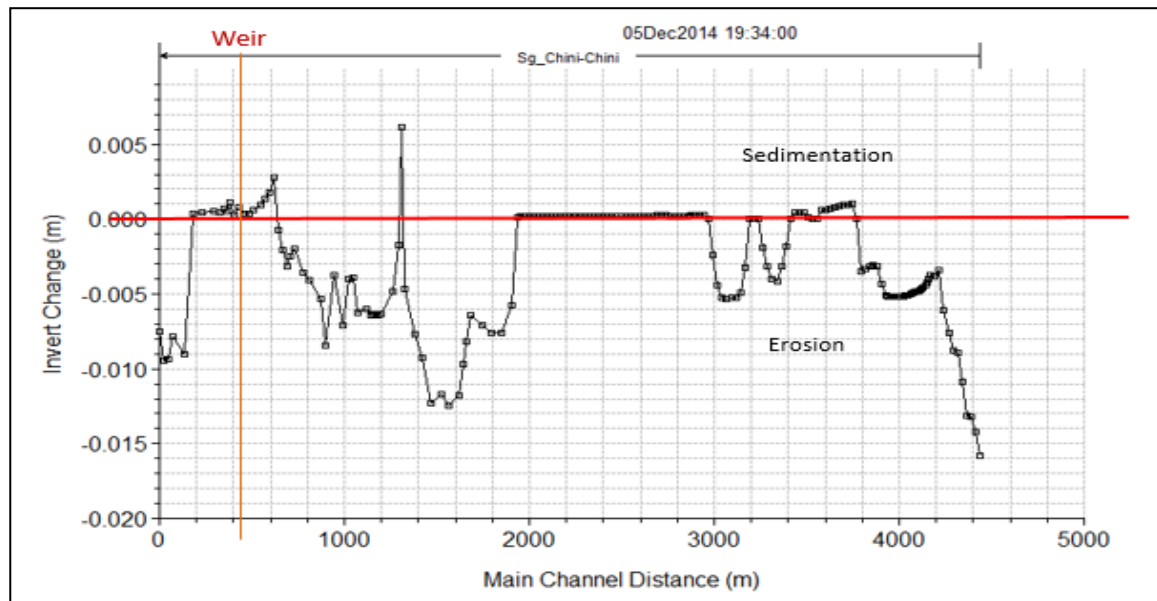


Figure 6. Invert change (m) of Sg Chini at all river sections after end of simulation (5 Dec 2014).

For example, the abrupt changes of slope between CH1800 and CH1600 cause the significant erosional effect. The accumulative weight of inflow and outflow reveal the extent of erosion and sedimentation in different sections. The total mass in during the simulation period of 18 November to 5 December is 907.97 tonnes and the mass out is 906.25 tonnes. Hence the total deposition of sediment along the river section is 1.72 tonnes.

The shear stress variation during the simulation period across the Chini River at each section has been shown in Figure-5. The highest value of shear stress is equal to 0.95 Pa in the section of CH4000 and the lowest is 0.00013 at CH2000. The shear stress variation when approaching the weir seem to decrease significantly especially from the CH800 to CH425 (Weir) due to the diminishing of velocity and drop slope. The shear stress at the weir is 0.07 Pa. The lower shear stress indicates the lower transport rate of coarse sediment at approaching the weir but increase in the deposition of coarse sediment but incessantly transporting the fine sediment.

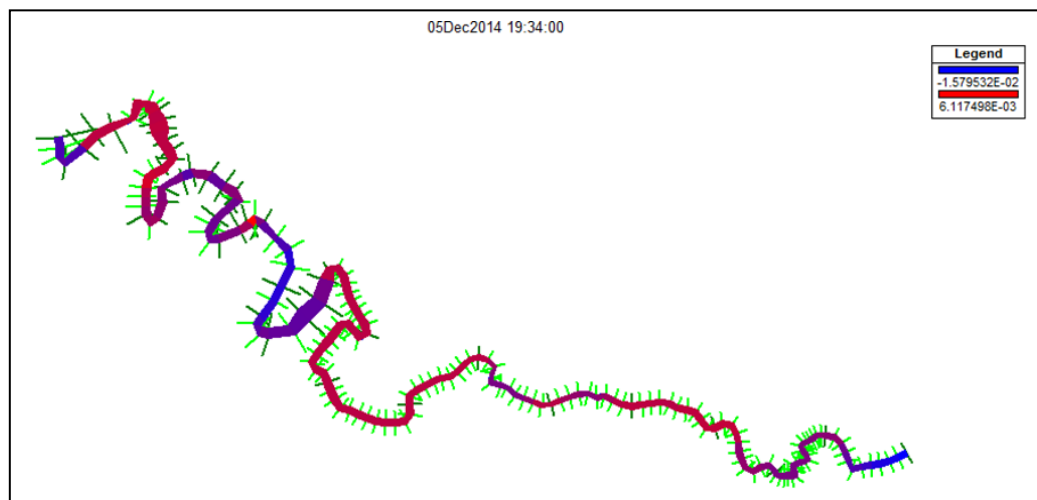


Figure 7: Schematic view of bed elevation change (m) of Sg Chini at all river sections at the end of simulation (5 Dec 2014).

The longitudinal profiles are shown in Figure-6 of Chini River along with the existing structures as well as sedimentation and erosion in different areas in the form of invert changes. It was observed that, riverbed erosion occurred at many locations along the river due to the high proportions of silt and clay (fine sediment) which can be transitionally transported as suspended sediment. These types of sediment is effortlessly can be moved from the riverbed.

Meanwhile, the bed elevation change along the Chini River represented by the pictographic view as in Figure-7. The sedimentations that occurred along the Sg Chini are symbolized by the red zone which having the positive value of bed elevation of the channel (increment of bed elevation). The blue zone represented the erosional zone which having the negative values indicating the decrease of bed elevation of the riverbed. The highest change in riverbed level due to depositional of sediment is approximately 0.0061 m. While the highest change in riverbed level due to erosion is approximately 0.016 m. The riverbed elevation change at the weir is 0.0025 m.

The expression of relative magnitude of the sediment transport capacity significantly related to flow velocity and interpreted through the Hjulstrom Curve [15]. From that curve, it is possible to identify ranges of flow velocities that will mobilize varying sediment sizes. Figure-8 illustrates potentials to erode on different particle sizes along the Chini River. It is expected that sand will only erode at the upstream of the Chini River in view of the fact that ample velocity to strain the sand particle from the riverbed. While the silt and clay has enough velocity to erode for any of the section in Chini River.

Anticipated sediment deposition form an important part of this study. Its characteristics may be observed from Figure-9 which illustrates potentials to deposit on different particle sizes along the Chini River in which the silt, clay, sand and gravel deposition area is alienated based on the velocity computed from the model simulation at each locations. As all-encompassing, it is expected that gravels will not be transported and will be deposited at the upstream of the river (CH4400-CH4250, CH1600-CH1400, CH925-CH750, CH100-CH00) because of the limited transport capacity due to deficient velocity. However it is noted that, finer materials are not likely to deposit in this reach because of it has sufficient velocity to transport these type of materials in the form of suspended sediment along the reach.

3.4 *Area of active of riverbed erosion and deposition*

The erosional and depositional process in the Chini River is a slow process since the lake impoundment cause the flow velocity to decrease. The sediment component on any sizes will deposit into the silt and clayey condition of the bottom bed of the lake. Hence, there is no significant changes of erosion and deposition part of the Chini River.

The area of deposition is significant at the weir of the Chini River and at the upstream part especially between CH2000 and CH3200. Whereas, the active erosion along the Chini River are located between CH800 and CH1800 due to high velocity compared to the upstream area.

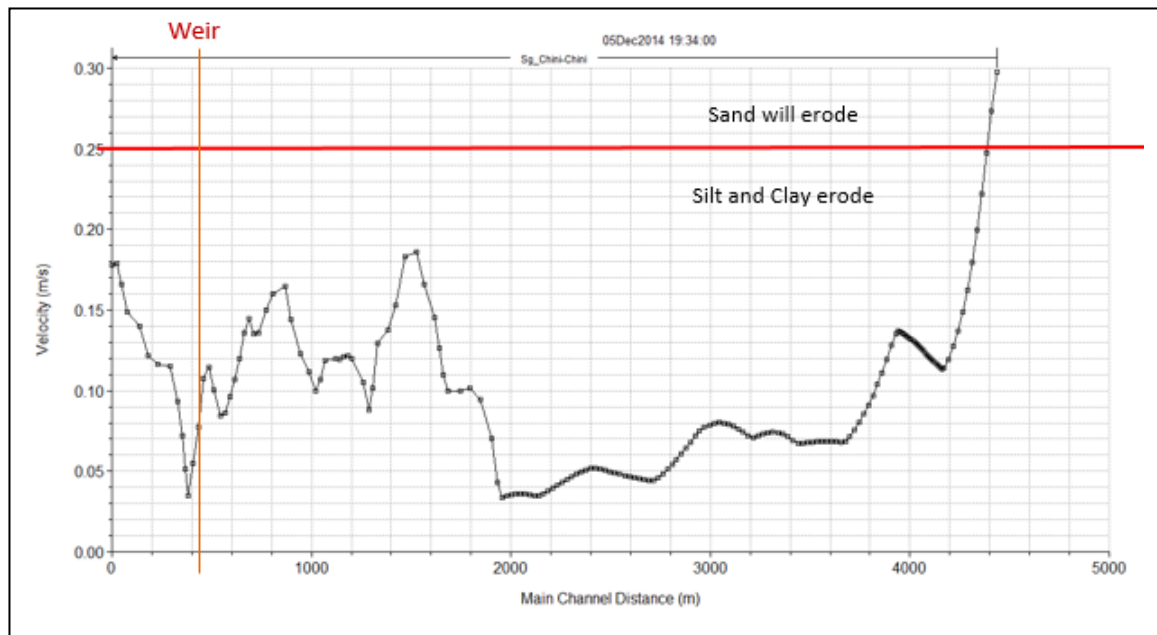


Figure 8. Susceptibility to Erode based on Hjulstrom curve.

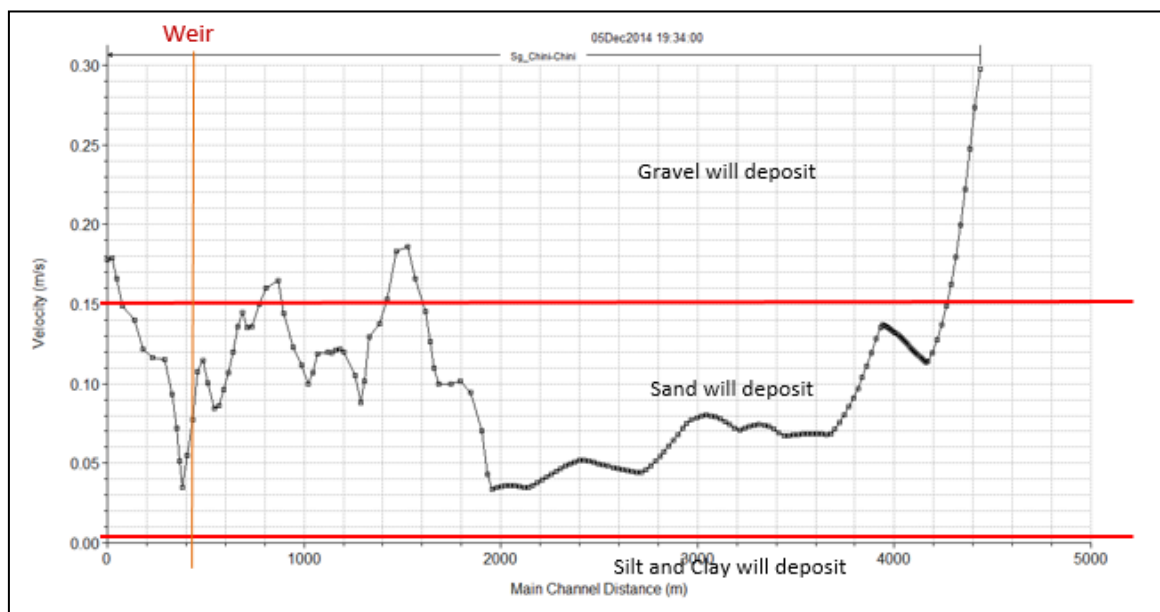


Figure 9. Susceptibility to Deposit based on Hjulstrom curve.

The erosional parts of the river mostly remain the same but the size of particles eroded is different for each event. As shown from the results, the silt and clay is potential to be eroded for the current scenario. However, sand and gravel has the potential to erode at the same part of the river especially during the high flow event.

3.5 *Abatement measures for riverbed erosion and deposition of sediment*

The sediment transport modeling indicated that the weir located at the downstream of Chini River is not subject to serious siltation problems (**Figure 6**); this is consistent with the site reconnaissance conducted during the project. Henceforth human intervention using structure or dredging is necessary to maintain navigation and passage of floodwaters that may otherwise causing excessive rise in water levels or velocities along the immediate up-stream reaches of Chini River.

To offset these estimated sediment loads discharging into Chini River, a system of sediment traps is proposed for the removal of portion of the tributary contributions. These sediment traps should have the flexibility to enable the sediment passing the trap to be adjusted if the removal is creating a sediment deficit or scour condition downstream. A de-silting program for the river channel is also required to pre-empt any excessive rise of floodwater levels that may otherwise cause overbank flooding in the areas.

The river sediment transport modeling using HEC-RAS indicated that Chini River will be subject to varying degrees of bed lowering in the short and long terms, which if not abated will undermine the stability of riverbanks. The areas of concern include the downstream reaches of the weir. However the threat of riverbank collapse to hinterlands is not imminent and it is proposed to introduce a monitoring program on riverbank stability or a detailed study to assess the need for mitigation.

3.6 *Future studies on sediment transport dynamic in Sg Chini*

It would be interesting to identify some possible scenarios for future studies. The following are prospective options to improve the results from the current study for future investigations:

1. Study of similar case with 2 or 3 other software and compare their results with observed data;
2. Study of similar case with 1D, 2D and 3D models and see if they offer the same results or if they differ and to what extent;
3. Study of two or more cases with the present model and by comparing results trying to find out under which circumstances the model perform well;
4. A combination of two or more of the above options;
5. It is suggested that a detailed and comprehensive study on cohesive sediment transport to be carried out using the more advanced numerical software to appraise further for the long term comportments of sedimentation and erosion assortment.

4. Conclusions

The HEC-RAS was engaged in the simulations and in general the model executed well, once all factors were set within their operative ranges. Conclusively, the current level of erosion is strongly related to the extent of land undergoing built up land use development, with the hilly areas being developed in the central portions of the Chini River catchment making major contribution to the sediment load in the Lake Chini system. More research in future is needed to imposed the details sediment transport dynamic in Chini River.

Acknowledgement

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