Effects of River Dredging as Mitigation for Lahar Accumulation Downstream of the Santo Tomas River

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ABSTRACT

Santo Tomas River, approximately 37.5 km long, with headwater at Mount Pinatubo, flows westward towards the West Philippine Sea. A case study of a proposed dredging operation as mitigation for lahar accumulation at the downstream reach of Santo Tomas River in the province of Zambales, Philippines is presented. Geotechnical, hydrologic, and hydraulic analyses were undertaken to assess the effects of dredging using Slide, HEC-HMS, and HEC-RAS software, respectively. Considering the dredged condition, the bank slopes are stable under static condition, but not under seismic condition where shallow failures with depths ranging from 0.1 m to 1 m are caused by erosion. To address the erosion, rock mattresses were considered as protection for the dredged area, which were also incorporated in the computer-based model. Results show that the rock mattress was adequate to address the possible erosion.

1 INTRODUCTION

The second-largest volcanic eruption of the 20th century, and by far the largest eruption to affect a densely populated area, occurred at Mount Pinatubo on June 15, 1991 (Newhall et al., 1997). The event displaced tens of thousands of locals and affected the whole Luzon Island. Eruptions of ash occurred occasionally through early September 1991, three (3) months after the eruption; and volcanic deposits reached up to 200 m thick. The impacts of the eruption to the West Pinatubo River System can still be observed today as ash deposits are continuously remobilized by monsoon and typhoon rains. These pyroclastic materials deposited from the 1991 eruption are continuously transported to the downstream of the river system in the form of rain-induced mudflows of volcanic materials.

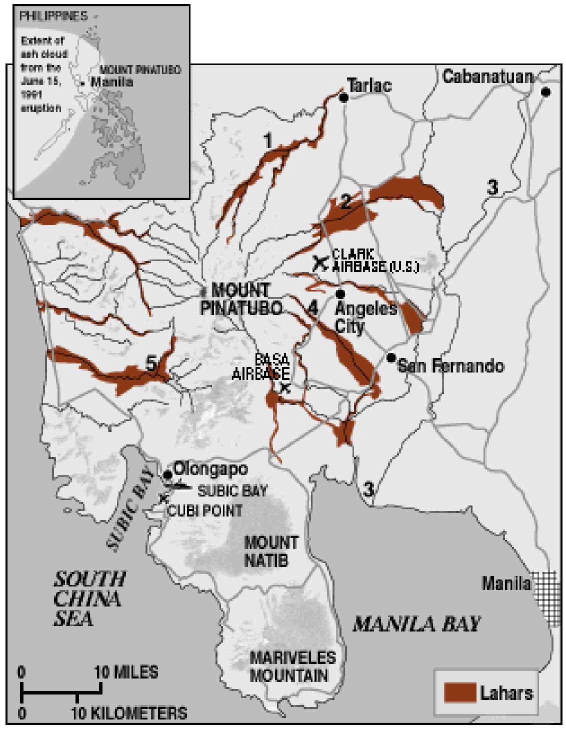

Figure 1. Distribution of lahars after the 1991 eruption (Newhall et al., 1997)

Subsequently, sediment aggradation occurs at the downstream reach of Santo Tomas River, leading to the rise in riverbed elevations. This poses a risk to the inhabitants of the surrounding lowlands and to Maculcol Bridge. The bridge carries the San Narciso – San Felipe National Highway as it traverses Santo Tomas River, and is located approximately 2.5 km east of the mouth of the river. Almost three (3) decades after the eruption, the local government is exploring possible flood mitigation procedures to address the rising riverbed (and consequently, rising water levels) of the river.

Dredging operations are typically conducted to remove excess sediment from a riverbed which increases the depth of the channel and reduces flood risk. In order to mitigate the aggradation of lahar and other sediments, dredging the river at the downstream of the bridge was recommended. Geotechnical, hydrologic, and hydraulic analyses were undertaken to assess the effects of dredging.

Geotechnical analysis was conducted to assess the stability of the slopes on either sides of Santo Tomas River - before, during, and after the dredging operation. Hydrologic models were generated to estimate the peak discharge of the river at 25-, 50-, and 100-year return periods. Lastly, hydraulic models were generated to compare the water profile at the downstream reach, as well as flow velocities and scouring potential at the bridge, at various return periods at pre-dredging and post-dredging conditions.

Project Area Data

The 1:50,000 Topographic Map from the National Mapping and Resource Information Authority (NAMRIA) shows that the elevations of the catchment decrease from east to west with the rivers branching from Mount Pinatubo, then draining to the West Philippine Sea. The elevations reach up to 1,131 meters above sea level (MASL) at the crater of Mount Pinatubo. Santo Tomas River has an average riverbed slope of 3.0%. The topographic map also shows that the area is characterized by a mixture of cultivated lands and scrublands with patches of built-up areas near the river mouths. Figure 2 shows the downstream portions of the Santo Tomas River.

Mount Pinatubo is an active stratovolcano of dacitic composition that has been erupted over the Zambales Range. In 1991, its summit was blown off forming a caldera which is now filled by a crater lake. The eruption produced thick pyroclastic and ashfall deposits which were remobilized by rains as massive lahar deposits. Lahar is characterized as cohesionless, and hence has high scouring and sediment transport potential.

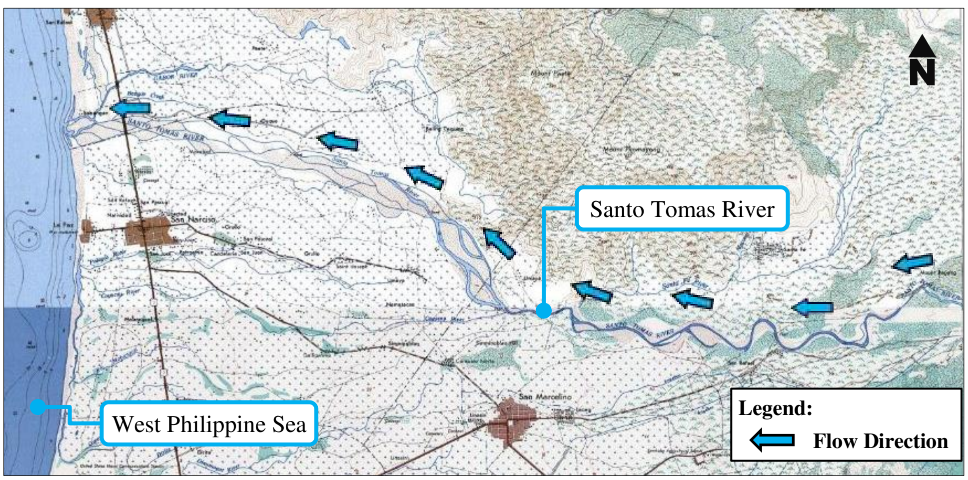

Figure 2. General topography of a portion of Santo Tomas River (NAMRIA Map 7073-III)

Based on the Modified Coronas Classification by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), the project area can be characterized as having Type I climate, which has two (2) pronounced seasons: dry from November to April, and wet during the rest of the year, with the maximum rain period from June to September. The area is somewhat shielded from the northeast trade winds but are open to rains brought in by the southwest monsoon and associated typhoons.

For this study, the Rainfall Intensity Duration Frequency (RIDF) data from Iba, Zambales Rainfall Station, which is approximately 33.5 km north of the study area, served as the basis for the design frequency storm used in the hydrologic analysis. Figure 3 shows the RIDF curves generated from the actual rainfall data based on 37 years of record, as well as the equations for rainfall intensities for different return periods.

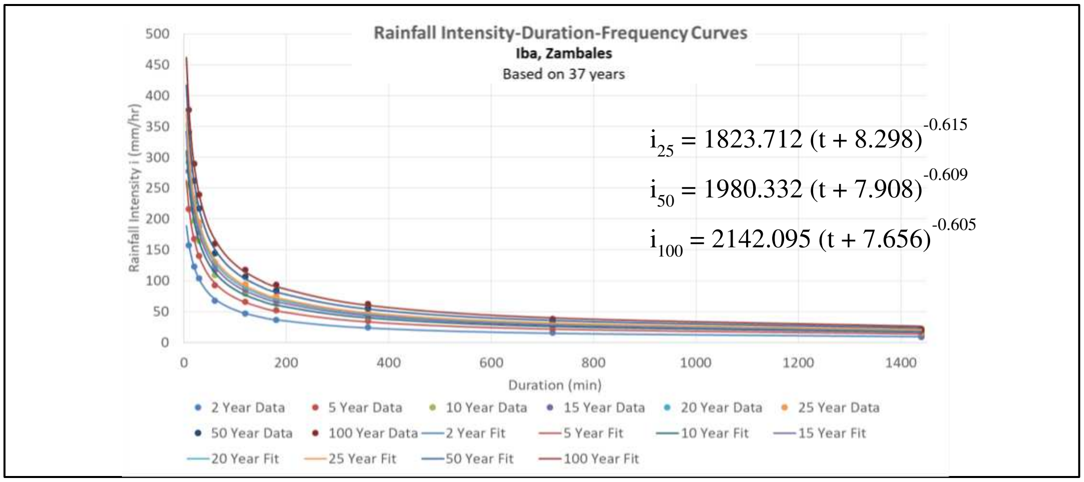

Figure 3. Rainfall Intensity Duration Frequency (RIDF) Curves for Iba, Zambales

During an inspection conducted last August 9, 2019, Santo Tomas River had rapidly flowing water due to monsoon rains enhanced by Typhoon Lekima, known in the Philippines as Typhoon Hanna. Parts of the lahar deposit riverbed were still above water at the time of observation. Concrete dikes are built along the riverbanks for flood protection. Vegetation can also be found on some portions of the riverbank. The surrounding area of the river is relatively flat and occupied with green fields except for portions with small houses and truck terminals.

Figure 4. Existing condition of the Santo Tomas River (photo taken on August 9, 2019)

2 METHODOLOGY

A brief description of input data, models, and software used in the geotechnical, hydrologic, and hydraulic analyses are given below.

2.1 Geotechnical Analysis

Computer-based modeling of the existing slopes within the area was done using the simplified Bishop's method which uses limit equilibrium concepts. In this method, the slope under analysis is assumed to fail along a circular failure surface. The slope models generated using Slide (version 6.0) software by Rocscience are based on the results of the geotechnical investigation conducted for the study. The modelling and analysis took into consideration static (i.e. normal condition) loads for dry and saturated conditions, and pseudo-static loads (i.e. earthquake) to simulate worst case condition of combined rainfall and earthquake-induced slope instability. The software was utilized to facilitate calculations for determining the minimum factor of safety for the two (2) conditions. The modelling and analysis considered three (3) scenarios: existing condition, dredged conditions, and dredged conditions with rock mattress for erosion control. For the dredged conditions, four (4) schemes were considered (Table 1). The topographic map generated for the study is shown in Figure 5.

Table 1. Dredge Schemes

Scheme	Depth	Side Slope
1	3 m	1V:2H
2	5 m	1V:10H
3	10 m	1V:10H
4	15 m	1V:3H

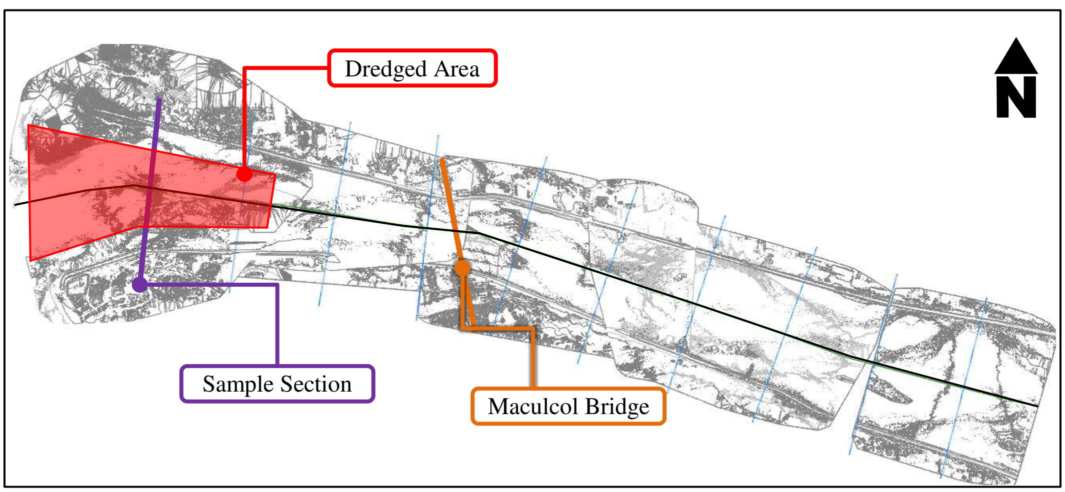

Figure 5. Sample section for slope stability analysis of the Santo Tomas River

The geotechnical parameters were determined from correlations with the Standard Penetration Test (SPT) N-values based on Foundation Analysis and Design (Bowles, J.E., 1988) (Table 2). The earthquake generator considered for the analysis is the East Zambales Fault, approximately 60 km northeast of the Santo Tomas River, which can generate a magnitude 7.4 earthquake. Using the attenuation model of Fukushima and Tanaka (In Thenhaus, 1994), the horizontal and vertical pseudo-static seismic coefficients were computed as 0.1g and 0.05g, respectively.

Table 2. Geotechnical Strength Parameters

Depth, m	SPT N-value	Remarks (Consistency/ Relative Condition)	Geotechnical Parameters		
			γ (kN/m^3)	c (kPa)	Φ (deg)
0.0 – 2.0	3 – 4	Very Loose	16	0	26
2.0 – 3.5	9	Loose	17	0	28
3.5 – 30.3	16 – 30	Medium Dense	18	2	33

2.2 Hydrologic Analysis

For this study, the assigned outfall for Santo Tomas River is Maculcol Bridge (Figure 6). Topographic data from NAMRIA and Google Earth, as well as the 30-m resolution Zambales ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model) from PhilGIS, were used to delineate the extent of the catchment. With the GRASS (Geographic Resources Analysis Support System) plugin, QGIS (Quantum Geographic Information System) (version 3.2.0 with GRASS 7.4.1) was also used for the delineation of the sub-catchments. The total area of the Santo Tomas River catchment is 284.86 km^2 with 22 sub-catchments (Figure 6).

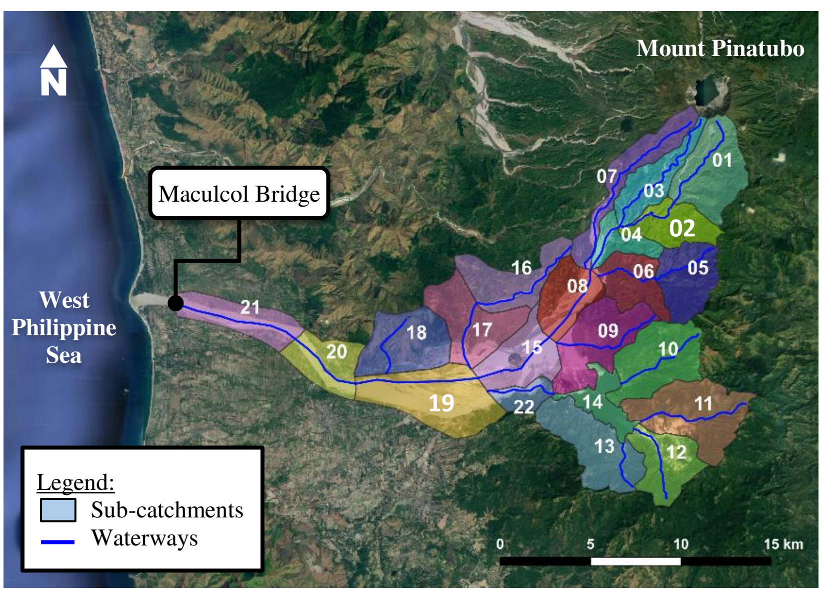

Figure 6. Catchment for Santo Tomas River (Google Earth)

Temporal distribution of rainfall was considered using the Alternating Block Method (Chow, Maidment, Mays, 1988). This method was used to develop the hyetographs from incremental precipitation values. For the 25-, 50-, and 100-year return periods, a 72-hour duration of rainfall was assumed.

The hydrologic model was generated using HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) version 4.3 by the US Army Corps of Engineers. For each sub-catchment, areas and channel lengths were determined from GIS; Hydrologic Soil Groups (HSG) were determined using soil maps from the Bureau of Soils and Water Management (BSWM); and the time of concentration was computed using the SCS (Soil Conservation Service) Lag Equation. These input data were used to model the sub-basins and their reaches.

2.3 Hydraulic Analysis

HEC-RAS (Hydraulic Engineering Center – River Analysis System) version 5.0.6 by the US Army Corps of Engineers was utilized to simulate one-dimensional steady flow on the waterway for the different peak runoff flows derived from the hydrologic calculations, as well as to evaluate bridge scouring. The topographic survey of the Santo Tomas River was used in getting the alignment and cross sections for the hydraulic model. Maculcol Bridge is located at Sta. 2+132.5 (Figure 7). The corresponding cross-section at the bridge is shown in Figure 17.

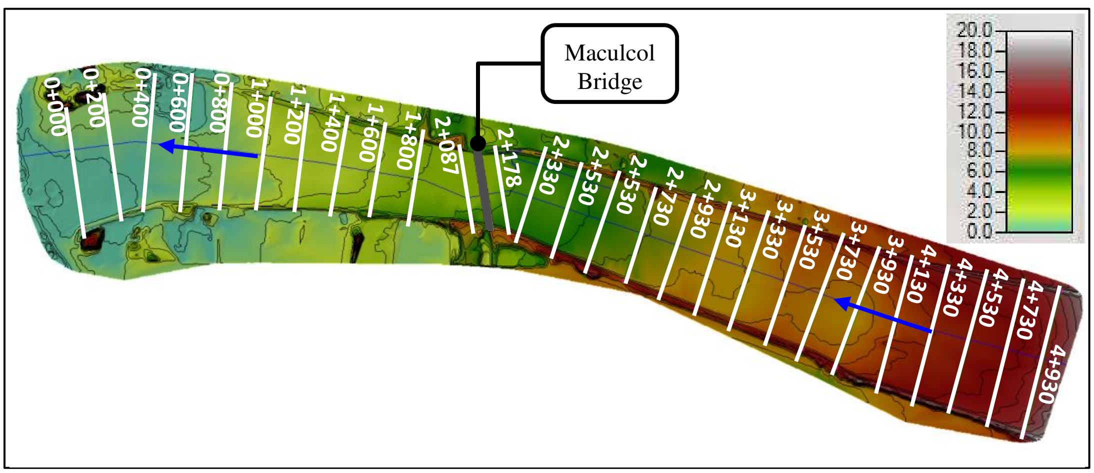

Figure 7. HEC-RAS Model of Santo Tomas River (Pre-Dredging)

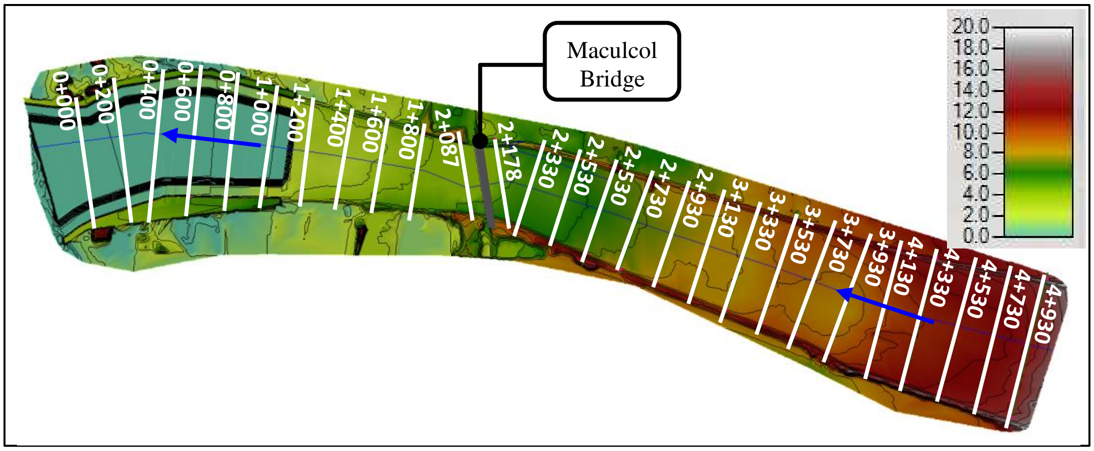

Figure 8. HEC-RAS Model of Santo Tomas River (Dredging Scheme 4)

After performing the water surface profile calculations for the various return periods, the bridge scour was evaluated, namely contraction scour and local scour at the piers and abutments. The contraction scour depths were computed using the Live-Bed Contraction Scour equation (Laursen, 1960), as follows:

$$y_2 = y_1 \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{K_1}$$

$$y_s = y_2 - y_0$$

The formula considers the mode of bed material transport (K_1), the channel width in the approach (W_1) and contracted (W_2) sections, the flow in the approach (Q_1) and contracted (Q_2) sections, the average depth at the approach section (y_1), and the average depths at the contracted section before (y_0) and after (y_2) scour. The local pier scour depths were computed using the Colorado State University (CSU) equation (Richardson, 1990), as follows:

$$y_s = 2.0 K_1 K_2 K_3 K_4 a^{0.65} y_1^{0.35} Fr_1^{0.43}$$

The formula considers the pier width (a), the flow depth (y_1) and Froude Number (Fr_1) directly upstream of the pier, and correction factors for the pier nose shape (K_1), the angle of attack of flow (K_2), the river bed condition (K_3), the armoring of bed material (K_4). The local abutment scour depths were computed using the Froehlich equation (Froehlich, 1989), as follows:

$$y_s = 2.27 K_1 K_2 (L')^{0.43} {y_a}^{0.57} Fr^{0.61} + y_a$$

The formula considers the length of abutment (L'), the average depth of flow at the approach section (y_a), the Froude Number at the approach section (Fr), and correction factors for abutment shape (K_1) and angle of attack (K_2). The correction factors used in the three (3) scour equations are summarized in Table 3.

Table 3. Correction factors used in scour analyses

Equation	Factor	Value	Remark
Live-Bed Contraction Scour	K_1	0.69	Mostly suspended bed material discharge
Colorado State University (CSU)	K_1	1.00	Group of cylinders
	K_2	1.00	Pier angle is zero degrees
	K_3	1.10	Clear-water scour
	K_4	1.00	
Froehlich	K_1	0.55	Spill-through abutment
	K_2	1.00	Both abutments are perpendicular to the flow

3 RESULTS

Slope stability analysis results of the existing condition show that all slopes on both the north and south banks passed the required factor of safety of 1.2 for the static condition and 1.1 for the seismic condition. Considering the dredged condition, the sections of all schemes are stable under static condition; but Schemes 1 and 4 are not stable under the seismic condition (FOS < 1.1). These can be considered as shallow failures that are caused by erosion due to induced velocity by the waves or waterflows, since these have depths ranging from 0.1 m to 1 m occurring in the very loose and loose sand layers.

To address the erosion, rock filled wire mattresses or gabions were used as protection for the dredged sections. Rock mattresses, in general provide channel protection on the existing riverbed by directly catching the waves or waterflows in any given conditions (steady, turbulent, etc.). Composed of plastic coated wire mesh cages and rocks, the rock mattress acts as one whole system, thus effective in resisting the force created by the wave that can cause movement of big enough particles, thus resulting to erosion.

The primary design considerations for mattresses are the sustained velocity and shear-stress thresholds that the gabions must withstand. The mattress design used for the study, with thickness of 0.6 m, can withstand velocities up to 6.4 m/s based on the Design Guidelines, Criteria, and Standards of the DPWH (Department of Public Works and Highways).

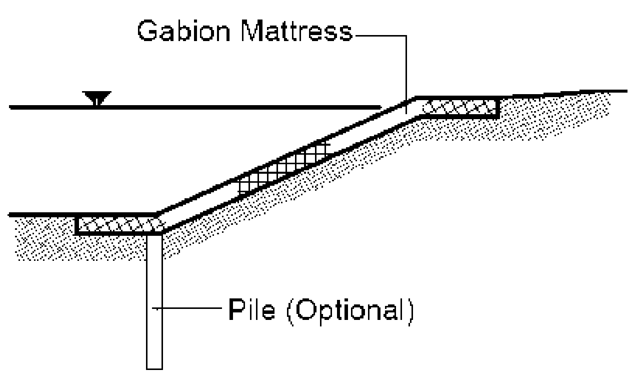

Figure 9. Typical Spread Type Rock Mattress (DPWH)

The rock mattress, extending all throughout the dredged section as well as the existing riverbed at both sides, was incorporated in the model. The resulting factors of safety for all sections are greater than 1.2 (for static) and 1.1 (for seismic), showing that the use of rock mattresses as protection helped address the erosion on the dredged scheme (Figure 10 and Figure 11).

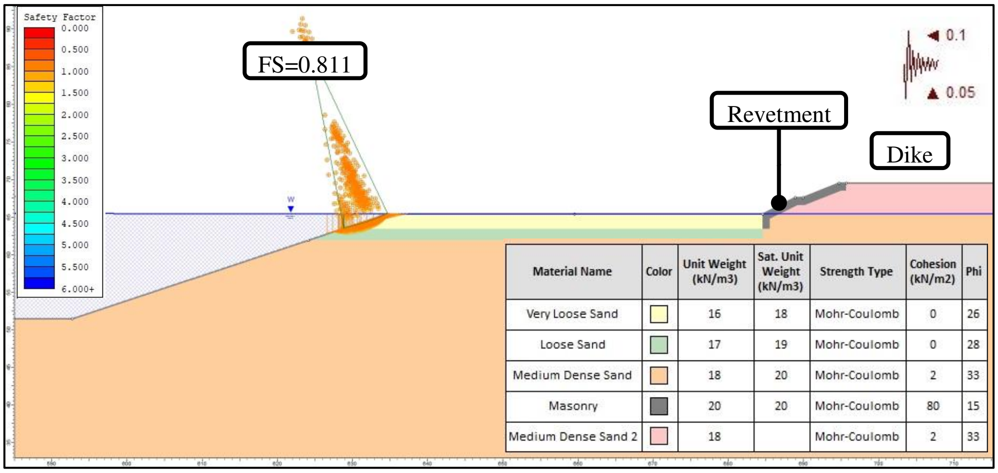

Figure 10. Scheme 4 without rock mattress at south bank (seismic loading condition)

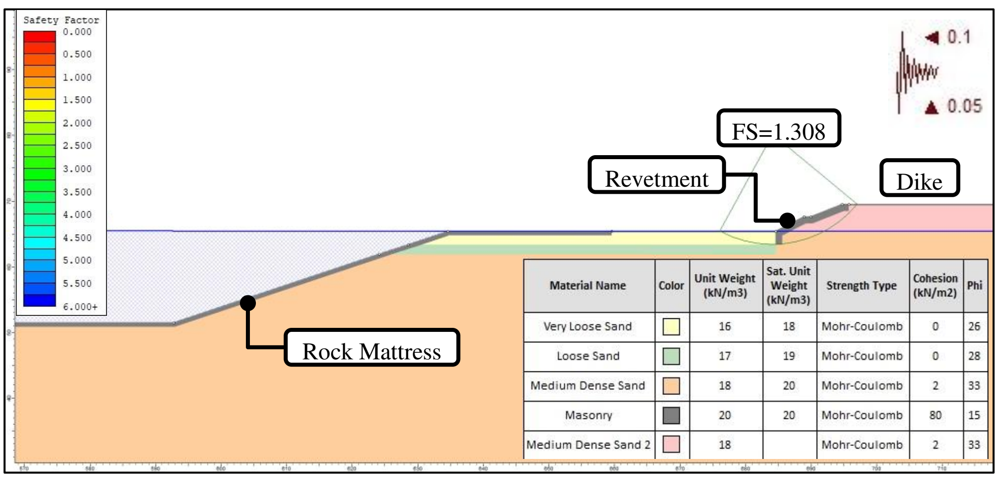

Figure 11. Scheme 4 with rock mattress at south bank (seismic loading condition)

Figure 12 shows the hydrologic diagram for the Santo Tomas River Catchment. The Unit Hydrograph Method was used to compute the corresponding peak discharges for each return period. The results of the hydrologic analysis are summarized in Table 4.

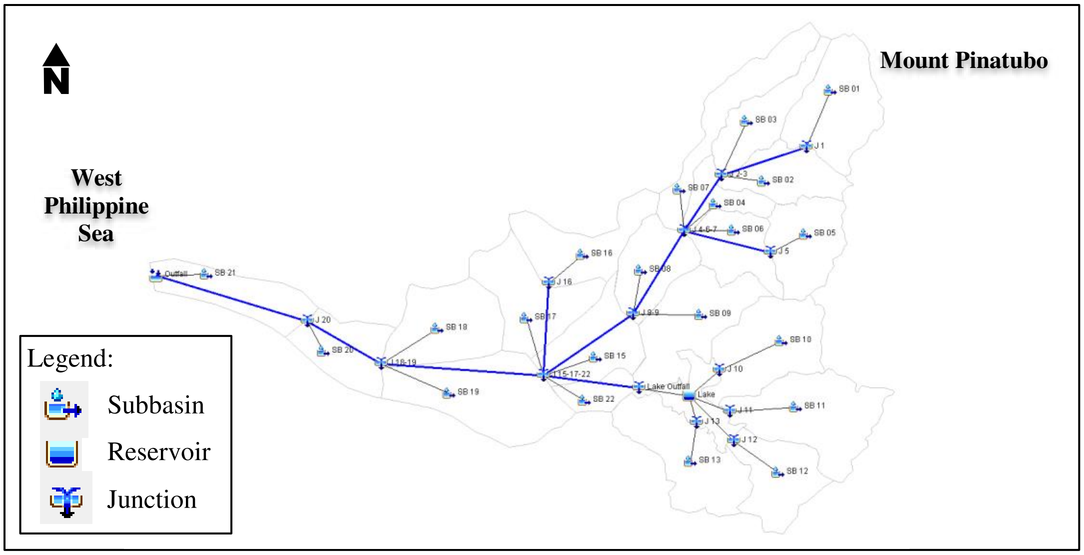

Figure 12. HEC-HMS model of the Santo Tomas River catchment

Table 4. Peak Discharges (m^3/s)

Santo Tomas Catchment	Return Period		
	25-year	50-year	100-year
Peak Discharge (m^3/s)	1,478.0	1,690.1	1,906.3

The estimated peak runoff flows were used to perform water surface profile calculations for the various return periods, and the resulting flood levels show that the water within the river overtops the banks at ten (10) stations downstream of the bridge (Figure 13). Figure 14 shows a sample section of the river with banks overtopped by 0.3 m of flood.

To increase the depth of the channel and reduce flood risk, the river bed will be dredged starting at 1 km from Maculcol Bridge until the mouth of Santo Tomas River. The Manning's roughness coefficients used were 0.025 for the existing terrain and 0.035 for the rock mattress. Figure 15 shows a sample dredged cross section from Scheme 4.

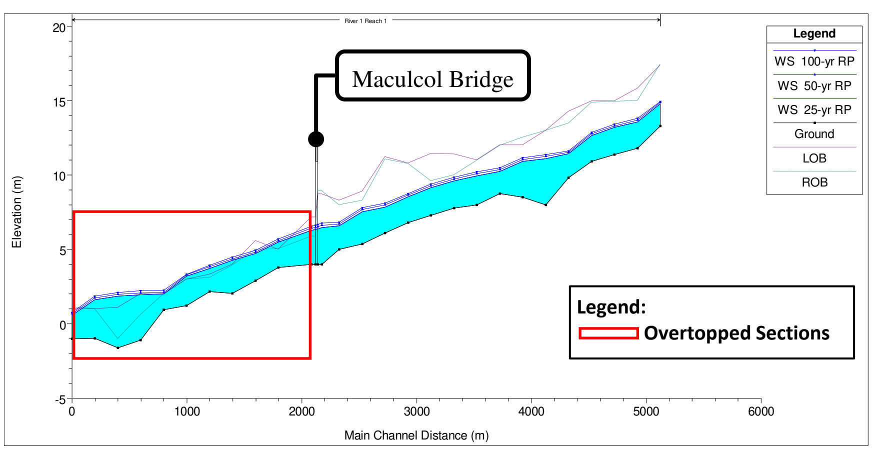

Figure 13. Profile view of the river bed and flood levels (pre-dredging)

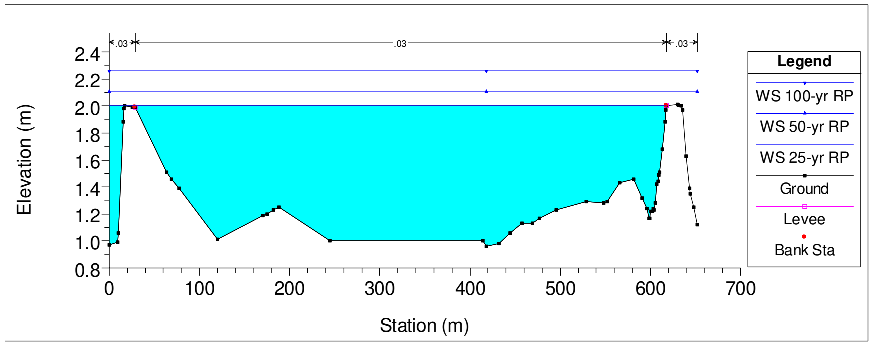

Figure 14. Overtopped banks at Station 0+800 (pre-dredging)

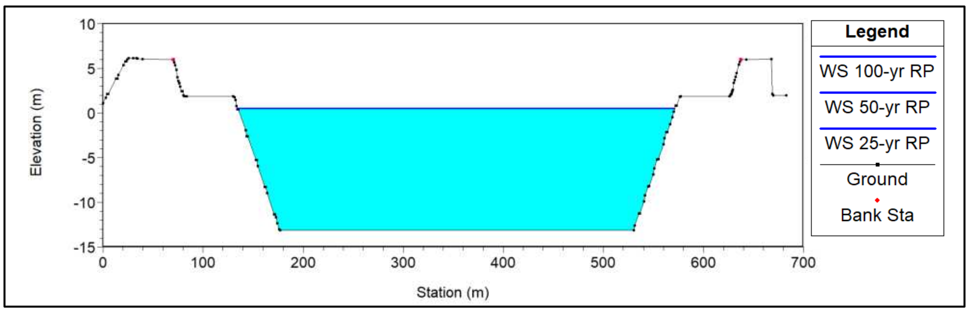

Figure 15. Sample dredged cross section (Scheme 4)

The following figure shows the profile view of the Santo Tomas River at post-dredging condition considering Scheme 4. The flood levels show that the water within the river no longer overtops the banks at the first six (6) stations from the mouth of the river. However, upstream of the dredged section towards Maculcol Bridge still resulted in overtopping (Figure 16). Scheme 4 resulted in the lowest flood levels and least overtopped sections.

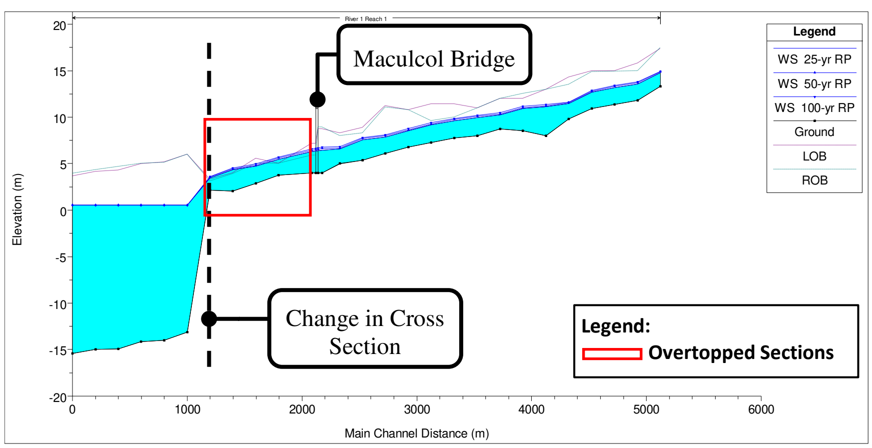

Figure 16. Profile view of the river bed and flood levels (Scheme 4)

Comparing the post-dredging hydraulic model results before and after the transition to the dredged area, results show that the flow velocities and flood levels (measured from 0 MASL) decreased for all return periods for all dredging schemes (Table 5).

Table 5. Hydraulic model results before and after the change in section (Scheme 4)

Return Period (years)	Q (m^3/s)	Sta. 1+000		Sta. 1+200	
		Flood Level (m)	Velocity (m/s)	Flood Level (m)	Velocity (m/s)
25	1,478.0	0.54	0.27	3.50	2.84
50	1,690.1	0.54	0.31	3.58	2.99
100	1,906.3	0.54	0.35	3.67	3.14

On the other hand, flood levels up to 100-year return period will not reach Maculcol Bridge regardless of the dredging operation. The flood levels and flow velocities at the bridge did not change before and after dredging. Similarly, all four (4) dredging schemes resulted in the same pier scour depths for each return period (Table 6). The resulting maximum local scour at the bridge, produced by the flows corresponding to the 100-year return period rainfall, are shown in Figure 17. Lastly, the Live Bed Contraction Scour equation and Froehlich equation indicate negligible scour potential for contraction and abutments, respectively.

Table 6. Local pier scour depths (m)

Pier No.	Return Period		
	25-year	50-year	100-year
1	2.05	2.20	2.32
2	2.30	2.41	2.51
3	2.49	2.59	2.68
4 – 12	2.60	2.70	2.78

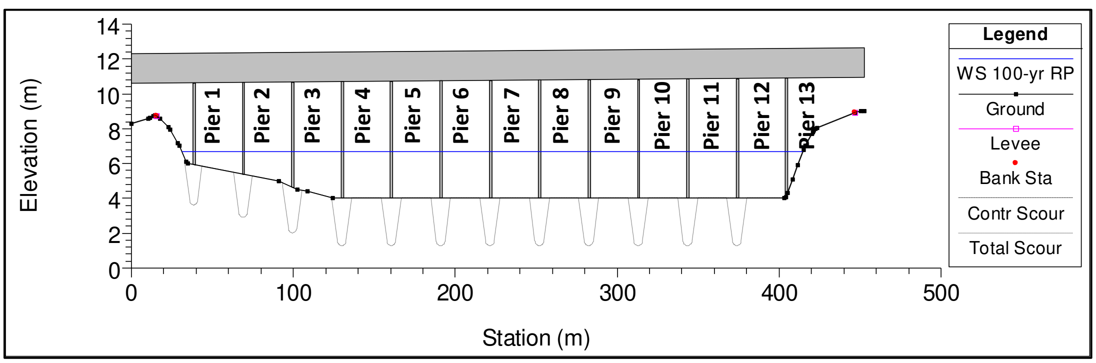

Figure 17. Maximum local scour at the bridge piers for 100-year return period

4 CONCLUSIONS AND RECOMMENDATIONS

Based from the results of the stability analysis for the existing section, the current embankments in the river are stable. Upon dredging, it is seen from the slope stability analysis results of Scheme 1 and 4 that erosion occurs in the very loose to loose sand layers with slip circle depths ranging from 0.1 to 1 m. With this, an analysis was done with the same dredging scheme but with an inclusion of a rock mattress. Results show that the mattress was adequate to address the possible erosion that will occur upon dredging. The longitudinal section will also have a slope of 1:3 with a rock mattress for erosion control.

It should be noted that although Maculcol Bridge will not be reached by flood levels in its existing condition the change in cross-section due to dredging might induce backflow at the downstream sections of the bridge, and result in higher flood levels.

Also, sediment eroded within the watershed would eventually be transported downstream and be deposited along the banks. Sediment accumulation on the downstream reach of the Santo Tomas River has a substantial effect on the river's flood levels and might aggravate flooding upstream.

The estimated sediment transport in the lower reach of the Santo Tomas River (at Maculcol Bridge) is around 3.5 million m^3/year, according to a study conducted by the Japan International Cooperation Agency (JICA) led by Shinsuke Hino (2003). In the same study, JICA conducted a Long Term Riverbed Movement Analysis using a one-dimensional sediment transport model and estimated an aggradation of around 1.5 m at the downstream reach of Santo Tomas River.

It is recommended that regular monitoring and periodic dredging of the river be done in order that the capacity of the waterway is maintained and in doing so, flooding upstream can be mitigated, thereby lessening the impact to the communities in the vicinity.

Moreover, due to the abrupt change in bed elevation, the entire profile of the river has potential for sediment transport and consequently shift downstream, causing bed degradation at the bridge. Also considering the potential local scour at the piers, corresponding bridge foundation scour protection is recommended to be put in place to protect the piers from strong flows, such as steel sheet piling.

Lastly, the case study is limited to assessing dredging as a method for flood mitigation and disaster risk reduction. The existing dikes terminate approximately 1.2 km from the mouth of the river, hence it is recommended to consider modelling dikes at this location as an alternative means to contain the flow and reduce flood risk.

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