Analysis of Sediment Transport on Ring Ngotok Canal's Morphological Changes

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Abstract. Ring Ngotok Canal is long storage in the Brantas River Basin which is managed under the authority of the Brantas River Basin Organization. It is estimated built-in 1925, with a length of ± 27.2 km and an average width of 30 m, to catch and divert the flow of 8 (eight) tributary of the Brantas River, as well as protect the ± 10.000 ha floodplain of Brantas River which is dominated by agricultural areas and at the same time supplying irrigation water for the irrigation area. The canal in recent years has decreased in capacity, so that it overflows, and causes flooding in settlements around the canal. Identification of the main cause of the capacity degradation is caused by local morphological changes, mainly due to sedimentation along the canal. By using the USLE equation, the value of the erosion rate is 177.16 tons/ha/year or 35.043,48 ton/day or 11,07 mm/year, this erosion value is included in the moderate category of erosion hazard class and the watershed is classified as critical (the limit value tolerance of land erosion rate in the watershed is 3 mm/year). With a Sediment Delivery Ratio (SDR) of 0.32, the amount of sediment transport from land erosion in Ring Ngotok Canal is 10,513 tons/day. Based on the sediment inflow outflow contability analysis, the net sediment at the bottom of the canal is 20 cm/year which changes the morphology of the Ring Ngotok Canal vertically. There is a horizontal morphological change (bend/meander) that needs to be handled. The value of the sediment rate in one year based on the simulation of the HECRAS software for sediment transport is close to the calculation results.

1. Introduction

Ring Ngotok Canal is long storage in the Brantas River Basin which is managed under the authority of the Brantas River Basin Organization. It is estimated built-in 1925, with a length of ± 27.2 km and an average width of 30 m, to catch and divert the flow of 8 (eight) tributaries of the Brantas River, as well as protect the ± 10.000 ha floodplain of Brantas River which is dominated by agricultural areas and at the same time supplying irrigation water for the irrigation area. The canal in recent years has decreased in capacity, so the overflows occur and cause flooding in settlements around the canal. The identification result showed the main cause of the capacity degradation is local morphological changes, mainly due to sedimentation along the canal. Therefore, studies and researches about the sediment transport is important. However, studies and researches related to the sediment transport in the Ring Ngotok Canal have not been found in the literature. The conditions of sedimentation in the Ring Ngotok Canal and flood events due to overflow of the Ring Ngotok Canal are shown in the Figure 1 below.

Figure 1. Sedimentation on the Ring Ngotok Canal and Flood Events in the Settlements Around the Canal in 2019 and 2020 and Occurs Every Year.

2. Study Area

The research was conducted on Ring Ngotok Canal which its upstream is administratively located in Jombang Regency starting from Tembelang Village to Sumberagung Village, the middle stream is located in Jombang Regency and Mojokerto Regency starting from Bongkot Village to Balongwono Village and the downstream is located in Mojokerto City from Mojorano Village to Village Pulorejo. Geographically, Ring Ngotok Canal is located at $07^{0}26'39''$ to $07^{0}32'19''$ South latitude and $112^{0}15'47''$ to $112^{0}25'38''$ East Longitude, with the boundaries of the hydrological area are as follows:

East : Brantas River
South : Watershed of the tributaries that empties into the Ring Ngotok Canal (Jombang Kulon Watershed, Jombang Wetan Watershed, Bening River Watershed, Bujel River Watershed, Sewedang River Watershed, Gunting River Watershed, Brangkal River Watershed)
West : Tembelang Watershed
North : Irrigation Area and Brantas River.

The length of the Ring Ngotok Canal is ± 27.2 km with a watershed area of ± 722 km2. The map of the study location and the Ring Ngotok Canal watershed is given in the figure below which shows that the canal is on the southern bank of the Brantas River.

Figure 2. Study Location Map.

3. Data

The data that used in this study are secondary data and primary data. The secondary data are rainfall data for 27 years starting from 1993 to 2019 at 5 rainfall station located in the Ring Ngotok Canal watershed (Sta. Ploso, Sta. Kesamben, Sta. Jombang, Sta. Blimbing and Sta. Wonosalam), river profile, Digital Elevation Model (DEM) data, land cover data, soil type, geology, topography, and watershed characteristic. There is no AWLR in this watershed, so for simulating the sediment transport along the canal, the boundary is daily discharge data for 1 year at the Ploso discharge station which its value is adjusted to the ratio of its catchment area to the Ploso station catchment area. The primary data are obtained from field measurements. Those are bed material, floating sediment concentration and instantaneous discharge data.

4. Result and Discussion

4.1. Sediment Transport

Sediment transport is an important parameter to study due to visually significant sedimentation along the Ring Ngotok Canal, also in the previous study report it was said that one of the causes of flooding from the overflow of the Ngotok Canal Ring was the silting of the Ngotok Canal Ring due to sedimentation [1]. However, the sedimentation rate is high but not enough discharge exists to carry sediment out of the Ring Ngotok Canal system, so that the capacity of the Ring Ngotok Canal is degraded which causes flooding in the vicinity as reported by the community and news of flood events in Jombang and Mojokerto. Then at this time the rehabilitation of a new cross section (capacity increase) of the Ring Ngotok Canal is being carried out by the Brantas River Basin Organization.

4.1.2 Sediment Transport from Land Erosion by USLE (Universal Soil Loss Equation)

The results of land erosion calculations using the USLE method have often been used by engineers (practitioners) where the results are quite accurate. The data needed in the analysis of the magnitude of land erosion (A) is rain erosivity (R), soil erodibility (K), slope length (L), slope (S), vegetation and plant management and conservation measures (CP).

The value of rain erosivity (R) is obtained from the Lenvain equation (1989), $R = 2.21\ P^{1.36}$, where P is the monthly rainfall in cm [2]. Based on the monthly rainfall value from 5 rain stations in the Ring Ngotok Canal watershed, the rainfall erosivity index is 1486.98. Based on the map of soil types in the Ring Ngotok Canal watershed and tables of the Research and Development Center of Water Resources (1985) [3], the value of the soil erodibility factor based on the type of soil in the Ring Ngotok Canal watershed is 0.23. From the topographic map, the average value of the LS factor in the watershed based on Kironoto (2000) [4] is 1.4. Based on the percentage of land use area in the Ring Ngotok Canal watershed, the CP factor value was 0.37 (Hammer, 1981) [5].

By using the USLE equation, A = R.K.LS.CP [6], the erosion rate value is 177.16 tons/ha/year or 17.715,8 ton/km2/year = 35.043,48 ton/day = 11,07 mm/year. Based on Suripin (2001) this erosion value was in the moderate category erosion hazard class [7]. Watershed is classified as critical (the limit value tolerance of land erosion rate in the watershed is 3 mm/year). Based on a study report on the Ring Ngotok Canal Flood Management System [8], the erosion rate in the Ring Ngotok Canal watershed was 155.33 tons/ha/year.

However, land erosion that exceeds the critical limit (4,500 tons/km^2/yr) does not all enter the Ring Ngotok Canal. There is a reduction in the potential for sediment entering from land erosion in the catchment area. Furthermore, the rate of Sediment Delivery Ratio (SDR) from land erosion is calculated using the empirical formula of the director general of PUPR in 1999 as follows :

$$SDR = S\ X\ \frac{(1-0.8683\ (A^{-0.2018}))}{2(S+50.n)} + 0.8686\ (A^{-0.2018}) \quad (1)$$

Where
SDR = the value is 0 < SDR < 1
A = watershed area (ha)
S = watershed slope
N = watershed surface roughness

Which the value of A = 722 km^2, S = 2% and N = 0.04, The SDR value obtained based on the empirical formula above is 0.32 which is included in the moderate category. Therefore, the value of sediment transport in the Ring Ngotok Canal from land erosion is SDR multiplied by the Potential Erosion Rate, which is 56.7 tons/ha/year will enter the river. If we take into account the sediment that occurs in the creeks that enter the Ring Ngotok Canal, the sediment transport will be less than 56.7 tons/ha/year.

4.1.2 Sediment Transport Equation

4.1.2.1 Bed Sediment Transport Equation

From the four sampling point locations along the Ring Ngotok Canal, 1 point in the upstream, 2 points in the middle of the canal and 1 point at the downstream of the canal, the grain size distribution curve is obtained as follows:

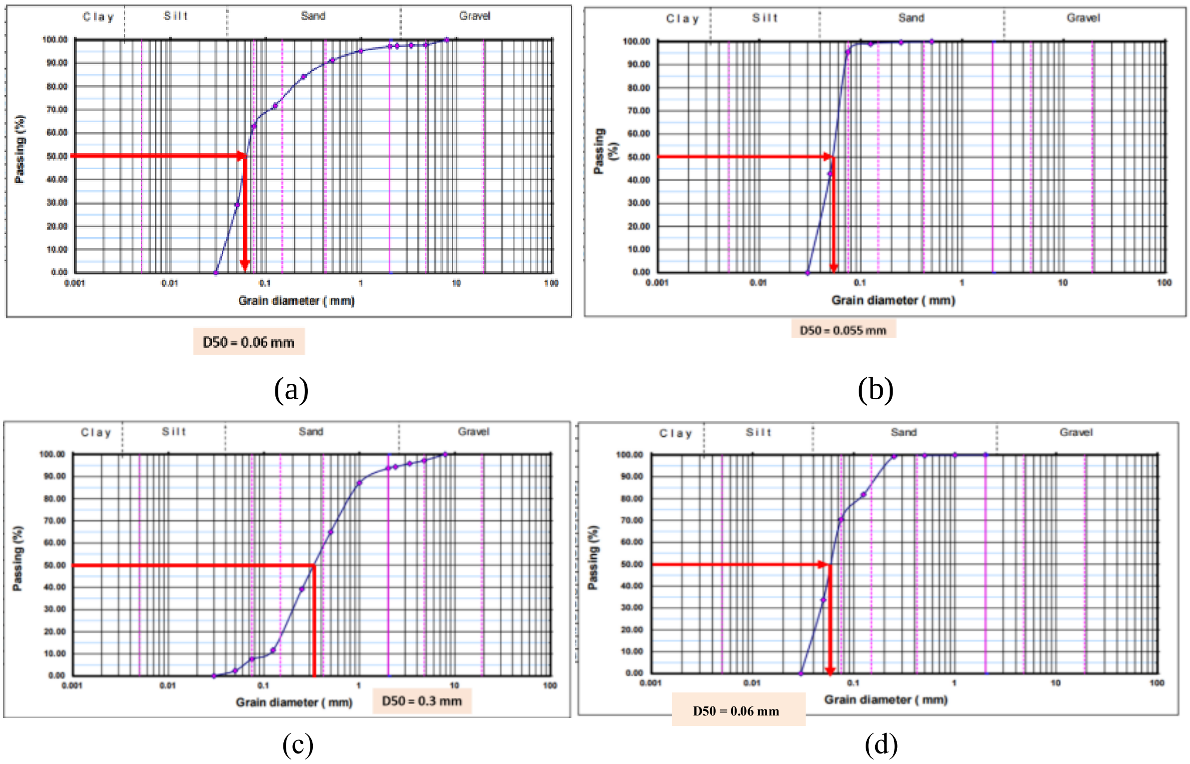

Figure 3. Grain Size Distribution Curve (a) Location 1 at upstream, (b) Location 2 at the middle of canal, (c) Location 3 at the middle of canal, (d) Location 4 at downstream

From the graph, the D50 value for each location is obtained, and the average D50 value = (0.06 mm + 0.055 mm + 0.3 mm + 0.06 mm)/4 = 0.12 mm. So it can be concluded that the characteristics of the sediment in the Ring Ngotok Canal based on grain gradation is sand. Then with the Duboys equation (1979) [9]:

$$q_b = \frac{0.173}{d^{0.75}} \tau_o (\tau_o - \tau_c) \quad (2)$$

where
q_b = bed sediment transport per unit width
τ_o = shear stress = ɣRS
d = diameter of sediment particles that 50% pass the sieve
τ_c = critical shear stress based on shield graph
R = hydraulic radius
S = slope

the value of bed sediment transport for each flow depth can be calculated as follows:

Table 1. Bed Sediment Transport with Duboys Method.

d50 (mm)	ɣ (kg/m3)	R (m)	S	τo (kg/m2)	τcr (kg/m2)	d50 (ft)	τo (lb/ft2)	τcr (lb/ft2)	qs (lb/s/ft)	Qs (lb/s)	Qs (kg/s)	Qs (ton/s)	Qs (ton/day)	Q (m3/s)
0.12	1000	0.5	0.00034	0.17	0.08	0.000394	0.035	0.016	0.04	2.61	1.18	0.001	102.16	3.87
0.12	1000	1	0.00034	0.34	0.08	0.000394	0.070	0.016	0.23	15.06	6.83	0.01	590.26	12.29
0.12	1000	1.5	0.00034	0.51	0.08	0.000394	0.104	0.016	0.57	37.36	16.95	0.02	1464.31	24.16
0.12	1000	2	0.00034	0.68	0.08	0.000394	0.139	0.016	1.06	69.51	31.53	0.03	2724.29	39.03
0.12	1000	2.5	0.00034	0.85	0.08	0.000394	0.174	0.016	1.70	111.51	50.58	0.05	4370.22	56.61
0.12	1000	3	0.00034	1.02	0.08	0.000394	0.209	0.016	2.49	163.36	74.10	0.07	6402.08	76.71
0.12	1000	3.5	0.00034	1.19	0.08	0.000394	0.244	0.016	3.43	225.05	102.08	0.10	8819.89	99.18
0.12	1000	4	0.00034	1.36	0.08	0.000394	0.279	0.016	4.52	296.59	134.53	0.13	11623.64	123.90
0.12	1000	4.5	0.00034	1.53	0.08	0.000394	0.313	0.016	5.76	377.98	171.45	0.17	14813.33	150.78
0.12	1000	5	0.00034	1.7	0.08	0.000394	0.348	0.016	7.15	469.22	212.84	0.21	18388.96	179.72
0.12	1000	5.5	0.00034	1.87	0.08	0.000394	0.383	0.016	8.69	570.31	258.69	0.26	22350.54	210.66
0.12	1000	6	0.00034	2.04	0.08	0.000394	0.418	0.016	10.38	681.24	309.01	0.31	26698.05	243.54
0.12	1000	6.5	0.00034	2.21	0.08	0.000394	0.453	0.016	12.22	802.02	363.79	0.36	31431.51	278.29

From the table, it is found that the relationship between the bed sediment discharge with the flow depth and discharge flow is as follows:

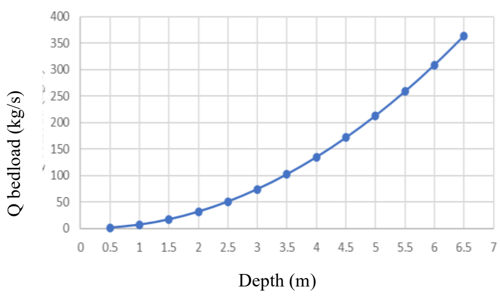

Figure 4. Relationship between Bed Sediment Discharge and Depth of Flow.

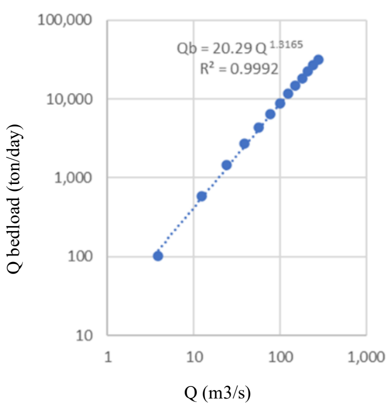

Figure 5. Relationship between Bed Sediment Discharge And Flow Discharge.

From the graph, it is found that there is a relationship between the bed sediment discharge and the flow rate is $Qb = 37.628\ Q^{1.2016}$

4.1.2.2 Suspended Sediment Transport Equation

The sediment concentration value was obtained from the results of the Total Suspended Solid test in the laboratory. Then to get the suspended sediment discharge value, the equation Qs = C. Qw is used, the concentration of suspended sediment times the flow rate. The table below is a recapitulation of laboratory test results, instantaneous flowrate measurements at the time of sampling and suspended solid discharge.

Table 2. Recapitulation of Laboratory Test results and Instantaneous Flow and Solid Flow.

Location	TSS (mg/L)	Q (m3/s)	Qs (ton/day)
Tembelang - Upstream	210	0.18	3.25
Jl. Sebani - Middle of Canal	180	0.89	13.87
Jl. Curah Malang - Middle of Canal	140	3.31	40.06
Pulorejo Bridge - Downstream	140	8.84	106.95
Tembelang - Upstream	130	0.02	0.22
Jl. Sebani - Middle of Canal	210	1.05	19.05
Jl. Curah Malang - Middle of Canal	200	6.24	107.78
Pulorejo Bridge - Downstream	110	5.89	55.98
Tembelang - Upstream	270	0.12	2.75
Downstream	100	134.26	1160.01

From the table, a relationship can be made between suspended sediment discharge and Ring Ngotok Canal flow discharge in a log-log graph as follows:

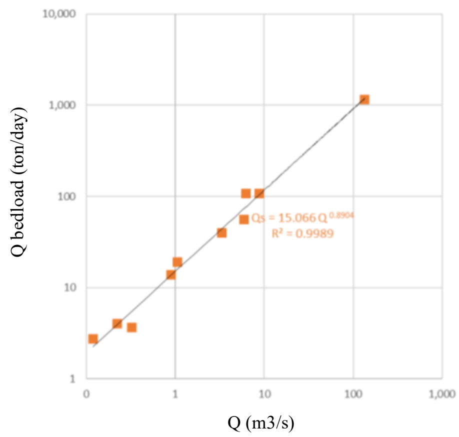

Figure 6. Relationship between Suspended Sediment Discharge And Flow Discharge.

It was found that there was a relationship between the suspended sediment discharge and the flow discharge is $Qs = 15.066\ Q^{0.8904}$

4.1.2.2 Total Sediment Transport Equation

The total sediment transport value is the sum of the bed sediment discharge and the suspended sediment discharge per unit width multiplied by the width of the canal. Then obtained the relationship between flow discharge with bed sediment discharge, suspended sediment discharge and total sediment discharge as follows:

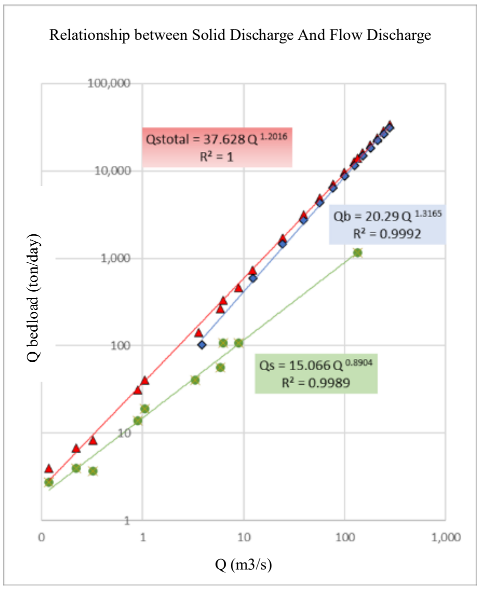

Figure 7. Relationship between Solid Discharge And Flow Discharge.

4.2. Flow Discharge

As given in the sediment transport equation above, daily discharge fluctuations are very important. In the Ring Ngotok Canal there is no discharge station to determine the daily discharge that occurs. Daily discharge data is taken from the Ploso discharge station in the Brantas River, with a daily discharge approach obtained by proportioning the area of the catchment area on the Ngotok Canal Ring with the area of the Ploso water catchment area. Where the average flow rate that occurs in one year in 2012 is 38.34 m3/s, this is in accordance with the results of the calculation of the average discharge in one year using annual average rainfall data at 5 rain stations for 10 years, with a simple rational method that is equal to 35.65 m3/s, with a value of C = 0.7, annual average rain = 2080.6 mm.

4.3. Morphological Changes

4.3.1 Vertical Morphological Change

4.3.1.1 Calculation of Vertical Morphological Changes

Sediment transport rate from land erosion = 10,513.04 tons/day is an estimation of sediment entering the Ring Ngotok Canal. Furthermore, the analysis of sediment transport rate along the canal was done by using the equation for the total sediment transport rate. The average annual flow rate that is used in predicting the analysis of the total sediment transport rate is 38.34 m3/s. The analysis of the annual sediment transport rate is shown in the following table :

Table 3. Sediment Transport Rate Analysis per Year.

Sediment In (ton/day)	Sediment Out Equation (ton/day)	Sedimen Transport (ton/day)	Sedimen Transport (ton/years)	Desc.
10,513.43	27,854.46	-17,341.03	- 1,213,872.30	Discharge when v>1 ms^{-1}
10,513.43	3,009.04	7,504.39	1,373,303.94	Average Discharge
Total Sedimen Transport (ton/year)			159,431.64	

Thickness of deposit along the canal (Δt) per year

$$= \frac{\text{sediment transport rate}}{\text{canal length}}\, x\, \frac{1}{\gamma s}\, x\, \frac{1}{canal\ average\ width} \tag{3}$$

$$= \frac{159.431{,}64\ ton/year}{27200\ m}\ \text{x}\ \frac{1}{1.15\ ton/m3}\ \text{x}\ \frac{1}{25\ m}$$

= 0.2 m / year = 20 cm / year
= 1 m in 5 years

Dredging volume per year
= 159.431,64 ton/year

Dredging volume in 5 years
= 797.158,2 ton
= 797.158,2 / 1.15 ton/m^3
= 138.636,21 m^3

Estimated operation and maintenance costs every 5 years
= 138.636,21 m3 x Rp. 50.000 / m3
= 34.659.052.837,93 = 34.7 billion Rp.

4.3.1.2 Simulation of Morphological Changes Vertically with HECRAS 1D Software

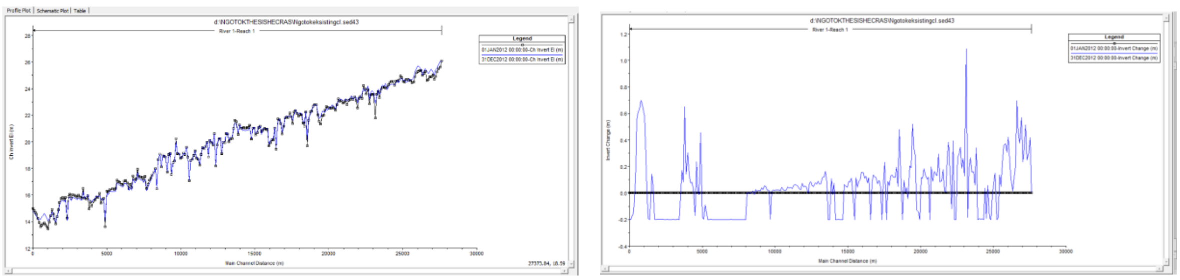

Figure 8. Location of Eroded and Sedimented Sections based on Running HECRAS 1D with Daily flow rate in 1 year

From the picture above, it can be seen that some sections are dominated by sediment, and some sections also have scour. Total Sedimentation Rate in 1 year based on HECRAS simulation is 145,726 tons. With a maximum height of 1.09 m sedimentation potential, and a maximum depth of erosion potential = 0.2

m. The value of the sediment rate in one year based on the simulation results is close to the calculation results.

4.3.2 Horizontal Morphological Changes (Meander)

Identification of meander development in the Ngotok Canal Ring is one part of the analysis of morphological changes in the Ngotok Canal Ring. The observation location is depicted in the following figure:

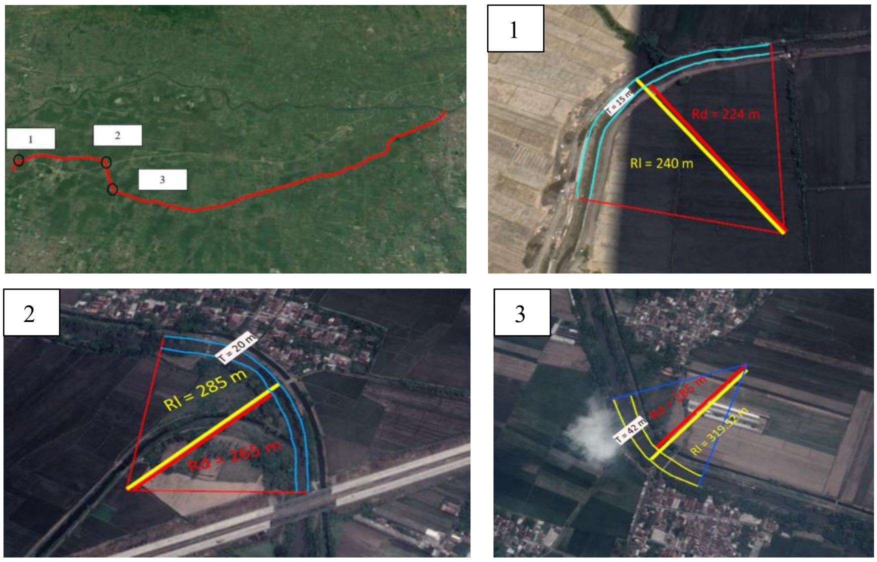

Figure 9. Meander Observation Locations at Ring Ngotok Canal.

By Ripley (1927) [10], the maximum inner and outer of meander radius are given as follows:
$Rd = 40 \times (A)^{0.5}$ (ft)
$Rl = 110 \times (A)^{0.5}$ (ft)
Where :
A = cross-sectional area (ft^2)
Rd = maximum radius of inside of bend (ft)
Rl = maximum radius of outside of bend (ft)

The maximum radius is the limit at which the meander doesn't develop anymore. The table below is the measurement of the existing bend radius and maximum bend radius.

Table 4. Measurement Of The Existing Bend Radius And Maximum Bend Radius.

Location	Rd (ft)	Rd Max (ft)	Rl (ft)	Rl Max (ft)
1	734.91	637.02	787.40	2776.31
2	869.42	735.56	935.04	2983.34
3	935.04	1507.46	1048.29	4270.86

From the table above, it is found that at the location 1, the outside bend meandering process is still developing. However, the construction of a parapet in this bend has been carried out. At location 2, the meandering process on the outer bend is still ongoing, it is necessary to strengthen the cliffs because there are irrigation networks and settlements that must be protected from damage/scouring threats/meanders that are still developing on the outer bend. Then at location 3, the meandering process is still running for the inner and outer bends, it needs handling to prevent the cliff from collapsing and keep the river flow stable because there are settlements on the outer bend and access roads that connecting the villages, then the meander process on inside bends can disrupt the river flow and reduce river capacity.

5. Conclusions

The results of the analysis and discussion in the following conclusions: 1. Study on the identification of the causes of the decline in canal capacity both as flood control and irrigation water supply, mainly due to sedimentation from land erosion from the watershed of 8 (eight) tributaries; 2. The rate of land erosion is 17,715 tons/km2/year; 3. With a Sediment Delivery Ratio (SDR) of 0.32; 4. The amount of sediment transport from land erosion in Ring Ngotok Canal is 10,513 tons/day; 5. Based on the sediment inflow outflow contability analysis, the net sediment at the bottom of the canal is 20 cm/year which changes the morphology of the Ring Ngotok Canal vertically; 6. There is a horizontal morphological change (bend/meander) that needs to be handled; 7. The results of the simulation of the HECRAS software for sediment transport obtained a net in the form of sediment qualitatively along the canal similar to the results of the calculation of sediment stability.

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