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Analysing Sediment Transport Mechanism and Related Hydraulic Structure Damage after Mt. Merapi Eruption in Gendol River

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ABSTRACT

An enormous sediment produced by multi-eruption of Mt Merapi in October – November 2010 has created new morphological conditions in the mountains-river‘s catchments area and in the stream. As the catchments area and river stream becomes different, the sediment transport mechanism in rivers stream will change due to the different of bed slope and the amount of produced free surface flow. In case of Gendol, one of river that originated in Merapi Summit with a lot of constructed hydraulic structures in it, this new condition stimulated the process of hydraulic structure damage especially in the first rainy season after eruption. By analyzing the data of riverbed slope up to April 2011, it was found that the mechanism of sediment transport has changed along the Gendol just after 2010 eruption. Then, based on data inventory of hydraulic structure damage, it can be concluded that its destruction process strongly related to the condition of river bed that created by deposited sediment and sediment transport mechanism. These relation shows by the pattern of damage type that depends on the pyroclastic distance in each eruption event.

KEYWORDS: multi-eruption, river morphology, mountain river, Gendol River, pyroclastic, destruction process.

INTRODUCTION

Two main effects of 2010 Merapi multi-eruption are discussed in this paper, namely the change of riverbed slope due to deposit sediment produced by eruption that further will influence sediment transport mechanism, and the process of hydraulics structure damage along the river stream of Gendol River. The aim of the research is to understand the process of hydraulics structure's destruction as influence of the change of sediment transport mechanism.

The types of sediment transport mechanism depend on the slope of the river bed and the ratio of free surface depth (h_o) to the diameter characteristic (D) [1]. If one of the parameters changes, then the sediment transport mechanism may change. Takahashi classified the torrential sediment transport into three types, namely debris flow, immature debris flow and individual bed transport base on the above mentioned parameters. By the eruption, produced sediment is deposited with varied thickness. In the river stream create a new slope while in landscape create new catchments area and the change of catchments area creates a new depth of the free surface flow. So in case of Merapi eruption, all three parameters of sediment transport mechanism are change. In order to understand this phenomenon, the case in the Gendol river catchments area is raised as a case study.

Ten of thirteen catchments area of rivers that originated from Mt. Merapi has covered by sediments produced by 2010 eruption. As the effect of it, some catchments area changes drastically on both in-stream and off-stream morphology. This causes the change of the sediment transport mechanism, especially in the river with such huge sediment deposit as shown by the problem in Gendol River. The total production of sediment by the 2010 Mt Merapi eruption was 140 million m^3 within less than two weeks. Two biggest eruption, namely on 26 October 2010 evening and 5 November 2010 morning produce more than 40 million m^3. That was such an extraordinary case, since the 2006 Mt Merapi eruption produced approximately only about 8 million m^3 within the period of April thru June 2006.

From the 140 million m^3 of pyroclastic deposit, 40 m^3 millions of it was deposited in Gendol and Upper Opak (Petit Opak) catchments area [2]. According to National Board of Disaster Mitigation, the Gendol catchments area got the most deposited sediment since the direction of 9 of 10 multi-phase pyroclastic flow to Gendol catchments area as shown by Table 1 [3]. Thereby the problem of deposit sediment in Gendol- Petit Opak catchments area due the change of the slope and its generated damage force is one of the harmless among other river.

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Table 1. Dominant direction of multi-eruption [3]

No	Date of occurance	Distance(km)	Dominan directions
1	October 26, 2010	7.5	Gendol (South), Senowo, Lamat (West)
2	October 28, 2010	2	Gendol (South)
3	October 30, 2010	3.5	Gendol, Boyong, Kuning (South), Senowo, Lamat (West), Krasak (Southwest)
4	October 31, 2010	2	Gendol (South), Senowo, Lamat (West), Krasak (Southwest)
5	November 1, 2010	4	Gendol (South),Woro (Southeast)
6	November 2, 2010	5	Gendol (South)
7	November 3, 2010	9	Gendol (South)
8	November 4, 2010	-	Senowo, Lamat (West)
9	November 12, 2010	4	Gendol, Talang (West)
10	**November 22, 2010**	**-**	**Gendol (South)**

Problem to be faced just after eruption is the lahar flow. The lahar occurs when the deposited sediment triggered by relatively high rainfall intensity in such a long time. The magnitude of lahar flow is strongly influenced by river slope as well as the ratio between free surface flow and deposited sediment depth. By morphological changes, the type of sediment transport mechanism changes. In this case, the change of slope is one of parameters that need to be investigated. Direct measurements of in-stream slope is quite dangerous matter, therefore in order to figure out the slope on the river an un-direct measurement is done. Global Positioning Systems (GPS) and Distance meter are used to measure elevation and distance of pointed location. The data of hydraulics structure damage is collected by the end of first rainy season, namely on May 2011.

On analysing the mechanism of sediment transport, the most important parameter is the rainfall intensity and the duration of each series of rainfall. Based on the data of rainfall of five Mt Merapi Observation Stations, namely in Kaliurang, Jrakah, Babadan, Srumbung and Selo it can be concluded that rainfall on year 2010 is potential to trigged the lahar flow. The main character should be analyzed are monthly rainfall, day of rainfall and intensity.

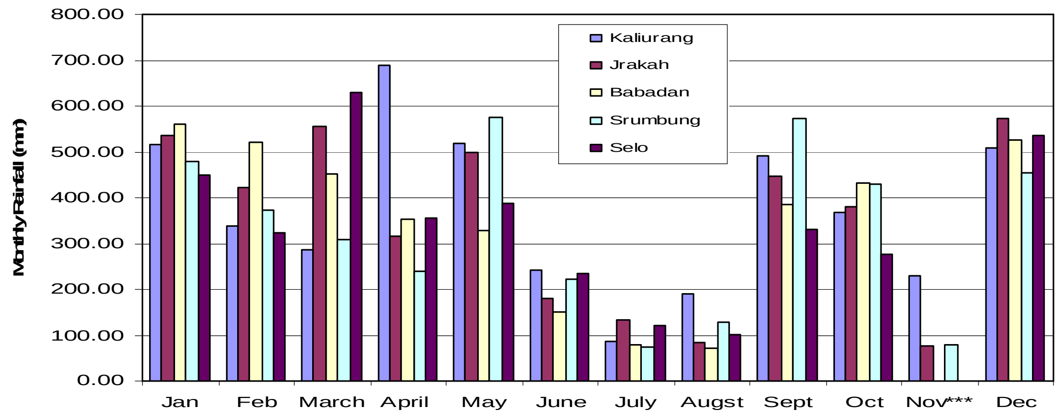


Figure 1: Monthly rainfall on Year 2010 at Mt.Merapi Observation Station

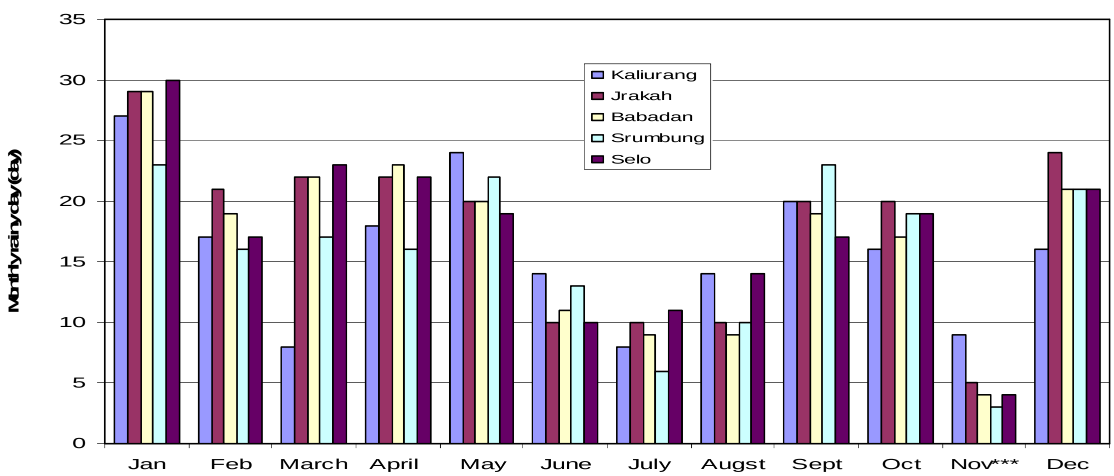


Figure 2: Total amount of rainy day per month on Year 2010

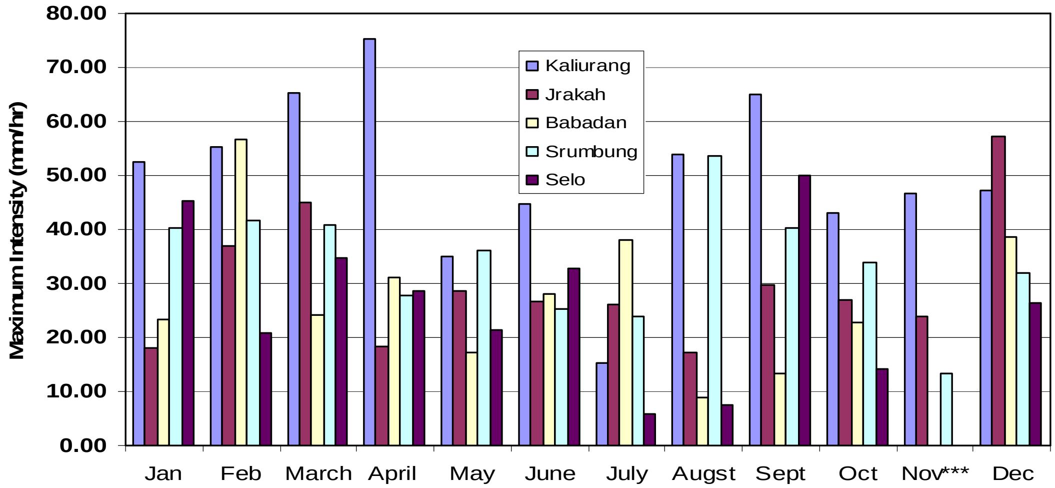


Figure 3: Monthly Maximum Intensity on Year 2010

Further, by focusing data analysis of the Observation Station in Kaliurang, the most nearer station to Gendol catchments area, the character of rainfall was quite high. It causes the occurrence of sediment movement that created dynamic morphological changes in river stream. Relation of long duration and high intensity of rainfall to the sediment movement can be explained as follow. Long duration rainfall increases the total amount of water in the soil. As the accumulation water increases, then the water pressure in the soil increases as well. This pressure will force the soil in certain slope to move downward [4, 5, 6]. Karnawati [7, 8] found that the most sensible factor on rainfall intensity responses to failure is the hydraulics gradient. Referring these all theory of sediment movement, in can be concluded that the rainfall character of Kaliurang Observation Station is potential to be trigger for sediment movement.

Gendol Catchments Area

The Gendol river with 22,525 km length and 36,772 km^2 catchments area lies between 110^0 26$'$ up to 110^0 30$'$ east longitude and 7^0 32$'$ up to 7^0 45$'$ south longitude, while Upper Opak (Petit Opak) flows parallel to and side by side with the Gendol. It can be said that the Gendol is actually the branch of the Opak River, since both rivers are finally join together in Rogobangsan tributaries at elevation of about 200 meter ASL. Flowing near equator, this area has two seasons: rainy season that generally starting in the middle of October and dry season that starting on the middle of April.

The yearly average rainfall is about 2,200 mm – 2,800 mm with the rainfall peak season on January up to February. The Gendol River flows from an elevation of +2968 meter ASL to about +200 meter ASL. Before the 2010 eruption, the average riverbed slope of the Gendol is about 0.123 and increases just after the eruption [4]. The change of riverbed slope leads to the change of sediment transport mechanisms, nevertheless the mechanism type is not considerably unchanged: debris flow in upper reaches, hyper concentrated flow in the middle reaches and individual sediment transport in the lower reaches.

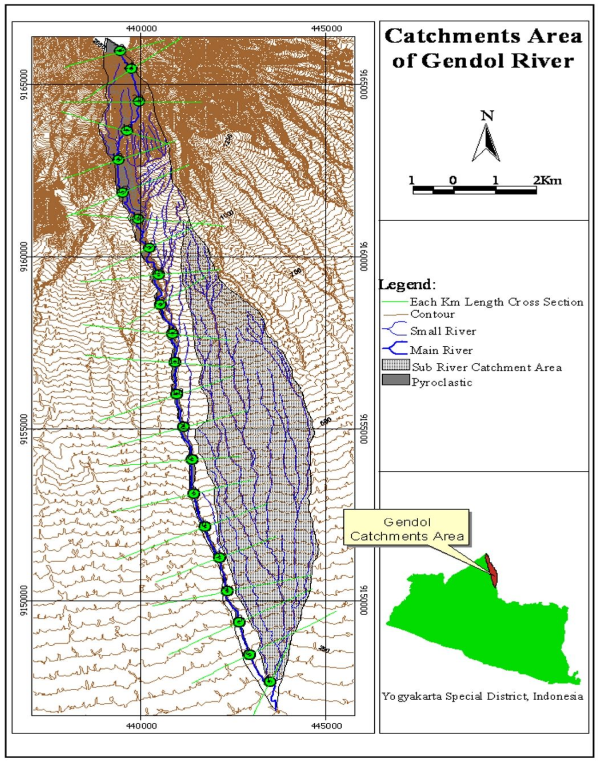


Figure 4: Gendol catchments area

Criteria of sediment transport mechanism

There are three types of sediment transport of torrential river namely debris flow, high concentrated/ immature debris flow and bed load/individual sediment transport. The types of sediment transport mechanism depend not only on the river bed slope but also on the ratio of free surface depth (h_o) and diameter characteristic (D). Since the free surface depth and diameter characteristics change over the time, then the ratio changes as well. As a consequence, the point of separation between hyper concentrated flow and individual sediment transport is always changing as a function of water depth. In case of Gendol river, the sediment produced by eruption is sandy and very porous, so in upper reach of the river where the slope is steep then the free surface depth is very thin and lasted only in a short time. In this case the slope will play an important role on generating debris flow. On the other hand, in lowest reach of the river, the free surface flow is always available. In the middle reach will strongly depend on the duration and depth of rainfall

Fujita classification

The impact of eruption is not only in environment sectors but also in social, medical, economic and infrastructures along the stream as well. Reffers to damage data of Sabo dam, especially in Kali Putih, Fujita et al [5] categorized the damage of sabo structures due to sediment runoff into four types.

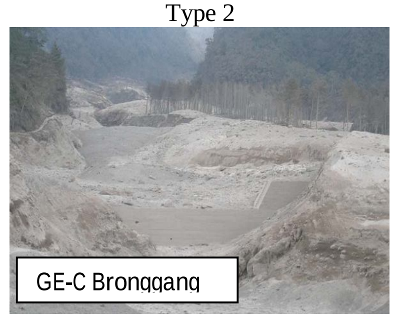
Table 2. Fujita classification [5]

No	Types	Descriptions
1	Type 1	• Characterized by abrasion or small damage to crest of main dam and wings since the main dams were suffered only by abrasion due to cold lahars, • Sediment was deposited on the apron and part of sub dam, • Some sub dams collapsed or heavily damage. • Example: GE-D1 Kepuharjo
2	Type 2	• Characterized by severe damage of main dam due to local scouring near the downstream foot of the dam, • Severe degradation breaks sub dams, • Main-dam also collapse by degradation extending to up stream but the main dam still stand up. • Example: GE-D5 Kopeng
3	Type 3	• Characterized by severe collapses of both main and sub dams, • Example:GE-C Cangkringan
4	Type 4	• Sabo dam is totally or mostly buried by sediment • Example: GE-C Bronggang

Type 1

Type 2

Type 3



Type 4

Figure 5: Example of each damage type in Gendol River

MATERIALS AND METHODS

Riverbed measurement

Considering the safety factor, the measurement of river bed elevation has done un-directly. Base on the Google-earth download map of November 2010, some positions or point of positions are measured by used of Global Positioning System (GPS) apparatus to check their coordinates and elevations. The measurement was only done in Kaliadem downward, since the condition downward of Kaliadem is strongly different. The top area, namely Kaliadem upward, is assumed remained unchanged. In river cross section near Jambu (+ 867 m ASL), the deposit in the river is more than 100 meter and gradually decrease up to the meeting point of Kali Opak.

The width of the river stream was measured using distance meter based on laser approach. The result of measurement then calibrated using some measurement of elevation done by Balai Sabo Yogyakarta [6]

The step of river bed slope calculation is as schematized by Figure 3.

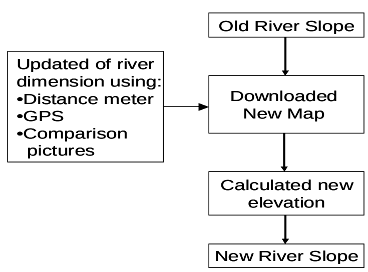


Figure 6: Calculation step of new river slope

The other parameter should be known well is the depth of deposit sediment of each cross section since it influence sediment balance along the river. Lack of sediment supply in one dam will lead to erosion/ degradation in the toe of sub-dam and in certain circumstance it would trigger the collapse of the main dam.

RESULTS AND DISCUSSION

The changes of sediment transport mechanism

It has been explained above that the type of sediment transport mechanism is classified as debris flow, immature debris/ hyper concentration flow and sediment transport. This classification is based on the relation water depth and the slope. When the slope changes then the type of sediment transport will change too. By calculating the minimum slope of each type, then the change of the type can be determined. According to Takahashi (1991) the minimum slope of each type can be calculated as:

For debris flow

$$\tan \theta d = \frac{C_*(\rho_s - \rho)}{C_*(\rho_s - \rho) + \rho(1 + 1/K)} \tan \phi ; K = ho / D \qquad (1)$$

For hyper-concentrated flow

$$\tan \theta h = \frac{C_*(\rho_s - \rho)}{C_*(\rho_s - \rho) + \rho(1 + ho / D)} \tan \phi \qquad (2)$$

It was found that minimum angle of debris flow occurrence using equation is θd = 14.77^o. The minimum angle of the occurrence of hyper concentrated flow is rather complicated since it is influenced not only by the angle but also by the ratio free surface flow and characteristic diameter *D*. So the value of θh is spatially and temporally very dynamics since the value varied along the water body. If the *ho/D* bigger then θh becomes smaller. Using simulation result of hydrology approach and sediment data of the river, it can be calculated that when *ho/D* is equal to 10, the value of θh is 3.15^0 and θh is 1.80^0 when *ho/D* equal to 100.

Based to the result of calculation of these equations, then the type of sediment transport mechanism before and after can be determined. The change of it is presented in Table 3.

Table 3. Sediment transport mechanism before and after 2010 eruption

Elevation (m)	Type of sediment transport Mechanism before 2010 eruption	Type Sediment transport Mechanism after 2010 eruption
0		
0.525	Debris	Debris
1.525	Debris	Debris
2.525	Debris	Debris
3.525	Hyper	Hyper
4.525	Hyper	Hyper
5.525	Hyper	Hyper
6.525	Hyper	Hyper/Bed Load
7.525	Hyper	Hyper/Bed Load
8.525	Hyper/Bed Load	Hyper/Bed Load
9.525	Hyper/Bed Load	Hyper/Bed Load
10.525	Hyper/Bed Load	Hyper/Bed Load
11.525	Hyper/Bed Load	Hyper/Bed Load
12.525	Hyper/Bed Load	Hyper/Bed Load
13.525	Hyper/Bed Load	Hyper/Bed Load
14.525	Hyper/Bed Load	Bed Load
15.525	Bed Load	Bed Load
16.525	Bed Load	Bed Load
17.525	Bed Load	Bed Load
18.525	Bed Load	Bed Load
19.525	Bed Load	Bed Load
20.525	Bed Load	Bed Load
21.525	Bed Load	Bed Load
22.525	Bed Load	Bed Load

The result of calculation is shown in Figure 7,

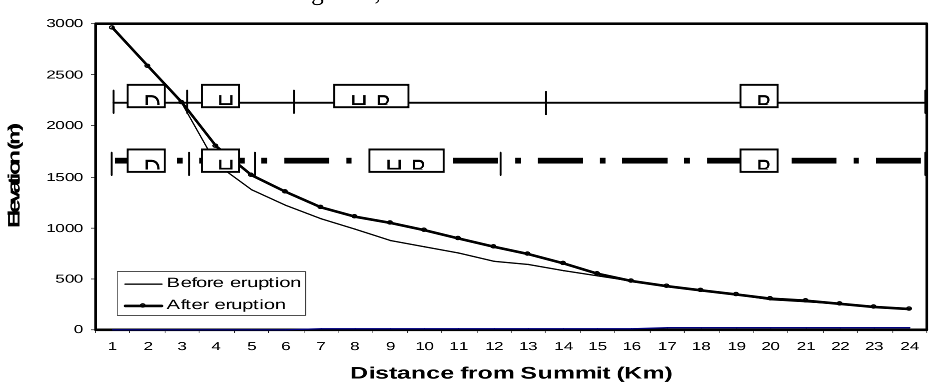


Figure 7: The change of river slope before and after 2010 eruption

where : D is defined as debris flow type,
H for high concentrated / immature debris flow,
H-B for transition type between High concentrated and bed load type,
B is for Bed load type

Hydraulic structure inventory data

The data collection of damage Sabo-dam has done on the end of first rainy season 2011. The total amount of damage hydraulics structures are 10 dams and 5 sub-dams [3]. Assuming buried dam as damaged Type 4, then the distribution of all 22 dam and consolidation dam along Gendol can be calculated as: One dam (type 1), Six dams (type 2), Two dams (type 3) and Five dams (type 4) and another Five dams are in a good conditions as shown by Table 4

Table 4. List of damaged dam/ consolidation dam

No	Name/Location	Description after 2010 eruption	Damage type
1	GE-D (Kaliadem)	Buried	Type 4
2	GE-D7	Buried since 2006 eruption	--------
3	GE-D5 (Kopeng)	Wing of dam is damaged	Type 2
4	GE-D4	Main dam totally damaged	Type 3
5	GE-D3 (Glagaharjo)	Buried	Type 4
6	GE-D2	Part of dam is damaged	Type 2
7	GE-D1(Kepuharjo)	Abrasion in main dam	Type 1
8	GE-C13	Totally damaged	Type 3
9	GE-C12 (Ngancar)	Totally damaged	Type 3
10	GE-C10 (Bakalan)	Totally damaged	Type 3
11	GE-C(Cangkringan)	Sub dam is damaged	Type 2
12	GE-C (Bronggang)	Sub dam is buried	Type 2
13	GE-C (Jetis II)	Totally damaged	Type 3
14	GE-C (Jetis I)	Totally damaged	Type 3
15	GE-C (Plumbon I)	Good conditions	--------
16	GE-C (Plumbon II)	Buried	Type 4
17	GE-C7 (Morangan)	Good conditions	-------
18	GE-C9 (Leses)	Part of main dam is eroded	Type 2
19	GE-C (Jambon)	Good conditions	-------
20	GE-C (Jerukan)	Scoured downstream of dam	Type 2
21	GE-C (Rogobangsang)	Good conditions	-------
22	GE-C (Tulung)	Good conditions	-------

In downstream of Bronggang that were two dams totally destroyed on 31 March 2011 by heavy rainfall that took place almost in the whole day. It started by intensive bed erosion downstream of the dam that cause the failure of the sub-dam. If such debris flow passes through the main structures, the hydrodynamic pressure will arise and trigger the collapse of main structure.

Refers to Fujita classification, it can be found that the damage dam Type 1 in Gendol is only one (1), damage Type 2 (4) , damage Type 3 (6) and damaged Type 4 (4). One dam has already buried before 2010 eruption, so the number of dam that buried due to 2010 eruption is 3. In Gendol River the damaged Type 3 is dominant since the destructions power of pyroclastic flow as well as the lahar flow is very strong. That was rather extraordinary comparing the fact of it in other river in Merapi. By this fact, it can be concluded that the force generated by lahar flow in Gendol is stronger than in Putih River. One of the reasons of it should be the amount of sediment that deposited in Gendol is bigger comparing with its in Kali Putih as a reason of multi-phase eruption. That why in case of Gendol there are a lot of dams either totally damaged or totally buried.

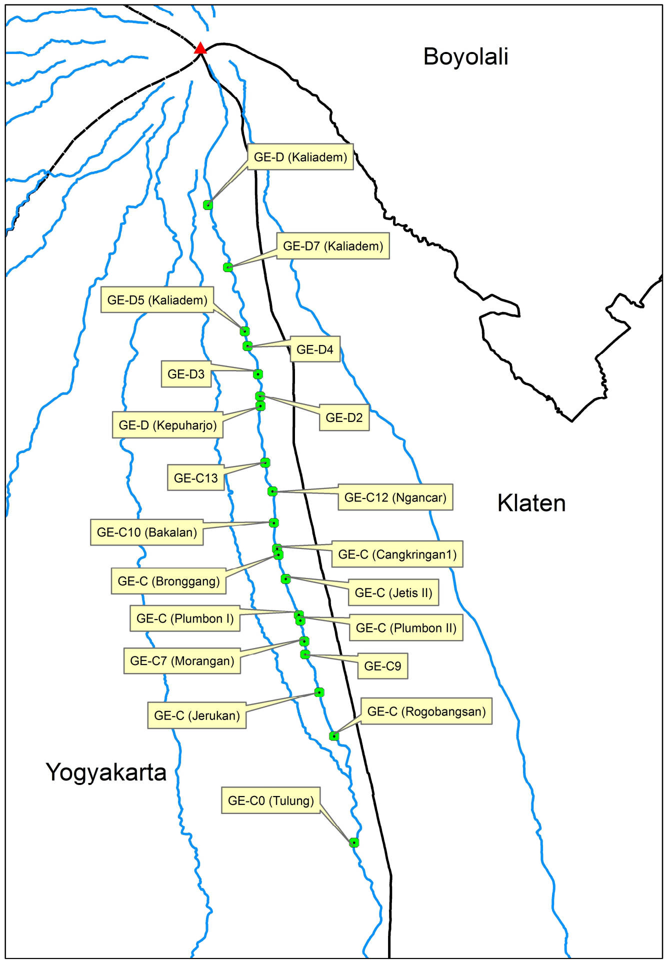


Figure 8: Sabo-dam structure along the Gendol River.

CONCLUSION

The multi-eruption of 2010 Mt. Merapi eruption generated huge amount of sediment. This sediment then triggered by high intensity of rainfall in that period of rainy season create very high destruction power. As an evident 10 of 22 Sabodam are collapsed or partly collapsed. This fact realizes that the effect of sediment transport mechanism driven by rainfall intensity to the damage process of hydraulic structure is very strong. Therefore monitoring of first season rainfall intensity after eruption is necessary in order to minimize the number of casualties.

The effect of the deposit sediment to the bed slope and generated force to damage of hydraulics structure is very significant. The first problems then lay on which rainfall characteristic actually has the most important roles: intensity, duration and frequencies. Therefore, further intense research about rainfall characteristic should be conducted in this area. It is actually not that simple research, since the variability of rainfall characteristics is very random but still stochastically analysable.

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