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Tectonic Geomorphology of Upper Cimanuk Drainage Basin, West Java, Indonesia

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***Abstract*— The upper Cimanuk drainage basin is an inter-mountain basin. It is surrounded by volcanoes such as Mt. Tampomas, Mt. Guntur, Mt. Dano, Mt. Kamasan, Mt. Papandayan, and Mt. Cikuray. The objective of this research is to identify the degree of tectonic activity based on quantitative geomorphology analysis. Data are obtained from a topographic map, Digital Elevation Model, geological map, and field observation. Various morphometric variables are bifurcation ratio (Rb), drainage density (Dd), and mountain front sinuosity (Smf) index. The integrated analysis of morphometric and field data provides evidence of tectonic activity in Cimanuk drainage basin. Their streams have 1st until seventh order. The research area is proved to be an active tectonic area. This is confirmed by values of Rb, Dd, and Smf showing that some area in Cimanuk drainage basin has been affected by the tectonic activity. Rb values are ranging from 0.74 to 3.99, Dd values are ranging from 0.53 to 7.20, and Smf index area ranged from 1.2 to 1.6. These values can be classified into a medium class of tectonic activity level. The geological structure can be found in the middle to downstream of Cimanuk drainage basin and showed by primarily northwest-southeast trends. On the other hand, drainage pattern such as rectangular and trellis can reflect geological structures. Rectangular control is by joint and fault structure whereas trellis by dipping or folded sedimentary rocks. The Jatigede Reservoir is located in a strongly deformed area, so monitoring is necessary to reduce the impact of the disaster if some of the faults in the area are active again.**

***Keywords*— quantitative geomorphology; tectonic activity; drainage basin; Cimanuk, Jatigede Reservoir.**

I. INTRODUCTION

The research was conducted in the upper Cimanuk drainage basin, precisely on segment Mt. Puncakgede - Garut - Malangbong - Tomo (Fig. 1). The construction of a reservoir in the region has resulted in this area becoming very strategic. This area is one of the inter-mountain basins in Indonesia. Many mountains surround this basin, bordered with other basins. Among others are Mt. Kareumbi, Mt. Mandalawangi, Mt. Kamasan, Mt. Dano, Mt. Puntang, Mt. Papandayan, Mt. Puncakgede, Mt. Cikuray, Mt. Kukus, and Mt. Gombong. A drainage basin is the total area of land that slopes towards the branches of a river system [1]. He also states that the boundaries between the two basins are known as a drainage basin. The peaks of these mountains line the formed Cimanuk drainage basin**.**

Geologically, the area has a complex geological feature, both of lithology and tectonic activity. The unique basin shape resembles the number 7 viewed from the south; it is clear there is a tectonic role in certain parts (Fig. 1). The regional appearance is also related to the pattern of geological structures located in West Java is associated with regional physiographic [2].

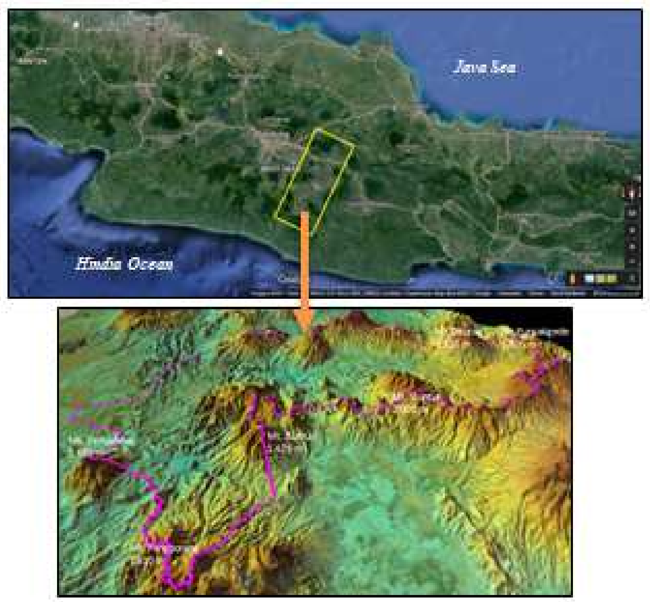

Fig. 1 Location of the research area in the upper Cimanuk drainage basin

The formation of the structures related to Java Geanticlines east-west trending began in the late Palaeogene, at the time of basement uplift activity was accompanied by the occurrence of multiple folding, especially in the Cimandiri valley. In the concept of global tectonics, this is related to the movement of the Indies-Australian plate that pushes the Asian plate to the north.

Several studies in this region have been conducted. Generally, the researchers are related to the geological setting and tectonic, erosion, and regional development. Some of them are M. Alzwar, *et. al.* [3], N. Sulaksana, *et. al.* [4], [5], [6], [7] E. Sunardi, *et. al.* [8], [9], [10], I. Haryanto, *et. al.* [11], Asep Nursalim [12]. Some authors provide their views related to the construction of the Jatigede Reservoir, namely Risdiana Cholifatul Afifah, *et al.* [13], Yuzar Purnama [14], and Junardi Harahap [15]. They studied the physical, social, economic, and cultural aspects. However, publications of tectonic geomorphology in the region have not been found. Meanwhile, the results of research related to geomorphology as a tectonic response in the area of West Java has been widely published; among others is E. Sukiyah et al. [16], [17], [18].

Geomorphology of the upper Cimanuk drainage basin varies from mountains and hills whose peaks serve as drainage basin boundaries to valleys and plains in the central and northern parts. The slope also varies from flat to steep. The drainage pattern consists of a variety ranging from sub radial to radial on mountain slopes and hills, sub-dendritic to dendritic, sub-parallel to parallel, sub-rectangular to rectangular, sub-trellis to the trellis, and anastomotic. These drainage patterns indicate tectonic influence in its development.

Based on previous publications, lithology setting of Cimanuk drainage basin consists of 27 rock formations [3]. In general, the lithology can be grouped into volcanic rock, plutonic rocks, sedimentary rocks and loose sediments. The age of lithology varies from the oldest (Oligo-Miocene) to the youngest (Recent). The physical properties of the various rocks are from loose boulders easily crushed to very hard, such as lava and intrusion. Older rocks (Tertiary and Pre-Tertiary) are generally sedimentary rocks between the fine and coarse-grained material and the plutonic rocks of andesite hornblende intrusion. Sedimentary rocks are grouped in Cinambo Formation, Halang Formation, Subang Formation, Kaliwangu Formation, and Citalang Formation. The physical properties of sedimentary rocks are relatively resistant to erosion, especially for roughly textured rocks. This lithology occupies the downstream part of the upper Cimanuk drainage basin, especially exposed in the areas of Tomo, Cadasngampar, Pamoyanan, Darmaraja, Wado, Ciherang, and Situraja. Some of these areas are now flooded into Jatigede Reservoir.

The tectonics in the upper Cimanuk drainage basin area is quite intensive, as indicated by the tectonic features of strike-slip and normal faults. The type of fault is easily recognizable when recorded on sedimentary rocks, but it is somewhat difficult to recognize if the affected volcanic rocks, especially of the Quaternary rocks. An indication of faults present in volcanic rocks is usually through geomorphology that forms the straightness of the ridge or weak zones reflected by the landslide phenomena. The strike-slip faults are generally running southwest-northeast. Meanwhile, the vertical movement fault in general trending west-east.

Since 1972, in the middle of the upper Cimanuk drainage basin has been planned the construction of Jatigede Reservoir [19]. Construction of the reservoir was realized in 2011. The reservoir, if the maximum function is expected to be able to control the floods in the area of Indramayu and Cirebon which previously the 25-year flood period to 100 years.

II. Material and Method

The objective of the research is to identify the degree of tectonic activity based on quantitative geomorphology analysis. Subjects in this research are morphometric and morphotectonic parameters of Cimanuk drainage basin consisting of bifurcation ratio (Rb), drainage density (Dd), and sinuosity of mountain front (Smf) index. Research activities are divided into several steps. These steps include preparation, data collecting, and data analysis. This research methodology relies on identification and interpretation of topographic map, Digital Elevation Model (DEM), and geological map in the laboratory and field observation to Cimanuk drainage basin. Identification and interpretation in the laboratory are used to identify and extract various morphometric and morphotectonic parameters such as Rb, Dd, and Smf index. This research requires Digital Topographic Maps Indonesia scale 1:25,000, Geological Map scale 1:100,000 [20], [3], [21], [22], DEM of Cimanuk drainage basin, and computer program supporting Geographical Information System (GIS) software. On the other hand, field observation aims specifically to look for field evidence of tectonic activity. The integrated analysis of morphometric and morphotectonic parameters provides evidence of tectonic activity.

Determination of Rb can be analyzed by stream order using segmentation method [23]. Every stream segment that does not have branching or ramification is referred as first-order streams. When the two first orders combine it will be second order, two-second orders form a third order; two third orders form a fourth order. (Fig. 2).

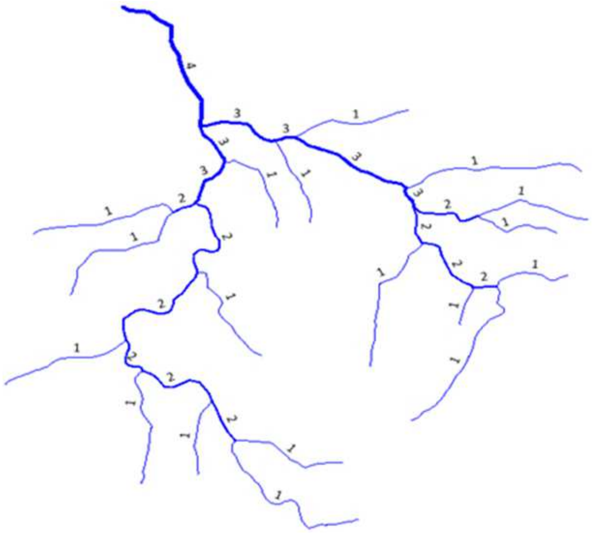

Fig. 2 Determination of stream order by segmentation method [23].

Bifurcation ratio (Rb), using Equation (1), can be defined as the ratio between the number of stream of order u (N_u) and some stream of order u+1 (N_{u+1}) [16]. Drainage basin has a value of bifurcation ratio (Rb) less than 3 or more than 5, then it is not normal [24], [8], [25]. This indicates that there has been a deformation that can be caused by tectonic activity [16], [23].

$$Rb = N_u / N_{u+1} \tag{1}$$

Drainage density is a number that indicates the amount of dissection of the drainage basin. It is a measure of how well or how poorly stream channels drain a drainage basin. Drainage density, using Equation (2), is total of all stream lengths in the drainage basin (L) divided by the area of basin (A) [17], [26].

$$D_d = \Sigma L / A \tag{2}$$

TABLE I
GEOMORPHOLOGICAL TEXTURE CLASSIFICATION BASE ON DRAINAGE DENSITY [23], [27]

Texture	Drainage density (Dd)
very rough	less than 1.38
rough	1.38 until 2.75
intermediate	2.76 until 4.13
rather smooth	4.14 until 5.51
smooth	5.52 until 6.89
very smooth	more than 6.89

Morphotectonics is landform characteristic associated with tectonics. Landform contained in the earth surface can be formed due to tectonic processes that occur on the earth. On a local and regional scale, the tectonic phenomenon can be recognized from some typical landform such as escarpment, valleys, lineament of hills and river, and drainage pattern [28].

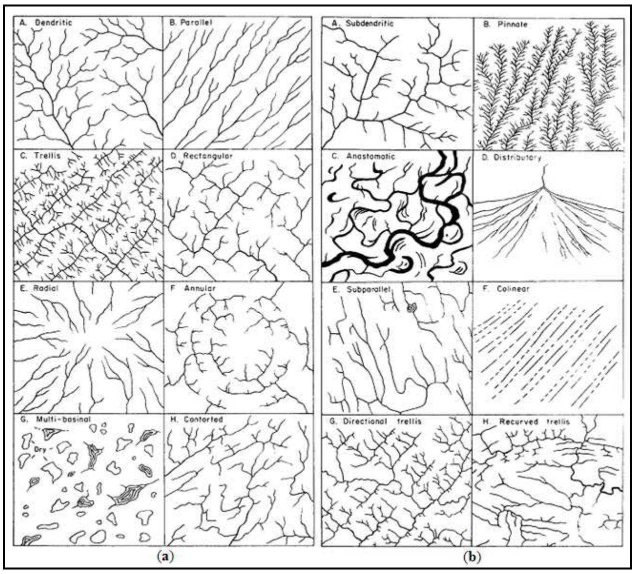

Fig. 3 Drainage pattern, (a) basic drainage pattern and (b) modified basic drainage pattern [24].

Drainage pattern reflects the geological condition of an area (Fig. 3). Drainage analysis is an essential tool of geologic interpretation on air photo or satellite imagery, particularly in areas of low relief. It may provide clues to inactive structural features exposed at the surface, to structural features currently rising, and possibly to buried structural features [24].

Morphotectonic analysis of the drainage basin will always be associated with mountain front sinuosity index (Smf). Mountain front sinuosity index, using Equation (3), can be defined as the ratio between the length of the mountain front (Lmf) and length of the mountain front projection onto a flat surface (Ls) [28].

$$Smf = Lmf / Ls \tag{3}$$

Based on Equation (3), tectonic activity occurred in an area can be determined. If mountain front sinuosity index close to 1 indicates that there has been an active tectonic uplift process. Classification of the tectonic activity degree can be seen in Table 2.

TABLE II
CLASSIFICATION OF TECTONIC ACTIVITY DEGREE [28]

Class	Smf	Tectonic Activity	Characteristics of Smf
1	1.2-1.6	Active	Associated with alluvial fan landform, drainage basin elongated, valley floor narrowed, steep slope.
2	1.8-3.4	Intermediate-weak	Associated with alluvial fan landform, drainage basin widened, steep slope, the valley floor is wider than floodplain.
3	2.0-7.0	Not active	Associated with pediment mountain front landform and embayment, steep slope only on resistant rock layers, the valley is slightly more comprehensive and integrated.

The data are obtained, both from literature study, data extract in studio and field observation, then analysed by using statistic approach. Lilliefors test tests the normality of data distribution before using comparative test (t-test). This test is to know the difference of tectonic activity in the western and eastern part of Upper Cimanuk drainage basin.

III. RESULT AND DISCUSSION

The characters geomorphological unique of the upper Cimanuk drainage basin is range from the hilly area in southern to valley and plains in northern of the research area. Their slopes are range from 0^o (flat) until 55^o (very steep), as shown by Fig. 4. Upstream of Cimanuk river is located in Mt. Puncakgede and downstream in Tomo area. This area is approximately 1,980 Sq km, and the total length of the main river is about 150 km.

The total of streams length is 4,544,440 meter which can be divided into several streams order, from 1st order to 7th order with a total of 5,411 stream segments (Table 3).

Bifurcation ratio is calculated by using Equation (1), and its values are range from 0.74 to 3.99. Regionally, this value range indicates that some part of the drainage basin is deformed due to the tectonic activity. The phenomena are reflected by the bifurcation ratios of order 1st to order 2nd, order 2nd to order 3rd, order 3rd to order 4th, order 5th to order 6th, and order 6th to order 7th. While the 4th order to order 5th is still considered normal as a result of the climate process.

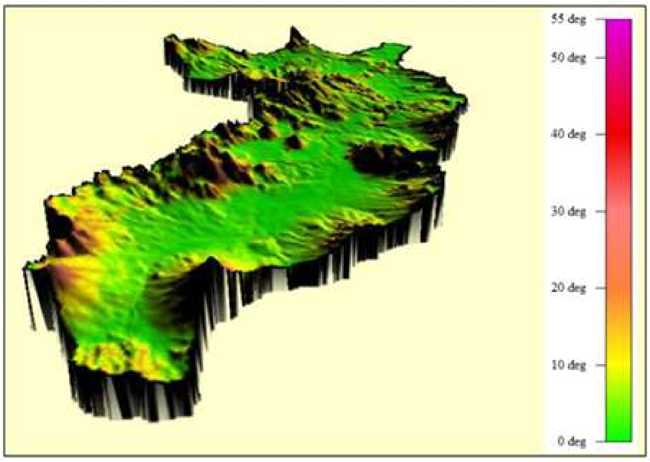

Fig. 4 The 3D view of upper Cimanuk drainage basin shows the distribution of the slope ranging 0° until 55°

TABLE III
THE DIMENSION OF STREAMS AND BIFURCATION RATIO

Stream Order	**Stream Length (meter)**	**The number of stream segments**	**Bifurcation Ratio**
1st	2,570,000	2,727	1.97
2nd	956,800	1,384	2.09
3rd	507,100	661	1.88
4th	264,700	351	3.99
5th	76,710	88	0.74
6th	103,700	119	1.47
7th	65,430	81	-
Total	4,544,440	5,411	

The value of drainage density may reflect the deformation occurring in the region. However, in this case, the lithology of its constituents should also be considered. Drainage density value also can describe the material properties and permeability condition in an area. The drainage density of Cimanuk drainage basin was calculated by using Equation (2). Drainage density values are range from 0.53 to 7.20. This value range can be classified into very rough until very smooth [23], [12]. Also, this value also shows that the flow of river passes through hard resistance rock so that sedimentary material transported by streams will be smaller. Some of the locations, the stream passing through soft rock or fractured and resulting texture of geomorphology become very smooth.

The appearance of geomorphology in the west and east of the upper Cimanuk drainage basin shows a difference (Fig. 5). Quantitative analysis of 16 areas as a unit of analysis spread evenly in the Samarang and surrounding areas, shows that there is a relationship between the morphometry of the drainage basin with tectonics. Some places indicate an active fault control. In areas controlled by active faults, drainage basins have relatively higher density values compared to relatively more stable areas. Similarly, the bifurcation ratio, where tectonic-controlled drainage basins range from 1.2 to 2.3. The result of the quantitative analysis is also reflected by the rectangular drainage pattern and the pattern of the landscape that relative form the straightness coincide with the fault zone.

TABLE IV
BIFURCATION RATIO IN THE WESTERN PART OF THE CIMANUK RIVER

Analysis unit	**Stream length (m)**	**The number of stream segments**	**Bifurcation ratio**	
			Rb_{1-2}	**Rb_{2-3}**
1	11,272	3	2.0	-
2	6,616	5	1.5	-
3	5,931	3	2.0	-
4	2,106	3	2.0	-
5	5,746	3	2.0	-
6	9,749	7	1.3	-
7	20,862	13	1.2	-

TABLE V
BIFURCATION RATIO IN THE EASTERN PART OF THE CIMANUK RIVER

Analysis unit	**Stream length (m)**	**The number of stream segments**	**Bifurcation ratio**	
			Rb_{1-2}	**Rb_{2-3}**
1	5,108	5	1.5	-
2	6,440	3	2.0	-
3	22,017	25	1.6	2.0
4	3,079	3	2.0	-
5	2,381	3	2.0	-
6	15,832	13	2.3	1.0
7	3,019	3	2.0	-
8	4,956	3	2.0	-
9	5,371	5	1.5	-

TABLE VI
DRAINAGE DENSITY IN THE WESTERN PART OF THE CIMANUK RIVER

Analysis unit	**Stream length (m)**	**Area (m^2)**	**Drainage density**
1	11,272	8,636	1.31
2	6,616	2,683	2.47
3	5,931	2,558	2.32
4	2,106	0,749	2.81
5	5,746	2,015	2.85
6	9,749	3,486	2.79
7	20,862	11,650	1.79

TABLE VII
DRAINAGE DENSITY IN THE EASTERN PART OF THE CIMANUK RIVER

Analysis unit	**Stream length (m)**	**Area (m^2)**	**Drainage density**
1	5,108	1,737	2.94
2	6,440	2,673	2.41
3	22,017	8,917	2.47
4	3,079	1,303	2.36
5	2,381	1,737	3.71
6	15,832	6,915	2.29
7	3,019	0,929	3.25
8	4,956	2,435	2.04
9	5,371	2,224	2.42

The drainage basins as unit analysis in the Cimanuk River in Samarang are divided into two populations: the population in the west and the east of the river. Table 4 and Table 5 show the calculation of bifurcation ratio (Rb). The average Rb_{1-2} in the drainage basins in the west is about 1.71 while the area on the east side shows an average of 1.88. This indicates that both areas in the west and east of the Cimanuk River are equally deformed. This phenomenon is quantitative proof of the existence of an active fault, especially around Samarang. Quantitative analysis is also conducted on the drainage density. The calculation results are shown in Table 6 and Table 7.

The statistical test is done to know the significance of geomorphological characteristics difference quantitatively. After going through the testing phase of normality and homogeneity, it is known that the data of drainage density (Dd) of each unit of analysis is reasonable and homogeneous. Normally distributed data means that the data can be considered representative of the population. Normality and homogeneity tests of data are also done for bifurcation ratio (Rb), in this case, is the value of Rb_{1-2} found in each unit of analysis. The test results show that the data distribution is normal and homogeneous.

To know the real difference between these variables is done with a t-test. It is known $t_{table(\alpha=0.05)} = 2.145$. Because t-calculate < t-table, it can be concluded that in the real level (α) of 0.05 there is no average difference between Dd on the western and eastern areas. However, if observed the average difference between them is significant, meaning that if the real level is increased it will appear a significant difference, such as 0.5 for a two-sided test. The same test is also carried out on the bifurcation ratio. The test results show that there is a significant difference when the real level (α) is used 0.5.

The results of Smf calculations also support the test results on the variables Dd and Rb. The morphotectonic condition of Cimanuk drainage basin can be determined through mountain front sinuosity (Smf). It was calculated by using Equation (3). Its values are ranging from 1.2 to 1.6 are shown in Table 8. This value range indicates that Cimanuk drainage basin is influenced by active tectonic control and associated with alluvial fan landform, drainage basin elongated, valley floor narrowed, and steep slope (Fig. 5).

TABLE VIII
SMF INDEX OF CIMANUK DRAINAGE BASIN

Smf Index in western of Cimanuk drainage basin	**Smf Index in eastern of Cimanuk drainage basin**
1.2	1.2
1.2	1.2
1.3	1.3
1.5	1.4
1.6	-

Morphotectonic characteristics of Cimanuk drainage basin which is an indication of active tectonics can be determined from lineament of hills and valleys by Digital Elevation Model (DEM) with a resolution of 90 meters, geological structure by Geological Map, and drainage pattern. An indication of geological structure (Fig. 5A) is not much different from Geological Map (Fig. 5B).

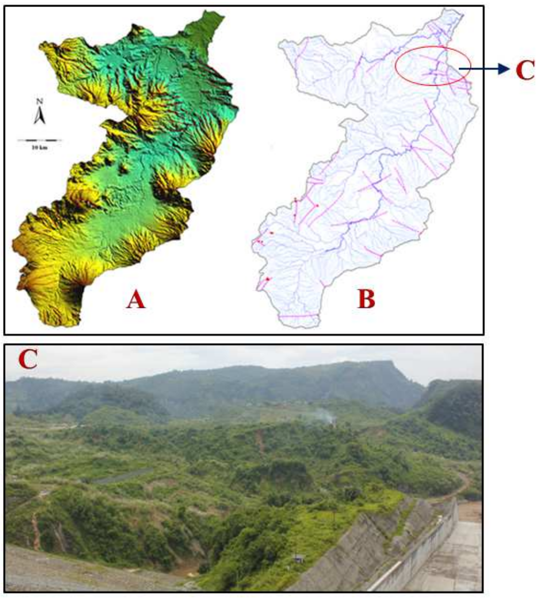

Fig. 5 Lineament interpretation using DEM resolution of 90 meters indicates active tectonic area (A), an indication of geological structure from Geological Map (B), and a photograph of fault scarp (C).

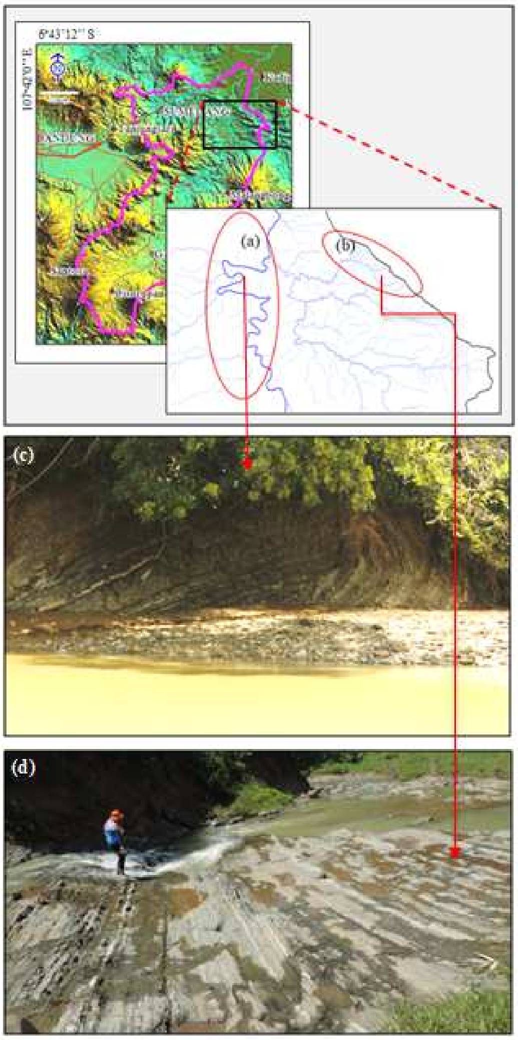

Fig. 6 Drainage pattern: (a) rectangular and (b) trellis, reflect geological structures developed as a response active tectonic in Cimanuk drainage basin. The fold structure is exposed on the Cimanuk river bank (c), and sedimentary rock bedding with almost vertical dips is exposed at the base of the Cimanuk river branch (d).

An indication of geological structure can be found in the middle to downstream of Cimanuk drainage basin, and it shows primarily northwest-southeast lineament trends (Fig. 5C). On the other hand, drainage pattern such as rectangular and trellis can reflect geological structures developed as a response active tectonics. The rectangular pattern indicates joint, and fault structure whereas trellis pattern indicates dipping or folded sedimentary rocks (Fig. 5 and Fig. 6).

Morphotectonic characteristics are reflected in the landscape of the Upper Cimanuk drainage basin, among which are:

- Lineament of the ridge, valley and stream
- River curvature is relatively angled around Garut to Tomo
- Scarp
- Alluvium and colluvium fan ranks
- The depression zone occupied by alluvium in the western part of Garut City
- Swamps and lakes are commonly found in the central part of the upper Cimanuk drainage basin.

In a strongly deformed area, now a giant reservoir has been built (Fig. 5C and Fig. 7). Reservoir construction process that takes a long time is understandable considering the geological conditions that are relatively unstable region. Landslides are frequent in these locations as a result of deformed land due to tectonics. Continuous monitoring and engineering should always be updated for disaster risk reduction in the event of any faults in the vicinity being reactivated. However, Jatigede Reservoir has strategic value. Here is the function of the reservoir:

- Irrigation area of 90,000 ha in the north, including Indramayu, Majalengka, and Cirebon.
- The 110 MW hydropower plant
- Flood controller
- Raw water supply 3,500 lt / sec.
- Tourism

Fig. 7 (A) The construction of a reservoir on the Cimanuk river segment in Jatigede area, Sumedang, West Java; (B) Jatigede Reservoir (https://www.google.co.id) [23]

IV. CONCLUSIONS

The tectonic activity occurred in the Cimanuk drainage basin can be identified through geomorphology, both quantitatively and qualitatively. Based on tectonic geomorphology analysis, the research area shows some various ridges lineament indicated active tectonic area. Based on quantitative analysis, bifurcation ratios are range from 0.74 to 3.99. This value indicates that active tectonic control influences area. Drainage density values are range from 0.53 to 7.20. This value can be classified into the middle class. Sinuosity mountain front index of research area range from 1.2 to 1.6. This value can be classified into medium active tectonics. Also, mountain front sinuosity index close to 1 indicates that there has been an active tectonic uplift process. Field data also support the results of geomorphological analysis quantitatively. Continuous monitoring of tectonic activity should be carried out, given the existence of a reservoir. It is expected that the risk of disaster can be minimized if at any time the faults in the area are active again.

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