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Morphotectonic of Citarik Watershed in Bandung Basin

Nendi Rohaendi [1*], *Emi* Sukiyah[2], *Dicky* Muslim[2], and *Athanasius* Cipta[3]

[1]Center of Human Resources Development for Geology, Coal, and Mineral, Sudirman 623, Bandung, West Java Province, Indonesia
[2]Facultiy of Geological Engineering, Padjadjaran University, Bandung – Sumedang Street KM, Jatinangor, Indonesia
[3]Geological Agency, Ministry of Energy and Mineral Resources, Bandung, West Java Province, Indonesia

Abstract. The Citarik watershed which is located in the upstream Citarum watersheds in Bandung Basin. The development plan of Bandung basin comprises five administrative areas including Bandung city, Cimahi city, Bandung regency, West Bandung Regency, and Sumedang Regency. The development of Citarik watershed correlates with recent tectonic deformation which is important for natural hazard evaluation and land use planning. The purpose of study was undertaken to evaluate relative tectonic activity in Citarik watershed using DEM data and Geographic Information System technique analysis. The result of six geomorphic indexes are as follows asymmetry factors (Af) from 26.3 to 74.5, hypsometric integral (Hi) from 0.1 to 0.3, basin shape (Bs) from 1.70 to 5.60, valley floor width-to-height (Vf) from 0.78 to 2.73, mountain front sinuosity (Smf) from 1.25 to 1.82, and stream length gradient index (Sl) from 75 to 440. Using the weighing method, the six geomorphic indexes are calculated to define relative tectonic activity. The activity was classified into three classes such as high, moderate, and low. The research result will benefit how to develop of urban areas based on physical aspects, including geological and geomorphological aspects.

1 Introduction

The Citarik watershed is one of the parts of the upstream Citarum watershed in Bandung basin. The basin is one of the strategic areas in Indonesia which is the place of four cities; Bandung city, Cimahi city, Bandung Regency, west Bandung regency, and some of Sumedang sub districts [1]. Upstream Citarum Watershed is divided into nine sub-watersheds, as we can see in Figure 1 such as the Cikapundung, Cikeruh, Cirasea, Cisangkuy, Citarik, Ciwidey, Cihaur, Ciminyak, and Cimeta watersheds [2]. The Citarik watershed spans 27,716.411 hectares in total, with the upstream watershed being in the conservation area of Kareumbi Masigit in Sumedang Regency and flowing into the Citarum River in the Bandung regency.

Administratively, Citarik watersheds are located in the Sumedang regency, Bandung regency, and Garut regency. The upstream Citarik watershed is mostly located in Cimanggung district in Sumedang regency and minor in Garut Regency, and the downstream is located in Rancaekek and Cicalengka districts in Bandung regency. The Rancaekek and Cicalengka areas with a high chance of land-use change as a result of the two districts developed into three main development zones, such as residential, industrial, and educational. The large number of people causes a decline in the level of groundwater because of uncontrolled groundwater extraction to suit the necessities of domestic use and industries [3]. Potential concerns from these situations include lack of clean water because of excessive water extraction, diminished water catchment areas because of land-use change, and land subsidence because of groundwater extraction in the Bandung basin [4].

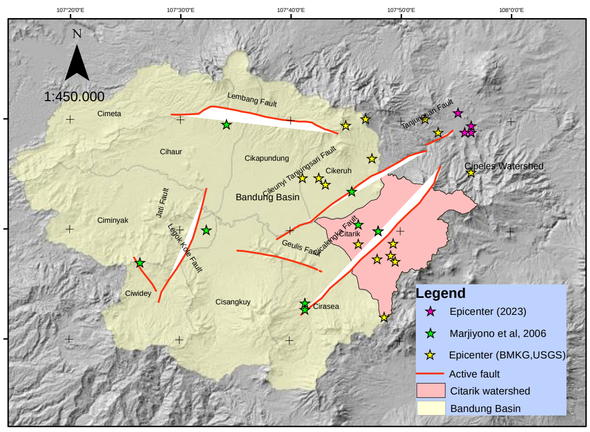

Fig. 1. Citarik watershed in Bandung basin in west Java province, Indonesia

Since the period of 2003-2008, there is significant land use change in Citarik watershed such as the number of settlements increased from 18.7% to 18.8%, the number of paddy fields, which increased from 19.4% to 29.9% [5]. Furthermore, the loss in a hydrological function that happened in the Citarik watershed region was followed by a rise in runaway water coefficient in 2000 – 2007 from 0.22 to 0.42 [5]. The research area comprises a range of critical land classes, such as very critical area of 3907.79 ha (11.29%); critical area of 16943.34 ha (48.95%); semi-critical area of 13037.03 ha

* Corresponding author: nendis@gmail.com

(37.66%); and potential critical area of 725.27 ha (2.10%) [6]. As a result, it is critical to undertake land conservation and land rehabilitation initiatives that are tailored to the findings of the analysis of existing land use patterns. The result of spatial analysis, as follows: one season crop agriculture of 1991.62 ha (4.27%); annual crop cultivation area of 23058.02 ha (49.45%); buffer zone of 13249.57 ha (28.42%); protected area of 8327.31 ha (17.86%) [6]. Therefore, an evaluation of the state of the water catchment areas of Citarik river is necessary. Some factors influencing water catchment areas, such as rainfall, slope, soil type, and land use, have been studied by earlier scholars [7].

The problem in Citarik watershed is not only an environmental problem but also a tectonic problem, since there are active faults such as Cicalengka fault, Cileunyi-Tanjungsari fault, and Gunung Geulis fault [8]. The occurrence of the fault is located by earthquake events and geological analysis. However, further study of the tectonic condition in that area is getting relatively little attention. For these reasons, the purpose of the research is to analyse morphotectonic indices using the Geographic Information System techniques and the Digital Elevation Model Nasional (DEMNAS). The free availability of a digital elevation model from the Geospatial Information Agency of Indonesia is very useful to conduct the research [9].

From the previous study using correlation analysis in Citarik watershed between some morphometric parameters such as slope, Rc, Dd, and the impact on average small river discharge in the volcanic landform, the result shows there are positive correlation between slope, river density, erosion cycle, and elongated shape of catchment, erosion cycle, the average river discharge [10]. Another study using the morphometric analysis in study area shows that the area has relatively high resistance to potential flooding [11]-[12].

Morphotectonics discusses everything that concerns the relationship between landforms and geological structures [13], [14]. Morphotectonics is determined by morphological conditions and tectonic processes that occurred in the past, since the tectonics concerns the time dimension and morphology concerns the space dimension. Tectonic landforms will express formations topography can be used as an indicator that tectonic changes have occurred. The changed form of topography can be observed using aerial photography and satellite imagery which displays morphotectonic features in the form of river flow patterns, river bends, straightness, fault scarps, shifting hills, and the appearance of river terraces [15].

2 Data and Methods

Geologically, Citarik watershed is consists of product from Pleistocene to Holocene such as Old undifferentiated volcanic material (Qvu), old volcanic product (Qvl), young volcanic product (Qyl) young undifferentiated volcanic material (Qyu), Lava/Tuff of Mandalawangi volcano (Qmm), tuff and brecia from Guntur, Pangkalan, and Kedang volcano (Qgpk), and lastly lake deposit (Ql) [16].

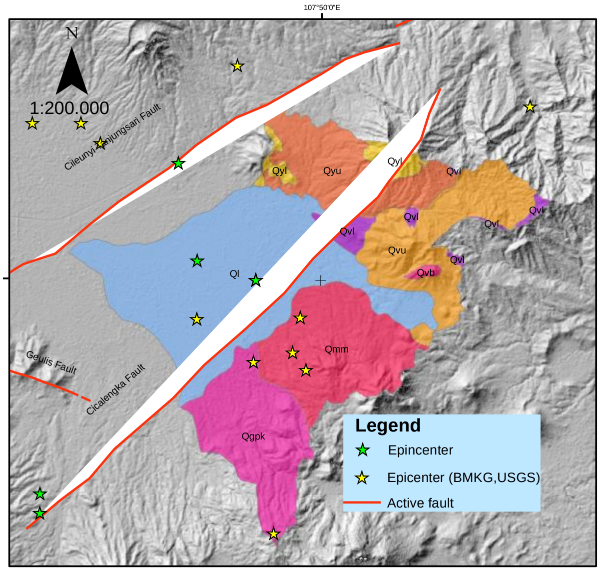

Fig. 2. Geological map of Citarik watershed

Recently, geomorphology approach, in most regions of the world, these types of observation and analyses have attracted the attention of specialists only during the past several decades [17]. The availability of data sets is also determining the quality of research. The techniques of Geographic Information System (GIS) are used to perform geomorphology indices analysis, lineament, and stream analysis, using a topography map with a scale of 1 : 25.000 and DEMNAS with a spatial resolution of 8 m from Geospatial Information Agency of Indonesia.

Table 1. The calculation of geomorphology indices

Parameter	Ref.
- Hypsometric integral $HI = (Elev_{mean} - Elev_{min}) / (Elev_{max} - Elev_{min})$	[18]
- Basin Asymmetry $AF = (A_r/A_t) \times 100$	[13]
- Stream Length Gradient Index $SL = (dH/dL)*L$	[13]
- Mountain Front Sinuosity $Smf = Lmf/Ls$	[19]
- Basin shape $Bs = Bl/Bw$	[20]
- The ratio of valley floor width to valley height $Vf = 2Vfw/ [(Eld – Esc) + (Erd – Esc)]$	[14]

Morphotectonic or geomorphology tectonic is the application of geomorphology to solve tectonic problems, including the evolution of landforms also the development of response to recent tectonic [13]. Based on DEM data analysis using GIS method, the geomorphology indices to analyse regional tectonic in table 1 such as hypsometry integral (HI), drainage basin asymmetry (AF), stream length gradient index (SL), mountain front sinuosity (Smf), basin shape (Bs), and the ratio of valley floor width to valley height (Vf) [19].

Hypsometric Index (HI) is the ratio of the distribution elevation per relief, which can be quickly calculated for any basin. Hypsometry curve describes of the maturity of basin. Basin Asymmetry factor (AF) is reflected in the tilting tectonic condition of the area, where A_r is the area of the basin to the right that facing downstream of the river, and A_t is total area of the watershed. Stream Length Gradient Index (SL) is for the area of interest, where; ΔH = the variation of elevation, ΔL = the length of the segment, and L_{tc} = the total channel length from the midpoint of the segment where the index is calculated. The study of active fault applied a geomorphological approach based on a mountain-front sinuosity (Smf) index, where; Lmf is the length of along the mountain-piedmont junction and Ls is the total length of the mountain front. Basin shape (Bs) is the tectonic geomorphology is calculated based on the comparison between basin length and basin width. The ratio of valley floor width to valley height (Vf), This tectonic geomorphology is calculated based on the equation where V_{fw} is the width of the valley floor, E_{ld} is the elevation of the divide on the left side of the valley, E_{sc} is the average elevation of the valley floor, E_{rd} is the elevation on the right side. Then 10 sub watersheds has been classified into three classes of relative tectonic activity.

3 Result and Discussion

For this study, we calculate all of geomorphological indices using GIS methods for ten sub-watersheds. The ten of sub-water shed is based on the calculation in four river order.

The bifurcation ratio (Rb) in ten Citarik watershed ranges from 2 to 7 and the mean from 2.9 to 4.3. It means a slow rise in the water level, means a relatively low potential for flash floods. Then, it means the absence of significant structural control [12].

Table 2. Bifurcation ratio of river order

Watershed	Order 1	0rder 2	Order 3	Order 4	Rb1/2	Rb2/3	Rb3/4	Mean
Cimande	63	14	5	1	4,5	2,8	5,0	4,1
Sindulang	23	6	2	1	3,8	3,0	2,0	2,9
Cimulu	32	7	2	1	4,6	3,5	2,0	3,4
Cibodas	54	14	2	1	3,9	7,0	2,0	4,3
Cijalupang	36	8	2	1	4,5	4,0	2,0	3,5
Cikalage	22	5	2	1	4,4	2,5	2,0	3,0
Cikopo	20	6	2	1	3,3	3,0	2,0	2,8
Cigentur	32	7	2	1	4,6	3,5	2,0	3,4
Cisungalah	52	9	2	1	5,8	4,5	2,0	4,1
Cikaro	28	10	3	1	2,8	3,3	3,0	3,0

The map in figure 3 shows the distribution of ten watersheds in research area. The southern part of watershed is originated from mountainous area when the river goes from south to north, however, the northern part of watershed is although come from mountainous but relatively dominated by flat area.

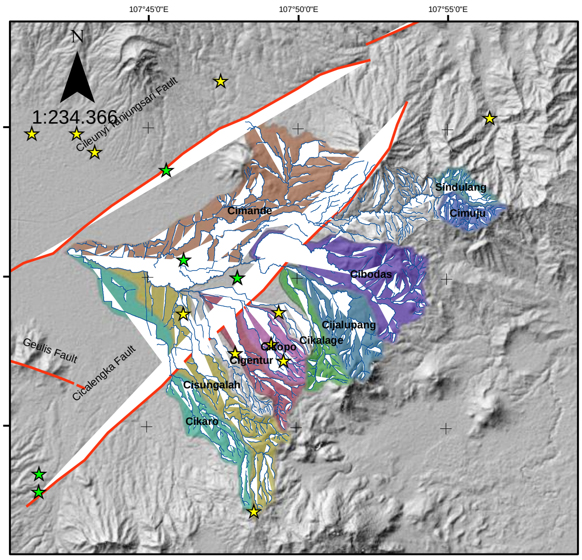

Fig. 3. Caption of the Figure 1. Below the figure.

3.1 Hypsometry Curve and Hypsometry Index

Based on DEM data and drainage patterns, Citarik watershed is divided into 10 sub-watersheds based on four river order. The 10 sub-watershed is namely based on the river name and geographical location. The watershed boundary is very important to determine the research. Hypsometry curve describes of the maturity of basin.

From figure 4, in example, we can see that river is mostly mature and combination of mature and young. It shows that erosional force is higher than structural force. The value of hypsometry index is range from 0.12 to 0.33, it means the area of Citarik watershed is dominated by inactive and medium active tectonic. Cimande, Cisungalah, and Cikaro watershed is lesser active than the rest of watersheds.

3.2 Asymmetry Factor (Af)

The purpose of Asymmetry factor analysis is to evaluate tectonic tilting at Citarik watershed. In stable area, the value of Af is close to 50, if Af factor more or less 50 mean the watershed is tilting or asymetry, as the result of tectonic activity or geologic structure. From ten watersheds such as Sindulang, Cijalupang, Cikopo and Cikaro watershed have higher structural controls than the others watersheds.

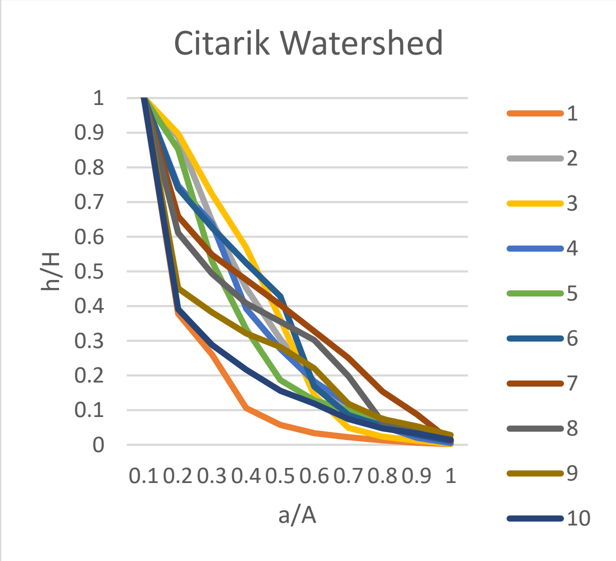

Fig. 4. The hypsometry curve of Citarik watershed

Table 3. The calculation of asymmetry factor

No	Watershed	At (km^2)	A right (km^2)	A left (km^2)	Af
1	Cimande	64,92	37,02	27,90	57,02
2	Sindulang	5,01	3,73	1,28	74,47
3	Cimuju	6,18	3,00	3,18	48,53
4	Cibodas	34,24	16,43	17,81	47,98
5	Cijalupang	17,83	4,69	13,14	26,29
6	Cikalage	9,67	5,04	4,63	52,13
7	Cikopo	12,87	4,67	8,20	36,30
8	Cigentur	12,79	7,24	5,55	56,63
9	Cisungalah	27,08	14,87	12,21	54,92
10	Cikaro	13,44	3,68	9,76	27,36

3.3 Valley Floor Width to Height Ratio (Vf)

From the main valley cross to mountain fronts of the study area, Vf index is calculated. The value of Vf is depend on basin size, stream discharge, and rock type [20]. The value of Vf is ranges from 0.78 to 2.73. It shows that the Citarik watershed area is ranging from active to inactive tectonic. Sindulang, Cikopo, Cigentur, and Cikaro watersheds are more active that the rest of watersheds.

Table 4. The calculation of Vf

No	watershed	Vfw	Erd	Eld	Esc	Vf
1	Cimande	50	717	729	695	1,786
2	Sindulang	25	1199	1201	1169	0,806
3	Cimuju	15	1209	1221	1200	1,000
4	Cibodas	15	707	700	692	1,304
5	Cijalupang	40	717	715	691	1,600
6	Cikalage	30	703	713	697	2,727
7	Cikopo	45	820	755	730	0,783
8	Cigentur	17	709	714	691	0,829
9	Cisungalah	50	739	741	717	2,174
10	Cikaro	20	731	726	703	0,784

3.4 Basin Shape (Bs)

The shape of basin in active tectonic area tend to elongated in shape normal to the topographic slope a mountain. The decreasing of tectonic activity, the shape more circular in shape. The value of Bs is from 1.72 to 5.61. Cimande, Sindulang, Cimuju, Cibodas, Cijalupang, and Cikalage watersheds are less active that the rest of watersheds.

Table 5. The calculation of basin shape

No	watershed	Length (KM)	Width (KM)	Basin shape
1	Cimande	13,67	8,01	1,71
2	Sindulang	3,33	1,91	1,75
3	Cimuju	3,95	2,02	1,95
4	Cibodas	10,66	6,19	1,72
5	Cijalupang	8,53	3,30	2,59
6	Cikalage	8,25	2,76	2,99
7	Cikopo	8,63	2,72	3,18
8	Cigentur	9,63	2,48	3,88
9	Cisungalah	14,67	2,62	5,61
10	Cikaro	19,55	2,33	4,22

3.5 Stream Length-Gradient Index (SL)

The SL index will increase were river and stream in active areas. The value of SL index is determined by tectonic, lithological, and/or climatic factors. The value of SL was classified into two classes semi active and in active. Cisungalah and Cikaro are medium (semi) active and the rest of watersheds are in active.

3.6 Index of Mountain Front Sinuosity (Smf)

Smf show a balance between erosive processes tending to erode a mountain front and into the front and active vertical tectonics, often coincidental with active faults or folds. The lower of value of Smf , the higher tectonic activity. Citarik watershed is dominated by active and semi active such as Cijalupang and Cigentur watershed are more active than the rest of watersheds.

3.7 Relative Active Tectonic (Iat)

The classification of relative active tectonics is based on table 3 including six geomorphological indices: Af, Hi, Bs, Sl, Smf, and Vf. Since the value of each parameter has a different scale, the value is must be to standardize.

Table 6. The calculation of six geomorphic indices

No	Watershed	Af	Hi	Bs	Sl	Smf	Vf
1	Cimande	57,02	0,12	1,71	85,83	1,60	1,79
2	Sindulang	74,47	0,31	1,75	74,61	1,51	0,81
3	Cimuju	48,53	0,32	1,95	92,66	1,60	1,00
4	Cibodas	47,98	0,29	1,72	125,51	1,49	1,30
5	Cijalupang	26,29	0,27	2,59	112,41	1,25	1,60
6	Cikalage	52,13	0,31	2,99	211,31	1,61	2,73
7	Cikopo	36,30	0,33	3,18	191,38	1,78	0,78
8	Cigentur	56,63	0,29	3,88	205,84	1,28	0,83
9	Cisungalah	54,90	0,22	5,61	316,14	1,48	2,17
10	Cikaro	27,40	0,16	4,21	439,60	1,82	0,78

In table 4, since the value of each parameter has a different scale, we need to standardize all values into 1 (active), 2 (semi-active), and 3 inactive. Finally, the index of relative active tectonics (Iat) is divided into four classes as follows: very high (VH) (1,0 <Iat< 1,5), High (H) (1,51 <Iat< 2.0), Moderate (M) (2,1 <Iat < 2,5) and Low (L) (3 > 2,5).

Table 7. The weighing and scoring of six geomorphic indices

No	Watershed	Af	Hi	Bs	Sl	Smf	Vf	Iat	
1	Cimande	1	3	2	3	2	1	2,2	M
2	Sindulang	1	2	2	3	2	1	1,8	H
3	Cimuju	2	2	2	3	2	1	2,2	M
4	Cibodas	1	2	2	3	1	1	2,0	H
5	Cijalupang	3	2	1	3	1	1	1,5	H
6	Cikalage	3	2	1	2	2	2	2,0	H
7	Cikopo	1	2	1	3	2	1	1,7	H
8	Cigentur	3	2	1	2	1	1	1,7	H
9	Cisungalah	3	3	1	2	1	2	2,0	M
10	Cikaro	1	3	1	1	2	1	1,5	H

From the table 4, the relative active tectonic related with empirical facts that the regional tectonic of the Bandung basin and its surrounding area consists of fault lineament and fault relative movement. From the geological map and satellite data, in Bandung basin, fault ruptures may be observed along the west-east, southwest-northeast, and north-south directions. The Lembang fault is located in the north and runs west-east, while the Mount Geulis and Citarum faults are in the south. The Cihideung-Bandasari fault runs north to south, while the Cicalengka and Cileunyi-Tanjungsari faults run southwest to northeast [4].

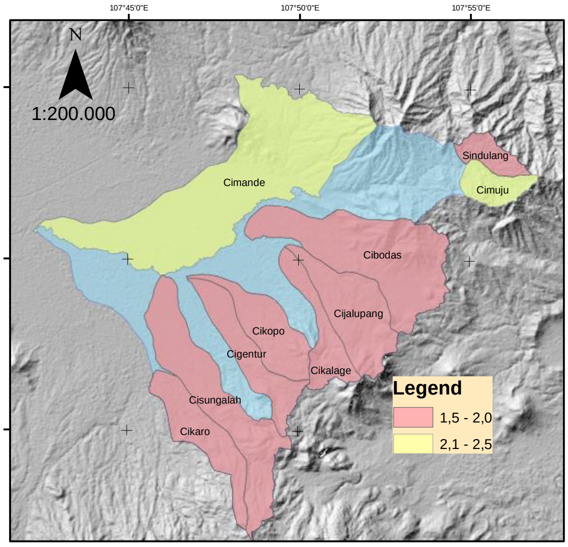

Fig. 5 Relative tectonic activity in Citarik watershed

4 Conclusions

This work was undertaken to highlight tectonic activity in Citarik watersheds based on the geomorphology index using DEM data and GIS techniques analysis. This Citarik watershed is divided into 10 watersheds of research area that classified as moderate level of tectonic activity such as Cimande and Cimuju watersheds, then high level of tectonic activity such as Sindulang, Cibodas, Cijalupang, Cikalage, Cikopo, Cigentur, Cisungalah, and Cikaro watersheds.

The result of index relative tectonic activity is dominated by high and moderate. There are six geomorphic indexes including drainage basis asymmetry (Af) from 26.3 to 74.5, hypsometric integral (Hi) from 0.1 to 0.3, basin shape (Bs) from 1.70 to 5.60, valley floor width-to-height (Vf) from 0.78 to 2.73, mountain front sinuosity (Smf) from 1.25 to 1.82, and stream length gradient index (Sl) from 75 to 440. Using the weighing method, the six geomorphic indexes are calculated to define relative tectonic activity. The activity was classified into two classes; high and moderate. Relative active tectonics based on the geomorphic indices of are helpful ways to evaluate the impact of active tectonics.

The development of DEM National (DEMNAS) as public domain data from Geospatial Information Agency of Indonesia is very useful and has a high spatial resolution of about 8 Meters for reconnaissance tools to study active tectonics.

Previous seismic events raised stakeholder knowledge about the possibility of an earthquake caused by an active fault in the near future. We should be informed that earthquakes occur recently in Sumedang regency and adjacent regions. West Java provinces are subject to both single and regional earthquakes, as the back-arc thrust in West Java represents a high seismic hazard.

References

1. N. Rohaendi, R. Robiana, E. Sukiyah, D. Muslim, and A. Cipta, "Seismic Hazard Zonation in Gedebage Future Development in Bandung City Using HVSR Inversion," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 11, no. 3, pp. 947–954, 2021, doi: 10.18517/ijaseit.11.3.14996.
2. N. Rohaendi, E. Sukiyah, D. Muslim, and A. Cipta, "Tectonic Geomporphology of Ciwidey and Cisangkuy Watershed in Bandung Basin," J. Geomin., vol. 6, no. 1, pp. 31–40, 2021, doi: DOI: 10.58522/ppsdm22.v6i1.31.
3. S. Wangsaatmaja, A. D. Sutadian, and M. A. N. Prasetiati, "A Review of Groundwater Issues in the Bandung Basin, Indonesia: Management and Recommendations.," *Int. rev. environ. Strateg.*, vol. 6, no. 2, pp. 425–441, 2006.
4. I. Gumilar, H. Z. Abidin, L. M. Hutasoit, D. M. Hakim, T. P. Sidiq, and H. Andreas, "Land Subsidence in Bandung Basin and its Possible Caused Factors," Procedia Earth Planet. Sci., vol. 12, pp. 47–62, 2015, doi: 10.1016/j.proeps.2015.03.026.
5. E. Suryadi, D. R. Kendarto, K. Amaru, and G. I. Syahputri, "Identification of the critical level of water recharge area in the Citarik subwatershed," IOP Conf. Ser. Earth Environ. Sci., vol. 443, no. 1, pp. 1–9, 2020, doi: 10.1088/1755-1315/443/1/012093.
6. D. A. Kaligis and G. J. Maulany, "Utilization of Geographic Information System Technology As A Tool For Evaluating Watersheds," Int. J. Mech. Eng. Technol., vol. 10, no. 03, pp. 1873–1879, 2019.
7. S. Hanifa, M. P. Tambunan, and K. Marko, "Rainfall distribution in relation to flooding in upper Citarum watershed, Indonesia," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 500, no. 1, pp. 1–9, 2020, doi: 10.1088/1755-1315/500/1/012088.
8. Marjiyono, A. Soehaimi, and Kamawan, "Identifikasi Sesar Aktif Daerah Cekungan Bandung dengan Data Citra Landsat dan Kegempaan," JSDG, vol. XVIII, no. 2, pp. 81–88, 2008.
9. N. Rohaendi, E. Sukiyah, D. Muslim, and A. Cipta, "Geotourism Land Suitability Analysis of Citatah Karst Area in Bandung Basin Using Spatial Multi Criteria Evaluation (SMCE)," Geoj. Tour. Geosites, vol. 39, no. 4, pp. 1346–1353, 2021, doi: 10.30892/gtg.394spl04-777.
10. E. T. Haryanto, E. Sukiyah, P. P. Raditya Rendra, Hendarmawan, and Suratman, "Implication of catchment morphometric on small river discharge of upper Citarik river, West Java," Indones. J. Geogr., vol. 51, no. 2, pp. 224–230, 2019, doi: 10.22146/ijg.36472.
11. P. P. R. Rendra and N. Sulaksana, "Karakteristik Morfometri DAS Citarik Hulu Dan Implikasinya Terhadap Potensi Banjir," *J. Geomin.*, vol. 6, no. 1, pp. 1–16, 2021.
12. P. P. R. Rendra, E. Sukiyah, M. S. D. Hadian, S. B. Daliman, and N. Sulaksana, "The Quantitative Geomorphology of Upper Citarik Watershed and Its Implication to the Flash Flood Potential," BIO Web Conf., vol. 73, pp. 1–10, 2023, doi: 10.1051/bioconf/20237304010.
13. E. A. Keller and N. Pinter, Active Tectonics: Earthquakes, Uplift, and Landscape. 2002.
14. W. B. Bull, "Tectonic Geomorphology," J. Geol. Educ., vol. 32, pp. 310–324, 1984.
15. W. B. Bull, Tectonic Geomorphology of Mountains: a New Approach to Paleoseismology, vol. 1, no. 1. 2007. doi: 10.1111/j.1745-5871.2008.00564.x.
16. P. H. Silitonga, "Peta Geologi Lembar Bandung," 1973.
17. D. W. Burbank and R. S. Anderson, Tectonic geomorphology, vol. 32, no. 5. Blackwell Publishing, 2001. doi: 10.5408/0022-1368-32.5.310.
18. A. N. Strahler, "HYPSOMETRIC (AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY," *Bull. Geol. Soc. Am.*, vol. 63, no. 23, pp. 1117–1142, 1952, doi: 10.1130/0016-7606(1952)63.
19. E. A. Keller and T. K. Rockwell, "Tectonic geomorphology, Quaternary chronology, and paleoseismicity," in Developments and applications of geomorphology, 1984, pp. 203–239. doi: 10.1007/978-3-642-69759-3_7.
20. R. El Hamdouni, C. Irigaray, T. Fernández, J. Chacón, and E. A. Keller, "Assessment of relative active tectonics , southwest border of the Sierra Nevada (southern Spain)," Geo*morphology*, vol. 96, pp. 150–173, 2008, doi: 10.1016/j.geomorph.2007.08.004.