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Estimated sediment exports and erosion in Central Citarum watershed

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Abstract. In addition to the problem of water availability and quality, the Citratum watershed is also experiencing problems with soil erosion and sedimentation. Climate change and land use cover are the leading causes of this. Therefore, monitoring water conditions and soil erosion is prioritized in the central Citarum watershed covering an area of 227,020 hectares. The purpose of this study was to determine soil erosion and the spatial distribution of sediment exports. The InVEST SDR method was used to calculate sediment exports and soil erosion. The results showed that the total sediment export of the Central Citarum watershed was 4.61 x million tons/year or an average of 20.31 tons/ha/year. Significant distributions occur in several sub-watersheds, including Cilawang, Cihalaya, Cipada, Citarum 58, and Cimurah, each contributing 36.56%, 14.83%, 13.70%, 4.73%, and 4.53 %. Meanwhile, total soil erosion is 23.16 million tons/year or an average of 102 tons/ha/year, with the most extensive distribution in the Cilawang sub-watershed, 35.12%. High sediment discharge occurs in areas with steep slopes, high rainfall, and dry land agriculture. Furthermore, efforts to reduce sediment exports to the Cirata and Jatiluhur reservoirs should focus on these five sub-watersheds.

1. Introduction

Geology, slope, topography, soil type, climate, and vegetation all have an impact on how quickly soil erodes within a given area. In the process of soil erosion, there are four stages: detachment, transport/redistribution, breakdown, and sediment deposition. Soil erosion produces sediment, whether it takes the form of upland surface erosion, movement of soil mass, hillslope and gully erosion, streambank erosion, or bed erosion [1]. The primary determinants of sediment dynamics are the climate (particularly the rain intensity), soil characteristics, topography, and vegetation [2].

In addition to experiencing problems with water availability and quality, the Citratum watershed is also experiencing issues with soil erosion and sedimentation. The climate change impacts and land use cover are the primary causes of reduced yields, water quality, and sediment and soil erosion trade. Thus, monitoring water conditions and soil erosion is prioritized in the Central Citarum watershed, with an area of 227.020 hectares.

Furthermore, anthropogenic factors such as urbanization and development, forestry practices (e.g., clearcutting, land preparation), dam construction and operation, also agricultural activities (incl. harvesting) are regarded as the most important causes of sedimentation transfer and erosion [2-3].

In this study, the sediment delivery ratio (SDR) of InVEST (Integrated Valuation of Environmental Services and Tradeoffs) model was used. This model has been extensively used in instream water quality maintenance and reservoir management to visualize the production and distribution of overland sediment to streams [4].

After adjustment with observation data, this model has been shown to perform well and has been successfully utilized to describe the spatial distribution of sediment export and estimate sediment retention services [5]. The resulting outputs include maps of soil loss, sediment delivery ratio, and sediment export maps, which were used to examine the connections between land use and individual results. Such analyses help us understand how different land use changes affect sediment delivery, sediment source, and, consequently, sediment export.

Because of specific land use and urbanization policies, land use in the study basin has changed dramatically. We seek to explain sediment export changes brought by land use changes in our study by analyzing changes in soil loss as well as SDR that use the InVEST SDR model.

The aims of this study are to estimate the spatial distribution of sediment exports and soil erosion in Central Citarum

2. Materials and Methods

2.1. Study area

The research was conducted in 2022 in the Central Citarum sub-watershed, including 17 (seventeen) small sub-watersheds, namely the Cilawang, Cihalang, Cibalagung, Cipada, Cikareo, citarum108 and 58, Cimanggu, Cisubah, Ciburial, Cimurah, Cisokan, Cipatunjang, Cikidang, sub-watersheds. Cibungur and several other subs. Geographically it is located between 107°22'50,606"L – 107°56'46,297"L and 6°45'40,112"LS – 7°14'27,018"LS as represented in Figure 1

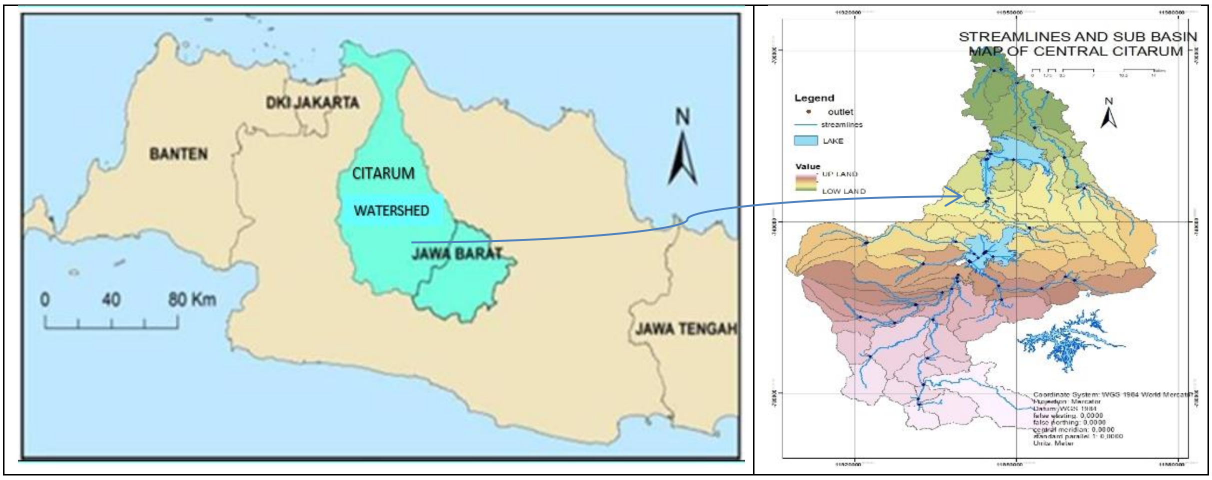

Figure 1. Location of the study

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2.2. Data
A digital map of Indonesia (scale 1:25 000), a 1:100,000 soil type map from Puslittanak Bogor, a 1:100,000 2019 land cover map, and an 8 m resolution DEM (Digital Elevation Model) map interpretation results were used as secondary data. This National DEM belongs to the Geospatial Information Agency and is equipped with watermark protection that can be recognized in its derivative products but does not affect its accuracy[6].

Spot imagery, and climate data (monthly average wind speed, duration of sun exposure, relative humidity, monthly max and min temperatures) were obtained from the Meteorology, Climatology, and Geophysics Agency from the closest station. In comparison, daily rainfall data was obtained from the Department of Water Resources Management of West Java Province and Jasa Tirta. The data needed in this study are shown in Table 1.

Table 1. List of required data inputs for the InVEST models.

Data	Data Type
Digital Elevation Model (DEM)	Raster file (.tif)
Iso-erosivity map (R factor)	Raster file (.tif)
Soil erodibility map (K factor)	Raster file (.tif)
Boundary shapefile (watershed)	Vector file (.shp)
Land cover map	Raster file (.tif)
Non-spatial data Biophysical table	matrix (.csv)

2.3. Methods
The SDR model was executed utilizing the InVEST 3.9.0 software from Natural Capital Project. The sediment delivery module is a spatially-explicit model that operates at the spatial resolution of the input DEM raster. The model first computes the yearly soil loss from that pixel, followed by the SDR, which is the proportion of soil loss that reaches the stream.

The conceptual approach is employed in the model. The SDR for each pixel is a function of the downslope flow path and upslope area [2].

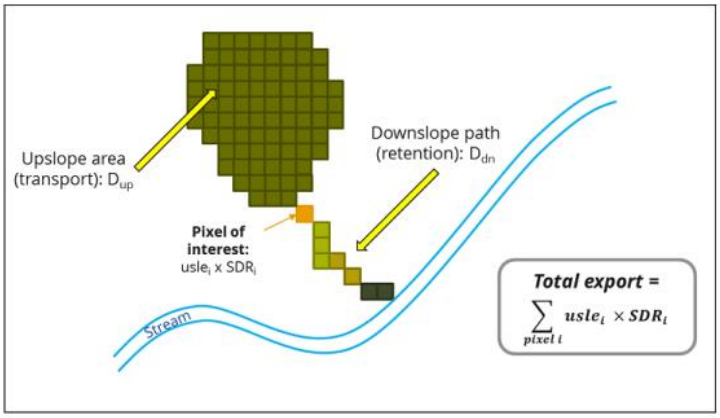

Figure 2. The conceptual approach used in model S [2]

The InVEST SDR model was chosen based on input data, model uncertainty, and complexity. It computes sediment export by combining a soil loss algorithm [7] with a sediment connectivity algorithm [8] and outputs maps of soil loss, sediment export, and SDR.

The primary data requirements and sources in the model are shown in Figure3

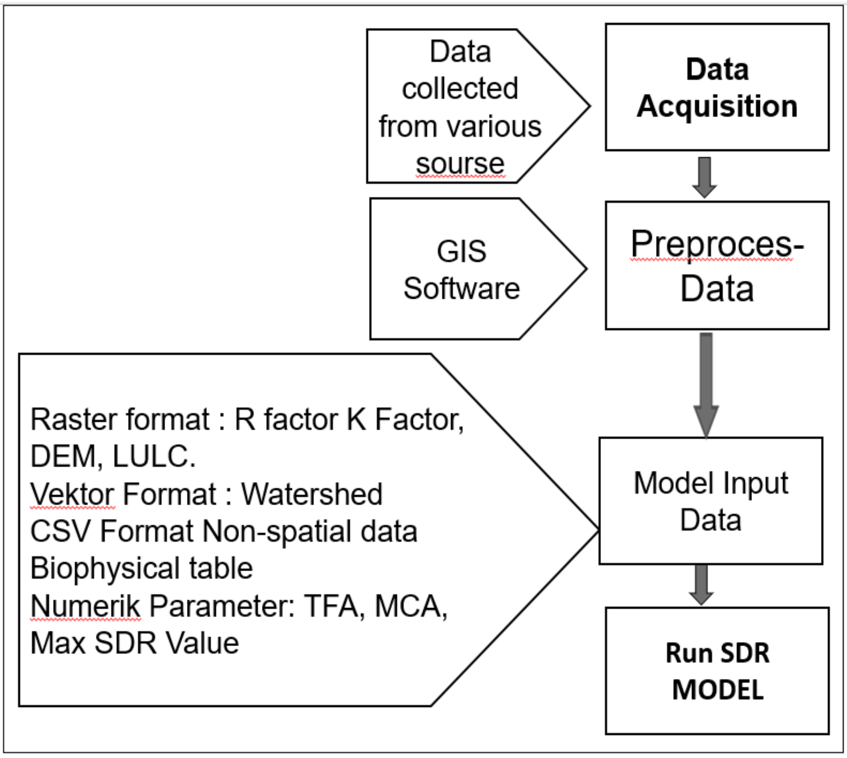

Figure 3. stages of data analysis activities.

SDR was calculated as a function of the hydrologic connectivity of the area derived from the DEM using the method described in [9]. The degree of hydrological connectivity of a pixel to a stream is represented by an index of connectivity, IC. It was measured in this case by its flow path to the stream and upslope contribution [9]. The SDR can be computed as:

$$SDR_i = \frac{\mathrm{SDR}_{max}}{1 + exp\left(\frac{IC_o + IC_i}{k}\right)} \quad (1)$$

The sediment load formula from a given pixel E_i is:

$$E_i = SDR_i \; x \; USLE_i \quad (2)$$

so that equation (3) can be presented :

$$SDR_i = \frac{E_i}{USLE_i} \quad (3)$$

Where USLE*i* is the average amount of yearly soil loss (ton/ ha/year) on a pixel i.

SDRi is the sediment delivery ratio for a pixel i.

The total catchment sediment load E (ton/ha/year) formula is:

$$E = \sum_i E_i$$

Soil loss (USLEi) is computed with the RUSLE model [7] :

$$USLE_i = R_i \times K_i \times LS_i \times C_i \times P_i \quad (4)$$

Where R is the rainfall erosivity (MJ mm (ha hr)$^{-1}$);
K is the soil erodibility (t ha hr (MJ.ha.mm)$^{-1}$);
LS is the slope length–gradient factor;
C is the vegetation cover-management factor and
P is the support practice factor.

3. Result

3.1 Sediment export

According to the results of the SDR sub-model analysis, the value of sediment export is obtained (Table 2)

Table 2. Sediment expot in Central Citarum year 2018

No	Sub Watershed	Area	Sediment Export		
			Total		Average
		10^3 Ha	10^6 ton/year	**Procent**	Ton/ha/year
1	Cilawang	94.47	1.69	36.56%	17.84
2	Cihalang	21.54	0.68	14.83%	31.73
3	Cipada	16.67	0.63	13.70%	37.88
4	Cihalayang	12.08	0.27	5.78%	22.08
5	Citarum58	9.46	0.22	4.73%	23.08
6	Cimurah	10.28	0.21	4.53%	20.30
7	Cimangu	17.78	0.19	4.17%	10.82
8	Citarum108	8.16	0.19	4.15%	23.42
9	Cirameuwah	5.43	0.13	2.89%	24.57
10	Cimangsud	4.32	0.13	2.84%	30.36
11	Cicariu	7.92	0.11	2.34%	13.63
12	Ciburial	3.22	0.06	1.23%	17.68
13	Cihalayang	3.52	0.05	1.04%	13.59
14	Cibodas	3.47	0.04	0.91%	12.12
15	Cisokan	3.77	0.01	0.13%	1.59
16	Ciroyom	2.33	0.01	0.11%	2.23
17	Cikidang	2.62	0.00	0.05%	0.89
		227.02	4.61	100.00%	20.3

Referring to Table 2, the total export of sediment from the Central Citarum watershed was 4.61 million tons/year, or an annual average of 20.31 million tons/ha/year. By the largest distribution: sub-Watershed Cilawang 1.69 million tons/year(36.56%), sub-Watershed Cihalang 0.68 million tons/year (14.83 %), sub-Watershed Cipada 0.63 million ton/year (13.70 %), sub-Watershed Cihalayang 0.27 million ton/year (5.78 %), and sub-Watershed Citarum 58 0.22 million tons/year contributed (4.73%
, respectively.

Meanwhile, the average sediment export ranges from 0.89 – 37.88 tons/ha/year, with an average value of 20.31 tons/ha/year. According to the average value of sediment exports, the largest are Sub

Watershed Cipada, Sub Watershed Cihalang, Sub Watershed Ciamangsud, Sub Watershed Cirameuwah, and Sub Watershed Citarum 108, with a sediment size of 37.88 tons/ha/year, 31.73 tons/ha/year, 30.36 tons/ha/year, 24.57 tons/ha/year and 23.42 tons/ha/year, respectively.

The distribution of sediment exports is presented in Figure 4a, while Figure 4b shows the distribution of sediment retention. Sediment retention is the difference between the amount of sediment in the current condition and the sediment in the state without land cover / bare land (prediction).

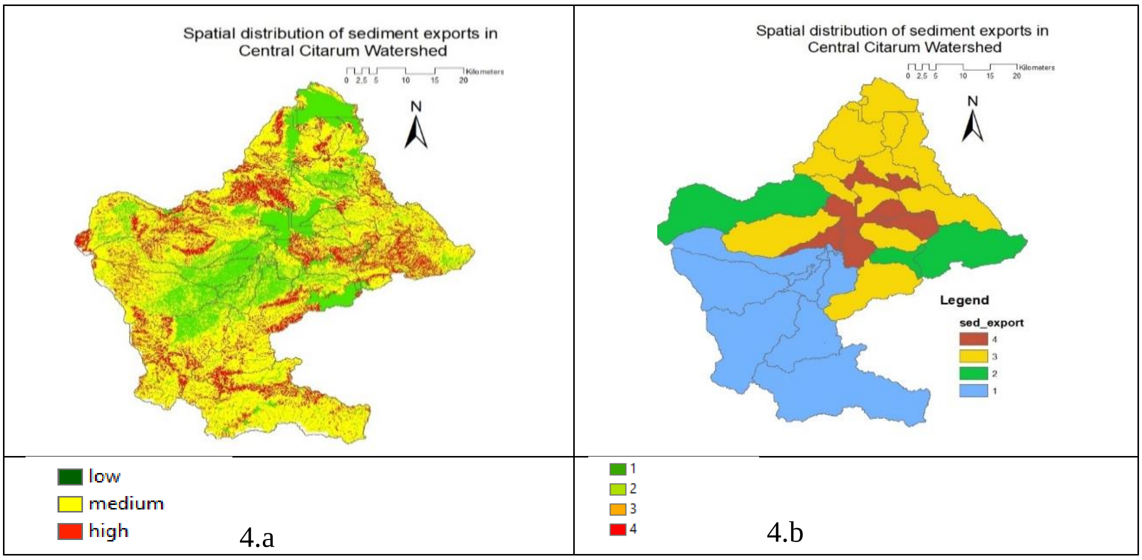

Figure 4. Spatial distribution of sediment exports in Central Citarum Watershed

Figure 4a shows the total amount of sediment exported on average, ranging from 0 - 15,277 tons/pixel. While Figure 4b shows the difference between the current and estimated amount of sediment in the condition without land cover (vacant land) on average, ranging from 0 - 45,451 tons/pixel. It can be seen that when all the land turns into empty land, there is an increase in sediment export by three times the initial condition.

The existence of differences in sediment exports in the watershed is influenced by natural factors, such as soil properties and types, topography and vegetation, and rainfall intensity, also anthropogenic factors, such as land clearing activities for agriculture [3]. According to [10], the amount of soil erosion produced and the ability of sediment storage is determined by land cover factors and soil properties. Therefore, changes in land cover within watersheds influence the temporal dynamics of sediment rates.

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3.2 Soil Erosion

In accordance with the results of the SDR sub-model analysis, the value of soil erosion is obtained (Table 3)

Table 3. Soil erosion in Central Citarum year 2018

No	Sub Watershed	Area	soil erosion loss Total		Average	Class of soil erosion loss		
		10^3 ha	10^6 tons/year	procent	ton/ha/year	Class	10^3 ha	procent
1	Cimangsud	4.32	0.85	3.68%	197.31	4.00	4.32	1.96%
2	Cipada	16.67	2.70	11.65%	161.79	3.00		
3	Cihalang	21.54	2.95	12.73%	136.85	3.00		
4	Cirameuwah	5.43	0.74	3.21%	136.85	3.00		
5	Cibodas	3.47	0.40	1.72%	115.12	3.00		
6	Cimurah	10.28	1.17	5.04%	113.47	3.00		
7	Citarum108	8.16	0.92	3.98%	113.01	3.00		
8	Cihalayang	12.08	1.35	5.84%	111.99	3.00	213.99	94.26%
9	Citarum58	9.46	1.03	4.45%	109.02	3.00		
10	Ciburial	3.22	0.31	1.34%	96.64	3.00		
11	Cilawang	94.47	8.13	35.12%	86.09	3.00		
12	Cicariu	7.92	0.66	2.83%	82.87	3.00		
13	Cimangu	17.78	1.47	6.34%	82.60	3.00		
14	Cihalang	3.52	0.25	1.09%	71.88	3.00		
15	Cisokan	3.77	0.16	0.69%	42.16	2.00		
16	Ciroyom	2.33	0.04	0.17%	17.29	2.00	6.10	2.68%
17	Cikidang	2.62	0.03	0.12%	10.17	1.00	2.62	1.15%
		227.02	23.16		102.01		227.02	100.00

Total soil erosion is 23.16 million tons/year, or an annual average of 102.01 tons/ha/year, with the most extensive distribution: sub-watershed Cilawang at about 8.13 million tons/ha/year (35.12 %), sub-watershed Cihalang about 2.95 million tons/ha/year (12.73 %), sub-watershed Cipada about 2.70 million tons/ha/year (11.65 %), sub-watershed Cimangu about 1.47 million tons/ha/year (6.34 %), and sub-watershed Cihalang about 1.35 million tons/ha/year (5.84 %) The spatial distribution of soil erosion is presented in Figure 5.

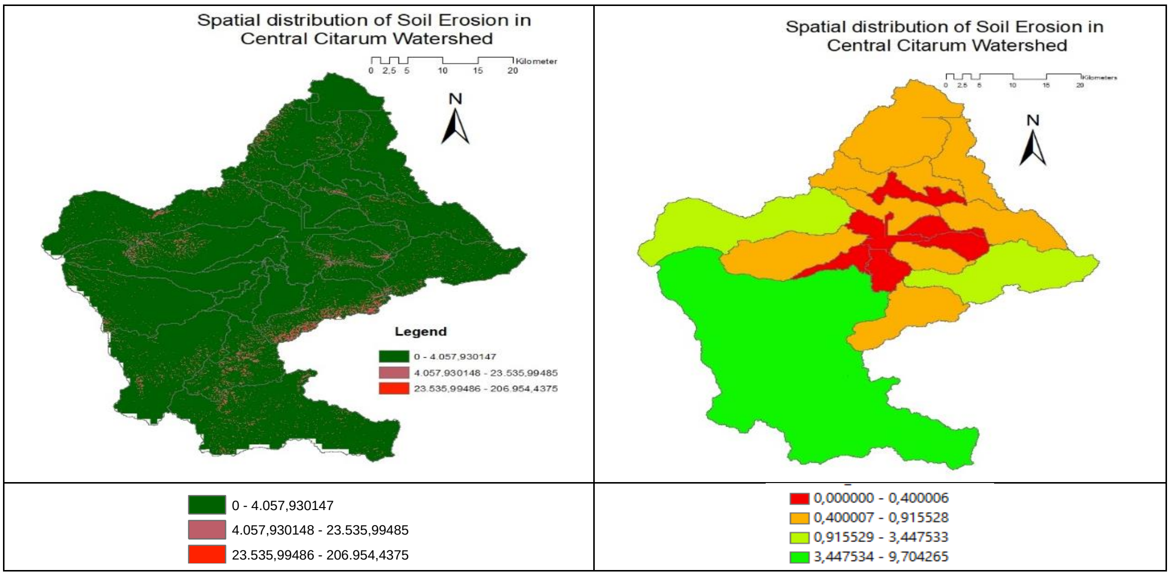

Figure 5. Spatial distribution of soil erosion in Central Citarum Watershed

3.3 Sediment Delivery Ratio (SDR)

In accordance with the results of the SDR sub-model analysis, the value of the sediment delivery ratio is obtained (Table 4)

Table 4. The sediment delivery ratio (SDR) in Central Citarum year 2018

No	Sub Watershed	Area	usle_tot	sed_export	SDR	
		10^3 Ha	10^6 tons/year	10^6 tons/year		Percent
1	Cipada	16.67	2.70	0.63	23.41%	7.34%
2	Cihalang	21.54	2.95	0.68	23.19%	9.49%
3	Citarum58	9.46	1.03	0.22	21.17%	4.17%
4	Citarum108	8.16	0.92	0.19	20.73%	3.60%
5	Cilawang	94.47	8.13	1.69	20.72%	41.61%
6	Cihalayang	12.08	1.35	0.27	19.72%	5.32%
7	Cihalang	3.52	0.25	0.05	18.90%	1.55%
8	Ciburial	3.22	0.31	0.06	18.29%	1.42%
9	Cirameuwah	5.43	0.74	0.13	17.95%	2.39%
10	Cimurah	10.28	1.17	0.21	17.89%	4.53%
11	Cicariu	7.92	0.66	0.11	16.45%	3.49%
12	Cimangsud	4.32	0.85	0.13	15.39%	1.90%
13	Cimangu	17.78	1.47	0.19	13.10%	7.83%
14	Ciroyom	2.33	0.04	0.01	12.89%	1.02%
15	Cibodas	3.47	0.40	0.04	10.53%	1.53%
16	Cikidang	2.62	0.03	0.00	8.74%	1.15%
17	Cisokan	3.77	0.16	0.01	3.77%	1.66%
		227.02	23.16	4.61	19.91%	100 %

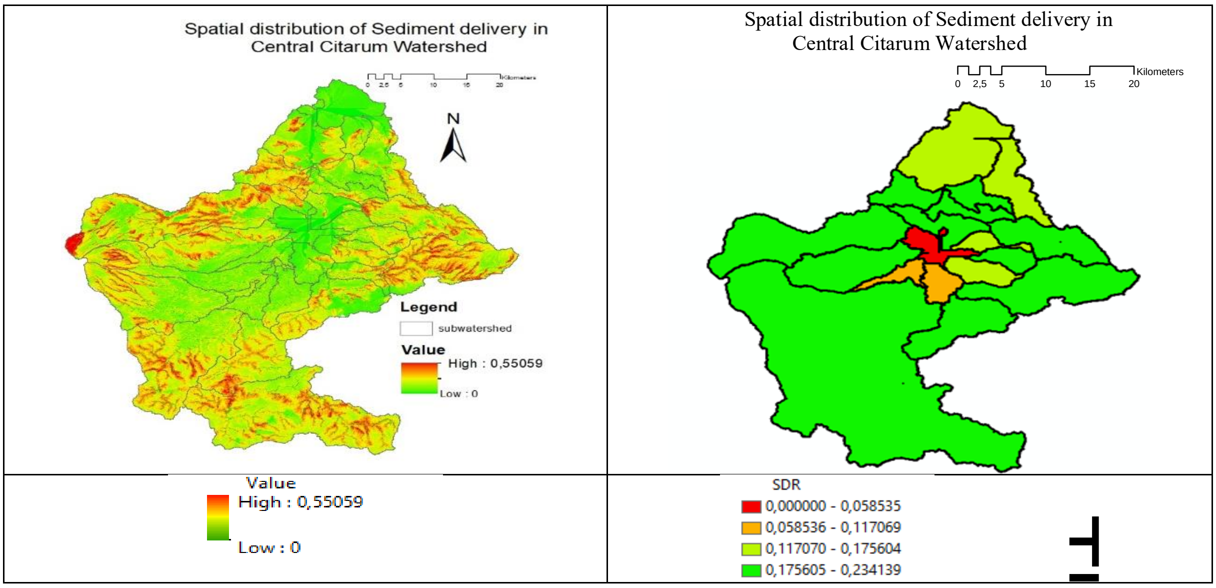

Figure 6. Spatial distribution of Sediment delivery in Central Citarum Watershed

The SDR for Central Citarum is 19.91. With values ranging from 3.77% - 23.41%. The sub-watersheds with the highest SDR values were the Cipada sub-watershed, Cihalang sub-watershed, Citarum sub-watershed 58, Citarum sub-watershed 108, and Cilawang sub-watershed, with an SDR value of 23.41 %, 23.19 %. 21.17%, 20.73%, and 20.72%, respectively. The large Sdr value indicates that the proportion of soil erosion that can be deposited is more than the small Br.

Based on the distribution, the sub-watersheds with the largest distribution were the Cilawang sub-watershed (41.61%), the Cihalang sub-watershed (9.49%), the Cimangu sub-watershed (7.83%), the Cipada sub-watershed 7.34%, and the Cihalaya sub-watershed 5.32%, respectively.

4. Discussion

4.1. Sediment export

The existence of differences in sediment exports in the watershed is influenced by natural factors, such as soil properties and types, vegetation and topography, rainfall intensity, and anthropogenic factors, such as land clearing activities for agriculture [3]. Further explained by [10], the amount of soil erosion produced and the ability of sediment storage is characterized by land cover factors and soil properties. Therefore, changes in land cover within watersheds influence the temporal dynamics of sediment rates.

4.2. Soil Erosion

According to the Indonesian government standard document [11], the central Citarum area has an average soil erosion of 10.17 – 197.31 tons/ha/year, dominated by moderate class 3 covering an area of 213.99 x 103 ha (94.26 %), class 2 Severe covering an area of 6.10 x 103 ha (2.68 %), class 4 slight covering an area of 4.32 x 103 ha (1.98 %), class 1 very severe covering an area of 2.62 x 103 ha (1.15%) and not finding class 5 very slight In general, the TBE level is in the moderate class.

Based on the average soil erosion value, the sub-watersheds that have the highest values are the Cimangsud sub-watershed, Cipada sub-watershed, Cihalang sub-watershed, Cirameuwah sub-watershed, and Cibodas sub-watershed with soil erosion values of 197.31, 161.79, 136.85, and 115.12 respectively. Soil erosion loss in the Central Citarum area is 23.16 million tons/year, or an annual average of 102.01 tons/ha/year, according to research in the upstream Citarum watershed area conducted by Chaidar [12]. From 1990 – 2013, the amount of soil erosion was 62.04 – 137.66 tons/ha/year, with an average value of 107.99 tons/ha/year. There is a pattern of increasing the amount of soil erosion that occurs in Citrarum every year.

Karlina's research [13] on the Erosion of the Upstream Citarum Watershed in Bandung Regency gave the results that the erosion class in the Upstream Citarum Watershed area was dominated at level 2 (16-60) with dry land farming, a land cover of rice fields, and level 3 (60-180) land cover of mixed gardens and secondary forest.

Further research [14] showed that the level of erosion depends on the types of plants that are on it. For example, the amount of erosion in the upper Citarum area in 2020 (village at Mandalahaji village, Bandung sub-district, West Java province) gives a value of 14.95 tons/ha/year in areas with monocultures and 1.5 tons/ha/year in areas with agroforestry crops.

Judging from the level of erosion that occurs between 1.77 – 284 tons/ha/year, the erosion conditions in central Citarum are equivalent to Adimihardja's research [15], which ranges from 35 to 220 tons/ha/year, which is the amount of erosion that occurs in the territory of Indonesia. Referring Ambarwulan's research [16] showed that the erosion class was smaller than the findings of Ambarwulan's research in the Middle Citarum watershed, where the erosion ranged from 0.87 to 495.30 tons/ha/years, which has a broader study area, thus enabling higher erosion values, which is derived from differences in land cover and a more diverse class of slopes

4.3. Sediment Delivery Ratio

The findings of the value of Br in Central Citarum, with an average value of 19.91%, are smaller than the findings of Haryanto's research. Referring to Haryanto's research [17] in the Hulu Citarum Watershed in 2002, the sediment delivery ratio was 27.6%, where the total erosion in the upstream Citarum watershed was 15,206,301 tons/ha/year, while the total deposition in the water was 4,197,152 tons, so that "Sediment delivery ratio" is 27.6%.

Referring to the research by Siswanto & Francés [18], in the Upper Citarum area in 1994, the sedimentation rate was 14 tons/ha/year with a soil erosion rate of 75.24 tons/ha/year. Thus the sediment delivery ratio is 18.60 %. Meanwhile, based on data in the 2014 simulation using the TETIS model, it was obtained that in 2029 the orientation occurred 29 tons/ha/year with soil erosion of 134.37 tons/ha/year, so the sedimentation delivery ratio was obtained at 21.58%.

The average sediment in the upper Citarum area is 9.00 /ton/ha/year to 70.00 tons/ha/year. Refer to Poerbandono [19] that soil erosion of 46.15 to 264.15] in the upper Citarum in the period 1994 (19.99 – 26.40 %) to 2001 was 19.80 % - 26.5%. Meanwhile, referring to Rinaldi's research [20], the SDR value based on the results of the 2007 announcement was 0.733.

5. Conclusion

The findings revealed that the SDR value in Central Citarum was 3.77% – 23.41%, with an average value of 19.91 %. Central Citarum is mostly 213.99 x 103 ha (94.26%) and is level III. (moderate), the average sediment export in Central Citraum is 20.31 tons/ha/year. Furthermore, initiatives to reduce sediment exports to Cirata and Jatiluhur reservoirs must also be concentrated on five of the sub-watershed, mainly Cilawang Subwatershed**.**

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