Quantification of Citarum watershed damage for flood control efficiency

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Abstract. Watersheds damage causes disturbance to the river system and floods. Watershed performance can be monitored regularly through parameters to avoid damage. The purpose of this study is to formulate a quantification of watershed damage based on the flood parameters. This research was conducted in the Citarum River Basin located in West Java Province, Indonesia. The method used is an analysis of the rainfall-runoff model on four Citarum tributaries, namely Citarik, Cisangkuy, Cilember, and Cimahi River. The unit hydrograph resulting from modeling is derived to load discharge using the convolution method. Effective rainfall is determined based on runoff coefficients derived from land-use maps. The discharge capacity of the river is determined by measuring the cross-section of the river near the branching location. Indicator of watershed damage is the ratio between load discharge (Qload) and river capacity discharge (Qcap). The watershed is categorized as damaged if Qload / Qcap > 1. The level of watershed damage is measured by the damage index ID = ∆Q / Qcap. Damage categories are low, moderate, and severe. Based on the results of the study, Cimahi river area is not damaged. Citarik River and Cisangkuy River are categorized as low damaged and Cilember River is heavily damaged.

1. Introduction
The problem of the Citarum river has a very broad impact on various levels of society. Damage of the Citarum watershed includes the amount of critical land reaching 79,668.25 ha and causing sedimentation of up to 8,465 tons/year. The sources of Citarum waters pollution include pollution from agricultural and animal husbandry activities, domestic and industrial waste, and pollution from floating net cage (KJA) aquaculture activities that are developing rapidly in reservoir waters [1]. The problems with damage to the Citarum watershed are flooding, erosion and misuse of land use. This Citarum watershed is a vital resource used by many stakeholders. Around 16% of the population of West Java is along the Upper Citarum Watershed with a population growth rate of 2.3% [2].

In the upstream area of the Citarum River, flooding often occurs in 12 Rancaekek villages with five villages experiencing the heaviest floods namely Linggar, Bojongloa, Bojongpulus, Jelekong and Sukamanah villages which are floods with heights of more than one meter and an average inundation duration of fewer than 24 hours. Floods that occur on the road that connects Bandung-Garut still occur even though there is no overflow from the Cikijing river, a tributary of the Citarik river. The efforts
being carried out by stakeholders are dredging, structuring local drainage and making communal infiltration wells.

Rancaecek District is a meeting place of the Citarik river with the Citarum river. This region is also the location where the Cikijing and Cimande rivers meet the Citarik river. River branching like this is also the cause of flooding in the Cimahi city of Melong, namely the meeting of the Cilember river with the Citarum river [3]. The middle part downstream of a river area is generally a flood-prone area if no integrated management that integrates the river area and the urban regional area. This happens because the middle part of a river area will receive the impact of increased river discharge due to changes in land cover in the upstream area without spatial planning referring to the planned regional layout plan [4]. Changes in land use provide a dominant influence factor on water management and groundwater conservation which has an affects on increasing drainage coefficient [5]. Prevention of flood hazards in the province of Izmir, Turkey, is done by detecting potential flood areas using radar with five parameters and qualification levels namely very low, low, medium, high and very high [6]. The Flood Risk Index map was developed to estimate flood hazard and vulnerability in the Bukit Duri sub-district of Tebet, Jakarta, upstream of the Manggarai floodgate. The flood hazard index was analyzed based on inundation maps that were verified with field data. Based on the research risk map, the study area is a high flood risk area due to dense population housing and inadequate flood mitigation [7].

2. Methods of the study

The method used in this study is an analysis of the rainfall-runoff model on four Citarum tributaries, namely Citarik, Cisangkuy, Cilember and Cimahi river. The unit hydrograph resulting from modeling is derived to load discharge using the convolution method. Effective rainfall is determined based on runoff coefficients derived from land-use maps. The discharge capacity of the river is determined by measuring the cross-section of the river near the branching location.

Watershed damage occurs due to the disruption of the hydrology system due to changes in land use. The elements of land use that have changed generally are forests, agricultural land and settlements. The Sumpur Singkarak watershed, West Sumatra is addressing increasing land-use change by monitoring using satellite imagery interpretation and forest protection [8]. Floods in the Palu river occur because the capacity of the river is not able to accommodate the discharge load of more than 550 m³/s where the discharge occurs for a return period of 25 years. If the discharge load exceeds that number, floods occur. The decline in the capacity of the Palu river is due to sedimentation in the riverbed which results in aggradation [9]. Recent floods have occurred in Jayapura, Paniai and Manokwari. The cause of increased runoff during the rainy season is the conversion of forests into oil palm plantations. The solution is a land conservation program, sediment dredging and building a retaining wall [10].

Floods are caused by the power of water damage. In general, the definition of flood is the overflow of river water so that the water flows in residential land and causes disaster [11]. Flood disaster according to the level of damage is a function of the extent of the inundation area, the length of inundation time and inundation height. Research on flooding continues to grow, starting from river flow analysis, analysis of water runoff on the ground, analysis of runoff routing mechanisms and analysis that integrates water quantity with characteristics.

A watershed can be assumed to be a lumped linear system in which the amount of water stored in a hydrological system is associated with inflow and outflow [12]. The main physical characteristics of a watershed are area, shape, elevation, slope, orientation, soil type, drainage network, water storage capacity and land cover. The effect of these types of characteristics varies. Soil types can control infiltration, surface water reservoirs, and groundwater. The combined effect of all factors is the classification for small and large watersheds [13].

The rainfall-runoff model used in this study is Nakayasu synthetic unit hydrograph method that has been calibrated based on the characteristics of the watershed [14],

\[ Q_p = \frac{0.99AR_n}{3.7(0.1T_p + T_{0.3})} \] (1)
where Peak discharge ($Q_p$) is the function of watershed area ($A$), watershed characteristic coefficient ($C = 0.99$), unit rainfall ($R_o$), time lag ($T_p$) and time required to discharge reduction up to 30% peak discharge ($T_{0.3}$). The direct runoff discharge in each river is determined by the convolution method which is the function of effective rainfall and unit hydrograph. Discrete convolution equation for the linear system used is shown in equation 2,

$$Q_n = \sum_{m=1}^{n_{cap}} P_m U_{n-m+1}$$  \hspace{1cm} (2)

where $Q$ is direct runoff discharge, $P$ is effective rainfall and $U$ is unit hydrograph ordinate.

The land use of a watershed shows the type of land cover of the watershed. Land surface affects the abstraction into the soil and becomes a determining variable in the amount of drainage coefficient or runoff coefficient \[15\][16],

$$C = \frac{r_d}{\sum_{m=1}^{M} R_m}$$

$$\sum_{m=1}^{M} R_m = \text{total rainfall}$$  \hspace{1cm} (3)

where $C$ is runoff coefficient and $r_d$ is the runoff depth.

The indicator of watershed damage is the ratio between load discharge ($Q_{load}$) and river capacity discharge ($Q_{cap}$). The load discharge is the direct runoff discharge coupled with the base flow of the river. The watershed is categorized as damaged if

$$\frac{Q_{load}}{Q_{cap}} > 1$$  \hspace{1cm} (4)

The level of watershed damage is measured by the damage index $I_D$

$$I_D = \frac{Q_{load} - Q_{cap}}{Q_{cap}} = \frac{\Delta Q}{Q_{cap}}$$  \hspace{1cm} (5)

Damage categories are low ($I_D < 0.2$), moderate (0.2 ≤ $I_D < 0.6$) and severe ($I_D \geq 0.6$).

3. Results and discussion

3.1. Study area

Geographically, the Citarum watershed is located at 106° 57’ 51” - 107° 56’ 59” East and 5° 54’ 53” - 7° 14’ 38.517” S with the area of 6596 km$^2$. The length of the Citarum river is 297 km with the headwaters at Cisanti Lake which is located at the foot of Mount Wayang, Bandung Regency and empties into the North Coast of Java Island, Muara Gembong, Bekasi Regency. The flow of the Citarum watershed crosses 11 cities including Bandung Regency, West Bandung Regency, Purwakarta Regency, Karawang Regency, Bekasi Regency, Bandung City, Cimahi City, part of Sumedang Regency, part of Cianjur Regency, part of Bogor Regency, and part of Garut Regency. In addition to being a source of raw water for drinking water, the Citarum River also being an irrigation water source for hundreds of thousands of hectares of rice fields and power plants for Java and Bali. In the Citarum river, there are three large reservoirs, namely Saguling, Cirata, and Jatiluhur. The map of Citarum watershed is shown in figure 1,
Based on the land use map, the runoff coefficient of Cimahi, Cilember, Citarik, and Cisangkuy river is 0.57, 0.57, 0.51, and 0.61 respectively.

3.2. Observed cross-section of the river
The cross-sections of rivers in this study which the location are near the branch of Citarum are shown in Figure 2 below.
Based on the cross-section, the maximum capacity discharge of the Cimahi river is 88.28 m$^3$/s. Cilember River which is located adjacent to the Cimahi River has a cross-section as is shown in Figure 3,

![Figure 3. Cilember River cross-section](image)

Cilember river has a very narrow cross-section with a maximum discharge of 9.62 m$^3$/s. The Citarik River, which meets the Citarum River is located in the Rancaekek sub-district, the cross-section of the river after being normalized is as is shown in Figure 4,

![Figure 4. Citarik River cross-section](image)

The maximum discharge of the Citarik river in the cross-section is 348.1 m$^3$/s. The Cisangkuy river which meets the Citarum river in Banjaran sub-district has the cross-section as is shown in Figure 5,

![Figure 5. Cisangkuy River cross-section](image)

The maximum discharge of the Cisangkuy river at the cross-section is 328.1 m$^3$/s. The unit hydrograph parameters of each river are shown in table 1 below,
### Table 1. Parameters of unit hydrograph

| Name of The River | Unit Hydrograph Parameter | Q_p (m³/s) | T_p (hour) | T_b (hour) |
|-------------------|---------------------------|------------|-----------|-----------|
| Cimahi            |                           | 3.52       | 2.80      | 20.00     |
| Cilember          |                           | 0.75       | 2.44      | 25.00     |
| Cisangkuy         |                           | 5.37       | 4.00      | 21.00     |
| Citarik           |                           | 4.31       | 3.54      | 30.00     |

Based on the above table, it can be seen that the Cilember watershed has a small capacity with a peak discharge of 0.75 m³/s. Narrowing the river as much as 60% of its capacity, as well as drainage constraints in the downstream areas at its meeting with the Citarum river, indicate severe river damage.

#### 3.3. The monthly load discharge

Load discharge analysis in this study is made monthly to be able to detect flood events in detail. Discharge is calculated with a return period of 50 years using the convolution method. The monthly discharge for all four rivers can be seen in Table 2 below,

### Table 2. Load and capacity discharge

| River Name | January | February | March | April | Mei | June | July | August | September | October | November | December |
|------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Cimahi     | 39.98   | 42.74    | 40.22 | 55.87 | 60.16 | 32.72 | 32.07 | 22.26  | 36.15     | 63.51   | 54.82    | 48.55    |
| Q_cap(m^3/s)|         |          |       |       |      |      |      |        |           |         |          |          |
| Cilember   | 25.93   | 27.73    | 26.09 | 36.24 | 39.02 | 21.23 | 20.80 | 14.44  | 23.45     | 41.20   | 35.56    | 31.49    |
| Q_cap(m^3/s)|         |          |       |       |      |      |      |        |           |         |          |          |
| Cisangkuy  | 259.44  | 351.62   | 293.70| 303.60| 264.38| 211.50| 186.45| 162.68 | 228.52    | 281.14  | 386.01   | 392.80   |
| Q_cap(m^3/s)|         |          |       |       |      |      |      |        |           |         |          |          |
| Citarik    | 256.58  | 298.93   | 399.92| 225.87| 267.48| 213.18| 158.93| 126.89 | 151.04    | 407.58  | 407.58   | 397.41   |
| Q_cap(m^3/s)|         |          |       |       |      |      |      |        |           |         |          |          |

Based on the calculation results of the monthly discharge shown in the above table, there are different flood categories for each river. Cimahi River does not experience floods throughout the year. Cisangkuy and Citarik rivers flooded only in a particular month, while the Cilember river flooded throughout the year. Cilember River flows through a densely populated area in South Cimahi sub-district which is also an industrial area. More than 100 industries are located on the banks of the Cilember river with the collection and disposal of waste into this river. Cisangkuy River is in the Bandung Basin region with its headwater in Pangalengan District at an elevation of 1475 m MSL. The meeting of this river with the Citarum river is in the sub-district of Baleendah which is the heaviest flood area in the Bandung Basin. Citarik River is a second-order river that empties into the Citarum river, Rancaekek sub-district, Bandung Regency at geographical coordinates of 107.94°BT and 6.96°LS at 616.81 m MSL. Citarik River has a length of 51.8 km and its upstream is in South Sumedang, Sumedang Regency at coordinates 107.7°BT and 6.99°LS at an elevation of 1210 m MSL. This watershed area is 332 km² with an average slope of 8.7%. The flood inundation area is located at an average slope of 1.1%, in the area where the river meets the Citarum river. The inundation area is approximately 50% of the area of the Rancaekek sub-district and 7.2% of the area of the Citarik River Basin.

This category can be quantified based on the index of watershed damage, I_D. The results are shown in Table 3,
Table 3. The index of watershed damage ($I_D$)

| River Name | January | February | March | April | Mei | June | July | August | September | October | November | December |
|------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Cimahi     | Q_{load}(m^3/s) | 39.98 | 42.74 | 40.22 | 55.87 | 60.16 | 32.72 | 32.07 | 22.26 | 36.15 | 63.51 | 54.82 | 48.55 |
|            | Q_{cap}(m^3/s) | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 | 88.28 |
|            | Q_{load}/Q_{cap} | 0.45 | 0.48 | 0.46 | 0.63 | 0.68 | 0.37 | 0.36 | 0.25 | 0.41 | 0.72 | 0.62 | 0.55 |
|            | I_0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Level of damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage | no damage |
| Cisangkuy  | Q_{load}(m^3/s) | 25.93 | 27.73 | 26.09 | 36.24 | 39.02 | 21.23 | 20.80 | 14.44 | 23.45 | 41.20 | 35.56 | 31.49 |
|            | Q_{cap}(m^3/s) | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 | 9.62 |
|            | Q_{load}/Q_{cap} | 2.70 | 2.88 | 2.71 | 3.77 | 4.06 | 2.21 | 2.16 | 1.50 | 2.44 | 4.28 | 3.70 | 3.27 |
|            | I_0 | 1.70 | 1.88 | 1.71 | 2.77 | 3.06 | 1.21 | 1.16 | 0.50 | 1.44 | 3.28 | 2.70 | 2.27 |
| Level of damage | severe | severe | severe | severe | severe | severe | severe | severe | moderate | severe | severe | severe | severe |
| Citaruk    | Q_{load}(m^3/s) | 256.58 | 298.93 | 399.22 | 225.87 | 267.48 | 211.50 | 348.10 | 348.10 | 88.28 | 9.62 | 328.10 |
|            | Q_{cap}(m^3/s) | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 | 328.10 |
|            | Q_{load}/Q_{cap} | 0.79 | 1.70 | 1.90 | 0.93 | 0.81 | 0.64 | 0.57 | 0.50 | 0.70 | 0.86 | 0.70 | 1.00 |
|            | I_0 | 0.00 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 |
| Level of damage | low | low | low | low | low | low | low | low | low | low | moderate | low | low |

Based on the results of the above table, the Cimahi river area is not damaged. Citaruk River and Cisangkuy River are categorized as low damaged and the Cilember River is heavily damaged.

4. Conclusion
Quantification of watershed damage is needed to quantitatively measure the level of watershed damage. With this quantification value, monitoring changes in watersheds can be carried out so that watershed damage can be determined earlier and helping scale priorities for river basin improvement as a guideline for stakeholders. Noteworthy is the validity of the quantification formula so that it approaches its actual condition.

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