fluids

Article

Hydrological Response of Land Use and Climate Change Impact on Sediment Rate in Upper Citarum Watershed

Evi Anggraheni [1,*], Abdul Halim Hamdany [1], Farouk Maricar [2], Neil Andika [3], Dian Sisinggih [4], Fransiskus Sean Tanlie [1] and Fransiskus Adinda Rio Respati [1]

[1] Civil Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia; abdul.halim04@ui.ac.id (A.H.H.); fransiskus.sean@ui.ac.id (F.S.T.); fransiskus.adinda41@ui.ac.id (F.A.R.R.)
[2] Civil Engineering Department, Faculty of Engineering, Hasanuddin University, Makassar 90245, Indonesia; fkmaricar@yahoo.com
[3] Civil Engineering Department, Faculty of Engineering, Gadjah Mada University, Yogyakarta 55281, Indonesia; neil.andika@ugm.ac.id
[4] Water Resources Engineering, Faculty of Engineering, Brawijaya University, Malang 65145, Indonesia; singgih@ub.ac.id
* Correspondence: evi.anggraheni@eng.ui.ac.id

Abstract: The Citarum Watershed is indeed a critical water resource in Indonesia, playing a significant role in providing water to Jakarta and other areas in West Java. However, it faces severe environmental stress due to land use changes and climate changes. The Upper Citarum Watershed, considered to be a conservation area, has experienced rapid development due to human activities and economic growth. Climate change not only affects the rainfall value but also the rainfall patterns and sediment flow. The sedimentation process significantly impacts the soil characteristics around the river body. Several factors such as topography, flow velocity, and soil texture influence the sediment characteristics. Given the critical condition of climate and land use change, this study aims to analyse the impacts of the hydrological response of land use and climate change on the sediment rate in the Upper Citarum Watershed. The land use change analysis was conducted by comparing the land use data in 2000, 2010, and 2023 in the Upper Citarum Watershed. The deposition process of solid particles such as sand, silt, and gravel that are transported in the Upper Citarum River were examined in a soil investigation. The sediment rate and deposition by river flow were analysed using HEC-RAS quasi-unsteady flow. The impact of climate change in this study was assessed by simulating the discharge in three conditions, with the first simulation using the discharge from 2000 to 2010, the second simulation using the discharge from 2011 to 2023, and the last simulation using the discharge from 2000 to 2023. Due to the land use change, the developed area increased from 4% to 24% between 2000 until 2023. The magnitude of low flow during the simulation step for three discharge gauges (Majalaya, Dayeuhkolot, and Nanjung) decreased up to 48%, but, on other hand, the sediment rate increased by 20% in Dayeuhkolot.

Keywords: land use change; climate change; sediment rate; hydrological responses; Upper Citarum

check for updates

Academic Editor: D. Andrew S. Rees

Received: 1 December 2024
Revised: 18 January 2025
Accepted: 24 January 2025
Published: 31 January 2025

Citation: Anggraheni, E.; Hamdany, A.H.; Maricar, F.; Andika, N.; Sisinggih, D.; Tanlie, F.S.; Respati, F.A.R. Hydrological Response of Land Use and Climate Change Impact on Sediment Rate in Upper Citarum Watershed. *Fluids* **2025**, *10*, 36. https://doi.org/10.3390/fluids10020036

1. Introduction

Climate change has increasingly caused more frequent floods, droughts, and heatwaves, significantly impacting various sectors, including water resources. The impact of climate change is reflected in the increase of design rainfall values by 20–35% in Australia [1].

In a situation with frequent change in land use conditions, updated land use should be considered in simulations as it improves model performances comparing to static land use [2]. It shows that updated land use holds a crucial role in flow and sediment transport, especially in mountainous areas. Changes in LULC (land use/land cover) significantly impacts stream flow, sediment yield, flow volume into reservoirs, and hydrological components.

The frequency and severity of environmental hazards are not only affected by LULC change but also by climate change [3–5]. A good governance system to manage these conditions is of great importance in order to control the rate of soil erosion. An increase in the rate of soil erosion due to climate and land cover changes leads to an increase in the magnitude of sediment transport, negatively affecting the life expectancy of hydropower reservoirs [6]. In order to reduce such impacts, afforestation can reduce soil erosion and sediment yield at the sub-basin level [7].

Sedimentation refers to the deposition process of solid particles such as sand, silt, and gravel transported by water flow in a river. The characteristics of soil around the riverbank and watershed significantly impacts the sedimentation process. Several factors such as topography, flow velocity, and soil texture influence the sediment characteristics. Coarse-grained soils (such as gravel and sand) tend to settle more quickly in upstream areas with higher flow velocity due to their larger particle size. On the other hand, fine-grained soils (such as silt and clay) are more prone to suspension and may contribute to sediment transport over long distances, resulting in downstream sedimentation with lower flow velocity. Therefore, it is essential to understand the relationship between soil characteristics and sedimentation for watershed management.

The Upper Citarum Watershed is located in the West Java Province, Indonesia, and spans an approximate area of 2500 km^2 as shown in Figure 1. This watershed is one of the most crucial water resources in Indonesia, supporting the economy, the water supply, and the overall development in Jakarta through the West Tarum Canal [8]. The watershed experiences a monsoonal climate influenced by monsoon winds from Australia and Asia, making it vulnerable to El Niño events [9–11]. As the largest watershed in West Java, it plays a vital role in regional water management [12].

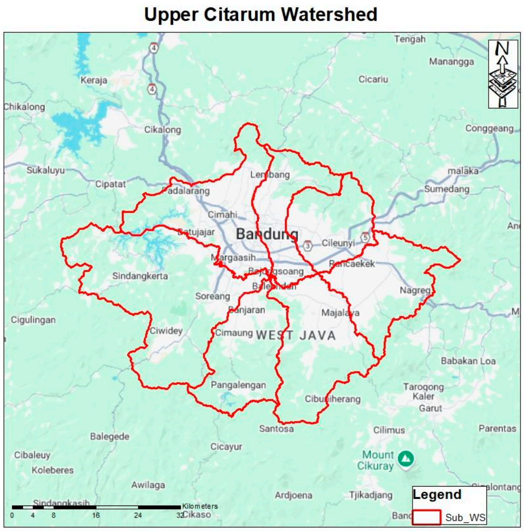

Figure 1. Upper Citarum Watershed.

High economic growth in the area has resulted in significant land cover changes. These significant land cover changes have left the Citarum Watershed in critical condition. These changes in land cover have caused increased discharge during the rainy season, increased drought during the dry season, increased flood frequency, a high sedimentation rate, and increased debris [13]. The mountainous topography surrounding the area from the Upper Citarum Watershed to the Saguling Reservoir, which was previously dominated by a forest area, has been converted into agricultural land, thus causing flash floods that carry debris and sediment loads to the Saguling Reservoir [14,15].

This study aims to analyse the impacts of the hydrological responses of land use change and climate change on the sedimentation rate of the Citarum River. The geological, topographical, and soil conditions of the Upper Citarum Watershed are firstly evaluated for their impact on soil erosion and sediment types in the Citarum River. The land cover change of the Upper Citarum Watershed in the last three decades are obtained from high-resolution satellite data. It is then used with the rainfall data obtained from the Citarum River Basin Agency under the Ministry of Public Work for modelling. The modelling was conducted using the HEC-RAS approach to simulate the sediment transport on the Citarum River.

2. Materials and Methods

The geological condition of the study area was evaluated by examining maps from a series titled Systematic Geological Map Indonesia. The maps were released by the Geological Research and Development Center, Indonesia. The maps represent the distribution of different types of rock and surficial deposits, as well as the locations of geological structures. The regional geological map can be utilised as a preliminary study to evaluate the characteristics of the soil in a particular area based on information of the rock types and surficial deposits.

The soil characteristics in the watershed were required to confirm the soil conditions in the study area. The soil investigation was conducted by the Citarum River Basin Agency. Soil samplings were carried out around the watershed at four locations along the Citarum river:

1. Cikeruh Sediment Trap
2. Nanjung Diversion Tunnel
3. Citarum Main River
4. Component C Check Dam

The soil investigation locations are spread upstream and downstream along the river. These locations are presented in Figure 2.

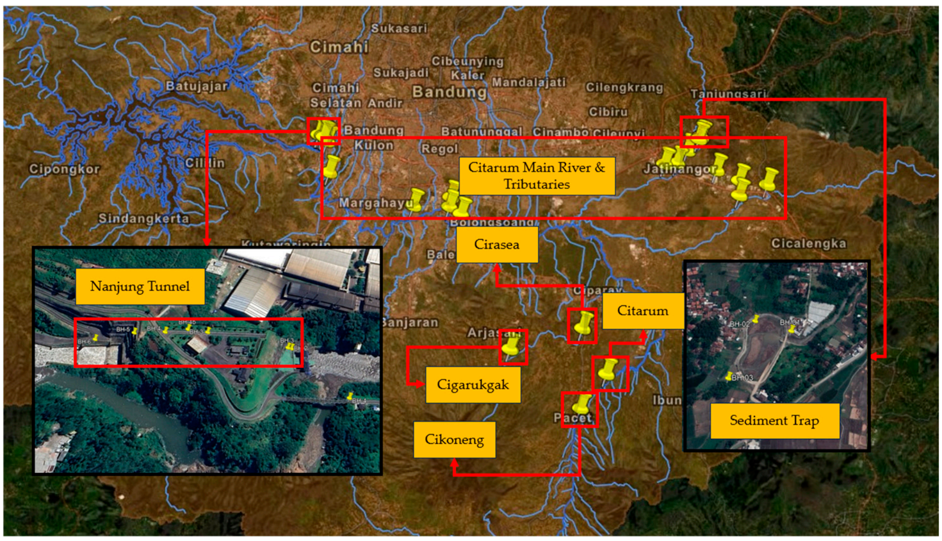

Figure 2. Soil investigation locations around the Citarum River.

The analysis of LULC change in the Upper Citarum Watershed was conducted by comparing the changes in land cover from three different times in the last three decades.

Figure 3 shows the land cover map obtained from high-resolution satellite imagery in the years 2000, 2010, and 2023, respectively. The red colour in the map represents the developed residential area. The red, developed, areas have significantly increased in extent from 2000 to 2010 to 2023. The maps clearly show the huge transformation of residential areas in the Upper Citarum Watershed.

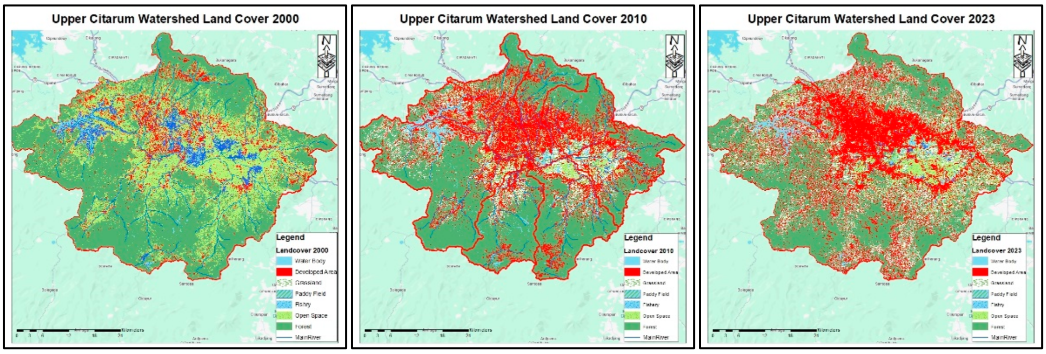

Figure 3. Land Use Change from 2000, 2010, and 2023 in the Upper Citarum Watershed.

Sediment computations in the HEC-RAS leverage one-dimensional, cross-sectional, averaged hydraulic properties derived from the RAS hydraulic engines to simulate sediment transport rates and dynamically update channel geometry through sediment continuity calculations. The main goal is to replicate the core functionalities of HEC-6 within the HEC-RAS framework. Sediment transport models depend on precise hydraulic parameters, so the HEC-RAS computes hydraulic conditions at each time step before routing sediment or updating cross sections. The HEC-RAS, used with specific parameters, is capable of computing sediment transport with either quasi-unsteady hydraulics flow or unsteady hydraulics flow.

The river flow that was used for this analysis was based on the discharge gauge measurements at Majalaya, Dayeuhkolot, and Nanjung in the 2000–2023 period. An unsteady hydrodynamics flow approach was used in this simulation by considering the data availability and output from the HEC-RAS model. An unsteady flow approach simulation can be run in the HEC-RAS without the sediment data. Unsteady flow conserves mass and accounts explicitly for volume change, which is particularly applicable for reservoir modelling, models with lateral structure flows, and reverse flows.

The transport function of the MPM equation is one the most widely used function for calculating the transport and mobility parameters illustrating a simple excess shear relationship. The MPM equation is shown below.

$$q_b^* = 8\,(\tau^* - \tau_c^*)^{3/2}\,,\ \tau_c^* = 0.047 \quad (1)$$

The variables are defined as follows:

q_b^* = Einstein bedload number, which correlates with the bedload transport
τ^* = Shields stress
τ_c^* = Critical Shields stress, to assess sediment movement

The HEC-RAS approach implements the Modified Meyer—Peter and Müller (MPM) Equation (2) as adapted by Vanoni (1975) in the ASCE Manual 54, which is the same version utilised in HEC-6.

$$\left(\frac{k_r}{k_r'}\right)^{\frac{3}{2}} \gamma RS = 0.047\,(\gamma_s - \gamma)d_m + \left(\frac{\gamma}{g}\right)^{\frac{1}{3}} \left(\frac{\gamma_s - \gamma}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}} \quad (2)$$

The variables are defined as follows:

g_s = Unit sediment transport rate in weight/time/unit width.
k_r = A roughness coefficient.
k_r' = A roughness coefficient based on the grains.
γ = Unit weight of water.
γ_s = Unit weight of sediment.
g = Acceleration of gravity.
d_m = Median particle diameter.
R = Hydraulic radius.
S = Energy gradient.

3. Results

Figure 4 presents the geological maps of the Upper Citarum Watershed (a) Cikeruh Sediment Trap; (b) Nanjung Diversion Tunnel; (c) Citarum Main River; and (d) Component C Check Dam. Based on these geological maps, the watershed is mainly located around areas high in Lake Deposits Formation (Ql), which consists of tuffaceous clay, sandstone, gravel, and conglomerate. Locally, the soil forms horizontal layers and contains limestone concretions, plant remains, freshwater molluscs, and bones of vertebrates. However, the central part features a mix of volcanic sediments from the Malabar–Tilu Volcanic Formation (Qmt). It contains ancient lakebed deposits in certain areas and also river alluvial sediments within the narrow valleys of major rivers.

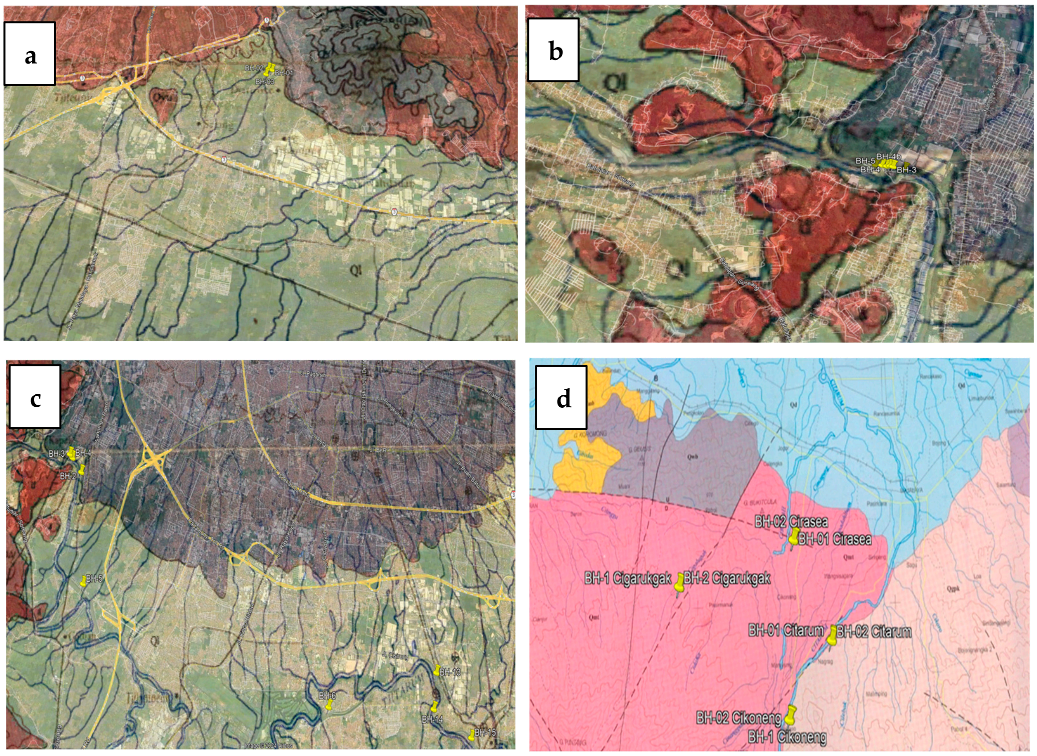

Figure 4. Geological map of the Upper Citarum Watershed (**a**), Cikeruh Sediment Trap, (**b**) Nanjung Diversion Tunnel, (**c**) Citarum Main River, and (**d**) Component C Check Dam.

A sieve analysis test was conducted in the laboratory on the soil samples collected in the selected locations. This test is used to separate particles into size ranges and to determine the soil classification (fine or coarse material) for each sample. The grain size distribution result in the Citarum Watershed is listed in Table 1. It was found that the topsoil layer can be classified as sandy silt in most of the area. This result is in line with the geological evaluation that this area contains limestone concretion. This limestone is often encountered in the Upper Citarum Watershed. Finer soil type (clayey silt) was found in the Citarum Main River.

Table 1. Grain size distribution results.

		Grain Size (%)				
Location	**Bore ID**	**Depth (m)**	**Gravel**	**Sand**	**Silt**	**Clay**
Cikeruh Sediment Trap	BH-01	3.30	2.52	33.92	50.72	12.84
		13.30	20.73	36.65	39.73	2.89
		15.30	57.76	37.31	4.81	0.12
Citarum Main River	BH-06	2.00	0.00	7.50	58.05	34.45
		8.00	0.00	26.38	41.78	31.84
Component C Check Dam	Cirasea BH-01	1.55	8.90	34.37	45.75	10.98
		5.55	45.51	38.44	15.03	1.02
		7.55	20.14	48.45	28.39	3.02

Figure 5 presents the geometry data in the Upper Citarum Watershed. These data were essential for sediment transport analysis. Topographical conditions in the study area are very contoured according to the elevation data of the Upper Citarum Watershed, river cross section, and discharge gauge. The contoured topography can significantly influence the potential land erosion. The interplay between soil types and topography in the Upper Citarum Watershed leads to significant erosion and debris flow into the Citarum River, resulting in sediment accumulation in the Saguling Reservoir.

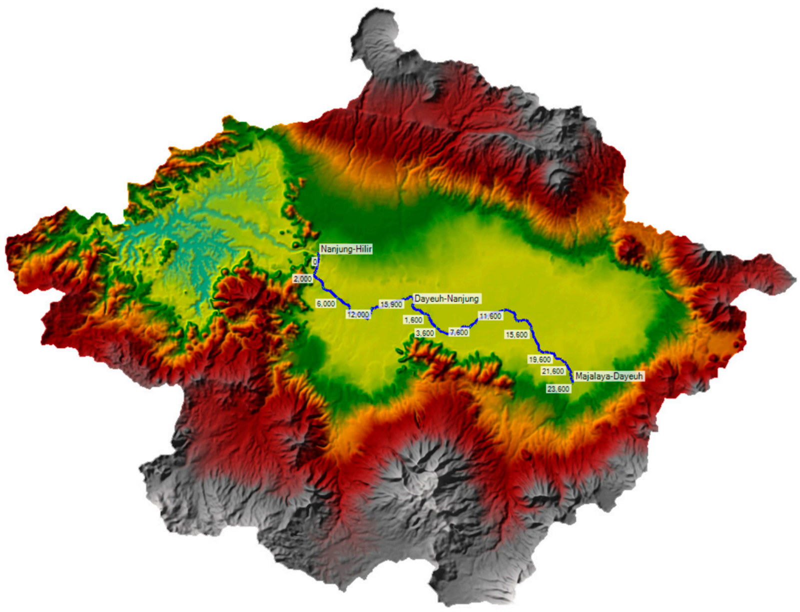

Figure 5. Geometry data of the Upper Citarum Watershed.

The rainfall data were obtained from the Citarum River Basin Agency under the Ministry of Public Work. There are 26 rainfall stations available that cover the Upper Citarum Watershed. However, the longest rainfall record, which are data collected from the years 2000 to 2023, was obtained from only 14 rainfall stations. According to the rainfall data recorded, the design rainfall was calculated using two conditions to demonstrate climate change in the Upper Citarum Watershed. Table 2 summarises the analysis of design rainfall. The design rainfall was calculated based on the data collected from the selected 14 rainfall stations.

Table 2. Design rainfall analysis in the Upper Citarum Watershed.

No.	Rainfall Station	Design Rainfall (mm/day) (2000–2010)				Design Rainfall (mm/day) (2011–2023)			
		10	25	50	100	10	25	50	100
1	Cibereum Kertasari	113.99	131.80	145.01	158.13	105.89	130.12	148.09	165.92
2	Cicalengka	96.19	109.54	119.44	129.27	115.06	130.61	142.14	153.59
3	Cipanas Pangalengan	89.37	103.48	113.96	124.35	94.66	105.84	114.14	122.37
4	Cipeusing	64.30	78.61	89.22	99.76	104.66	143.76	172.76	201.56
5	Cisondari Pasirjambu	95.54	115.09	129.6	144	123.76	150.72	170.73	190.59
6	GN Halu	97.13	110.45	120.33	130.14	137.4	168.27	191.18	213.91
7	Jatiroke–Jatisari	81.96	92.06	99.56	107.01	125.76	156.01	178.45	200.72
8	Kertamanah	99.36	112.03	121.43	130.76	99.15	111.8	121.19	130.5
9	Margahayu	118.35	136.73	150.37	163.9	138.03	168.81	191.64	214.30
10	Cipaku–Paseh	110.01	126.61	138.92	151.14	146.03	169.58	187.05	204.4
11	Tanjungsari	111.03	124.3	134.15	143.92	118.76	136.60	149.84	162.98
12	Cileunca Dam Pulo	98.36	107.85	114.89	121.87	103.43	152.32	203.44	254.17
13	Kayu Ambon	86.31	93.16	98.24	103.29	108.79	127.72	141.77	155.71
14	Lembang	84.73	90.65	95.03	99.39	104.06	125.27	141.52	157.36

4. Discussion

The Citarum Watershed is significantly vulnerable due to climate change impacts, including extreme events such as floods and droughts, alongside long-term consequences like rising sea levels, altered rainfall patterns, and increasing temperatures. In the Upper Citarum Watershed, according to the data recorded from 2000 to 2023 by numerous rainfall stations, the rainfall seems increased during the rainy season with extreme rainfall occurring in several months. This condition affected the erosion and sediment value over the Citarum River.

The land use change in the last three decades is summarised on Table 3. It clearly shows the rapid development in the Upper Citarum Watershed. The percentage of the developed area was 4% in the year 2000 and increase rapidly to 15% and 24% in the years 2010 and 2023, respectively. The percentage of the developed area significantly increased by more than six times in 2023 compared to the developed area in 2000. The developed area mainly consists of residential area that were initially an open space.

These new conditions have caused the flood frequency in Bandung City (located close to the Dayeuhkolot gauge) to increase. However, during these periods, the low flow that can affected the sediment settling was shown to have rapidly decreased. Table 4 listed the average flow of the Upper Citarum River from three locations.

Table 3. Land use change in the Upper Citarum Watershed.

Land Use	Surface (km^2)		
	2000	**2013**	**2023**
Developed Area	12.5231	53.5738	84.6750
Open Space	145.5552	47.3399	22.4464
Vegetation area	230.6255	189.4819	135.9602
% Developed Area	4%	15%	24%

Table 4. Average Flow of the Upper Citarum River.

No.	Station Location	Years of Flow Data		Average Flow (m^3/s)	
		Starting	**Recent**	**2000–2010**	**2011–2023**
1	Citarum–Majalaya	2000	2023	80.69	71.91
2	Citarum–Dayeuhkolot	2000	2023	1031.32	529.56
3	Citarum–Nanjung	2000	2022	893.42	874.65

The hypothesis of the impact of land use change and climate change on the sedimentation rate has been proven by the modelling of sediment deposition in three gauge stations. The first station is Majalaya Station, which represents the upstream part of the Upper Citarum Watershed. The second location is Dayeuhkolot Station, which represents Bandung and the surrounding city. The last gauge station is Nanjung Station, which represents the inlet of the Saguling Reservoir (the downstream part of the Upper Citarum Watershed). The sediment deposition of the three location is described in Figure 6.

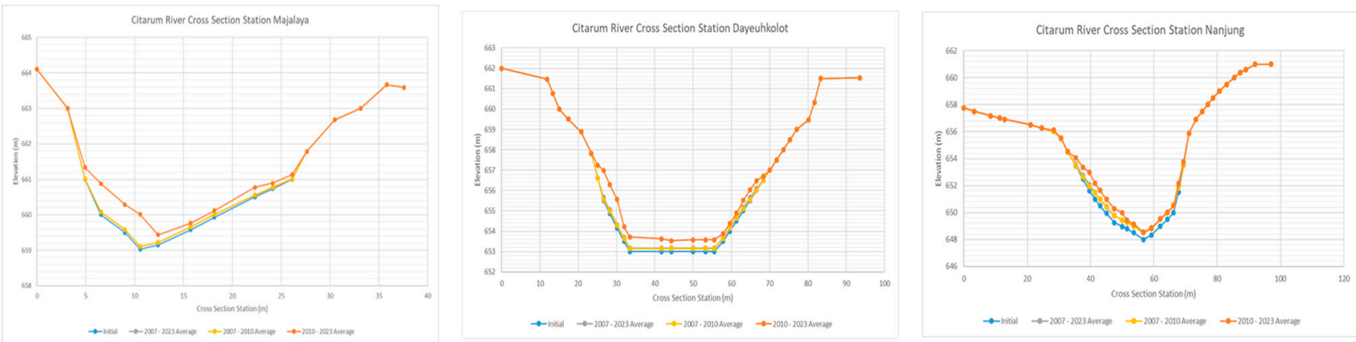

Figure 6. Sediment deposition in the Upper Citarum Watershed.

According to Table 2, the climate change impact affected the design rainfall value on 14 rainfall stations throughout the Upper Citarum Watershed. The design rainfall increased up to 30% on average due to the climate change impact. This condition affected the sediment transport that was assessed in the three locations shown in Figure 5.

5. Conclusions

Climate change will alter temporal rainfall patterns that will then affect sediment production factors. An increase in rainfall will proportionally increase sediment discharge. For an accurate estimation of sediment discharge, the effect of slope failure and grain size change in mountain rivers on erosion and sediment transport should be considered.

It was found in this study that a large increase in sediment discharge was caused by change in the rainfall patterns, which increased the frequency of slope failures following increases in short-term heavy rainfall as well as from increases in fine-grained sediment supplied from the slopes which then increases sediment transport capacity in mountainous channels.

Author Contributions: Conceptualization, E.A. and D.S.; Methodology, E.A. and A.H.H.; Software, N.A., D.S., F.S.T. and F.A.R.R.; Formal analysis, E.A., F.M. and N.A.; Investigation, A.H.H.; Resources, E.A., F.M. and D.S.; Data curation, A.H.H., N.A., D.S. and F.S.T.; Writing—original draft, E.A.; Visualization, F.S.T. and F.A.R.R. All authors have read and agreed to the published version of the manuscript.

Funding: This study is funded by Directorate of Research and Development, Universitas Indonesia under Riset Kolaborasi Indonesia (RKI) Program (Grant No. NKB-753/UN2.RST/HKP.05.00/2024).

Data Availability Statement: The data used in this study is available upon request to the coresponding authors.

Acknowledgments: The authors would like to express their gratitude to the Program Riset Kolaborasi Indonesia for funding this research, which has enabled a comprehensive investigation into the impact of sedimentation on the Saguling Reservoir. We also extend our sincere thanks to PT Indonesia Power and the Citarum River Basin Agency, Ministry of Public Works of Indonesia, for generously providing the data for this study. Their support and collaboration have been invaluable in advancing the understanding of sedimentation.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Li, J.; Evans, J.; Johnson, F.; Sharma, A. A comparison of methods for estimating climate change impact on design rainfall using a high-resolution RCM. *J. Hydrol.* **2020**, *547*, 413–427. [CrossRef]
2. Tram, V.; Somura, H.; Moroizumi, T. The Impacts of Land-Use Input Conditions on Flow and Sediment Discharge in the Dakbla Watershed, Central Highlands of Vietnam. *Water* **2021**, *13*, 627. [CrossRef]
3. Asselman, N.E.; Middelkoop, H.; Dijk, P.M. The impact of changes in climate and land use on soil erosion, transport and deposition of suspended sediment in the River Rhine. *Hydrol. Process.* **2003**, *17*, 3225–3244. [CrossRef]
4. Chen, C.-N.; Tfwala, S.S.; Tsai, C.-H. Climate Change Impacts on Soil Erosion and Sediment Yield in a Watershed. *Water* **2020**, *12*, 2247. [CrossRef]
5. Liu, W.; Shi, C.; Yongyong, M.; Li, H.; Ma, X. Land use and land cover change-induced changes of sediment connectivity and their effects on sediment yield in a catchment on the Loess Plateau in China. *CATENA* **2021**, *207*, 105688. [CrossRef]
6. Kido, R.; Inoue, T.; Hatono, M.; Yamanoi, K. Assessing the impact of climate change on sediment discharge using a large ensemble rainfall dataset in Pekerebetsu River basin, Hokkaido. *Prog. Earth Planet. Sci.* **2023**, *10*, 54. [CrossRef]
7. Leta, M.; Demissie, T.; Koriche, S. Impacts of Land Use Land Cover Change on Sediment Yield and Stream Flow: A Case of Finchaa Hydropower Reservoir, Ethiopia. *Int. J. Sci. Technol. (IJST)* **2017**, *6*, 763–781.
8. Boer, R.; Dasanto, B.D.; Perdinan, P.; Marthinus, D. Hydrologic Balance of Citarum Watershed under Current and Future Climate. In *Climate Change and the Sustainable Use of Water Resources*; Springer: Berlin/Heidelberg, Germany, 2012.
9. Aldrian, E.; Susanto, R.D. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *Int. J. Climatol.* **2003**, *23*, 1435–1452. [CrossRef]
10. D'Arrigo, R.; Seager, R.; Smerdon, J.E.; LeGrande, A.N.; Cook, E.R. The anomalous winter of 1783–1784: Was the Laki eruption or an analog of the 2009–2010 winter to blame? *Geophys. Res. Lett.* **2011**, *38*, 163–189. [CrossRef]
11. Jun-Ichi, H.; Mori, S.H.; Yamanaka, M.D.; Haryoko, U.; Lestari, S.; Sulistyowati, R.; Syamsudin, F. Interannual Rainfall Variability over Northwestern Jawa and its Relation to the Indian Ocean Dipole and El Niño-Southern Oscillation Events. *SOLA* **2012**, *8*, 69–72.
12. Hengsdijk, H.; Jansen, H. *Agricultural Development in the Central Ethiopian Rift Valley: A Desk-Study on Water-Related Issues and Knowledge to Support a Policy Dialogue*; Plant Research International B.V.: Wageningen, The Netherlands, 2006.
13. Lu, X.; Li, Y.; Washington-Alle, A.R.; Li, Y. Structural and sedimentological connectivity on a rilled hillslope. *Sci. Total Environ.* **2019**, *655*, 1479–1494. [CrossRef] [PubMed]

14. Coulthard, T.J.; Van De Wiel, M.J. Modelling long term basin scale sediment connectivity, driven by spatial land use changes. *Geomorphology* **2017**, *277*, 265–281. [CrossRef]
15. Marselina, M.; Burhanudin, M. Trophic Status Assessment of Saguling Reservoir, Upper Citarum Basin, Indonesia. *Air Soil Water Res.* **2017**, *10*, 117862211774666. [CrossRef]