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Sediment trapping analysis of flood control reservoirs in Upstream Ciliwung River using SWAT Model

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Abstract. The plans of Sukamahi dam and Ciawi dam construction for Jakarta flood risk reduction purpose had been proposed as feasible solutions to be implemented. However, the risk of the dam outlets clogging, caused by the sediment, is important to be anticipated. The prediction of the max sediment concentration in the reservoir is crucial for the dam operation planning. It is important to avoid the flood outlet tunnel clogging. This paper present a hydrologic sediment budget model of The Upstream Ciliwung River Basin, with flood control dam existence scenarios. The model was constructed within SWAT (Soil and Water Assessment Tools) plugin and run inside the QGIS framework. The free hydrological data from CFSR, soil data from FAO, and topographical data from CGIAR-CSI were implemented as the model input. The model resulted the sediment concentration dynamics of the Sukamahi and Ciawi reservoirs, on some suspended sediment parameter ranges. The sediment trapping efficiency was also computed by different possible dam capacity alternatives. The research findings will give a scientific decision making base for the river authority, in term of flood control dam planning, especially in The Upstream Ciliwung River Basin.
Keywords: sediment, flood, swat, ciawi, dam, ciliwung

1. Introduction

Watershed damage occurred almost in all watersheds in Indonesia as well as in the Upstream Ciliwung [1]. Watershed Damage, such as land conversion from native forests into plantations and the construction number of residential, hotels, and villas cause a reduction trend of the water infiltration areas and caused water flows directly into the river. This situation is causing flood in the downstream area, which is The Special Region of Jakarta, The Nation Capital. Floods occurred almost in every year, which causing the loss of property, interrupt daily economic activities, and the lack of comfort for the people that live in the area [2]. One of the effort to reduce the flooding is to build dams in the upstream Ciliwung. The aim is to use the reservoir storage as much as possible, so that the water coming into the river does not flow directly into the downstream area [3–5]. The flood water volume will be hold for a certain period in the reservoir. This strategy can at least minimize the flooding that occurred in Jakarta. Ciawi Dam is proposed to be located in the Ciawi village at Ciliwung River, while Sukamahi dam will be located in the Sukamahi village at Sukabirus River. Sukamahi and Ciawi Dam are located at Megamendung District, Bogor, West Java Province, Indonesia. Ciawi Dam proposed location is at 106º52'20" East Longitude, 06º39'28" South Latitude and the Sukamahi Dam proposed to be located in 106º52'20" East Longitude, 06º40'12" South Latitude. The location map of the proposed reservoirs are depicted in Figure 1.
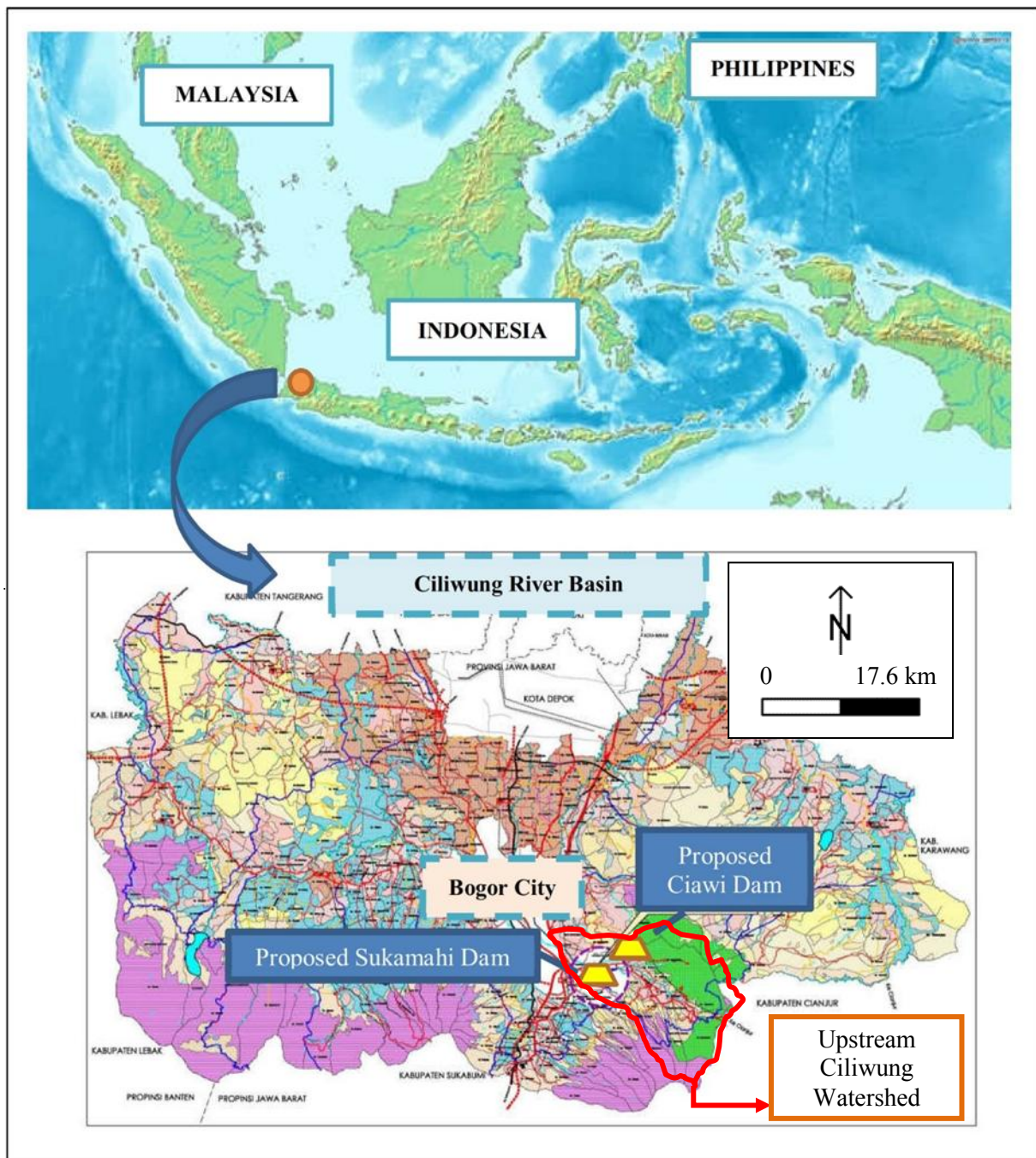
Figure 1. The maps of Ciliwung River Basin as a case study location [6].

The proposed planned dams to be built in Upper Ciliwung Watershed are Ciawi Dam and Sukamahi Dam. Besides as flood control dams, the dams are expected to provide other benefits such as water supplies to the surrounding area, in to some certain limitations [7]. Land use changes on upstream Ciliwung watershed cause erosion and lead to sedimentation in the river. A percentage of the projected sediment will be settled in the Sukamahi and Ciawi dam. Sedimentation that occurs and settles in reservoirs will reduce the life of service ability of the reservoirs. In this paper, analysis and prediction of Sukamahi and Ciawi Dam sedimentation will be considered. The research results hopefully can define the proper Ciawi and Sukamahi dam operational use in the near future.

2. Data and Method

The model that is used to simulate the hydrological condition of the Upstream Ciliwung River basin is the Soil and Water Assessment Tool (SWAT). The software is free used and can be easily operated using QSWAT in GIS environment. The tools can be downloaded from the SWAT TAMU webpage (http://swat.tamu.edu/software/qswat/). The QSWAT module helps the user in formatting the input file to match with the SWAT required format. The user just needs to determine the outlet of the watershed and the reservoir location. Later on, QSWAT will divide the watershed into several Hydrological Response Units (HRU). Each HRU represents a certain hydrological condition.

In order to build up the Ciliwung hydrological model, the required data are the land cover map, the soil map, the digital elevation model, and the hydro climatological data. The land cover, soil and topographic of the river basin are used to generate the watershed HRU, as figured out in Figure 2. The MODIS LC map is used as the land cover data source for this project [8]. The FAO Digital Soil Map of The World data are occupied as a soil data source [9]. The CGIAR CSI SRTM DEM is adopted for the topographical base in this project [10]. As the measured hydro climatological data, the National Centres for Environmental Prediction Climate Forecast System Reanalysis (CFSR) data are used for the SWAT simulation [11].

The detail design of the Ciawi and Sukamahi dam had been done by the river authority in 2015. The detail design report provides the information of the proposed reservoir locations and the reservoir parameters [12]. In order to reveal the proposed reservoir performances, in terms of its sediment budget, several set of parameter scenarios were set up, as listed in Table 1. Each of the parameter has descriptions that are noted in the Appendix section. The parameter can be inputted to the model by modifying the default parameter values range in the SWAT reference database beforehand.
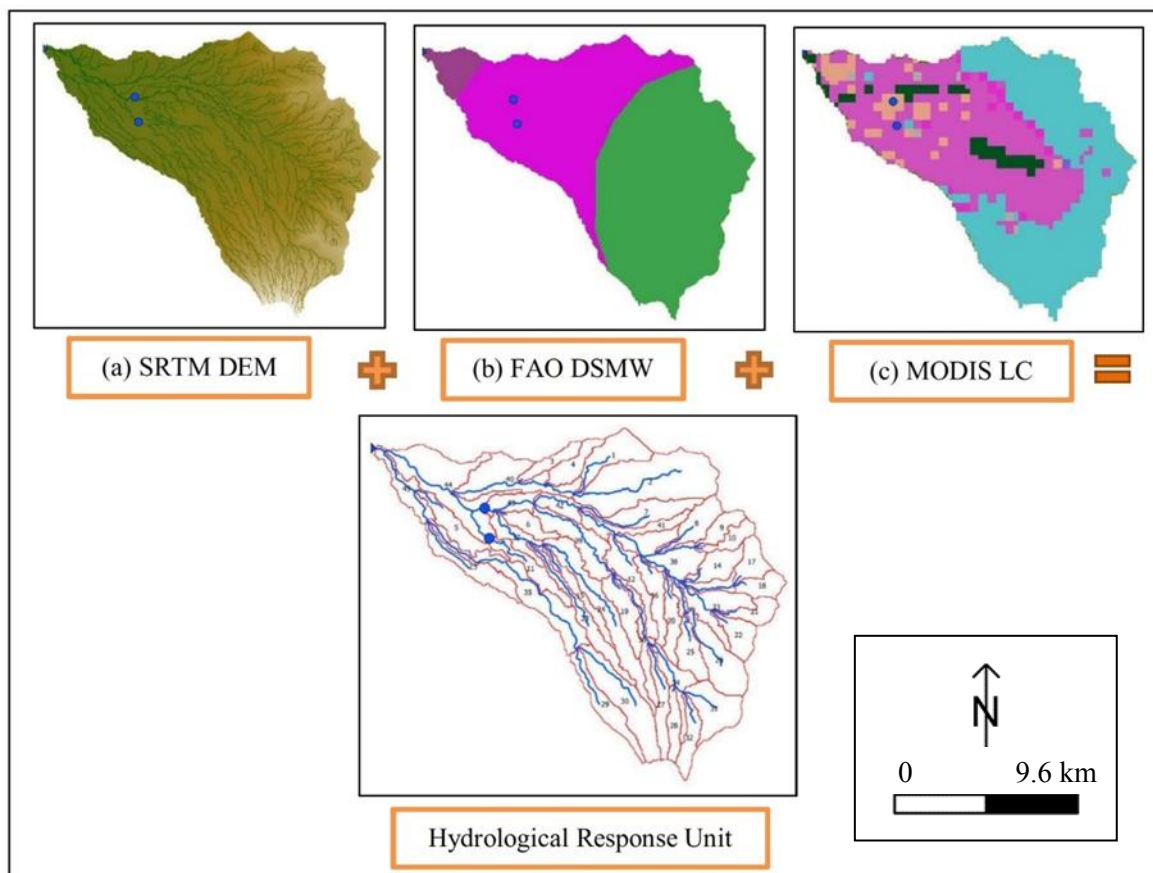

Figure 2. The data input for the SWAT Upstream Ciliwung Model.

Table 1. The parameter value arrangements for each reservoir modelling scenarios.

Scenario	Common Parameter			Ciawi Dam Parameter						Sukamahi Dam Parameter					
	RSED	RNSED	RD50	RESA	REVOL	RPSA	RPVOL	RVOL	R_RR	RESA	REVOL	RPSA	RPVOL	RVOL	R_RR
	(mg/l)	(mg/l)	(um)	(ha)	(1E4 m^3)	(ha)	(1E4 m^3)	(1E4 m^3)	(m^3/s)	(ha)	(1E4 m^3)	(ha)	(1E4 m^3)	(1E4 m^3)	(m^3/s)
Basic	4000	4000	10	38.56	503	25.707	385	385	10.48	9.85	132	6.567	42	42	0.284
NoStorage	4000	4000	10	38.56	503	3.856	5.03	5.03	10.48	9.85	132	0.985	1.32	1.32	0.284
CoarseD50	4000	4000	63	38.56	503	25.707	385	385	10.48	9.85	132	6.567	42	42	0.284
FineD50	4000	4000	2	38.56	503	25.707	385	385	10.48	9.85	132	6.567	42	42	0.284
Mildly Turbid	1200	1200	10	38.56	503	25.707	385	385	10.48	9.85	132	6.567	42	42	0.284
Clear	300	300	10	38.56	503	25.707	385	385	10.48	9.85	132	6.567	42	42	0.284
NoStorage1	4000	4000	10	77.12	1006	2.571	1.006	1.006	15.72	14.76	198	0.657	0.198	0.198	0.332
NoStorage2	4000	4000	10	115.7	1509	2.571	1.006	1.006	20.96	19.70	264	0.657	0.198	0.198	0.379

The main consideration that is faced by the river authority is to ensure the reservoir standard operations. The main option is to utilize the proposed reservoir as a flood reduction dam only. However, there is also another view based on the needs of the Ciliwung River Community, which is to utilize the exceed water for domestic purposes [13]. The two leading options have different implication to the reservoir operation. The first idea desires the reservoir to contain as less water as possible. The following option insists the reservoir operator to control the reservoir water storage. The first scenario is the basic scenario, where most of the reservoir parameter values are adopted from the river authority design report. Some parameters, such as the equilibrium sediment concentration was leaved by default in the basic scenario due to the no data availability. The basic scenario still accommodates some portions of the reservoir volume as a storage column. The second scenario is the No Storage Scenario, where the reservoir is set to have no space for storing water during the non-flood event. The extreme definition requires the reservoir to have 0 (zero) m3 of storage. However, in order to avoid the SWAT model crash due to zero reservoir storage, a small minimum storage is set in the parameter table. The No Storage 1 and No Storage 2 scenarios adopt the same setting with the No Storage scenario. However, the reservoir capacity and the reservoir release parameters were set to be proportionally higher compared to the one in the No Storage scenario. The rest of the scenarios explore the effect of sediment turbidity and sediment grain size to the sediment budget. The water sediment density criteria were adopted from the WHO standard [14]. The clear water is assumed to have 300 mg/l sediment concentration and 1200 mg/l for the mildly turbid water. The sediment median grain size is categorised as coarse D50 (63 μm) and fine D50 (2 μm) [15]. The simulation was conducted from 1 Jan 1979 until 31 July 2014 based on the hydro climatological data existence. It was assumed that the reservoir was constructed since in the beginning of the simulation. This approach was used to see the dam's performance based on long term measured data (± 30 years).

3. Result and Discussion
The upper Ciliwung Watershed SWAT model results sediment budget and sediment concentration within the designed reservoirs. The model results present detail profiles of the sediment budget fluctuation in different reservoir release conditions. The model also provides the correlation of sediment concentration with the reservoir water storage conditions. The result analyses neglect the first five years of the simulation results. The purpose is to remove the initial condition effects from the results. It was confirmed that the sediment dynamics in the reservoir were highly dependent on the reservoir storage capacity, reservoir release rate, and the suspended sediment concentration of the water. In this case study, the sediment profile is distinct, especially between the condition when the reservoirs were operated in its flood control mode and water storage mode.
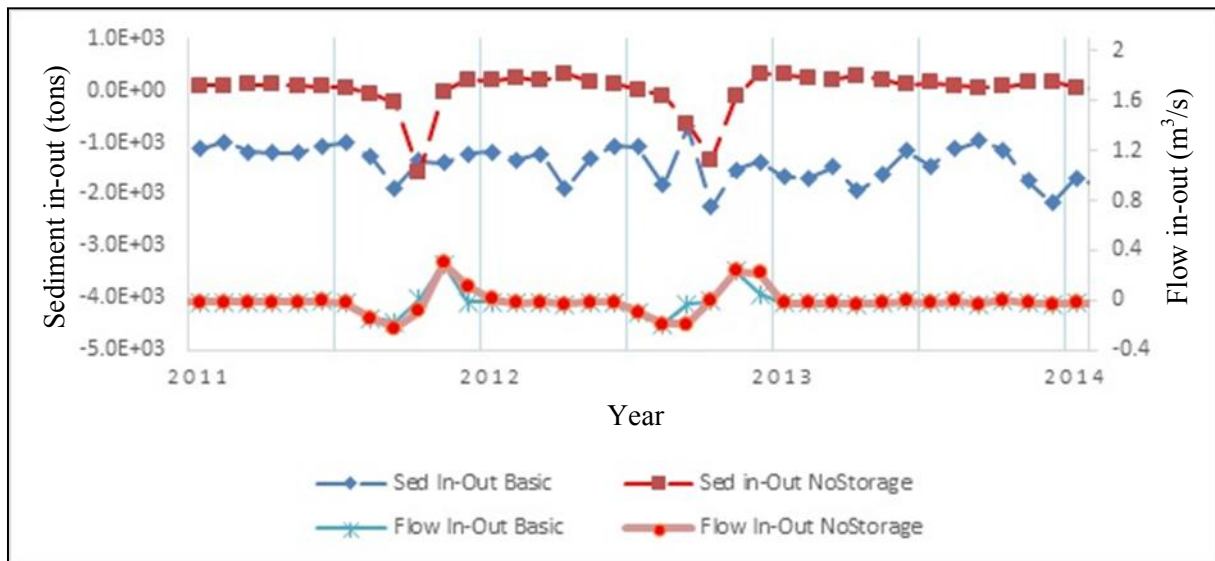
Figure 3. Flow – sediment budget time series profile of designed Sukamahi Reservoir.

In Figure 3, there is a correlation between the sediment in-out and the flow in-out of the reservoir. When there is a sharp decrease on the flow in-out value, there would be a sharp increase on the sediment in-out value too. If the reservoir is filled up, there would be a sedimentation in the reservoir body. The different situation happens for the basic storage mode, where there is no diverse link among the sediment in-out and the flow in-out variables. The situation was caused by the reservoir storage damping effect. The reservoir input flow is not always linear with the reservoir release flow. It means the reservoir operation affects the sedimentation in the reservoir that has storage volume. In this case, the basic scenario assumes that the average reservoir annual release is 10.48 m^3/s (Ciawi Dam).

Figure 4. Flow – sediment budget time series profile of designed Ciawi Reservoir.

The result still shows the risk of reservoir sedimentation in the scenario of no storage reservoir. Therefore, the result of no storage reservoir scenarios were explored and displayed in Figure 4. In the no storage scenario, the reservoir can hold the flood for a certain period [16]. Afterwards, the captured flood volume will be released based on the reservoir release parameter. The wider the flood tunnel opening will correlate with higher sediment release from the reservoir. It can be shown by comparing the sediment budget of the no storage 1 scenario and no storage 2 scenario. It means that there would be a negative margin between the sediment entering the reservoir and the sediment released from it. The flood trapping efficiency of a flood control reservoir can be assessed based on the different of the flow entering the reservoir and the flow that is releasing from the spillway. In this scenario, the flood was captured until the reservoir filled up to the spillway elevation. In the time the water reach the reservoir primary spillway, the primary reservoir release is starting. If the flood is exceeding the primary storage, the reservoir will continuously filled up until the emergency spillway. The food that is exceeding this level will be directly flowed down to the downstream.

In the NoStorage2 scenario, the Ciawi Reservoir capacity was tripled. It can be shown from Figure 4 that the Ciawi reservoir was projected to capture the extreme flood up to ± 4.073 million cubic meter in the 2012-2013 period. The Figure 4 shows that there is a correlation between the reservoir filling periods with the sediment in-out pattern. The reservoir dewatering will be followed with the decrease in the reservoir sediment budget variable. However there is no significant different of the reservoir sediment budget state between the storage and no storage scenario. It means that the reservoir scenario will produce almost similar sediment transport to the downstream. The suspended sediment trapping efficiency of the reservoir is less than 2%, which is found as less risky. The reservoir release is more sensitive to the sediment trapping efficiency rather than the reservoir storage capacity. The average sediment concentration in the Sukamahi reservoir depends on the reservoir volume. If the reservoir storage decrease, then the sediment concentration will be increased, as shown in Figure 5. The average reservoir sediment concentration parameter has strong impact to the sediment concentration within the period of simulation. It is especially on suspended D50 < 10 μm condition or on clear to mildly turbid condition. If there is a stable reservoir volume, than the modelled sediment concentration will recover to the initial inputted average value. There is also another finding that in 10 μm < D50 < 63 μm condition, which is mostly silt suspended material, the Sukamahi reservoir will have a stable sediment concentration range of about 1.000 to 2.000 ppm. The recognised implication is that fine sediment management in the upstream of the reservoir catchment area will highly reduce the Sukamahi average reservoir sediment turbidity.
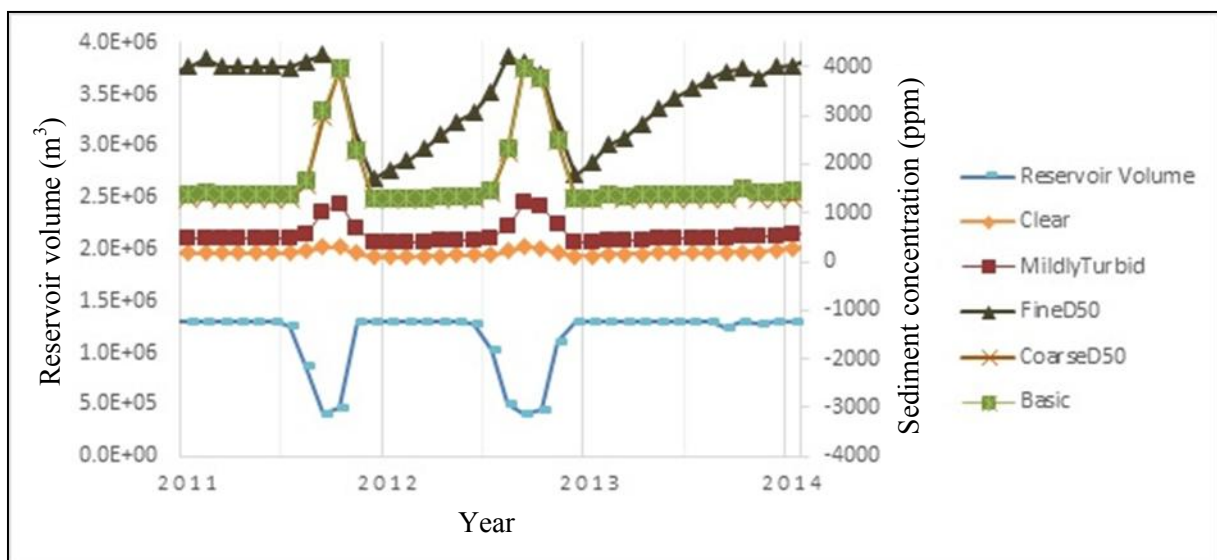

Figure 5. Designed Sukamahi reservoir sediment concentration correlation with the reservoir volume.
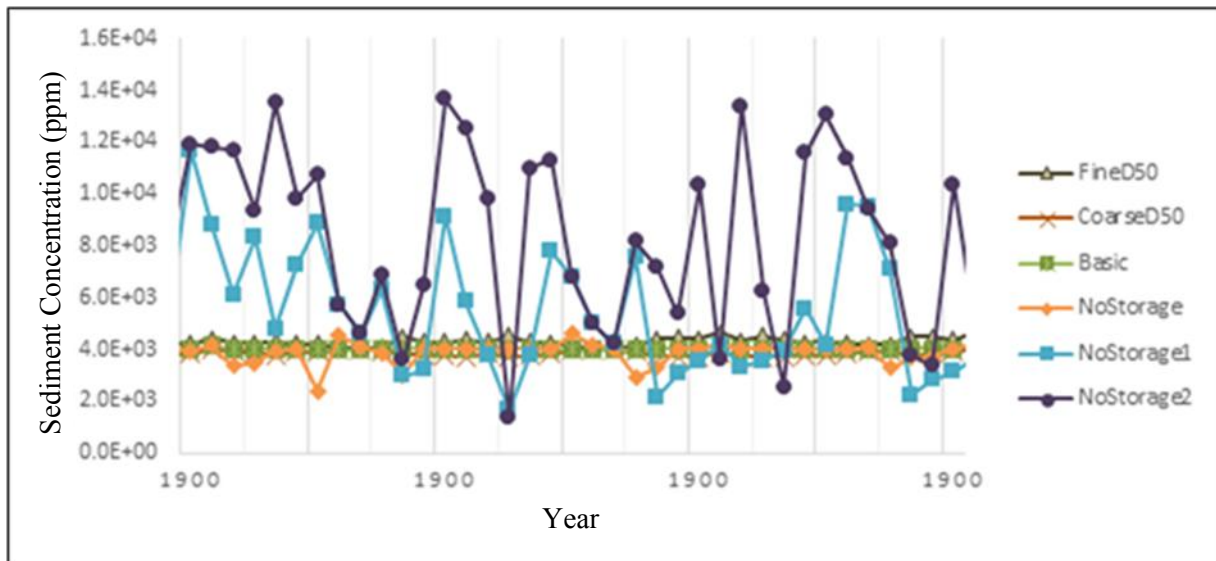
Figure 6. Designed Ciawi Reservoir sediment concentration correlation with the reservoir volume.

In the larger reservoir application, as in this case is the Ciawi reservoir, the average reservoir sediment concentration is highly governed by the average sediment input parameter value. Moreover, the variation of the suspended particle D50 parameter will also affect the sediment concentration in the reservoir in the range of ± 500 ppm, as depicted in Figure 6. The model tries to reduce the sediment concentration out of the reservoir, which also similarly shown from the negative sediment budget pattern in Figure 4 before.

The reservoir annual release rate was also proofed as a dominant cause of turbid reservoir condition. The higher reservoir release means there is a higher water circulation in the reservoir. It is caused by the high transition of water flowing in and releasing out of the reservoir. Therefore there is no time for the sediment to settle in the reservoir water body. The reservoir sediment concentration is almost nearly the same with the input water sediment concentration from the river, which located of the upstream of the reservoir. Finally, it can be summarized that there is a chance to keep some small storage in the designed Ciawi and Sukamahi reservoir. The reason is that the sedimentation risk can be overcome with higher reservoir release strategy and fine sediment management in the catchment.

4. Conclusion

The Upper Ciliwung SWAT (Soil and Water Assessment Tool) Hydrological model can result a thorough sediment budget profile with proposed Ciawi and Sukamahi reservoir scenario. The limitation of data availability in the sediment modelling effort can be answered by the use of free hydrological data from the online accountable data sources. It can be concluded that the sediment budget within the reservoir is mainly govern by the reservoir release parameter. Although the NoStorage reservoir is the common strategy to avoid the reservoir sedimentation, the reservoir design that is proposed by the river authority still allows the reservoir to store some amount of water for other domestic purposes. However, the acceptable storage must be decided by the optimum sediment in-out and flow in-out correlation as proposed in this paper. It is also recommended for a good fine sediment management in the up streamed river basin, before the sediment enters the reservoir. The fine sediment is a main source for high sediment concentration in the proposed reservoirs.

5. Acknowledgements

6. References

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7. Appendixes

RSED   The initial average sediment concentration in the reservoir (mg/l).

RNSED The equilibrium of average sediment concentration in the reservoir (mg/l).

RD50   The median of the suspended particle in the reservoir (μm).

RESA   The impounded surface area when the reservoir is filled till the emergency spillway (ha).

REVOL The required water volume to fill the reservoir up to the emergency spillway (10^4 m^3).

RPSA   The impounded surface area when the reservoir is filled till the principal spillway (ha).

RPVOL The required water volume to fill the reservoir up to the principal spillway (10^4 m^3).

RVOL   The initial reservoir volume (10^4 m^3).

R_RR   The average daily principal spillway release discharge rate (m^3/s).