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Development of Protocol for Reservoir Sedimentation Prediction in Indonesia

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Abstract. Dead storage of reservoir usually designed by soil erosion rate of catchment area result in certain year without considering land use and precipitation dynamic in the catchment and sedimentation distribution analysis at the bottom of the reservoir as well. Development of protocol is needed for more accurate prediction of reservoir sediment transport to describe the real condition and accommodate data limitations. It will give good perspective in design, operation and maintenance strategy for reservoir. The proposed protocol is consisted of long-term soil erosion prediction, modelling long-term sediment discharge, modelling spatial-temporal reservoir sediment transport and predicting reservoir sediment volume and distribution in the future. The case study is in Wonogiri reservoir, Indonesia. Simulation of the proposed protocol at the case study began by obtaining long-term soil erosion prediction from 1993 – 2019. Sediment discharge was modelled from soil erosion and synthetic long-term hydrographs using the FJ Mock method and validated with sediment rate measured directly in the field. Reservoir sediment transport model was using MIKE software. The simulation gives volume and distribution of sedimentation validated by bathymetry result of the reservoir. Prediction of future sedimentation was using the modular regression method. This protocol promotes spatial reservoir sediment transport model and sedimentation prediction by modular regression. The prediction result of reservoir sediment volume in 2069 is 146.7 million m^3.

Keywords: Reservoir sedimentation prediction; Reservoir sediment transport; Sediment discharge

1. Introduction

Reservoirs play significant role for water resources management to fulfil the need for irrigation, raw water supply, flood control, hydro power, etc. Process of planning, operation and maintenance play significant role to ensure reservoir lifetime. Sedimentation is reservoir problem that can reduce its lifetime service. Based on previous research result in Indonesia, sedimentation is reducing reservoir volume about 1-3% every year (Armidoa *et al*., 2020; Brontowiyono, 2019; Sucahyanto, Setiawan, and Septiani, 2018; Fauzi and Wicaksono, 2016; JICA, 2007). The other problem to manage sedimentation in Indonesia is limited data especially for continues discharge and sediment rate data. (Sutjiningsih Soeryantono, and Anggraheni, 2015) Material of soil erosion in catchment area of reservoir is transported by river discharge to become bed load and suspended load. Meanwhile bed load deposited in the upper side of river, suspended load transport to reservoir and when it meets zero velocity in reservoir area, it will be deposited in reservoir bed by gravity.

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(Khorrami and Banihashemi, 2018) Suspended load is the most dominant material in reservoir bed. (Mulu and Dwarakish, 2015) The size of suspended load is very small, it is almost impossible to analyse by physical model. (JICA, 2007) Soil erosion potential is dynamic recently because it is influenced by land use change and precipitation dynamic. (Sukisno *et al.*, 2021) Hydrodynamics of reservoir involves large area of water, one or several inflow(s), reservoir depth and many other factors. Those factors influence sedimentation distribution. (Hanmaiahgari *et al.*, 2018) Modelling hydrodynamic and sediment transport of reservoir in one-dimension model is not realistic, especially because reservoir bed has three-dimensional feature. (Tadesse and Dai, 2019) Based on those reasons, sediment transport volume and distribution should be predicted more accurate for planning, operating and maintenance of the dam and reservoir, especially in Indonesia. This research developed a protocol for reservoir sedimentation prediction in Indonesia. It consists of soil erosion prediction that accommodate the change of land use and precipitation dynamic in catchment area, modelling long term sediment discharge, three-dimension reservoir sediment transport modelling, and prediction for reservoir sedimentation in the future. The aim of the research is to improve the accuracy of prediction for reservoir sedimentation volume and distribution on reservoir bed through development of protocol. The protocol can be used to develop more effective strategy and managing during planning, operating and maintenance stage of reservoir, especially in Indonesia (Legono, 2019).

2. Methods

Case study for this research is Wonogiri reservoir, built in the eighties and located in Wonogiri Regency, Central Java Province, Indonesia. Catchment area of Wonogiri Reservoir is about 1,350 km^2 and reservoir area is about 88,000 ha. Wonogiri Reservoir is chosen because it has got complicated sedimentation problems in recent years. There are six main inflows to Wonogiri reservoir, which are Keduang river, Tirtomoyo river, Patemon River, Bengawan Solo River, Alang river and Wuryantoro river. Therefore, it will give a good perspective for sedimentation distribution analysis. (Susilo, Wicaksono, and Yanti, 2016) Bathymetry data of Wonogiri reservoir is sufficient for calibration and validation, since there are three-year available data which are 1993, 1998 and 2004. (JICA, 2007) Until now, reservoir sedimentation analysis based on soil erosion of catchment area in certain year. In recent year when land use and precipitation radically change in a lot of area in Indonesia, it is needed to revise the prediction of potential soil erosion for reservoir. (Sudarsono, Sukmono, and Santoso, 2017) Reservoir hydrodynamic phenomena involves certain forces like velocity from inflow and sediment discharge in x,y,z vectors, tension from reservoir banks controlled by shape and size of reservoir, particle size and gravity force at very least (Imanshoar *et al.*, 2014).

In recent times, development of hydrodynamic software such as Hec-ras, Hec HMS, MIKE and many more helping us to do two or three-dimension reservoir hydrodynamic analysis to predict sediment transport distribution in reservoir bed which is very important for reservoir sediment transport analysis. (Jang *et al.*, 2015) It is mandatory to include three-dimension reservoir hydrodynamic analysis in the improved proposed protocol, hereinafter referred to as new protocol for reservoir sedimentation prediction. (Ateeq-Ur-Rehman *et al.*, 2018) Three-dimension reservoir hydrodynamic analysis require continues sediment discharge. The problem is lacked of continues inflow discharge data in most of reservoirs in Indonesia. To bridge the gap, a certain method is needed to transform bulk result from soil erosion analysis to continues sediment discharge. By exercising revised prediction of potential soil erosion and revised prediction for reservoir sediment transport distribution, dead storage design can be re-evaluated. Moreover, the economic value of reservoir can be revised and a new strategy for reservoir maintenance can be created. There are four stages of problem solving for the protocol that can meet recent condition and limitation. First stage is method for soil erosion potential prediction that accommodate land use and precipitation dynamic in catchment area. Second stage is modelling long term daily sediment discharge without long term inflow discharge data. Third stage is modelling spatial-temporal reservoir sediment transport. Fourth stage is prediction of reservoir sediment volume and distribution in the future.

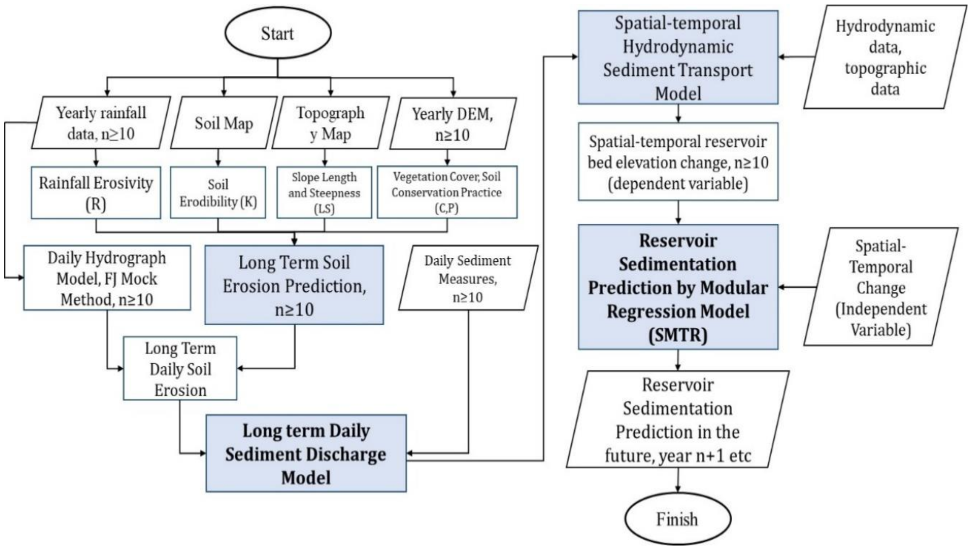

Figure 1 Flow Chart of Protocol for Reservoir Sedimentation Prediction

2.1. Method for soil erosion prediction

Yearly soil erosion potential is analysed using USLE method. USLE method is used to accommodate lack of data, especially run off and discharge data. (Gwapedza, Hughes, and Slaughter, 2018) To accommodate precipitation and land use dynamic in catchment area, soil erosion is analysed in long term, at least ten years, using land use map and precipitation data in the same years. (Abdulkareem *et al.*, 2019) Precipitation is factor that always change from time to time. (Anggraheni *et al.*, 2018) Precipitation data based on climatology data in catchment area can be input. (Juniati *et al.*, 2019) The change of precipitation's trend will give influence to amount of soil erosion potential. (Sardar *et al.*, 2014) Land use in reservoir catchment area in Indonesia changes rapidly. Land use change is exercised in yearly basis. Analysis trend of land use change in USLE method, represented in C and P, is basic concept to analyse dynamic soil erosion potential in reservoir catchment area. Since USLE method is used, it is assumed the only external force for soil erosion is precipitation (Abdulkareem *et al.*, 2019; Pham, Degenera, and Kappasa, 2018).

2.2. Method for Sediment Discharge Modelling

Reservoir hydrodynamic analysis is very important step in this improved protocol. One of main input for reservoir hydrodynamic process is long term sediment discharge, from every inflow to reservoir. By using continues inflow discharge data and sediment concentration, measured from reservoir site, sediment discharge can be modelled comfortably. (JICA, 2007) The problem is limited long term inflow discharge data in most of reservoir in Indonesia, some method should be created to model sediment discharge which is transformed from yearly soil erosion result as the steps is described in Figure 2.

Yearly soil erosion result is obtained by using USLE method from year 1993 to 2019. Yearly soil erosion is distributed to daily soil erosion using Daily discharge hydrograph, modelled by FJ Mock method. (Sadtim *et al.,* 2019) FJ Mock method is transforming daily precipitation into surface run off with considering loss by evapotranspiration and infiltration. (Sudinda, 2019) By using this method, hydrograph of six inflow can be modelled based on each watershed hydrology characteristic. (Sunaryo, 2019) Sediment discharge is measured from reservoir inflow to get sediment rate and properties data. Sediment samples are taken from March 7th, 2021, to March 23rd, 2021. Since sediment samples are taken in 2021 and soil erosion prediction is analysed from 1993 to 2019, The sampling result is validated by Oceanic Nino Index (ONI) data to match the index data. After validation process, daily sediment discharge equation is modelled from daily sedimentation rate in March 2021 and soil erosion rate curve, in validated year by ONI. Calibration use correlation coefficient for equation model. The correlation coefficient value should be more than 0.6 (Moe *et al.,* 2015).

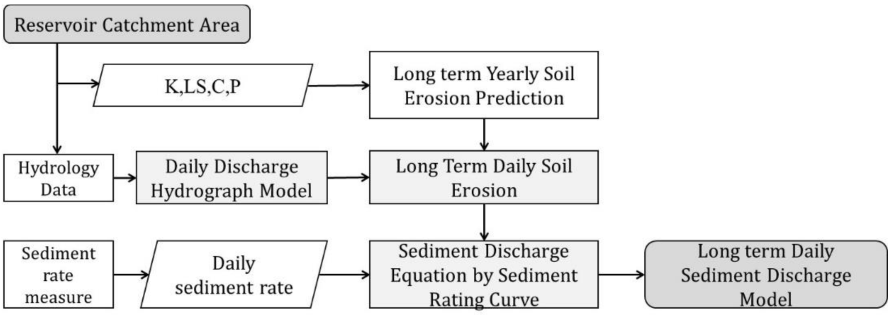

Figure 2 Steps for Daily sediment discharge model

2.3. Method for Reservoir Hydrodynamic Modelling

This improved protocol uses three-dimension model to predict sediment volume and distribution for reservoir. Three-dimension model accommodates inflow discharge and sediment transport in x,y,z vectors through reservoir which its shape and size is modelled in hydrodynamic process so it gives satisfying result of sediment volume and the distribution in reservoir bed. (Khorrami and Banihashemi, 2019) MIKE software is used to model hydrodynamic mathematical model for reservoir sedimentation, see Figure 3. In MIKE, hydrodynamic process for channel or reservoir is processed in discrete through finite volume method which every form is divided in spatial to become smaller elements. (Morianou *et al.,* 2015) Reservoir three-dimension model and upstream rivers that flow to the reservoir, based on bathymetry result, is modelled as meshes with certain elevation and dimension based on topography survey applied in MIKE, calibrated with 1993 hydraulic and bathymetry data. Sediment discharge flow from rivers to reservoir through continues inflow discharge from six inflows. The result is reservoir bed elevation change that transformed to volume and distribution result. Sediment transport result from MIKE is validated with 1998 and 2004 bathymetry result.

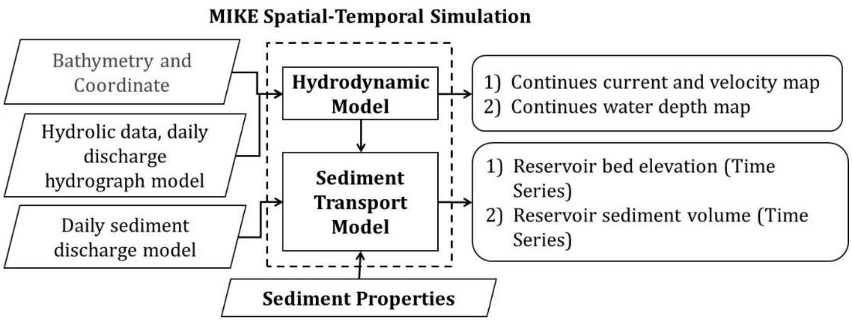

Figure 3 Steps for reservoir sedimentation hydrodynamic model

2.4. Method for Reservoir Volume Prediction in the Future

Reservoir sedimentation volume in the future can be predicted using modular regression model. (Adam *et al.*, 2015) Reservoir bed is divided by a lot of modules based on bathymetry point. (Hosseinjanzadeh *et al.*, 2015; Khaba and Griffiths, 2015) Spatial-temporal change of Reservoir bed elevation from MIKE simulation result is used as independent variable. Reservoir bed elevation is dependent variable. Modular regression model is computed by Spatial-Multi Target Regression (SMTR) method. (Garg and Jothiprakash, 2013) Each module is computed using this method to predict elevation change in the future. SMTR is modelled by using equation 1 dan 2. Steps for reservoir sedimentation prediction in the future is described in Figure 4. SMTR method uses Python software for numeric computation. (Wehle, 2017; Solomatine, See, and Abrahart, 2008) Calibration use validated sedimentation result from third stage, each module (54.885 modules) is calibrated using bathymetry data from 1993, 1998 and 2004.

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i t_i) x_{ik} + \varepsilon_i, i = 1,2, \dots, n \quad (1)$$

$$\beta_i = (x^T w_i x)^{-1} x^T w_i y \quad (2)$$

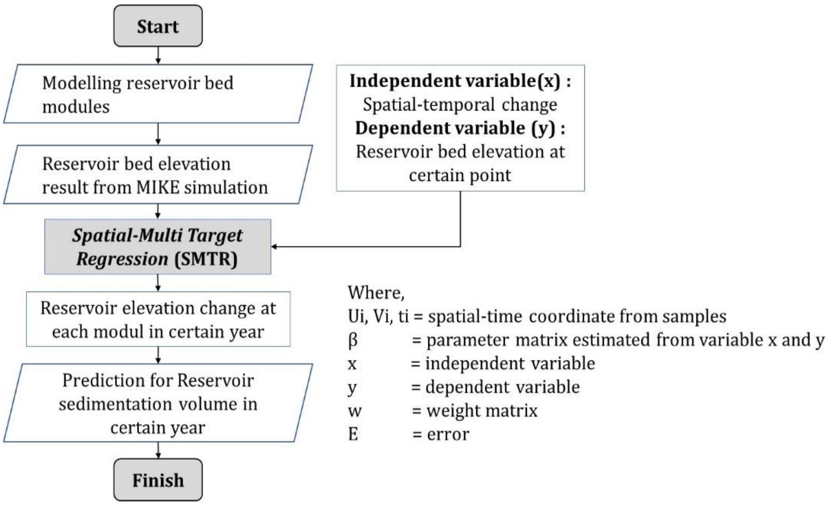

Figure 4 Steps for Reservoir Volume Prediction in the Future

3. Results and Discussion

3.1. Soil Erosion Prediction Result

USLE method is used for soil erosion prediction in Wonogiri reservoir catchment area from 1993 to 2019, that said 27 years data. From those data some interesting result can be found, such as:

- Soil erosion fluctuating result is influenced by dynamic precipitation and land use change. From 2017 and 2018, land use was drastically changed, C and P values increased. In 2019, there was replantation effort in catchment area, so C and P values decreased. See Table 1.
- There is very low erosion rate in 1997 while in the contrary in 2010 the rate is very high. Those numbers are highly influenced by yearly precipitation value. Soil erosion prediction is not only influenced by land use change but also influenced by precipitation.
- Dead storage designed by only one year soil prediction to represent reservoir lifetime is not appropriate. Long term yearly soil erosion prediction is mandatory to design dead storage and sediment transport prediction, especially in recent time.

Table 1 Yearly precipitation in catchment area

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	
Precipitation (mm)	1,950	2,018	2,369	1,872	1,176	2,405	2,410	2,304	2,150	1,897	1,828	2,182	2,035	
Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Precipitation (mm)	2,117	2,364	2,250	2,061	3,325	2,338	2,059	2,827	2,178	2,046	3,422	2,605	1,980	2,028

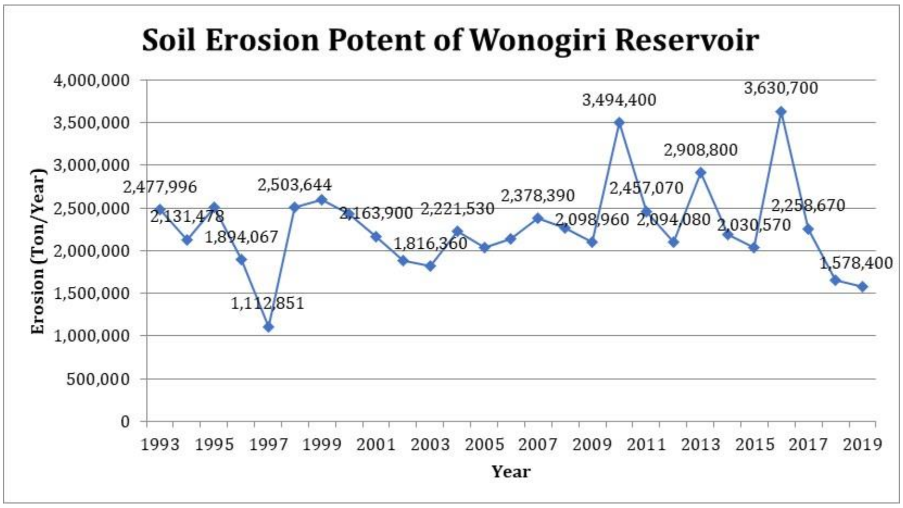

Figure 5 Soil erosion prediction in year 1993 – 2019

3.2. Sediment Discharge Model Result

Modelling sediment discharge from yearly soil erosion prediction is one of main contribution of this research since it bridges the gap between limited data and requirement of sediment discharge as the important input in modelling three-dimension sediment transport analysis. Sediment discharge is analysed from three variable, which are soil erosion result, hydrograph from FJ Mock method and inflow sediment concentration, measured from six inflow to reservoir. Daily discharge hydrograph model from each inflow by FJ Mock method is representative since it considers baseflow, so there is no zero discharge in the hydrograph. Daily sediment rate was measured from the field from March, 7th 2021 to March, 25th 2021. Soil erosion prediction is analysed from 1993 – 2019. Measured sediment rate data is validated with Oceanic Nino Index. Index of March 2021 is similar to March 2018. Sediment discharge equation is modelled from sediment rate to erosion rate curve. Correlation coefficient value is 0.7861, see Figure 6. More data of inflow sediment concentration will increase correlation number. Correlation and determination value of sediment discharge equation is less than 1 indicating that soil erosion prediction and sediment flowing to reservoir is not same amount. This happens because of:

- It is not every eroded soil flowed to the river
- Eroded river bed and river bank material is not calculated in USLE method

Table 2 Sediment and erosion value

Date	7th	9th	11th	13th	15th	17th	19th	21st	23rd	25th
Sediment (kg/day) (March 2021)	28,603	35,767	20,694	15,914	20,489	14,480	12,263	9,731	8,229	10,889
Erosion (kg/day) (March 2018)	30,594	16,224	10,008	6,008	14,652	13,033	3,114	2,327	2,669	4,413

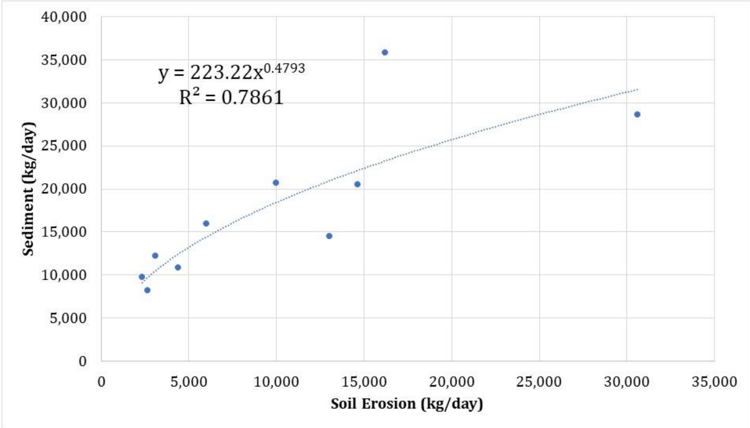

Figure 6 soil erosion-discharge curve by power function

3.3. Spatial-temporal Reservoir Sediment Transport Analysis Result

Sediment transport model use MIKE software to process in three-dimension model. Sediment transport is analyzed from 1993 to 2019 and sediment volume result is validated by bathymetry data measured in 1998, and 2004. Determination coefficient is 0.93 and 0.84. Based on Size and shape of Wonogiri reservoir, it requires 0.1 s time step process. Outflow is assumed 29.3 m^3/second, requirement for hydropower in Wonogiri reservoir. Evaporation and precipitation in reservoir are negligible since reservoir area is relatively very small compared to catchment area (8.8/1,350). Sediment transport analysis in Wonogiri reservoir using MIKE software. See Table 3 and Figure 7. More detail topography result will give more efficient time process. By the result, it is understood that sediment from Keduang River gave influence to reservoir life time more than other rivers based on its position and sediment supply because it can cover intake of the dam faster than sediments from other rivers.

Table 3 Result simulation of reservoir sedimentation

Sedimentation (m)	Area (km^2)					
	1993-1994	1997-1998	2003-2004	2015-2016	2017-2018	2019
Total Volume (mill.m^3)	9.12	22.72	44.49	86.50	92.36	94.96

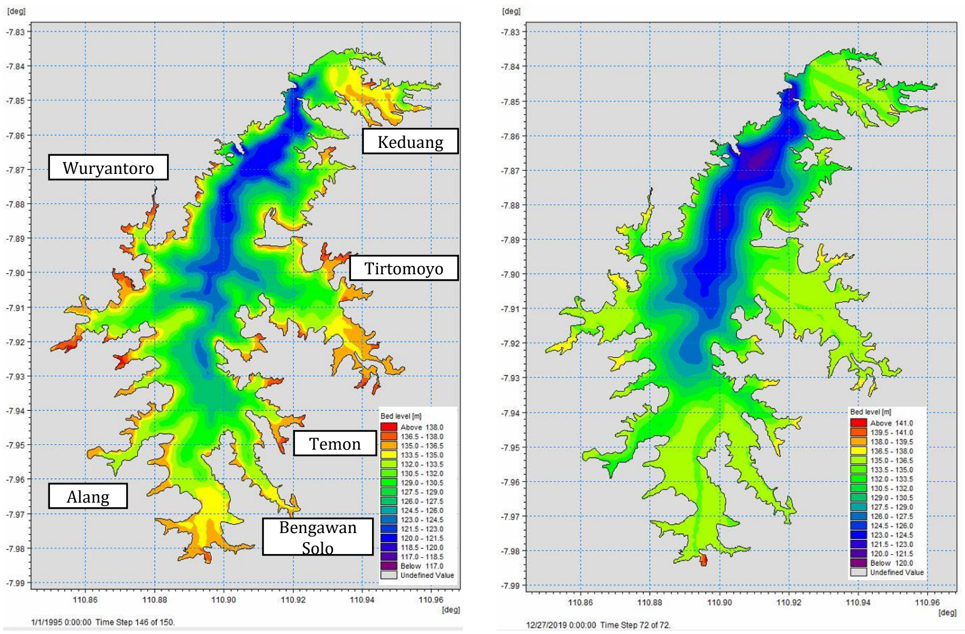

Figure 7 Sediment transport analysis result in year 1993 (left) and 2019 (right)

Table 4 Result Comparison from other studies

Study	Prediction
JICA 1974	5.2 million/year
Research and Development Center of Water Resources, 1982 and 1984	1.2 million/year
Faculty of Geography, Gajahmada University, 1984 and 1985	6.6 million/year
Bengawan Solo Project and Brantas Project, 1985	8.1 million/year
BRLKT Watershed Solo, 1985	6.6 million/year
JICA, 2000	4.5 million/year
JICA 2007, 1993-2004	2.9 million/year
This Research	3.14 million/year

3.4. Reservoir Sedimentation Prediction Result

Prediction for reservoir sedimentation uses Spatial-Multi Target Regression (SMTR). It weighs on modular data of reservoir bed area. Reservoir bed is divided discreetly in 54,885 modules. The elevation change of each module is analysed by regression. This method is better than averaging reservoir bed area elevation change then processed by regression method. The result of SMTR method is very detail because it is processed in each module then merged in one reservoir bed area, see Figure 8 and Table 5. Sediment volume and distribution can be predicted more accurately with this method. It will give more detail result if it is combined with distribution of sediment particle size, but it requires another research and more process time. Based on prediction, reservoir life time will end before 2044 because in 2044, sediment will cover intake of the dam. In 2069, reservoir sedimentation volume prediction is 146.7 million m^3.

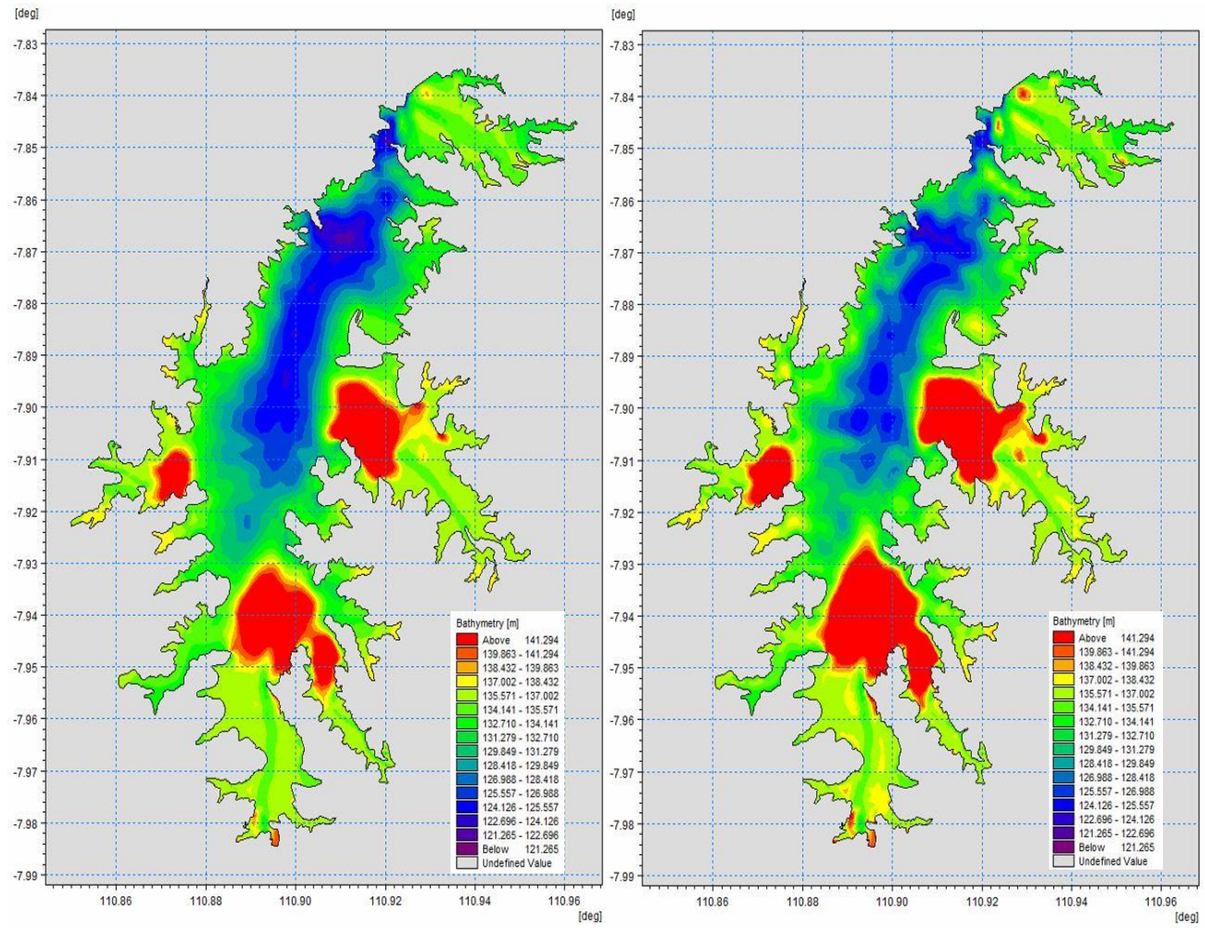

Figure 8 Sediment transport prediction result in year 2044 (left) and 2069 (right)

Table 5 Prediction result of Reservoir Sedimentation

Sedimentation (m)	Area (km^2)				
	2019-2024	2024-2029	2029-2044	2044-2069	2019-2069
Total Volume (mill.m^3)	15.44	15.48	46.05	78.97	146.70

3.5. Discussion

The improved protocol produces reliable and satisfying result, but there are some limitations needed to be considered for another research such:

- Correlation and determination value of equation for daily sediment discharge model is less than 1 because not every eroded soil is flowed to the river and eroded river bank and river bed material transported to the reservoir is not part of soil erosion prediction.
- Local erosion from reservoir bank is also negligible. Since soil erosion prediction in catchment area using USLE method, it is assumed the only external force is precipitation, neglecting wind force as well. Another research is required to include local erosion from reservoir bank and wind as external force for soil erosion prediction.
- Modelling sediment discharge requires a lot of inflow sediment rate data to increase the correlation value between soil erosion and sedimentation.
- Three-dimension transport sediment model using MIKE require a lot of time to process with time step is 0.1 seconds. It requires more detailed topography survey to reduce time process. Another research about this matter is needed so the protocol become more practical. Considering the matter, this research uses one dominant specific gravity. Using each specific gravity for each particles gives finer result.

4. Conclusions

Simulation of the proposed improved protocol at the case study is began by obtaining continuous predictive data on land erosion to accommodate land cover/land use change and precipitation dynamic. Sediment discharge was modelled from land erosion and daily discharge hydrographs using the FJ Mock method and validated with measured sediment rate. It is novel method to gap limited continues input discharge data. Reservoir sediment transport is spatially modelled using MIKE software. Spatial model is important to analyse sediment volume and distribution. Prediction of future sedimentation is developed based on reservoir bed elevation analysis using the modular regression method. This protocol gives accurate result for reservoir sedimentation prediction. The result will give better understanding of characteristic and trend of a reservoir sedimentation phenomena. It also gives input to create a better strategy to operate dams and maintain reservoirs. The novelty of this research is: Modelling long term daily sediment discharge from yearly soil erosion prediction result and daily precipitation; Reservoir sedimentation prediction by modular reservoir bed elevation regression method; Protocol for reservoir sedimentation prediction. There are four steps. First step is predicting long term yearly soil erosion in reservoir catchment area. Second step is modelling long term daily sediment discharge. Third step is modelling spatial-temporal reservoir sediment transport. Fourth step is predicting reservoir sedimentation in the future.

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