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Reservoir sedimentation under land use and climate variation: case study of Ringlet, Cameron Highlands

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Abstract: Ringlet Reservoir in Cameron Highlands has suffered from severe sedimentation due to active agriculture and urbanisation in the catchment, leading to flooding in Bertam Valley in October 2013 and severe storage reduction affecting hydropower operation. This research focuses on the prediction of long-term sediment inflow in Ringlet reservoir under land use and climate variation based on the SWAT sediment yield model. From this study, the sediment yield rate for the catchment ranges from
33.1 to 56.9 ton/ha/year, with Lower Bertam, Habu, and Ringlet being the most sediment-prone areas. These rates are higher than in any other areas in Malaysia and it also shows that sediment yield was greatly influenced by land use, slope, catchment area, and runoff. Under land use change 1997, 2006, 2010, 2015 and 2030 modelled in SWAT, the average annual inflow into Ringlet Reservoir is averaged at 8.02 m3/s, with a range from 5.54 m3/s to 10.35 m3/s while annual sediment load into Ringlet Reservoir is averaged at 342,614 m3/year with projected increase up to 461,886 m3/year by 2025. This is equivalent to 1.2% of annual storage loss. This puts Ringlet Reservoir at high risk in terms of sedimentation rate. Integrated sediment management is needed, focusing on preventive and corrective measures to ensure its sustainable operation.

Keywords: Reservoir sedimentation, climate variation, Cameron Highlands

1. Introduction

Here introduce the Climate change effect and human disturbances have influenced the rainfall-runoff process in the catchment, thus affecting rainfall erosivity and the erosion-sediment yield process [1]. This leads to a common understanding that land use type is the most dominant determining factor for sediment yield [2]. Higher sediment yield was noted at sub catchments of mostly forest and agricultural-dominated areas [3]. Cameron Highlands has been an active agricultural area for tea, flowers, and vegetables as well as a favourite tourist attraction due to its lower average temperature of 19.4ºC as compared to Malaysia's average of 25.8ºC [4]. Development has taken place at an accelerating rate in terms of roads, steepland farming, housing, commercial areas, and urbanisation. Steep slopes and heavy rainfall aggravate sediment production and induce high runoff peaks, causing more flash floods, slope failures, and high sediment load transport [5]. This excessive land degradation has affected the whole Cameron Highlands-Batang Padang Hydroelectric Scheme, particularly the Ringlet Reservoir, Bertam Intake, and Jor Power. Figure 1 illustrates the sediment-laden Ringlet Reservoir.

The Malaysia Dam Safety Management Guidelines (MyDAMS) published by the DID [6] showed that more than 40% of dams in Malaysia are more than 50 years old, and reservoir sedimentation is one of the issues affecting dam safety that must be managed to ensure the dams are safe and continue to fulfil their designed function. In Malaysia, methods to quantify reservoir sedimentation are not well documented, categorised, or even assessed in terms of their accuracy.

1.1 Study area

Ringlet Reservoir with a surface area of 0.5 km2 is located in the state of Pahang, and is part of the Cameron Highlands – Batang Padang Hydroelectric Scheme. The reservoir serves as a regulating reservoir to generate electricity

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and flood control for the Bertam Valley area. Figure 2 illustrates the location of Ringlet Reservoir and its contributing catchment and major features of Cameron Highlands

– Batang Padang Hydroelectric Scheme. Its storage is diverted from the catchment of Cameron Highlands using various transfer tunnels. The reservoir was fully impounded in 1963 following the construction of the Sultan Abu Bakar Dam, which is designed to impound water for power generation at the Sultan Yussof Power Station at Jor in the state of Perak.

Figure 1. Highly sedimented Ringlet Reservoir [7]

The catchment which comprises 183km2 was dominantly forest in the 1960s but rapidly converted into an agricultural area, townships, and urban area. Cameron Highlands has three active townships, namely Ringlet, Tanah Rata, and Brinchang. With steep slopes and a high average of 2400mm to 2700mm rainfall throughout the year, this area is prone to heavy soil loss. This leads to an increase in sediment load transported by the river network and eventually an increase in sediment inflow into Ringlet Reservoir. It is still debatable whether it is a rural area or an urbanised area. This is mainly because the catchment is composed of small agricultural units with artificial slopes and conduit systems of paths, tracks, and roads, thus limiting the application of the standard hydrological model.

Figure 2. Location of Ringlet Reservoir, Cameron Highlands – Batang Hydroelectric Scheme and its contributing catchment (Source: TNB)

Land use changes in the catchment have been significant since 1947 but remained relatively similar from 1997 to 2015 with forest covering 62% to 64% of the area. Meanwhile the agricultural area varies from 18% to 22%, and urbanisation has increased from 1% to 4%. This is shown in Figure 3, whereby forest is marked by green shaded areas, agricultural activities (yellow shaded areas) and urbanisation (red shaded areas). Future land use in 2030 indicates that forests will constitute 69.3% of the area, followed by agricultural land use (25.5%) and urbanisation (4.6%). This shows that agricultural activities will be higher compared to 2015 but similar to that of 2010. Increased sediment load is therefore predicted based on this future land use.

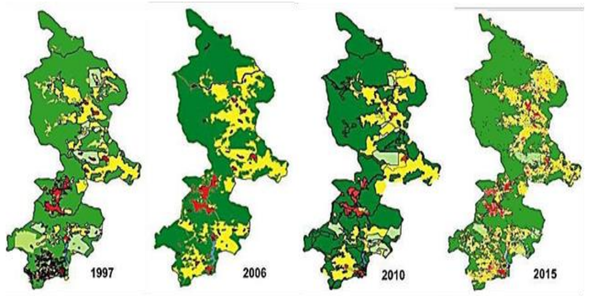


Figure 3. Land use map of Cameron Highlands from 1997 to 2015 (Source: Dept of Agriculture and PLAN Malaysia)

2. Methodology

The Soil and Water Assessment Tool (SWAT) is a physically-based catchment model which was developed to simulate the rainfall-runoff process, erosion, sediment yield, and pollutant load resulting from climate change, land use change, and management plan in the catchment on the long term daily and sub-daily time scale [8]. SWAT processes input data such as meteorological data, land use, and soil in GIS layers, allowing spatial representation of the model and results. SWAT comprises land phase and stream phase with water balance, erosion, and sediment yield, calculated at each Hydrological Response Unit (HRU) in the land phase, while the streamflow, sediment, and nutrients are routed in the stream phase. SWAT computes runoff using the SCS curve number method. Erosion and sediment yield are determined based on USLE and MUSLE equations. Sediment load at the rivers is based on modified Bagnold's equation, of which excess sediment will be deposited in the channel [8].

The SWAT model was configured by ArcSWAT 2012 running on the ArcGIS 10.3.1 platform. The setup of the SWAT model uses a digital elevation model (DEM), soil data, land use and river network. The catchment is delineated into sub-basins and hydrologic response unit (HRU), followed by uncertainty and sensitivity analysis, calibration and validation in SWAT CUP to obtain the calibration parameters for the next scenario analysis. Land use maps for the years 1997, 2006, 2010, 2015 and 2030 were obtained from the Department of Agriculture and PLAN Malaysia. The dominant land use was forest, orchard, residential and urban as well as rangeland and water body. Slopes were divided into three categories: 0-20%, 20-35% and >35%. Weather data from 1997 to 2018 and future rainfall from 2019 to 2030 from the NAHRIM Climate Change model were statistically analysed and input into the SWAT weather database. Soil characteristics are based on the FAO soil series. Figure 4 illustrates the model setup to generate HRUs in SWAT.

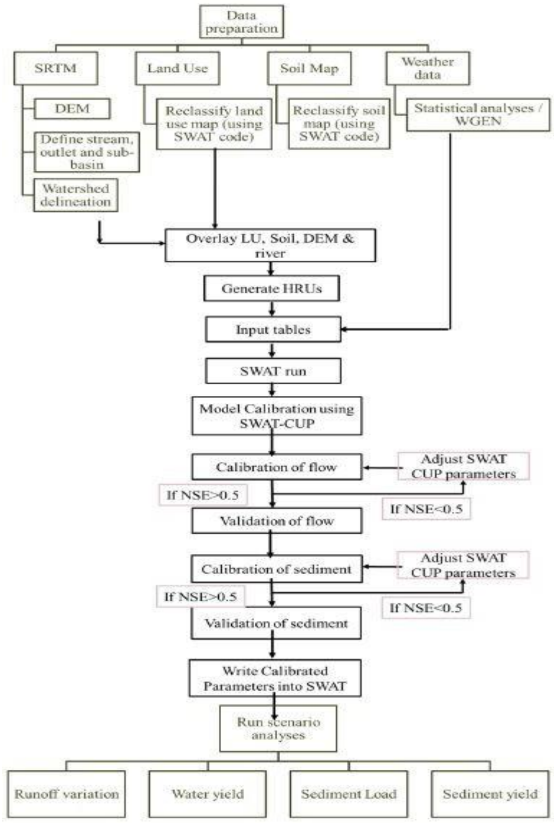


Figure 4. Methodology to simulate inflow and sediment yield using SWAT [9]

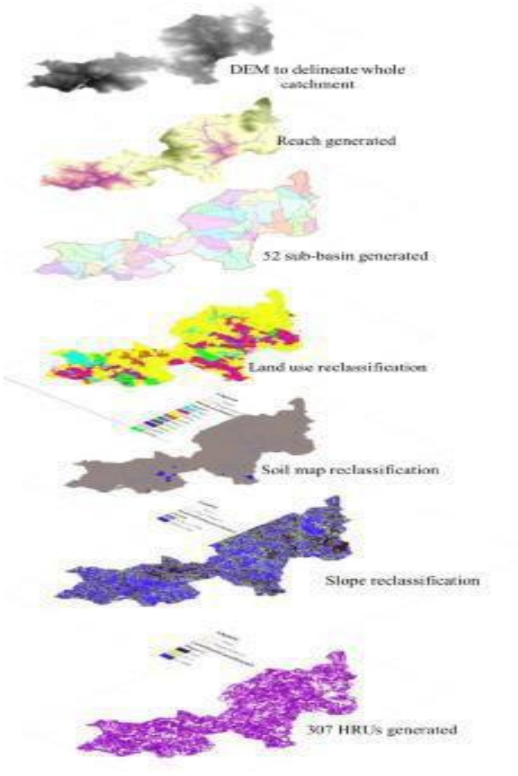
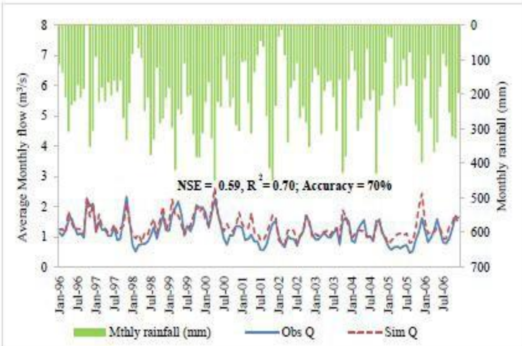


Figure 5. Observed and simulated monthly flow in Sg Bertam during calibration (2010 – 2015)



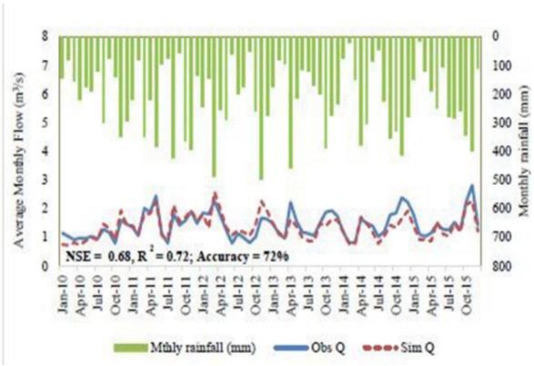


Figure 6. Observed and simulated monthly flow in Sg Bertam during validation (1996 - 2006)

3. Results and discussion

Equations and formulae Model calibration and validation from 2010 to 2015 and 1996 to 2006 were carried out using monthly stream flow data at Sg Bertam to investigate the potential changes in calibration parameters due to the high rainfall that occurred in 2014. Data from 2007 to 2009 were not considered in this study due to an incomplete continuous dataset during this period. The monthly calibration plot revised in Figure 5 indicated a good match between simulated and observed monthly flows from 2010 to 2015. The validation plot revised as shown in Figure 6, has a satisfactory match between the observed and simulated flows although simulated monthly flows in 2005 were higher than the observed. Using statistical analysis, streamflow model calibration and validation at Sg Bertam from 1996 to 2015 were in moderate performance, with NSE and R2 between 0.58 and 0.72. These results were in agreement with 72% of the 127 calibrations and 55% of the 105 statistical results using SWAT that achieved NSE

> 0.5, as reported by Tuppad et al [9]. The results from this study were also better than the SWAT stream flow calibration and validation results in Cameron Highlands because the earlier study in

[11] achieved NSE of 0.5 and 0.1, using stream flow records at Sg Jelai at Kuala Medang for 5 years of calibration and 2 years of validation period respectively. This shows that it is important to use a streamflow record of a river that exhibits characteristics of a higher gradient and is surrounded by a similar land use ratio, i.e. agricultural and urbanised.

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Observed sediment data at Sg Bertam from 2010 to 2015 and 1996 to 2006 were used for model calibration and validation, respectively. SWAT successfully matched the observed monthly sediment load as shown in Figure 7 and Figure 8, although there was an overestimation from August to November 2005 and an underestimation from April to May 2004. This is still considered acceptable as the results (NSE = 0.69 and R2 = 0.71) are within the range of good performance as explained by Moriasi et al., [12] and Da Silva [13]. These results signified that SWAT simulated the sediment load well as the SWAT-used measured sediment parameters that were obtained from fieldwork such as D50 and suitable sediment transport equation.

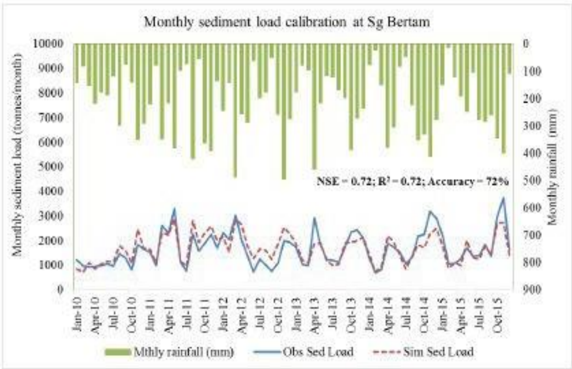

Figure 7. Observed and simulated monthly sediment load in Sg Bertam during calibration (2010 – 2015)

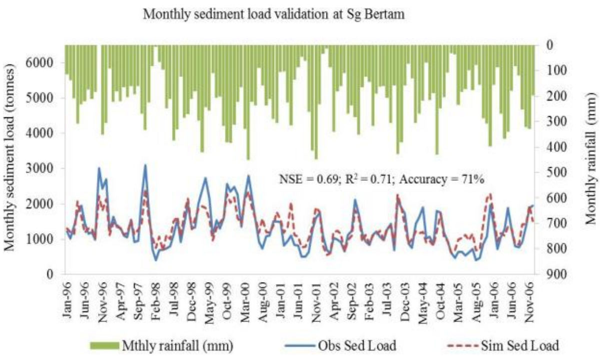

Figure 8. Observed and simulated monthly sediment load in Sg Bertam during validation (1996 - 2006)

SWAT calibrated parameters and land use from 1997, 2006, 2010, and 2015 were input into SWAT to determine the impact of land use change on the variation of flows, surface runoff, water yield, sediment yield, and sediment load in major rivers in the catchment and annual sediment load into Ringlet Reservoir. Soil and topography data was maintained in the simulation. Monthly flow simulated at Sg Habu, Sg Bertam, Sg Ringlet and Sg Kial showed a relatively similar trend over 20 years from 1999 to 2018, while Sg Telom showed a slight increase in trend (p<0.05). The average annual inflow from 1999 to 2018 is 8.02 m3/s, with a minimum of 5.54 m3/s and a maximum of 10.35 m3/s. Mann – Kendall tests showed no significant increase or decrease in annual average inflow (p>0.05). Annual sediment inflow into Ringlet Reservoir was calculated based on the sediment load transported by Sg Bertam, Sg Habu, Sg Ringlet and Sg Telom. Based on Figure 9, Sg Telom and Sg Bertam are the main sediment load contributors, with an average of 208,826 tonnes/year and 189,960 tonnes/year respectively, or 40% and 34.6%. The average flow rates of Sg Telom and Sg Bertam are 4.24m3/s and 3.62m3/s respectively. Sg Habu carried 96,353 tonnes/year of sediment or 17.5% while Sg Ringlet carried 31,369 tonne/year (6%). The annual sediment load into Ringlet Reservoir is 549,723 tonnes/ year or 342,614m3/year. These variations are illustrated in Figure 9.

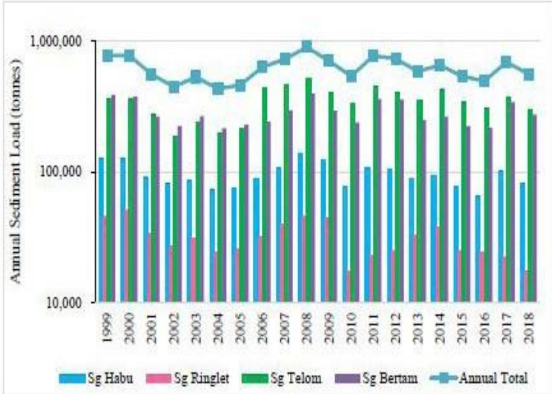

Figure 9. Annual sediment load of major rivers in Cameron Highlands

Land use changes analysis showed that forest coverage remains relatively the same from 1997 to 2015, while the change in agricultural areas were reciprocated with urban areas. The annual sediment load remains relatively high at 342,614 m3/year. The SWAT sediment yield rate ranged from 33.1 to

56.9 ton/ha/year, with Lower Bertam, Habu, and Ringlet producing the most sediment. However, the future projected annual sediment load into Ringlet Reservoir from 2019 to 2030 will be highest at 461,886 m3/year in 2025 due to high rainfall in 2025 and increased in agricultural area by 3%. The increase of sediment load in future is about 2% as compared to the average of 342,164m3/year. This leads to an average annual storage loss of 1.2%, which is higher than the world annual average of 1%. This is illustrated in Figure 10. Annual storage loss is an indicator showing the criticality and severity of the reservoir, which would lead to the selection of reservoir sediment management strategies such as sediment removal, sediment diversion or control at the source.

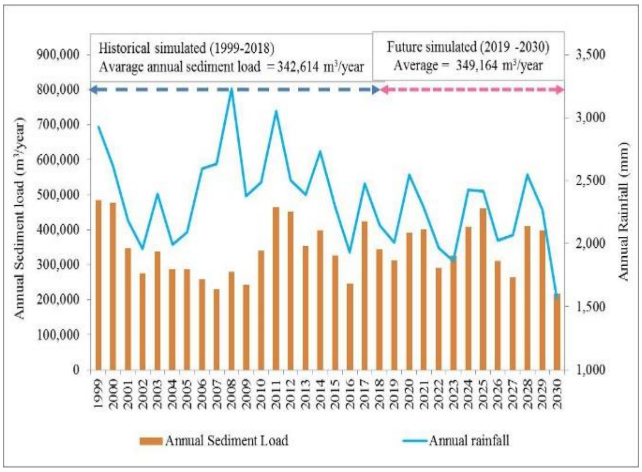

Figure 10. Long term annual sediment inflow into Ringlet Reservoir

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4. Conclusion

The land use ratio of forest, agriculture and urbanisation in Cameron Highland's catchment is relatively 63% to 20% to 3% from 1997 to 2015. SWAT was used to simulate rainfall runoff and sediment generation in the catchment as sediment was transported by the river network, under the land use change from 1997 to 2030 and projected future rainfall. From the satisfactory calibration and validation, SWAT was used to simulate the annual sediment load of Ringlet Reservoir from 1999 to 2018, which varies between 230,585 m3/year to 485,331 m3/year and an average of 342,614 m3/ year. The SWAT sediment yield rate range from 33.1 to 56.9 ton/ha/year, with Lower Bertam, Habu, and Ringlet producing the most sediment. A 2% increase in future sediment load is expected based on future land use in 2030 and high projected rainfall in 2025. The analysis also shows that annual storage loss is predicted at 1.2%, which is higher than the world average of 1%. This shows that the reservoir is at high risk and requires both immediate and long-term sediment management strategies, focusing on the removal of sediment from the reservoir and control at the source.

This study shows the suitability of SWAT as a predictor of sediment yield in a reservoir as well as to determine sediment-prone areas based on the land use change over the years and the impacts of future rainfall variation on the catchment sediment yield.

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