Future impacts of climate change on sediment influx rate in hydropower reservoir using SWAT

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Abstract. Climate change causes more frequent and intense rainfall events, leading to severe
erosion in the catchment and sediment transferred into rivers and reservoirs. This study focus on
long term sediment load in major rivers in Cameron Highlands and prediction of annual sediment
inflow into Ringlet Reservoir from 2000 to 2030. Soil Water Assessment Tool (SWAT) is used
as the simulation tool, utilising future gridded rainfall 2017 to 2030 under CCSM and future land
use 2030. Future annual rainfall is minimum at 1551 mm (in 2030) and maximum at 3150 mm
(in 2029). The future projected annual sediment load into Ringlet Reservoir from 2017 to 2030
is averaged at 354,013 m$^3$/year, ranging from 216,981 to 461,886 m$^3$/year. Comparing between
the historical period of 2000 to 2016 and future projection (2017–2030), annual sediment load
shows an increase of 12 %. To combat the increase sediment yield, catchment management such
as erosion control plan, drainage and runoff control must be developed to minimise sediment
yield and subsequent effect of high sediment load transport via rivers and drainage network.

Keywords: Climate change, land use, future rainfall, sediment yield, hydropower reservoir

Track Name: Land, Water, Forests and Food Security

1. Introduction

Average rate of global reservoir sedimentation is estimated to be 1 % [1] while Basson [2] estimated an
average of 0.93 % sedimentation loss per year. A decrease in storage due to excessive sedimentation
reduces the storage availability for hydropower generation, water supply, and irrigation. This directly
reduces the revenue but increases the operation cost to remove sediment or clearing intake blockage.
Flood storage reduction increasing the possibility of using spillways more frequently to divert
floodwaters. This could increase the risk of flooding to downstream areas [3, 4]. Modern dam
engineering standards have been modified and improved to ensure that dams are designed properly to
an acceptable limit. Future development and impact of climate change would affect the hydrological
regime and sediment generation, thus these must be incorporated in the design methodology.

Based on the study on impact of future climate change on the hydrologic regime and water resources
of Peninsular Malaysia [5] both the historical and future simulations of the hydro-climate of Peninsular
Malaysia were performed by downscaling the climate simulations of CGCM from 2000 to 2100. The
results of these analyses indicated an expected increase in inter-annual and intra-seasonal variability with increased hydrologic extremes events (higher high flows, and lower low flows) in Kelantan, Pahang, Terengganu, and Kedah watersheds in the future. An increase up to 51% in maximum monthly rainfall over the North East Coastal Region and 10% increase of annual rainfall for Kelantan, Terengganu and Pahang are expected [6].

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 [7, 8]. SWAT application is also dominant in Southeast Asia, primarily in land use impacts and climate change assessment on water yield, sediment, and nutrient transport with limitations on extreme events simulation [9]. SWAT computes runoff using the SCS curve number method, while erosion and sediment yield is 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 [10]. SWAT needs extensive input data to meet the requirement for prediction but if data are lacking, then careful calibration and validation must be carried out.

This paper describes the process involved in simulating the future impacts of climate change and land use on annual inflow and sediment load into Ringlet Reservoir, a hydropower reservoir located in Cameron Highlands using SWAT model.

2. Study Area
Ringlet Reservoir is located in the state of Pahang. It is part of Cameron Highlands–Batang Padang Hydroelectric Scheme, which is used mainly as a regulating reservoir to generate electricity. Figure 1 illustrates the location of Ringlet Reservoir and its contributing catchment and major features of Cameron Highlands–Batang Padang Hydroelectric Scheme. Water impounded in Ringlet Reservoir is originated mainly from Sg Bertam, Sg Telom, Sg Habu, Sg Ringlet, Sg Kial, Sg Kodol and Sg Plauur in the catchment of Cameron Highlands. The catchment, which comprises an area of 180.6 km², has been facing rapid changes in land use since the 1960s due to highland agriculture and urbanisation. Increase in soil loss has increased the sediment load transported by the river network, causing an increase in sediment inflow into Ringlet Reservoir. Cameron Highlands has three active townships, namely Ringlet, Tanah Rata and Brinchang.

The elevation ranges from EL1068 m to the highest of EL2168 m above mean sea level with monthly temperature ranges from 14°C to a maximum of 23°C. The catchment is subjected to two rainy seasons; from April to May and from September to November with an average annual rainfall of 2400 mm to 2700 mm. Monthly rainfall ranges from minimum of 100 mm in January and maximum of 300 mm in October to November while evaporation is averaged at 1.8 mm/day [11].
3. Materials and Methodology

Cameron Highlands has a good hydrological network involving several rainfall and stream flow stations and meteorological station, which were installed and maintained by Tenaga Nasional Berhad (TNB), Department of Irrigation and Drainage (DID) and Meteorological Department of Malaysia (MMD). Long term sediment discharge data from 1986 were used to derive the sediment rating curves, which was coupled with observed stream flow at Sg Bertam to generate continuous sediment load. Land use, soil type, soil map and topography were obtained from the Department of Agriculture (DOA), Food and Agriculture Organisation (FAO) and TNB Research respectively. Rainfall, evaporation, humidity, wind speed and solar radiation, were obtained from Tenaga Nasional Berhad (TNB), Department of Irrigation and Drainage (DID) and Meteorological Department (MMD). Table 1 summarises data used in this study.

An ensemble approach to project future climate is based on four emission scenarios of which the best possible is represented by SRES B1, the worst possible is SRES A1FI, the most likely scenario is SRES A1B, and the second worst possible is SRES A2 [12]. Therefore, future rainfall data under climate change scenario of CCSM3 SRES A1B (most likely) and CCSM3 SRES A2 (second worst possible) are obtained from NAHRIM.
Table 1. Input data in this study.

| Data type                        | Year     | Resolution       | Source                                      |
|----------------------------------|----------|------------------|---------------------------------------------|
| Topography Digital Elevation Model (DEM) | 2000     | 30 m horizontal resolution | SRTM                                        |
| Soil Map                         | -        | 1:5,000,000      | FAO                                         |
| Land use map                     | 2006, 2010, 2015 and 2030 | NA                | DOA, Majlis Daerah Cameron Highlands (MDCH) |
| Rainfall data                    | 2000 to 2016, Daily | TNB DID, MMD     |                                             |
| Future rainfall data             | 2017 to 2030, Daily | NAHRIM           |                                             |
| Streamflow data at Sg Bertam     | 2000 to 2016, Daily | TNB              |                                             |
| Sediment data at Sg Bertam       | 1986 to 2016, Instantaneous | TNB             |                                             |

3.1 Land use analysis (2006 to 2030)
The land use changes in Cameron Highlands are mainly due to forest conversion to urbanization and agricultural activities. As shown in Figure 2, forest occupies an average of 65% of the entire catchment from 2006 to projected future in 2030 while agricultural activities show increasing trend from 18% in 2006 to 25% in 2030. Urbanisation increase marginally by 1% in the period of 24 years. Other land use activity such as tea, grassland, scrub forest and water body remain fairly constant throughout those years. This shows that there will be increase in runoff and sediment yield if the future rainfall follows the similar patterns of historical data.

Figure 2. Long term land use change from 2006 to 2030.

3.2 Long term rainfall analysis (2000–2030)
By analysing historical and future rainfall under climate change scenario CCSM3 SRES A1B and CCSM3 SRES A2, average total monthly rainfall data from 10 stations from 2000 to 2030 (Figure 3) shows that there is decreasing trend of rainfall especially in the future period of 2016 to 2030, based on Mann-Kendall trend analysis (p<0.1) for both scenarios. However, CCSM3 SRES A1B shows higher extreme in 2028 with maximum average of 752 mm in Oct 2028 while minimum average of 10 mm in May 2021.
Figure 3. Long term average monthly rainfall in Cameron Highlands from 2000 to 2030 (Left: CCSM3 SRES A1B, Right: CCSM3 SRES A2).

Similar decreasing trend on annual rainfall from 2000 to 2030 is also observed under both scenarios of CCSM3 SRES A1B and CCSM3 SRES A2. Referring to Figure 4 and Figure 5, the extreme low occur in 2023 and 2030 respectively, while the extreme high occurs in 2029 for CCSM3 SRES A1B but none for CCSM3 SRES A2. Based on these trends, inflow and sediment load into the reservoir is expected to be greatly affected under scenario CCSM3 SRES A1B especially in the year 2029 and 2023.

Figure 4. Long term average annual rainfall in Cameron Highlands from 2000 to 2030 under CCSM3 SRES A1B.
Figure 5. Long term average annual rainfall in Cameron Highlands from 2000 to 2030 under CCSM3 SRES A2

3.3 SWAT Model Setup, Calibration and Validation

The catchment and its reaches were both delineated in Arc SWAT using DEM and stream network layer, and overlaid with maps of soil, land use and slope to produce 52 reaches, 52 sub-basins and 305 HRUs. Land use maps for the year 2006, 2010, 2015 and 2030 were reclassified using SWAT land use code namely forest (FRST), orchard (ORCD), residential (URMD), rangeland (RNGE) and water body (WATR). Slopes were divided into three categories: 0-20 %, 20-35 % and >35 %. Weather data from 2000 to 2016 included humidity, temperature, solar radiation and wind speed were statistically analysed and input into the SWAT weather database. Daily future rainfall data under climate change impact from 2017 to 2030 was analysed as future scenario input.

Monthly streamflow, sediment load and sediment yield from 2001 to 2015 were simulated, of which observed streamflow and sediment load at Sg Bertam from 2001 to 2006 and 2010 to 2015 were used for model calibration and validation, respectively. Performance of model during calibration and validation was evaluated using Nash Sutcliffe efficiency index (NSE), volume percent bias (PBIAS) and ratio of RMSE (RSR). If the simulated results obtained NSE > 0.5, RSR < 0.7, PBIAS < ±25, the model is considered calibrated. Hence, the parameters can be used to simulate for other scenarios. In this study, the calibrated parameters that control hydrological process are CN2, SOL_AWC, GW_DELAY, OV_N, ALPHA_BF, GWQMN, SOL_BD, SOL_K, GW_REVAP, REVAPM and RCHR. High CN2 leads to more runoff and high peak flows. For sediment routing in the channels, the parameters used are PRF, SPEXP, SPCON, CH_EROD, CH_COV, while parameters of USLE_P, USLE_C, USLE_K, SLOPE, SLSOIL and LATSED are used for sediment yield from the catchment. Summary of research methodology is shown in Figure 6.
4. Results and Discussion

SWAT delineated catchment of Cameron Highlands into 52 sub-basins (sub-catchments) and 52 reaches, assigned using numerical order from 1 to 52. Observed stream flow and sediment load data at Sg Bertam (at Robinson Falls) were used for calibration and validation. Total inflows and total sediment load into Ringlet Reservoir were accumulated stream flows from reach 18 (Sg Telom), reach 21 (Sg Kial), reach 46 (Sg Bertam) and reach 51 (Sg Ringlet).
4.1 Streamflow calibration and validation results
SWAT was able to simulate the rainfall runoff process and peak monthly flows although it overestimated the low flows that was less than 0.7 m³/s during calibration and validation period as depicted in Figure 7 and Figure 8, respectively. The monthly flow was well simulated from 2001 to 2006. The monthly validation plot in Figure 6 showed good match between simulated and observed monthly flows from 2010 to 2015 and the results also responded well with rainfall distribution. Statistical performance of calibration and validation of streamflow show good performance with NSE > 0.65, R² > 0.65 and PBIAS < ±10% [13].

![Figure 7](image1.png)

**Figure 7.** Monthly stream flow calibration plot from 2001 to 2006.

![Figure 8](image2.png)

**Figure 8.** Monthly stream flow validation plot from 2010 to 2015.

4.2 Sediment load calibration and validation results
Observed sediment data at Sg Bertam from 2001 to 2006 and 2010 to 2015 were used for sediment load calibration and validation, respectively. From Figure 9 and Figure 10 below, SWAT simulated the sediment load better in the validation period, as compared to calibration. Peak matches well for period 2010 to 2015 as compared to 2001 to 2006. Statistical performance of the model marked by NSE > 0.5 and R² > 0.5 showed that sediment load is simulated satisfactorily.
From these calibration and validation results, SWAT is able to simulate the flows and sediment load at Sg Bertam to an acceptable accuracy. This enables the model to simulate and predict the variation of flows, sediment yields and sediment loads in other sub-catchment and rivers in Cameron Highlands, thus the impacts of land use on rainfall-runoff-sediment transport processes can be predicted. Using the calibrated parameters, SWAT was employed to simulate stream flow in all rivers in the catchment using historical rainfall from 2000 to 2016 and future rainfall from CCSM3 SRES A2 of 2017 to 2030, under different land use from 2006, 2010, 2015 and 2030.

4.3 Annual inflow and annual sediment inflow under varying land use and climate change impact

SWAT simulated monthly stream flow of the major rivers such as Sg Telom, Sg Bertam Sg Ringlet and Sg Habu. They were summed up to determine the yearly variation of stream flow. Figure 11 illustrates the variation of annual inflow of Ringlet Reservoir based on the simulated flows in the sub-catchments. Using the historical rainfall from 2000 to 2016, future rainfall from CCSM3 SRES A2 and variation of land use from 2006, 2010, 2015 and 2030, the long term annual inflow from 2000 to 2030 ranged from 5.22 m$^3$/s to 10.2 m$^3$/s, with an average of 7.37 m$^3$/s. Based on the results of the Mann-Kendall tests (p<0.05), there is reducing trend on annual inflow from 2000 to 2030. From Figure 12, annual sediment load simulated from 2000 to 2030 showed an average of 548,257 tonne/year (or 338,430 m$^3$/year), with...
minimum and maximum of 311,644 tonne/year and 773,139 tonne/year respectively. Despite the annual rainfall is showing reducing trend under climate change scenario from 2017–2030, the annual sediment load shows higher average from 2017–2030 (354,013 m³/year) as compared to 2000 to 2016 (316,210 m³/year). Comparing between the historical and future projection, sediment load shows an increase of 12%.

![Annual Inflow into Ringlet Reservoir](image1.png)

**Figure 11.** Long term predicted annual inflow into Ringlet Reservoir.

![Annual Sediment Load into Ringlet Reservoir](image2.png)

**Figure 12.** Long term predicted annual sediment load into Ringlet Reservoir.

### 5. Conclusion
Cameron Highlands is located in highland area, surrounded by active agricultural and commercial activities. The catchment receives high amount of rainfall throughout the year, with average of 2400mm to 2700mm. Hydrological process of rainfall runoff and sediment load are successfully modelled using SWAT as physically based hydrological model. Model runs from 1999 to 2015 with 2 years warm up performed well, achieving good calibration and validation results, with NSE > 0.5, R² > 0.5, RSR < 0.7 and PBIAS < ±10%. By varying the land use using land use map of 2006, 2010, 2015, 2030 and using future projected rainfall under CCSM3 SRES A2 scenario, SWAT simulates flow and sediment load on monthly variation. Long term annual inflow from 2000 to 2030 ranged from 5.22 m³/s to 10.2 m³/s, with
an average of 7.37 m$^3$/s. Based on the results of the Mann-Kendall tests (p<0.05), there is reducing trend on annual inflow from 2000 to 2030. The future projected annual sediment load into Ringlet Reservoir from 2017 to 2030 is averaged at 354,013 m$^3$/year, ranging from 216,981 to 461,886 m$^3$/year. Comparing between the historical period of 2000 to 2016 and future projection (2017–2030), annual sediment load shows an increase of 12%. This shows that annual sediment load increases in future although the rainfall in future is on decreasing trend. Extreme high rainfall and extreme low rainfall are expected in the future, which could lead to the increase. To combat the increase in sediment yield, catchment management such as erosion control plan, drainage and runoff control must be implemented to minimise sediment yield and high sediment load transport via rivers and drainage network.

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