Prediction of reservoir sedimentation using Soil Water Assessment Tool (SWAT) towards development of sustainable catchment management

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Abstract. Sedimentation is considered as one of the major deterioration of a lake or reservoir, resulted from the sediment yield process in the catchment. To control reservoir sedimentation, the most effective method is to control sediment production at sources. This study initiates to determine reservoir sedimentation using Soil and Water Assessment Tool (SWAT). Cameron Highlands is an active agricultural area is chosen as study area, where meteorological data from 1997 to 2012 were used to simulate stream flow and sediment load at main rivers feeding into Ringlet Reservoir. Sensitivity analyses were conducted to determine the most sensitive parameters towards flow and sediment load simulation. Calibration and validation were performed from 2001 to 2006 and 2010 to 2012 respectively. Model performance ranges from satisfactory to good, as indicated by $R^2 > 0.5$, $NSE > 0.5$, $PBIAS <+10\%$ and $RSR<0.7$. Results are in the form of spatial distribution of flow, sediment load and sediment yield, which are useful to determine problematic sub-catchment to prompt for immediate sediment control measures.

1. Introduction
Lakes and reservoirs are highly valued for their multiple benefits to humankind, of which they used for water supply, flood control, hydropower generation, irrigation as well as being used for regulating purposes to support the existing ecosystem. They constitute important habitats for aquatic life and food resources. Lakes and reservoirs are also used for aesthetic, recreational, cultural and religious purposes. The condition of a lake and reservoir at a given time is the result of the interaction of many factors such as its watershed, climate, geology, human influence, and characteristics of the lake itself. [1]. In many cases, the human activities in its watershed as well as within the lake accelerate the lake degradation. If the causes of the changes are known, human intervention through good lake-management practices can control or even reverse those detrimental changes.

One of the most common reservoir and lake degradation is sedimentation, attributed by the excessive soil erosion resulted from excessive land clearing in the catchment. To control reservoir sedimentation, a holistic approach through catchment management is needed. An effective catchment management program would determine an acceptable level of development in the catchment that is sufficient to generate income and providing the required facilities for the community without causing excessive
erosion, sediment and alteration of hydrological regime. Effective control of water and soil losses requires implementation of the best management practices in erosion-prone areas of the catchment. The use of physically based distributed hydrological models, remote sensing techniques and geographic information systems can assist water authorities to identify the most vulnerable erosion-prone areas of a catchment and select appropriate management practices [2].

Estimation of reservoir sedimentation involves three major components; prediction of potential sediment yield generated from the catchment, transport of sediment through river network and sediment deposition in the reservoir [3]. Reservoir sediment inflow is estimated using empirical formula of Universal Soil Loss Equation (USLE) to determine the soil loss and Modified Revised Universal Soil Loss (MUSLE) to determine sediment yield. Both of these formula are embedded in Soil Water Assessment Tool (SWAT), a physically based hydrological to simulate land phase and hydrological process in a catchment. As reservoir acts as a catchment outlet, sediment yield concept is widely accepted to predict reservoir sediment inflow rate, even more so in Malaysia. Among studies conducted using this concept are for Bukit Merah [4], Bengoh in Sarawak [5] Cameron Highlands [6] [7] [8].

This study highlights how SWAT model is used to determine runoff variation and sediment yield from different sub-basins of Cameron Highlands’ catchment. This paper describes theory of SWAT, study area, model setup, sensitivity analysis, model calibration and validation and simulation of sediment yield at sub-catchments of Cameron Highlands and total sediment load into Ringlet Reservoir.

2. Theory of SWAT

The Soil and Water Assessment Tool (SWAT) [9] is a physical based hydrological model developed to simulate water quality and quantity, sediment yield and pollutant load resulted from land use changes, climate change and management plan in a catchment. The model in capable of simulating rainfall runoff, erosion and sedimentation, nutrient transport, channel routing, plant growth, and agricultural management components on daily and sub-daily time scale. It aggregates the catchment into smaller hydrological responses unit (HRU) and simulates hydrological, sediment and nutrient transport for each HRU before combining it all to compute for certain sub-basins. Soil and Water Assessment Tool (SWAT) is physically-based models used widely for catchment management, especially on water yield, sediment yield, and pollution map and climate change impact [10]. Catchment modelling in SWAT features two major phases; namely land phase and routing phase. The land phase simulates the generation of water, sediment and pollutant (nutrient and pesticides) into the main rivers. Routing phase simulates the movement of those through the channel into the basin outlet [12]. SWAT uses water balance to determine runoff, universal soil loss model for surface erosion and stream power sediment transport equation for sediment routing along river channel. Runoff generation is an important part of the model that uses curve number (SCS-CN) method to calculate surface runoff and infiltration. The CN depends on soil type, land use, and management practice. Higher CN value infers higher runoff and less infiltration. The total discharge at the outlet is the discharge accumulated from each HRU, sub-surface flow, lateral flow, and return flow. The flow in SWAT is either routed through Muskingum or a variable storage coefficient method. Similarly, sediment yield from each HRU and erosion is estimated from the Modified Universal Soil Loss Equation (MUSLE), which uses a modified Bagnold’s sediment transport equation for routing through the channel. SWAT is chosen owing to its availability in public domain and it operates on GIS-based interface. This allows the results to be presented in spatial and temporal variation, making it easier to view the effects of catchment changes.

SWAT is used in hydrological and sediment yield modelling of Langat River Basin [12], Bernam River Basin [13] and also for sediment yield study such as in central Iran [14] Chesapeake Bay [15], northeast Ethiopia [16], Blue Nile [17] and Bukit Merah, Malaysia [4].
3. Study area
Cameron Highlands is located in the state of Pahang, about 250km North of Kuala Lumpur. The average elevation of the area is approximately 1180m, of which 26% of the terrain is steeper than 25° and 60% of the land is steeper than 20° [7]. Since 1960s, forest has been converted to highland agricultural plot, township and commercial areas to support the increasing tourism and agricultural activities. Bertam and Telom are two major catchments of Cameron Highlands, with many tributaries feeding into the major rivers of Sg Telom and Sg Bertam. The catchment also drains into Ringlet Reservoir, a man-made lake constructed in 1960s which is operated by Tenaga Nasional Berhad, the national utility company of Malaysia. It is a multipurpose reservoir for hydropower generation at Jor Power Station and serves as flood control to protect residents of Bertam Valley from flooding impact. Figure 1 shows the location of Cameron Highlands, Ringlet Reservoir and the river network.

Throughout the year, the catchment is subjected to two rainy seasons; from April to May and from September to November with an average annual rainfall of 2,800 mm. Monthly rainfall ranges from minimum of 100 mm in January and maximum of 300 mm in October to November. Evaporation is fairly uniform with an average of 1.8 mm/day, while the mean annual temperature is 18°C [7]. As of year 2010, major land use within the area is forest (66%), followed by agricultural activities (30%) categorised as orchard, horticulture and tea. Other land use includes water body and urban area to represent townships and residential area.

Cameron Highlands is equipped with extensive hydrological network covering rainfall stations, weather stations and stream flow station, installed and maintained by three major parties namely Tenaga
Nasional Berhad (TNB), Department of Irrigation and Drainage (DID) and Meteorological Department of Malaysia (MMD). Most of the data is available since 1980s on daily and monthly time step. Weather station in Tanah Rata records temperature, relative humidity, solar radiation and evaporation. Stream flow is available from 1990s at Sg Bertam but sediment data is available from 2001 to 2006 and from 2010 to 2012. Sediment data collected is based on samples of Total Suspended Solids (TSS) that are analysed based on APHA 2540-D to determine the concentration in mg/L. This is later converted to tonnes/day by multiplication with the measured discharge at the time of sampling. Several hydraulic parameters are also measured such as width, depth, area of Sg Bertam section. Grab sampling is conducted to determine the average sediment size, characterised by D_50. Due to the soil properties for steepland (clay-loam) is not available from the published guidelines, soil type of Ao90-2-3c-4284 (clay-loam structure) from Food and Agricultural Organisation (FAO) is used for this study area. Table 1 summarises the input data used in the study.

| Data             | Year         | Resolution            | Source                                               |
|------------------|--------------|-----------------------|------------------------------------------------------|
| Digital Elevation Model (DEM) | 2000         | 30m horizontal resolution NA | Shuttle Radar Topography Mission (SRTM) NASA          |
| Land use map     | 2006 and 2010| NA                    | Department of Agriculture Malaysia                   |
| Soil map         | 1:5 000 000  |                       | Food and Agriculture Organisation of United Nations (FAO) |
| Meteorological data | 1999-2015   | Monthly               | Tenaga Nasional Berhad (TNB, Malaysia) and Malaysia Meteorological Department (MMD) |
| Stream flow data | 1999-2015   | Monthly               | Tenaga Nasional Berhad (TNB, Malaysia)               |
| Sediment data    | 2001-2006, 2010-2012 | Monthly | Tenaga Nasional Berhad (TNB, Malaysia)               |

4. Methodology

4.1. Model setup

Model is setup using ArcSWAT 2012 that runs on the ArcGIS 10.3.1 platform. SWAT model setup uses geospatial data such as Digital Elevation Model (DEM), soil data, land use and river network. The model setup includes data preparation in GIS-readable format, delineating the catchment into sub-basins, defining the hydrologic response unit (HRU), followed by uncertainty and sensitivity analysis, calibration and validation. Catchment area of 183 km² and reaches are both delineated in ArcSWAT using DEM and stream network layer, and overlaid with land use map, soil map and slope map to generate 52 reaches, 52 sub-basins and 305 HRUs, as shown in Figure 2. Land use is prepared following suitable and relevant SWAT code as described in the SWAT Land Use database. Dominant land use is forest (FRST) followed by orchard (ORCD), Residential (URMD), and others such as rangeland (RNGE) and water body (WATR). Slopes are categorized into three classes, namely 0-20%, 20% - 35% and >35%. Weather data from 1999 to 2012 including precipitation, humidity, temperature, solar radiation and wind speed are analysed statistically to determine their mean, standard deviation and skewness to form the SWAT weather database. ArcSWAT simulates runoff and sediment load on monthly time scale from 2001 to 2012, using 1999 to 2000 as warm up period. Warm up period specifies the initial soil moisture conditions of the catchment, which can vary from one to several years. This is to improve stability of the model for long term simulation. The stream flow and sediment data at Sg
Bertam from 2001 to 2006 and 2010 to 2012 are used for model calibration and model validation respectively.

Figure 2. Model setup to generate HRUs in SWAT

4.2. Sensitivity analysis, calibration and validation
Prior to calibration, sensitivity analysis of calibration parameters were carried using SUFI-2 algorithm in SWAT CUP program to identify and rank the parameters that have significant impact on specific model output [18]. SUFI-2 calculates the uncertainties to the parameters and aims to obtain the smallest
parameter uncertainty ranges, quantified by the 95% prediction uncertainty (95PPU) [19]. Sensitivity analyses is performed by assigning the range of values as given in the SWAT CUP manual to the parameters. Sensitive parameters are determined based on t-test of which larger absolute values are more sensitive) and p-values (where value close to zero has more significance) [20]. Based on t-test and p-value results, calibration parameters that influence surface runoff are CN2, SOL_AWC, ESCO and SURLAG. Higher CN2 leads to more runoff and higher peak flows. In addition, groundwater parameters such as ALPHA_BF, GW_DELAY, GW_REVAP, REVAPMN, RCHRG_DP and GWQMN are also used to calibrate stream flow. For sediment routing in the channels, parameters used are PRF, SPEXP, SPCON, CH_EROD, CH_COV, while for sediment yield from the catchment is based on USLE_P, USLE_C, USLE_K, SLOPE, SLSOIL and LAT_SED.

The aim of calibration is to achieve good fit between the simulated values and observed, measured by Nash – Sutcliffe Efficiency Index (NSE) > 0.5. The parameters related to runoff are first varied within iteration cycle of 50 to 200. For each cycle of iteration, the parameters are changed within the range, and model performance parameters such as R2, NSE, PBIAS, and RSR are calculated. Based on this and the performance parameters, the parameter range is reviewed and edited, and new parameters could be added one by one based on literature and existing data. As observed and simulated stream flows achieve the desired performance value (such as NSE>0.5), then the sediment parameters are varied. The runoff parameters are usually affected but not too significant. The process of changing the parameter range, checking the sensitivity (using t-stat and p-value) and adding new parameters one by one continue until performance parameters for both stream flow and sediment achieve the desired values. Being a physically based hydrological model, SWAT is relatively more difficult to be calibrated as compared to other conceptual or lumped model. Range of parameters are big and differ from one geographical location to another. List of calibrated parameters affecting flow and sediment is shown in Table 2.

### Table 2. List of SWAT CUP calibration parameters for stream flow and sediment simulation

| No | Parameters name       | Calibrated value | Range of value |
|----|-----------------------|------------------|----------------|
| 1  | GW_REVAP (.gw)        | 0.1166           | 0.02 – 0.2     |
| 2  | ALPHA_BF (.gw)        | 0.4301           | 0 – 1          |
| 3  | CN2 (.mgt)            | 62.008           | 35 – 98        |
| 4  | SOL_AWC (.sol)        | 0.01             | 0 – 1          |
| 5  | GW_DELAY (.gw)        | 382.673          | 0 – 500        |
| 6  | GWQMN (.gw)           | 141.43           | 0 – 5000       |
| 7  | REVAPMN (.gw)         | 146.42           | 0 – 500        |
| 8  | RCHRG_DP (.gw)        | 0                | 0 – 1          |
| 9  | OV_N (.hru)           | 1.596            | 0.01 – 30      |
| 10 | SOL_K (.sol)          | 10.284           | 0 - 2000       |
| 11 | USLE_K (.sol)         | 0.035            | 0 – 0.65       |
| 12 | CH_ERODMO (.rte)      | 0.998            | 0 - 1          |
| 13 | SLSUBBSN (.hru)       | 150.38           | 10 - 150       |
| 14 | CH_N2 (.rte)          | -0.01            | -0.01 – 0.3    |
| 15 | SPCON (.bsn)          | 0.0006           | 0.0001 - 0.01  |
| 16 | CH_COV (.rte)         | 0.476            | -0.001 – 1     |
| 17 | USLE_P (.mgt)         | 1                | 0 – 1          |
| 18 | SPEXP (.bsn)          | 1.027            | 1 – 1.5        |
| 19 | LAT_SED (.hru)        | 592.9            | 0 – 5000       |

### 4.3. Model performance

Model performance during calibration and validation was assessed by comparing observed and simulated hydrographs in terms of peak and low flows as well as other statistical parameters such as...
Nash Sutcliffe Efficiency Index (NSE) (Nash and Sutcliffe, 1970), Percent Bias (PBIAS), Coefficient of Determination (R2) and Ratio of RMSE (RSR). Calibration and validation performance was evaluated based on the values summarised in Table 3 below. The coefficient of determination (R2) explains the degree of linearity between the measured and simulated data of which R2>0.5 greater than 0.5 is considered acceptable. For models that achieve NSE > 0.5, it is considered satisfactory, and good if NSE is from 0.5 to 0.65. PBIAS indicates the average tendency of the simulated data to be larger or smaller than the observed data which zero value indicates perfect match. As calibration and validation for stream flow and sediment achieve the desired values, the calibrated parameters obtained from SWAT-CUP are then used in SWAT to simulate runoff and sediment from the three main sub-basins namely Ringlet, Bertam and Telom that drain into Ringlet Reservoir.

| Rank            | RSR       | NSE                   | PBIAS (%) Streamflow | PBIAS (%) Sediment |
|-----------------|-----------|-----------------------|----------------------|--------------------|
| Very good       | 0.00 < RSR ≤ 0.50 | 0.75 < NSE ≤ 1.00       | PBIAS < ±10          | PBIAS < ±15        |
| Good            | 0.50 < RSR ≤ 0.60 | 0.65 < NSE ≤ 0.75       | ±10 < PBIAS < ±15    | ±15 < PBIAS < ±30  |
| Satisfactory    | 0.60 < RSR ≤ 0.70 | 0.5 < NSE ≤ 0.65        | ±15 < PBIAS < ±25    | ±30 < PBIAS < ±55  |
| Unsatisfactory  | RSR > 0.70  | NSE < 0.5              | PBIAS > ±25          | PBIAS > ±55        |
| Acceptable      | RSR > 0.70  | 0.4 < NSE ≤ 0.7        |                      |                    |

5. Results and Discussion

5.1. Stream flow Calibration and Validation
The observed and simulated monthly stream flow for the calibration period from 2001 to 2006 is shown in Figure 3. SWAT simulates the peak monthly flow well except for some peaks in 2004 and in 2002. The low flows are well simulated throughout the calibration period except in July 2001. Validation results from 2010 to 2012 is shown in Figure 4. It shows good match with peak and low monthly flows, except in 2011 where the monthly rainfall is on the highest side of the records. Model is further assessed statistically using NSE, R2, PBIAS and RSR and summarised in Table 4. With PBIAS < ±10%, SWAT is capable to simulate the total volume very well and the model performed satisfactorily with RSR (0.66) and NSE (0.57).

![Figure 3. Observed and simulated monthly stream flow at Sg Bertam during the calibration period](image-url)
SWAT model performed better statistically in validation period, with higher NSE and R2. RSR is slightly lower indicating better performance, but PBIAS of 8.2% shows higher deviation between total observed volumes to that of total simulated volume. However, model performance is still within satisfactory level as suggested by Moriasi et al [21] and Santhi et al [22]. It is anticipated that the actual land use condition might be slightly different as compared to land use map utilised in this study, affecting runoff curve no (CN2) used for this analysis.

5.2. Sediment Load Calibration and Validation
Sediment load simulation in this study is based on routing of sediment along Sg Bertam, taking into account sediment yield generated at the same catchment. Sediment load simulation in SWAT is relatively difficult to calibrate as it involves channel processes such as deposition and degradation. The graphical comparison of monthly sediment data during calibration period 2001 to 2006 is shown in Figure 5. Peak sediment load range is averaged at 1600 tonnes/month, about 3 times higher than the average sediment load. SWAT underestimates the peak sediment load measured at Sg Bertam especially during the wet season that occur in May and October in 2003 to 2004. This is common in Cameron Highlands, as the land use activities such as mixed farming are conducted up to river reserves, and some river banks are not stable causing large sediment load transport during high flow. The land use map normally does not represent this dynamic behaviour at site. Similar model performance is illustrated during validation period of 2010 to 2012, where peak sediment load up to 3500 tonnes in May 2011 is underestimated by SWAT. This is illustrated in Figure 6.
Figure 5. Observed and simulated monthly sediment load at Sg Bertam during calibration

Figure 6. Observed and simulated monthly sediment load at Sg Bertam during validation

Model performance is further assessed using statistical results. The values of R², NSE and RSR in both calibration and validation indicate satisfactory model performance but the PBIAS < ±15% indicate very good model performance, as summarized in Table 5.

| Variable                        | Sediment Load                  |
|--------------------------------|--------------------------------|
|                                | R²    | NSE   | PBIAS (%) | RSR  |
| Monthly calibration 2001-2006   | 0.63  | 0.54  | -4.6      | 0.68 |
| Monthly validation 2010–2012    | 0.79  | 0.67  | 4.8       | 0.57 |
SWAT model is capable to simulate flows and sediment load at the selected location within an acceptable accuracy. This allows the model to be used to simulate and predict variation of flows, sediment yield and sediment load at other sub-catchment and rivers.

6. Prediction of monthly stream flow and sediment load from other sub-basins

6.1. Monthly inflow into Ringlet Reservoir
The calibrated parameters obtained from SWAT-CUP were then used in SWAT to simulate runoff from the other sub-basins within the study area. Monthly stream flow variation from 2001 to 2012 from different sub-catchments in Cameron Highlands is shown in Figure 7. Sg Telom (reach no 18) and Sg Bertam (46) are the two major catchments draining into Ringlet Reservoir, contributing an average of 3.88 m$^3$/s and 3.33 m$^3$/s respectively, while Sg Ringlet directly feeds into Ringlet Reservoir with an average of 0.47 m$^3$/s. Sg Habu and Sg Kial are represented by reach 40 and reach 21 show an average monthly flow of 1.22 m$^3$/s and 1.17 m$^3$/s respectively. The results provide sufficient information to predict the monthly and yearly inflow into Ringlet Reservoir. Average monthly inflow into Ringlet Reservoir ranges from 4.03 m$^3$/s to 11.86 m$^3$/s, with an average of 6.91 m$^3$/s. This is agreeable to an average of daily value of 6.55 m$^3$/s simulated using MIKE NAM [3]. This shows that SWAT performs well with other conceptual lumped hydrological model such as MIKE NAM. The figure also indicates at upward trending of inflows from 2001 to 2012, with high correlation with annual rainfall variation.

![Figure 7. Predicted monthly stream flow from different rivers in Cameron Highlands](image)

6.2. Monthly sediment load into Ringlet Reservoir
SWAT also simulates sediment load variation into Ringlet Reservoir, contributed by sediment load at Sg Telom, Sg Bertam, Sg Habu and Sg Ringlet which are represented by Reach 18, Reach 46, Reach 40 and Reach 51 respectively. As shown in Figure 8, the highest sediment load into is contributed by Sg Telom (Reach 18) and Sg Bertam (Reach 46), which are governed by their higher flow rate. Sg Telom contributes an average of 14,669 tonne/month, followed by 13,205 tonne/month carried by Sg Bertam and 1,549 tonne/month by Sg Ringlet directly into Ringlet Reservoir. From the analysis, it is estimated that annual sediment inflow into Ringlet Reservoir range from 245,987 tonnes/year to 484,847 tonnes/year or equivalent of 151,844 m$^3$/year to 299,288 m$^3$/year. Using this value, with the existing
total storage of 2.7 million m$^3$ based on bathymetry survey in 2015, Ringlet Reservoir could survive for the next 15.7 years if there is no sediment management strategies undertaken. However, as dead storage of Ringlet Reservoir is fully occupied, there is a strong need for an effective land use management plan to control the development within this catchment such that Ringlet Reservoir can function well for its design lifetime.

Figure 8. Predicted monthly sediment load from different rivers in Cameron Highlands

6.3. Catchment management
As SWAT operates on GIS interface, it allows the results to be presented in map format. Spatial distribution information such as water yield and sediment yield provides the catchment manager to identify source of erosion and sediment prone areas. As illustrated in Figure 9, it is understood that development has taken place rapidly in sub-catchment of Lower Bertam and Habu based on land use activities in 2010, causing high sediment yield (between 54 to 147 ton/ha). To control the excessive incoming sediment from flowing and depositing in Ringlet Reservoir, control at source mitigation measures such as check dams, buffer zone, settling basin and terracing can be proposed at these sub-catchments.
7. 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 more than 2800mm. Rainfall runoff, erosion and sediment yield processes in the catchment are successfully modelled using SWAT as physically based hydrological model. Model runs from 1999 to 2012 with 2 years warm up performed satisfactorily, achieving satisfactory calibration and validation results, with NSE > 0.5, R2 > 0.5, RSR < 0.7 and PBIAS < ±10%. Sensitivity analyses carried out indicate that groundwater and soil parameters mainly control the hydrological process while basin and channel parameters govern the sediment load parameters. Using the model, yearly inflow and sediment inflow into Ringlet Reservoir are estimated at 4.03m$^3$/s to 11.86m$^3$/s and 151,844 m$^3$/year to 299,288 m$^3$/year respectively. SWAT also generate the spatial distribution of sediment prone areas in catchment, allowing the catchment manager to plan for suitable sediment and erosion control measures at source. However, model performance can further be improved by verifying and updating the land use and soil maps to reflect the actual site conditions. This whole exercise indicates that SWAT is capable to predict reservoir inflow and reservoir sedimentation and it can be used to develop sustainable catchment management plan.

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