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Differentiation of Reservoir Sediment Inflow Forecasting using RUSLE-SDR, Rainfall – Runoff - Sediment Discharge Rating Curve (RR-SRC) and SWAT

Z. Abdul Razad[#1], L. M. Sidek[*2], H. Basri[3], K. S. Jung[#4]

[1]*Civil Engineering and Geoinformatics Unit, TNB Research Sdn Bhd, No 1, Lorong Air Hitam, Kawasan Institusi Penyelidikan Bangi, 43000 Kajang, Selangor, Malaysia*

[1]azwin.razad@tnb.com.my

[2,3]*Sustainable Technology and Environment Group, Institute for Energy and Infrastructure, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia*

[2]Lariyah@uniten.edu.my

[3]Bhidayah@uniten.edu.my

[4] *International Water Resources Research Institute, Chungnam National University, Daejon, Republic of Korea*

[4]ksjung@cnu.ac.kr

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Abstract:
Sediment inflow prediction is needed for the development of sediment management strategies to ensure the sustainability of hydropower. There are many methods to predict and forecast reservoir sedimentation, focusing on the sediment yield catchment, sediment transport along the river network and sediment deposition inside the reservoir. This study compare three main methods in predicting the sediment inflow into Ringlet Reservoir, a hydropower reservoir located in active agricultural highland area in Cameron Highlands, Pahang. It compares sediment inflow prediction using 1) soil loss and sediment delivery ratio (RUSLE-SDR); 2) integration of rainfall runoff and sediment discharge rating curves (RR-SRC) and 3) processed based sediment yield model using SWAT. Accuracy of the annual prediction from each method is assessed based on the available bathymetry survey results, proving that SWAT performs the best.

Keywords: *SWAT, sediment yield, soil loss, sediment delivery ratio, reservoir sedimentation, rainfall-runoff*

I. Introduction

Sediment inflow for any reservoir must be estimated and designed for its entire service duration. This is even more important for a proposed reservoir located within an actively developed catchment. This is to ensure that the sediment management strategies or plan considers catchment evolution and its impact on hydrological process, erosion and sediment transport and water quality which have direct impacts on the multiple functions of the reservoir. The best estimates of average long-term sediment yield are obtained using bathymetric surveys [1] [2][3] and long terms sediment gauging record upstream of the reservoir.

In the absence of long term continuous sediment gauging records, prediction of reservoir sedimentation is made using flow duration curve –

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sediment rating curve (FCD-SRC) or continuous stream flow - sediment rating curve [4] [5] [6] [7] [8]. Hydrological model can be used to generate stream flow for ungauged catchment, and coupled with sediment rating curves to determine total sediment inflow into a reservoir (RR-SRC) [9] [10] [11].

Universal Soil Loss Equation (USLE), Modified Revised Universal Soil Loss (MUSLE) and sediment delivery ratio (SDR) have gained interest as method for prediction of reservoir sediment inflow in many areas worldwide and in Malaysia, such as in Bukit Merah [12], Bengoh in Sarawak [13], Cameron Highlands [14] [15] [16]. Sediment Delivery Ratio (SDR)is calculated based on empirical formula [17] [18] [19]. Soil Water Assessment Tools (SWAT), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS), Water Erosion Prediction Project (WEPP), Agricultural Non-point Source pollution model (AGNPS) and Hydrologic Simulation Program FORTRAN (HSPF) are physically based model capable to simulate sediment erosion and sediment yield in in the catchment and sediment inflow into a reservoir.Of all these models, SWAT is the most dominant sediment yield which has been used worldwide to predict reservoir sedimentation and in Malaysia. Application of SWAT for reservoir sedimentation is studied in Ringlet [20], Bukit Merah[12] and Langet river basin[21] [22] and Bernam River Basin [23].

This aim of this study is evaluate the application of 1) Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR), 2) Rainfall-Runoff and Sediment Rating Curve (RR-SRC) and 3) physically based SWAT model to predict long term sediment inflow into a reservoir.

II. Study Area

Cameron Highlands is located in the highlands 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 25º [15]. Forest has been converted to highland agricultural plot, township and commercial areas since 1960s bringing massive sediment load especially during heavy rainfall to Ringlet Reservoir through main rivers of SgBertam, SgTelom, SgHabu and Sg Ringlet.

Ringlet Reservoir is a multipurpose reservoir mainly for hydropower generation and flood control to protect residents of Bertam Valley. The hydropower scheme is maintained and operated by TenagaNasionalBerhad (TNB) through Cameron Highlands – Batang Padang Hydroelectric Scheme. Location of Cameron Highlands, Ringlet Reservoir and the river network is shown in Fig. 1.

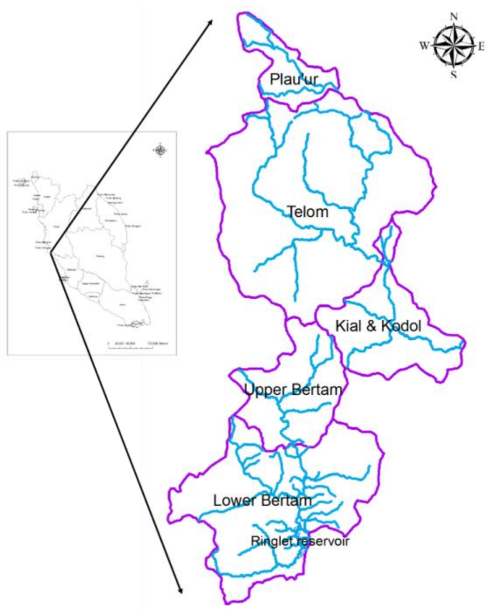

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Fig. 1 Location of Ringlet Reservoir and its catchment

Throughout the year, average annual rainfall in the catchment is 2,800 mm with monthly rainfall ranges from minimum of 100 mm in January and maximum of 300 mm in October to November. Average evaporation is 1.8 mm/day while mean annual temperature is 18°C. As of year 2010, major land use within the area is forest (66%), followed by agricultural activities (30%) categorised as orchard, horticulture and tea.

III. Material and Methodology

Three methods are used to derive annual sediment inflow, using 1) Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR), 2) rainfall runoff and sediment rating curve(RR-SRC) and 3) physically based SWAT sediment yield model.

A. *Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR)*

The most common and widely used erosion estimation method is Universal Soil Loss Equation (USLE) which is later revised to Revised Universal Soil Loss Equation (RUSLE). Using ArcGIS 10.3, soil loss for Cameron Highlands is calculated using the following equation.

A = R.K.L.S.C.P (Equation 1)(Renard et al., 1997)

Rainfall erosivity factor, R-Factor is computed based on the formula by Bols [24]. It is expressed in unit of cumulative value of storm rainfall erosivity index (EI), over a fixed period of time. The mean annual rainfall (P) for each grid cell is obtained from rainfall data 1999 to 2015. The Rainfall Erosivity Map shows that R-factor ranges from 730 to 870 MJ mm/ha/year over the entire catchment area. Soil erodibility, K Factoris based on Department of Agriculture Malaysia in 2003, which has established K–Values for 170 types of soil series based on soil composition and profile. The recommended K value is 0.0659. Length Factor, L Factor is defined as the horizontal distance from the origin of flow to outlet point for each grid cell. Topography data with 20 m interval contours are used to generate the flow direction and flow accumulation, associated with LS factor for the catchment using ArcGIS 10.3. The L Factor and S factor are both determined using Moore and Burch [26]. Crop Management factor, C-factor and Conservation practice, P Factor are based on the 2nd Edition of Manual for SaliranMesraAlam (MSMA) [27] in reference to land use map of 2006, 2010 and 2015 produced by Department of Agriculture.

B. *Rainfall-Runoff and Sediment Rating Curve(RR-SRC)*

To determine the amount of sediment carried by the rivers into Ringlet Reservoir, stream flow simulation is first carried out using MIKE NAM. MIKE NAM is a conceptual, lumped hydrological model capable to simulate runoff, stream flow and base flow in a catchment. Model setup requires digitising Cameron Highlands into several sub-catchments, as summarised in Table 1. Daily

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rainfall from five rainfall stations, daily evaporation, and land use from 2006, 2010 and 2015 from 1999 to 2015 are used for model simulation while daily stream flow data at Sg Bertamis used for calibration and validation. Calibration period is from 2001 to 2006, followed by model validation from 2010 to 2012. Calibration parameters are verified during validation and then adjusted based on the land use variation in each sub-catchments. The calibrated model is then used to simulate stream flow at Sg Habu, Sg Ringlet, Sg Telom and Sg Bertamto determine the total inflow into Ringlet Reservoir.

TABLE I
SUB CATCHMENTS OF RINGLET RESERVOIR, CAMERON HIGHLANDS

Sub catchment	Area (km^2)
Plau'ur	9.7
Kial	22.7
Kodol	1.3
Telom	76.7
Upper Bertam	21
Lower Bertam	4.3
Middle Bertam	13.4
Habu	19.1
Ringlet	9.7
Reservoir	2.8
Total	180.7

Results of sediment sampling at Sg Habu, Sg Ringlet, Sg Telom and Sg Bertamfrom 1980's to 2016 are used to derive the empirical equation or sediment rating curve (SRC). SRC is developed by plotting the sediment concentration against the measured stream flow. The best fit line of the plot represent sediment rating curves (SRC) which is commonly described as power function or power function with constant [28] or linear function [29]. Among all sediment rating curves, power function is the most common to describe relationship between streamflow (Q) and suspended sediment concentration (SSC) or sediment load (Q_s) for a certain location [29]. Typical equation of sediment rating curve is shown in Equation 2 below.

$$Q_s = aQ^b \qquad \text{(Equation 2)}$$

Daily simulated stream flow (Q) from MIKE NAM model is tabulated and multiplied with associated coefficient (a) and (b) (as in Equation 2) to determine daily sediment load transported at the respective rivers. This daily sediment load is then summed to obtain annual sediment inflow into Ringlet Reservoir.

$$Annual\ Sediment\ Inflow = \sum_{i=1}^{n} Q_{s,i} = \sum_{i=1}^{n} a\, Q_i^{\,b}$$

(Equation 3)

C. SWAT sediment yield

SWAT delineates catchment into sub-basins and hydrologic response unit (HRU) based on slope, soil and land use classification using SWAT code. Catchment area of 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 Fig 2.

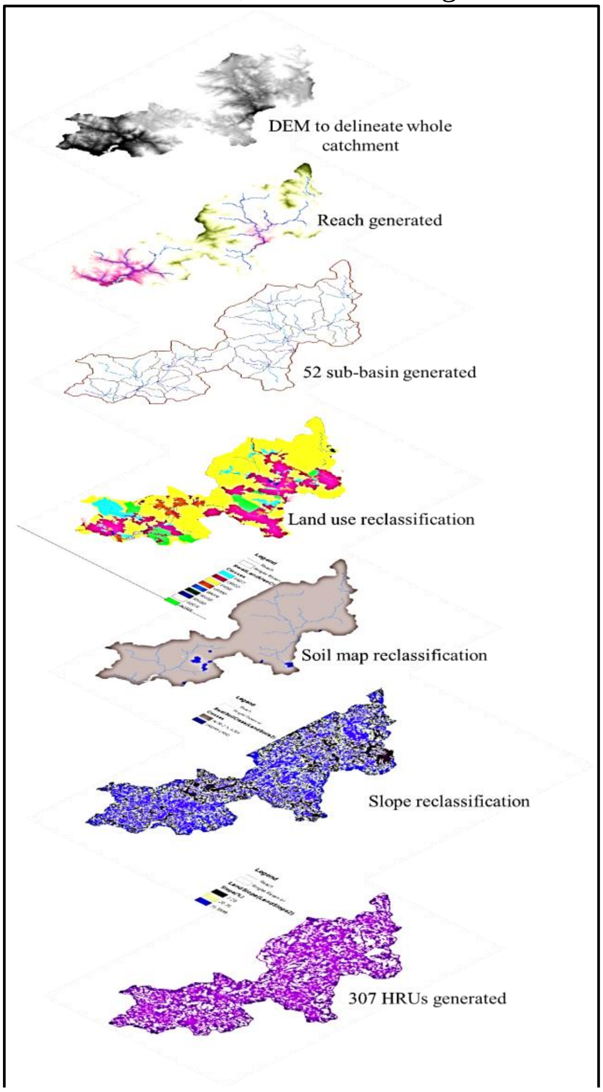

Fig. 2 SWAT model setup

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SWAT simulates runoff using SCS Curve No, and route the flow through the channel using Muskingum or a variable storage coefficient method. Erosion and sediment yield from sub-basins is calculated using USLE and Modified Universal Soil Loss Equation (MUSLE) respectively, while sediment load is routed through the channel using a modified Bagnold's sediment transport equation.

Similar to other hydrological and sediment yield model, SWAT requires calibration, validation and sensitivity analysis for rainfall – runoff and sediment yield using SWAT-CUP module. Calibrated parameters are obtained based on the calibration results that achieve good match between the simulated stream flow and sediment load to that of observed values. Statistical parameters such Nash – Sutcliffe Efficiency Index (NSE) > 0.5, Percent Bias (PBIAS) <±10% and Coefficient of Determination (R2) > 0.5are good indicators of the calibration and validation [31]. Calibrated parameters obtained from SWAT-CUP are then used in SWAT to simulate runoff and sediment from the four main sub-basins namely Ringlet, Habu, Bertam and Telom that drain into Ringlet Reservoir.

IV. Results and Discussion

Annual sediment inflow into Ringlet Reservoir are calculated based on three methods of calculation using 1) Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR), 2) Rainfall-Runoff and Sediment Rating Curves (RR-SRC) and 3) SWAT sediment yield model.

A. *Annual Sediment Inflow from Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR)*

Total soil loss in Cameron Highlands modelled using RUSLE in GIS is estimated at 345,263 m^3/year, 311,049 m^3/year and 966,510 m^3/year for 2006, 2010 and 2015 respectively. Sediment delivery ratio (SDR) ranges from0.32 to 0.49 is then multiplied by the soil loss to produce the total sediment yield into Ringlet Reservoir. Using RUSLE-SDR method, total sediment yield at Ringlet Reservoir are 129,911 m^3/year, 117,027 m^3/year and 422,365m^3/year based on land use of year 2006, 2010 and 2015, as shown in Fig 3. Sediment yield rate for Cameron Highlands range from 11 ton/ha/year to 17.4 ton/ha/year is significantly higher than sediment yield rate in Sg Perak River basin, Sg Kelantan [32] and Sabah [33]. Sediment yield in Sg Pahang river basin ranged from 0.01 ton/ha/year to 1.38 ton/ha/year with average of 1.19 ton/ha/year [34]. This illustrates the critical stage of sediment yield in Cameron Highlands as compared to other areas in Malaysia under similar land use characteristics.

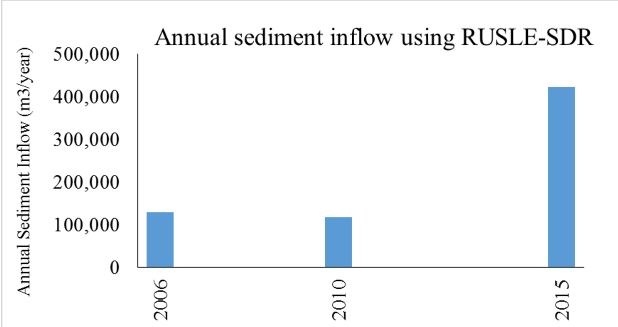

Fig. 3 Annual sediment inflow using RUSLE – SDR

B. *Annual Sediment Inflow from Rainfall-Runoff and Sediment Rating Curve (RR-SRC)*

The calibration results for 1999 to 2006 and validation results for 2010 to 212 using stream flow data at Sg Bertam achieve NSE value of 0.663 and 0.569 respectively. This is considered satisfactory performance. The adjusted calibration parameters are put back to the model to simulate daily stream flow at Sg Habu, Sg Ringlet, Sg Bertam and Sg Telom. The results show that average daily inflow into Ringlet reservoir is 6.55m^3/s. using the simulated daily flow, average annual sediment inflow into Ringlet Reservoirare 142,731 m^3/year, 115,653 m^3/year and 261,277 m^3/year for 2006, 2010 and 2015 respectively. Sediment inflow simulated using daily flow requires some adjustment to reflect the high flow of sediment during short duration flow (30mins or hourly flow). Pergau dam feasibility study used an adjustment factor of 1.30 for annual estimation using daily flow while Pahang-Selangor water transfer used ratio of 1.20 [35]. Using this adjustment factor, annual sediment inflow into Ringlet Reservoir are of 185,550 m^3/year, 150,349 m^3/year and 292,187 m^3/year for 2006, 2010 and 2015 respectively, as illustrated in Fig 4.

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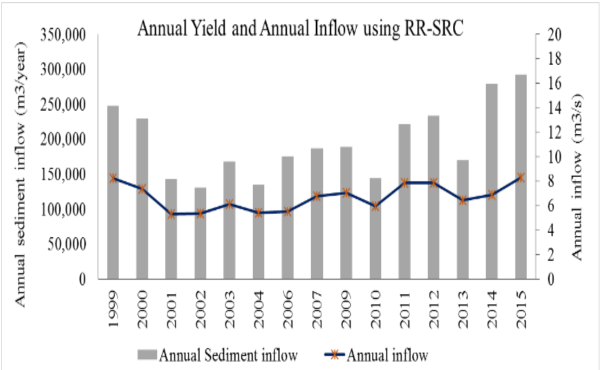

Fig. 4 Average annual inflow and annual sediment inflow into Ringlet Reservoir simulated using RR-SRC

C. *Annual Sediment Inflow from SWAT sediment yield*

Stream flow and sediment yield calibration and validation at Sg Bertam for period of 2001 to 2006 and 2010 to 2012 achieve satisfactory to good performance. This is shown by NSE > 0.57, R2 >0.59 and PBIAS <±8.2% during both calibration and validation period. Sg Telom and G Bertam contributes an average of 3.88 m^3/s and 3.33 m^3/s respectively, while Sg Ringlet flow is averaged at 0.47m^3/s. Sg Habu shows an average monthly flow of 1.22 m^3/s. using this simulated values, average monthly inflow into Ringlet Reservoir is 6.91m^3/s.

From SWAT, Sg Telom contributes an average of 14,669 tonnes/month, followed by 13,205 tonnes/month by Sg Bertam and 1,549 tonnes/month by Sg Ringlet. As illustrated in Fig 5, annual sediment inflow into Ringlet Reservoir for 2006, 2010 and 2015 are 257,960 $m^3/year$, 316,256 $m^3/year$ and 315,250 $m^3/year$ respectively.

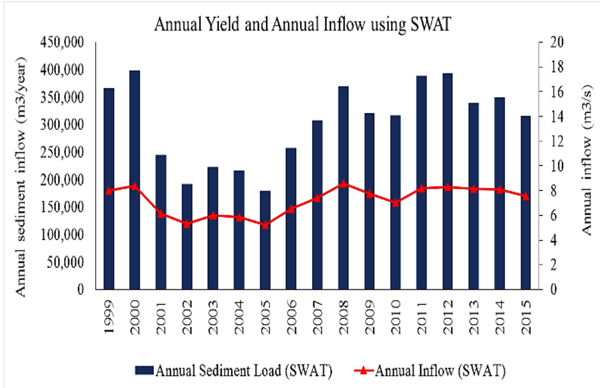

Fig. 5 Annual sediment inflow simulated by SWAT

D. *Comparative analyses with observed bathymetry survey and sediment removal record*

Annual sediment load predicted using 1) Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR), 2) Rainfall-Runoff and Sediment Rating Curves(RR-SRC) and 3) SWAT sediment yield model are evaluated against the observed bathymetry survey and dredging record. Bathymetry survey results in 2007 indicated that the total sediment inflow is between 150,000 to 250,000 $m^3/year$, while sediment removal record from 2010 to 2015 indicated annual sediment yield of 300,000 $m^3/year$. Results from the three (3) methods are summarised in Table 2.

TABLE 2
RINGLET ANNUAL SEDIMENT INFLOW

Method	**Annual sediment inflow ($m^3/year$)**		
	2006	**2010**	**2015**
RUSLE - SDR	129,911	117,027	422,365
RR-SRC	142,731	115,653	261,277
RR-SRC (adjusted)	185,550	150,349	292,187
SWAT	257,960	316,256	315,250
Observed survey / sediment removal	150,000 – 250,000	300,000	300,000

V. CONCLUSION

Sediment inflow prediction is needed for development of sediment management strategies to ensure sustainability of hydropower. This is more important for reservoir that is located within an actively developed area such in Cameron Highlands. Based on concepts of sediment generation in the catchment and sediment transported through river network, annual sediment inflow for Ringlet Reservoir from 2006 to 2015 is predicted using 1) Soil Loss Model and Sediment Delivery Ratio (RUSLE-SDR), 2) Rainfall-Runoff and Sediment Rating Curves (RR-SRC) and 3) physically based SWAT model. Inflow predicted using rainfall – runoff in MIKE NAM and SWAT are equally as good with NSE > 0.57. The use of empirical SRC in RR-SRC tend to produce lower the sediment inflow estimation, as they exclude the physical process of sediment routing and transport. Being the physically based sediment yield model, SWAT provides the most accurate sediment inflow prediction as compared to RUSLE-SDR and RR-SRC. It is also clear that the sediment inflow in showing an increasing trend from 2006 to 2015 from all the three methods.

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