ESTIMATION OF SEDIMENT INFLOW INTO A RESERVOIR USING COMBINED APPROACH OF RAINFALL – RUNOFF MODELLING AND SEDIMENT TRANSPORT ASSESSMENT

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ABSTRACT

Reservoir sedimentation can affect both operation and safety of dam if it is not properly managed. It adversely affects the multiple functions of dam and has become one of the major concerns for its owner and operator. This study describes methods to predict total inflow of sediment into the Ringlet Reservoir in Cameron Highlands using integrated approach of catchment rainfall runoff modeling and sediment rating curves derived from field sampling. MIKE NAM is used to simulate the runoff generated from the Cameron Highlands’ catchment. This model is developed, calibrated and validated using the flow data of Sg Bertam. Field sampling is conducted to measure the Total Suspended Solids (TSS), Bed Load and grab samples at major rivers of the catchment. Sediment rating curves are developed to describe the relationship between the total sediment load and discharge. The available sampling data, hydrology records and catchment ratio are used in determining the total sediment inflow into Ringlet Reservoir, which is between 150,000 m$^3$/year to 200,000 m$^3$/year. This information is useful for the reservoir manager to plan for the most suitable sediment management.

Keywords: Reservoir sedimentation; rainfall runoff model; sediment rating curve; dam; field sampling.

1 INTRODUCTION

Reservoir sedimentation can affect both operation and safety of dam if it is not properly managed. It adversely affects the multiple functions of dam and has become one of the major concerns for its owner and operator. Storage loss reduces the reservoir capacity hence affecting the available storage for power generation and flooding. Excessive sedimentation could also affect dam structural stability as well as disturbing the ecosystem that it supports; through the reduction of light penetration and sediment being the pollutant carrier. Abrasive sediment particles could also affect the mechanical equipment, increasing its rate of wear and tear (Abdul Razad et al, 2011). Although the storage loss is undeniably anticipated by the reservoir operators, reservoirs worldwide are experiencing accelerated sedimentation and losing the storage capacity rapidly, possibly as fast as 1% per year (Mahmood, 1987). Sedimentation in reservoir is characterized by the geometry of the reservoir, operation rules, inflow, and sediment material which govern the reservoir trapping efficiencies (Borland, 1960; Strand, 1982; Lara, 1962; Brune, 1953; Churchill, 1948). Large initial storage volumes and erosion control have traditionally been recommended to reduce sediment inflow to reservoir, however, these alone could not achieve the required reservoir stabilization (Morris, 1998). Furthermore, many erosion control programs are poorly implemented due to many reasons, and fail to achieve the desired reductions in sediment yield.

To design an effective sediment management, it is important to accurately estimate sediment load originating from the catchment and transported by the river system, by means of comprehensive monitoring, survey and combination of modelling works.

2 PREDICTION OF SEDIMENT INFLOW

Prediction of sediment inflow is predominantly based on reservoir survey information, obtained from the relevant bathymetry survey using echo sounding technique. Storage is calculated using either Triangular Irregular Network (TIN), simplified using GIS software or conventional cross section method. Difference in storage indicates sedimentation rate, provided that information on sediment removal via dredging, flushing or others is known. However, this method does not provide spatial and temporal variation of sediment inflow, but rather useful for long term sediment management and planning. The use of soil loss equation such as Universal Soil Loss Equation (USLE) is feasible to estimate potential erosion generated within the catchment, but the rate needs to be multiplied by the estimated Sediment Delivery Ratio (SDR) to determine the sediment yield. In
Malaysian context, Design Guides for Erosion and Sediment Control in Malaysia (DID, 2010) is available for estimation of potential erosion and sediment yield but it requires site verification to reflect the actual site condition. Another common method to predict sediment inflow is by using the trap efficiency concept, which is defined as the ratio between sediment deposition inside the reservoir and sediment inflow into the reservoir. This is further described by Brune (1953) and Churchill (1948).

In view of the temporal variation of the sediment load, sediment monitoring is preferred to estimate the sediment inflow. Sediment load is much higher during storm event, and can multiply by many folds in comparison to that of normal flow. Sediment monitoring consists of measuring the concentration of sediment and discharge to develop the sediment rating curves and if it is done on a continuous basis, information obtained can be used to generate the total sediment inflow on a yearly basis. In the event that continuous sediment data is not available, extrapolation or interpolation can be applied to compute the sediment load then applied to a much longer discharge record to estimate long-term sediment yield. However, monitoring sediment flow data over a long period and periodic reservoir survey are exhaustive and expensive (Silva et al, 2007). Therefore, the concept of modelling becomes useful to overcome the previous shortcomings. Models can be divided into empirical, conceptual and physical-based. Erosion, sediment and nutrient transport models generally consist of both hydrological and nutrient and sediment transport components. (Merritt et al, 2006). Bedri et al. (2014) developed the water quality prediction system which comprises an integrated catchment-coastal model and water quality database. Choudhury and Sundar Sil (2010) developed new models which combine Muskingum model and the sediment rating model leading to integrated water discharge–sediment concentration model (WSCM). In this view, the use of hydrological modelling is feasible to predict sediment inflow, provided that information on concentration – discharge is sufficient.

3 STUDY AREA
Cameron Highlands is located in the state of Pahang, near the mountain range of Peninsular Malaysia, as illustrated in Figure I. The area is famous for its active highland agriculture and tourism activities, owing to its nice and cool weather throughout the year. There are three (3) major catchments namely Bertam, Telom and Lemoi. Cameron Highlands is also a home to seven hydro power stations owned and run by the national utility company Tenaga Nasional Berhad (TNB). With the total installed capacity of 262 MW, the scheme is an important asset to TNB due to it being one of the sources of green energy (Abdul Razad et al, 2011).

Figure 1. Catchment of Cameron Highlands

Ringlet Reservoir is 0.5km² multipurpose reservoir located in Cameron Highlands, which is used to regulate flow from the upper catchment for hydropower generation at Jor Power Station. The reservoir has the original design storage of 6.7 million m³, of which 2 million m³ is dead storage and 4.7 million m³ is live storage. The reservoir and its Sultan Abu Bakar Dam also serves as a flood control in the downstream area of Bertam Valley, a home to almost 3000 residents. The total catchment area that drains into Ringlet is 183km², divided into two (2) major catchment of Bertam and Telom. Owing to its topography, 26% of the terrain of Cameron Highlands is steeper than 25° and 60% of the land is steeper than 20° (Abdul Razad et al, 2016). Prior to the completion of the hydropower scheme, most of the areas in Cameron Highlands were covered in forest and the sediment
concentrations in the rivers were not very high. It was estimated that the Ringlet Reservoir would have a useful life of approximately 80 years, with no special provisions to cope with sedimentation (Tenaga Nasional Berhad, 2000). It has been reported that Ringlet Reservoir has suffered storage reduction up to 53% of its storage due to sedimentation since its operation in 1963 (TNB Hidro, 2006). Study by various researchers specific to Cameron Highlands indicated critical soil loss and sedimentation rate, ranging from 150,000 m³/year up to 530,000 m³/year (Adroit, 2004; Toriman et al, 2010; TNB Hidro, 2006). Significant changes in land use within the catchment over the years associated with the high intensity farming and urban development on the steep valley slopes could have been the major contributor to the increasing rate of erosion and sedimentation from the catchment, which is eventually deposited into Ringlet Reservoir (Abdul Razad et al, 2016). Figure 1 illustrates the location of the study area and its contributing catchment.

During the course of a year, the Cameron Highlands’ catchment experiences two rainy seasons associated with southwest (April to May) and northeast (September to November) monsoons. Cameron Highlands receives an average annual rainfall of more than 2,800 mm. January and February are the driest month with rainfall amounts of 100 mm per month while October and November are the wettest with rainfall amounts of 350 mm per month (Cranbrook and Edwards, 1994). Changes in land use in Cameron Highlands have been significant from 1947 to 2010 with forest area reducing by 33%, while market gardening rose by 18%. Agriculture is the second major land use, represented by 23% of the total land area. Catchment urbanisation has increased by 4% since 1947. Tea and scrub forest remain fairly constant at about 7% of the total catchment area (Abdul Razad et al, 2011). Land use evolution between 1947 and 2010 in Cameron Highlands is shown in Figure 2.

![Figure 2. Land use changes in Cameron Highlands’ catchment](image)

4 METHODOLOGY

4.1 Rainfall runoff modelling

The objective of the hydrological assessment is to determine the hydrological characteristics of the rivers located within the study area. MIKE NAM rainfall-runoff analysis was used to derive the runoff hydrographs generated by the contributing sub-catchments of Cameron Highlands. Only the Bertam catchment was considered in the rainfall-runoff modelling. However, water channeled through the Telom tunnel (originating from the Telom catchment) was added as a constant source discharge in the hydraulic model. MIKE NAM is a parametric, lumped hydrologic model that simulates the land phase of the hydrologic cycle, of which the meteorological inputs to the model such as daily rainfall and daily evapotranspiration were used. Thiessen polygon was used to generate the areal rainfall for each sub-catchments. The general structure of the model with its four different and mutually interrelated storages and their corresponding flows is shown in Figure 3.
MIKE NAM model was prepared by digitizing the catchment of Cameron Highlands into several sub-catchments using GIS. Input data required to set up MIKE NAM include land use, rainfall, evaporation, topography, and streamflow data for calibration. In this model, at least five (5) rainfall stations and one (1) weather station located within Bertam Catchment were used, using complete ten (10) years of data available from 1999 to 2009, as shown in Figure 4. Double mass curve analysis showed straight line describing the data consistency for the model. To estimate the final NAM parameters, the model must be calibrated against the observed runoff, described by a streamflow station 6003 within Upper Bertam sub-catchment. The auto-calibration was used first followed by manual adjustment of the relevant parameters to achieve; (a) minimum error in the water balance error (%WBL) such that the average simulated agrees to the observed runoff; and (b) minimum error in the overall Root Mean Square Error (RMSE) for the entire flow spectrum to achieve overall agreement of the shape of the hydrograph, as explained by Madsen (2000, 2003). The key parameters involved in calibration are explained in Table 1.

The reliability of MIKE NAM can be evaluated based on Root Mean Square Error (RMSE) and Efficiency Index (EI) or known as Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). It is important to note that to achieve good calibration, a good rainfall dataset representative of the sub-catchment is needed. Depending on the aim of the model, calibration on event-basis as well as long term period would enhance the reliability of the model. Once the model was calibrated, MIKE NAM was used to simulate the inflows from various sub-catchments, using the calibrated parameters. Land use differences were used to determine the suitable NAM parameters.

Table 1. Associated NAM parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Final Value</th>
<th>Effect if increases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umax (mm)</td>
<td>Maximum water content in surface storage</td>
<td>10</td>
<td>20</td>
<td>15.1</td>
<td>Volume decreased</td>
</tr>
<tr>
<td>Lmax (mm)</td>
<td>Maximum water content in the root zone storage</td>
<td>100</td>
<td>300</td>
<td>171</td>
<td>Volume decreased</td>
</tr>
<tr>
<td>CQOF</td>
<td>Overland flow runoff coefficient</td>
<td>0.1</td>
<td>1</td>
<td>0.132</td>
<td>Volume increased</td>
</tr>
<tr>
<td>CKIF (hr)</td>
<td>Time constant for interflow</td>
<td>200</td>
<td>1000</td>
<td>200</td>
<td>Peak runoff decreased</td>
</tr>
<tr>
<td>CK1.2 (hr)</td>
<td>Time constant for routing interflow and overland flow</td>
<td>1</td>
<td>50</td>
<td>4.11</td>
<td>Hydrograph expands</td>
</tr>
<tr>
<td>TOF</td>
<td>Root zone threshold value for overland flow</td>
<td>0</td>
<td>0.99</td>
<td>0.0128</td>
<td>Peak runoff decreased</td>
</tr>
<tr>
<td>TIF</td>
<td>Root zone threshold value for interflow</td>
<td>0</td>
<td>0.99</td>
<td>0.409</td>
<td>Volume decreased</td>
</tr>
<tr>
<td>CKBF (hr)</td>
<td>Baseflow time constant</td>
<td>1000</td>
<td>4000</td>
<td>2301</td>
<td>Baseflow decreased</td>
</tr>
</tbody>
</table>
4.2 Sediment rating curves

Comprehensive sediment monitoring was conducted on major rivers such as Sg Bertam, Sg Habu and Sg Ringlet, by measuring total suspended solids (TSS), bed load and discharge, since 1999 until 2009. Bed material was collected using Van Veen gab sampler and analysed using particle size distribution. Bed load was sampled using Helley Smith sampler and analysed in the laboratory using drying and weighing technique. US DH-48 or US DH-59 Depth Integrating Suspended Sediment Sampler was used to obtain the TSS samples, and analysed in the laboratory according to APHA – 2540D. Attempts were made to capture samples during heavy flow event, as most sediment is transported in magnitude far greater than during the normal flow. In general, the observed TSS in rivers of Cameron Highlands was generally above that of the suggested limit for Class II (50 mg/l) and easily exceeded 1000 mg/L during heavy flow. Sediment rating curves were derived to obtain the relationship between the discharge (Q) in m$^3$/s and sediment load (Qs) in kg/s, which can be described as a power function, power function with constant (Asselman, 2000) and linear function (Tananaev, 2014). Among all sediment rating curves, the power function (refer Equation 1) is the most common function to describe the average relation between streamflow (Q) and suspended sediment concentration (SSC) or sediment load for a certain location (Wang et al, 2013).

The rating curves were derived from multiple data sets based on sampling period and compared for consistency by combining the rating curves with the discharge timeseries and annual sediment load contributed by the selected rivers. Summary of the data collected is tabulated in Table 2 below.

\[ Q_s = aQ^b \]

[1]

### Table 2. Summary of field data

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Discharge, Q (m$^3$/s)</th>
<th>Width B, (m)</th>
<th>Average Slope, S0</th>
<th>D$_{50}$ (mm)</th>
<th>Bed Load Transport, Tb (kg/s)</th>
<th>Suspended Load Transport, Ts (kg/s)</th>
<th>Total Load Transport, Tt (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sg. Ringlet</td>
<td>0.12-3.57</td>
<td>3-7.3</td>
<td>0.0037</td>
<td>1.2</td>
<td>0.003-6.217</td>
<td>0.001-9.326</td>
<td>0.014-15.543</td>
</tr>
<tr>
<td>Sg. Habu</td>
<td>0.69-5.84</td>
<td>3-7.3</td>
<td>0.0025</td>
<td>0.9</td>
<td>0.027-4.633</td>
<td>0.004-30.23</td>
<td>0.074-30.23</td>
</tr>
<tr>
<td>Sg. Bertam</td>
<td>3.23-9.16</td>
<td>14-16.5</td>
<td>0.0007</td>
<td>0.7</td>
<td>0.012-2.451</td>
<td>0.106-2.661</td>
<td>0.225-3.06</td>
</tr>
</tbody>
</table>

4.3 Estimation of sediment inflow

Using the rating curves derived at the sampling location and hydrographs simulated using MIKE NAM, sediment inflow from rivers namely Sg Habu, Sg Bertam and Sg Ringlet which flow into Ringlet Reservoir was calculated by multiplying the relevant discharge with the rating curves equations.
5 RESULTS AND DISCUSSION

5.1 Flow simulation from MIKE NAM

Model for Upper Bertam was calibrated with the observed discharge at Station 6003 Sg Bertam. Figure 5 and Figure 6 illustrate the simulated and observed discharge hydrographs during calibration period of 1999 to 2006. In this calibration, NSE value of 0.629, WBL percentage error of 2.4% and RMSE 0.386 were observed, which indicate good agreement between the observed and simulated runoff in terms of timing, rate and volume. The calibration parameters were then used in MIKE NAM to simulate flow from other sub-catchments, as illustrated in Figure 7.

![Figure 5. Observed and simulated runoff hydrograph during model calibration for Upper Bertam](image1)

![Figure 6. Observed and simulated accumulated runoff hydrograph for Upper Bertam](image2)

![Figure 7. Simulated total runoff hydrograph for Cameron Highlands catchment](image3)
5.2 Estimation of sediment inflow

Strong correlations exist between river discharge, TSS concentration and bed load for all rivers (p<0.05). The trend of sediment transport is almost identical for all rivers during low flow event but varies as the river discharge exceeded its baseflow. Rating curves developed based on sampling results using dataset from 1999 to 2009 indicated good correlation, of which $R^2 > 0.8$. Dataset 1 refers to data from 1998 to 2004, while dataset 2 refers to sampling data from 2005 to 2009. To derive a good rating curve, each data should be considered carefully prior to removing any outlier. Medium to high flow data should exhibit similar pattern of sediment transport. Figure 7, Figure 8 and Figure 9 below illustrates sediment load rating curve for Sg Ringlet, Sg Habu and Sg Bertam, respectively.

![Total Sediment Load Rating Curve for Sg Ringlet](image1)

**Figure 7.** Total Sediment Load Rating Curve for Sg Ringlet

![Total Sediment Load Rating Curve for Sg Habu](image2)

**Figure 8.** Total Sediment Load Rating Curve for Sg Habu
Sediment rating curves equations were multiplied with the simulated flow of the rivers feeding into Ringlet Reservoir to obtain the total sediment load. Using the specific density of 1.62 ton/m$^3$, the total sediment load flowing into Ringlet Reservoir is estimated at 150,000 to 200,000 m$^3$/year based on the dataset range from 1999 to 2009. This should serve as an early indication on how the sediment inflow can be predicted although it is acknowledged that certain sediment transport modelling along the rivers should be undertaken.

6 CONCLUSIONS

There are many methods capable of predicting sediment inflow into a reservoir. However, some are labour intensive and require high costs to be implemented. The use of calibrated rainfall runoff modelling such as MIKE NAM to simulate flow at relevant rivers in Cameron Highlands provides opportunity to understand the flow variations that goes into Ringlet Reservoir. The establishment of sediment rating curves at selected rivers and coupled with simulated flow is proven useful to allow estimation of sediment inflow into a reservoir. The concept is acceptable but it requires further dataset from sediment sampling and certain degree of assessment using sediment transport modelling. In summary, the total annual sediment inflow into Ringlet Reservoir is estimated to be between 150,000 m$^3$/year to 2000,000 m$^3$/year. This information is useful for the reservoir manager to plan for the most suitable sediment management.

DISCLAIMER
The information contained in this paper is purely based on research work and specifically for research purpose; it does not represent opinion of Tenaga Nasional Berhad and its subsidiaries.

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