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Prediction of Sediment Inflow to Kenyir Reservoir Using Combined Modeling

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ABSTRACT

In this study, assessment of the amount of sediment inflow and the total quantity deposited in the kenyir reservoir was made. Kenyir reservoir is the biggest man-made lake in Southeast Asia. Kenyir dam and reservoir are mainly designed for hydroelectric power generation and flood mitigation purposes. Recently it is observed that there is an increase in the sediment accumulation in front of the intake particularly during low water level in the reservoir. Prediction of sediment accumulation was undertaken by using GSTARS3 sediment transport model. One of the main problems encountered in employing GSTARS3 model for predicting the sediment accumulation in Kenyir reservoir is the lack of hydrological data, so HEC-HMS is used to overcome this problem. Statistical tests show that the modeling processes give outputs with reasonable accuracies. The errors in the model simulation are 5.5 % for Berang river thalweg, 7.5 % for Berang river cross section, 6.2 % for Kenyir river, and 7.6 % for Kenyir river cross section. The HEC-HMS and GSTARS3 can be used collectively to predict sediment accumulation for reservoir with limited hydrological data.

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INTRODUCTION

Reservoir sedimentation is the process of sediment deposition into a lake formed after a dam construction. Reservoir sedimentation involves entrainment, transport and deposition. They originate from the catchments area, rivers system and settle in reservoir.

As a river enters the reservoir, its cross section is enlarged, the water velocity is decreased and the major part of the sediment will be deposited at that location.

There are more than 45,000 large dams (height more than 15 m) built all around the world for several purpose such as power generation, flood control, domestic or industrial water supply. Malaysia had a total of 56 dams, of which 32 were more than 15 m high (large dams). The total dam capacity is estimated as 23.72 km^3 (FAO, 2010). The Department of Irrigation and Drainage, at the Ministry of Natural Resources and Environmental (Malaysia), manage 16 dams having a total capacity of 450 million m^3, located in various states. These dams fulfill the department’s role in providing adequate irrigation water, flood mitigation and silt retention (FAO, 2010).

In Malaysia and due to extensive development and deforestation, the sediment load in rivers is increased tremendously which results in an extensive sedimentation of dam reservoirs and reduction in reservoir s design age. Continuous dredging of reservoir is costly and needs surveying for reservoir sections. Modeling of the sediment deposition in reservoirs will help in reducing the cost of reservoir survey and dredging. This can be done by employing suitable and appropriate mathematical models.

Due to advances in mathematical modeling and computer technology, mathematical models for predicting reservoir sedimentation are increasing. Mathematical models are economically affective compared with the site monitoring and model selection is essential. Methods to predict reservoir sedimentation using one dimensional model has been studied by Thomas and Prashum (1977), Toniolo and Parker (2003), Chang (1984), Molinas and Yang (1986), Hamrick (2001), Andualem Gessese and Yonas (2008). Two dimensional models were applied by Afshini E. and Mitra J. (2011), Thomas and McAnally (1985), Spasojevic and Holly (1990), Luettich and Westerink (2004), and Lee *et al* (1997). Blumberg and Mellor (1987) and Olsen (1994) used three dimensional modeling.

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In some studies, the combination of two models especially for the area with a very limited calibration: achieve a good agreement in their prediction, (Duru and Hjelmfelt, 1993), (Fu et.al, 2004).

The main objective of the present study is to predict the sediment deposition into Kenyir reservoir and also to assess the sediment since the construction of the dam. This will be achieved through the following specific objectives:

1- To predict the streamflow runoff from Kenyir and Berang catchment using HEC-HMS in order to obtain a complete set of streamflow data that is necessary to run the GSTARS3 model.

2- To predict the quantity and location of sediment deposition discharged from Kenyir and Berang river systems to Kenyir reservoir, Terengganu, Malaysia by using GSTARS3 Sediment Transport Program.

The Study Area:

The main project site of kenyir reservoir is located at Kuala Kenyir (about 15 km from Kuala Terengganu, Malaysia), which was meeting point of the main Terengganu River and its tributary the Kenyir River as shown in Figure 1. The history of construction spanned for 15 years, from planning stage to completion. The construction was started in 1978 and completed in 1985. In 1987 the whole project was formally opened.

The catchment of Berang is vegetated with shrubs covering loose sandy soil while the main vegetation cover in kenyir catchment is tropical rain forest. It is normally dense but with relatively open ground layer, the main storey is 25 m to 30 m high and form a continuous layer while the under storey consist of small trees and cover of shrubs, herbs, palms and ferns. Inflow of river waters from Kenyir River and Berang River were observed to be high in sediment load and murky water was discharged from the turbine during the rainy seasons especially for the last few years.

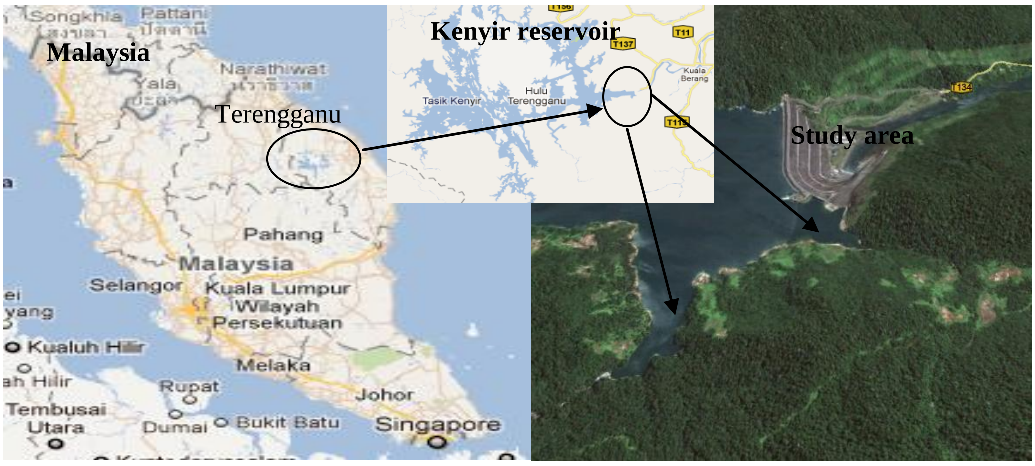

Fig. 1: location of kenyir reservoir and the study area.

Methodology:

The Methodology of this research includes data collection, data processing and model calibration and application. The model simulating the catchment was calibrated and verified before any flow and sediment transport simulation was carried out. The estimation of sediment inflow to the kenyir reservoir was demonstrates by using the HEC- HMS watershed and GSTARS3 sediment transport model.

The rainfall data for the Kenyir and Berang rivers since the operation of Kenyir dam is available, but unfortunately, there is inadequate data for streamflow. To overcome this limitation the hydrological program HEC-HMS is used to determine the surface runoff for the two rivers (Kenyir and Berang) and fill the missing data in historical record for the period from 1991 until 2006. The computed runoff data are used as input to the sedimentation program (GSTARS3).

In this study, the first step is the prediction of rainfall-runoff by using HEC-HMS for the study area which consist of two catchments namely Kenyir catchment and Berang catchment (Figure 2). A sixteen- year daily rainfall data of four stations within the study area have been obtained from the Department of Irrigation and Drainage, Malaysia. The soil type, vegetation cover and land use have been collected from Ministry of Agriculture.

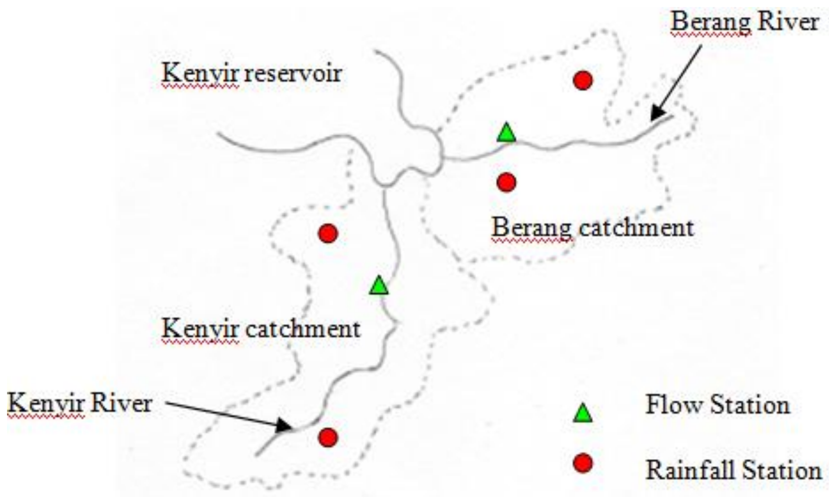

Fig. 2: Kenyir cachment and Berang cachment within the study area.

The HEC-HMS model consists of three main components, Basin, Metrological and control specification. Each component that is included in HEC-HMS has parameters. The value of each parameter must be estimated so that the model can be run to determine the runoff or routing hydrographs. Some methods can estimate the parameters from various watershed and channel properties. However, some of the submodels that are included in HEC-HMS have parameters that cannot be estimated by observation or measurement of channel or watershed characteristics. The unknown parameter can be found via the calibration if rainfall and stream flow observation are available.

The second step in this study is using the results obtained from the HEC-HMS as an input data to GSTARS3 sediment transport model. The procedure can be summarized by a flow chart as shown in Figure 3.

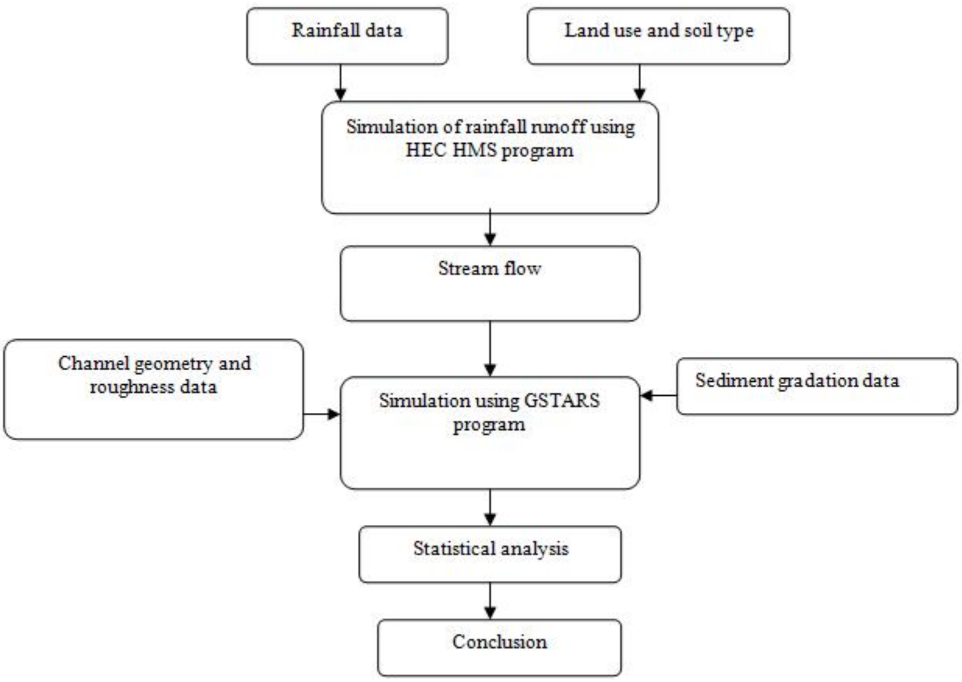

Fig. 3: General Steps for Applying HEC-HMS program and GSTARS3 program to simulate the Rainfall-Runoff and sediment inflow respectively.

The GSTARS3 sediment transport model was developed by the U.S. Bureau of Reclamation due to the need for a generalized water and sediment routing computer model that could be used to solve river engineering problems for which limited data and resources were available.

This model has a number of capabilities such as its ability to simulate and predict both hydraulic and sediment variations in longitudinal and transverse directions, as well as its ability to simulate and predict the change of alluvial channel profile and cross sectional geometry, regardless of whether the channel width is variable or fixed (Yang, et. al., 2005). The most important part in this model is the use of the stream tube concept, which is used in the sediment routing computations. Hydraulic parameters and sediment routing are computed for each stream tube, thereby providing a transverse variation in the cross section in a semi-two-dimensional manner.

Models Calibration and Validation:

HEC HMS Model:

HEC- HMS was calibrated for the storm event of September and October, 1990 (period 1). The rainfalls used were the daily rainfalls beginning at 8:00 a.m. each day. Precipitation data was taken from four rain gages that are located within the watershed. The total depth for this period varied from 0 to 275 mm for Berang catchment and varied from 0 to 41 for Kenyir catchment. The result is shown if Figures 4 and 5 for both catchments (Berang and Kenyir catchment) respectively.

The HEC –HMS model is validated in order to evaluate the performance of the model. Different rainfall period (November and December 1990) was used in validation process. This daily rainfall period began at 8:00 a.m each day and had total rainfall duration of 24 hours. The total depth of this period varied from 0 to 102 mm for Berang catchment and varied from 0 to 295 mm for Kenyir catchment. This was achieved using the parameters that were adjusted during the calibration process. The resulted error in daily average discharge was 8.3 % for Berang catchment and 12.12 % for Kenyir catchment. The comparison of the measured and simulated daily discharge for Berang catchment and Kenyir catchment, are shown on Figures 6 and 7 respectively. The agreements between the measured and simulated hydrographs are generally good. Table 1 shows the data of precipitation periods.

Table 1: Rainfall periods used for calibration (period1) and validation (period 2) for Berang and Kenyir catchments.

Catchment	Rainfall event	Period 1 1 Sept 1990- 31 Oct 1990	Period 2 1 Nov 1990- 31 Dec 1990
Berang	Rainfall Duration (hr)	24	24
	Rainfall depth range (mm)	0-275	0-102
Kenyir	Rainfall Duration (hr)	24	24
	Rainfall depth range (mm)	0-41	0-295

Parameter set:

The model calibrated for event 1 depending on soil type, land use and vegetated cover and according to the range of possible values given by Warren and Gary (2003). The values of parameter set used in the calibration run are shown in Table 2.

Table 2: HEC-HMS parameter values for calibration run.

Method	Parameter	Berang catchment	Kenyir catchment
Loss method SCS Curve Number	Curve Number CN	77	74
Transforms Method (Snyder's UH)	basin coefficient (C_t)	6.10	4.3
Recession Method (base flow model)	Recession constant ,k Peak ratio	0.81 0.1	0.75 0.15

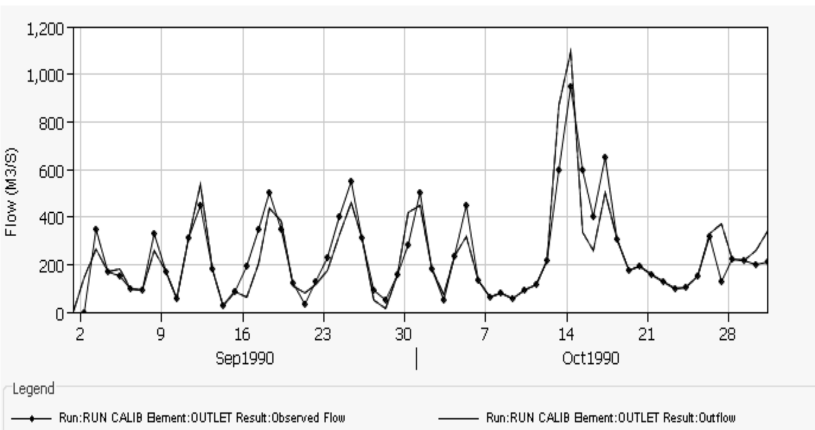

Fig. 4: Calibrated discharges of Berang catchment.

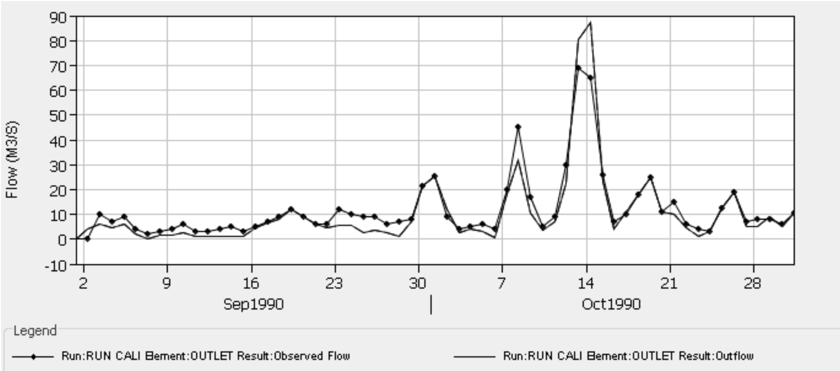

Fig. 5: Calibrated discharges of Kenyir catchment.

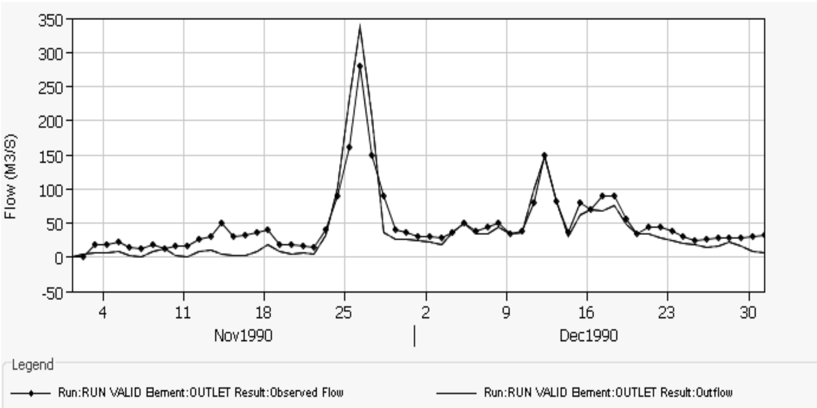

Fig. 6: Validation result of measured and simulated discharges for Berang catchment.

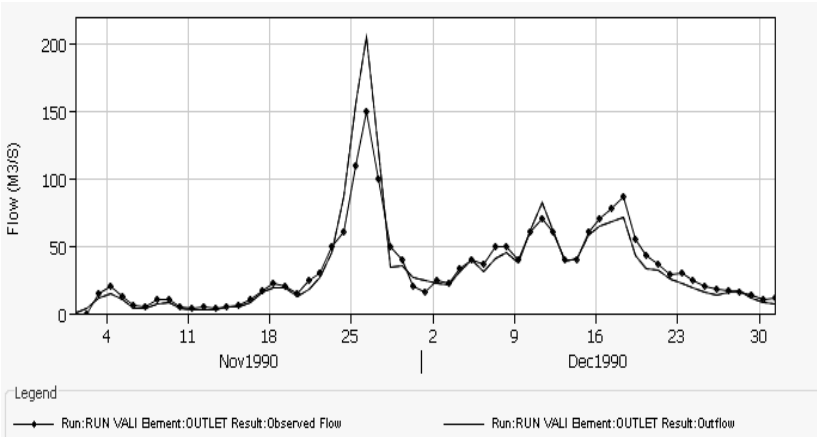

Fig. 7: Validation result of measured and simulated discharges for Kenyir catchment.

After calibration, validation of HEC-HMS was conducted. The program was run to fill the missing data for the period within sixteen years starting from 1991 until 2006. The total missing data for Berang river is equal to 17 months while that for Kenyir river is equal to 18 months. Thus, the HEC-HMS was run 28 times to compute a missing data and obtain a complete data set. The sets of data were divided into four 4-years intervals in order to use them as an input data in GSTARS3 sediment transport program to simulate the progress of sediment deposition from Berang river and Kenyir river at the location of their confluence with Kenyir reservoir. Figure 8 and Figure 9 show the hydrographs for Berang and Kenyir catchments respectively. The results show that the maximum discharge for Berang river exceed 400 m^3/sec, while the maximum discharge for Kenyir river not exceed 250 m^3/sec.

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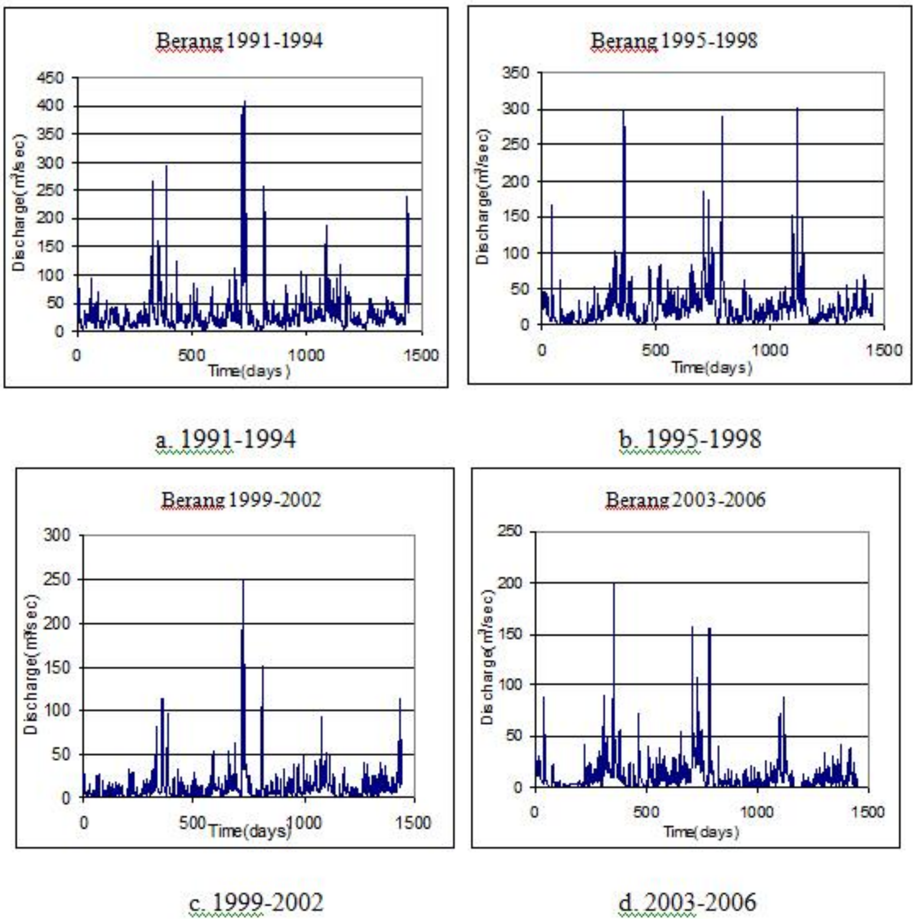


Fig. 8: Discharge for sixteen years for Berang catchment.

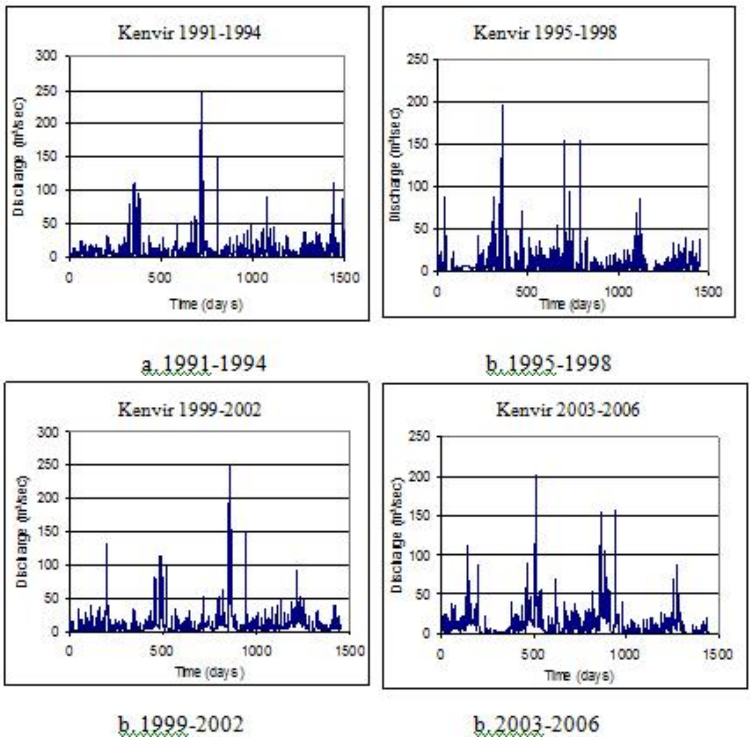


Fig. 9: discharge for sixteen years for Kenyir catchment.

GSTARS sediment transport model:

In this study, the hydrological data generated from the HEC-HMS model is used as an input data to GSTARS3 sediment transport model, in addition to another data such as channel geometry, roughness, sediment concentration and sediment gradation data. To run the GSTARS3 model, it is necessary to know the particle size distribution for the sediment transport and this was found by collecting samples from both Kenyir River and Berang River. The samples were taken to the laboratory for grain size analysis. Figures 10 and 11 show the sediment grain size distribution for Berang and Kenyir basin.

The rate of sediment transport was computed using the methods proposed by Yang (1973) for sand and (1984) for gravel (Molinas, J., and Yang, J.C.1986).

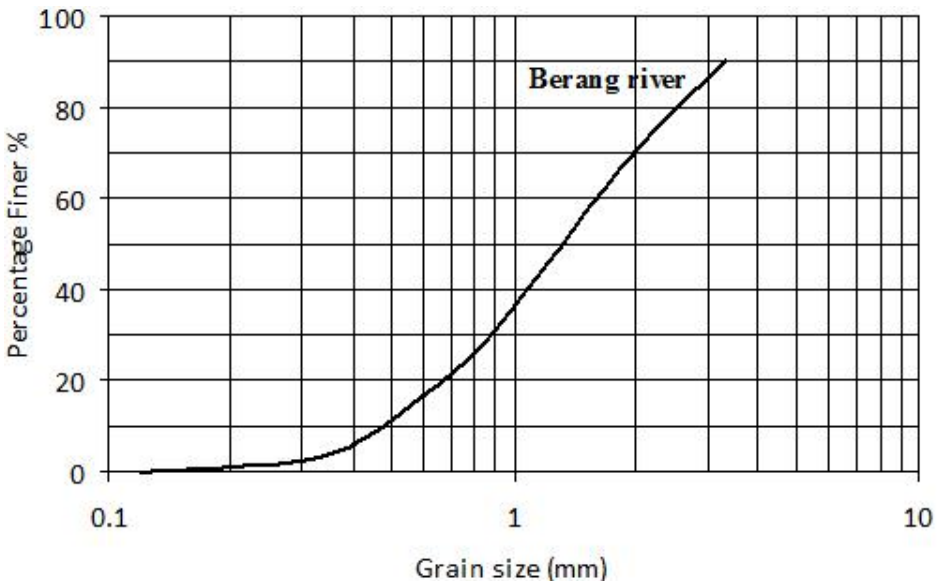


Fig. 10: Grain size Distribution Curve for Berang basin

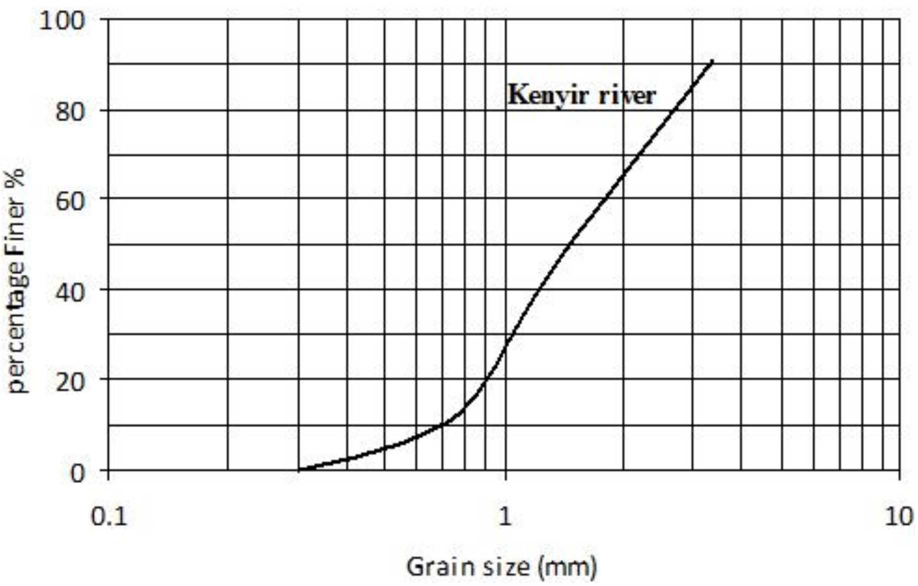


Fig. 11: Grain size Distribution Curve for Kenyir basin.

GSTARS Model Testing:

Performance of the GSTARS3 sediment transport model was statistically assessed. The assessment includes the computation of the coefficient of determination (R^2), the mean square error (MSE) and the mean absolute percentage error (MAPE). Mood *et al*. (1974) proposed to use the MSE and MAPE for model assessment. MSE was used to measure the error in the model prediction while MAPE is used to measure the error in percentage. MSE and MAPE are defined as:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(Ele_{measured} - Ele_{simulated}\right)^2 \quad (1)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|Ele_{measured} - Ele_{simulated}\right|100 \quad (2)$$

where Ele measured is the measured elevation (m) obtained from the survey, Ele simulated is the simulated elevation (m) obtained from the model output, and N is number of data used.

4.5 GSTARS3 Calibration:

GSTARS3 calibration was done by adjusting the sediment elevations for the thalweg profile until the results match with the historical records for both Berang and Kenyir river. This is needed to find the optimal parameters for minimizing the mean square errors (MSE) and mean absolute percentage errors (MAPE) between simulated data and observed data as demonstrated by Equations (1) and (2). Figures 12 and 13 show the comparison between measured and observed data for both Berang and Kenyir River respectively.

It is found that the mean square errors are 0.45 m for Berang river and 0.99 m for Kenyir river with a mean absolute percentage errors are 3.8 % for Berang river and 8.3 % for Kenyir river.

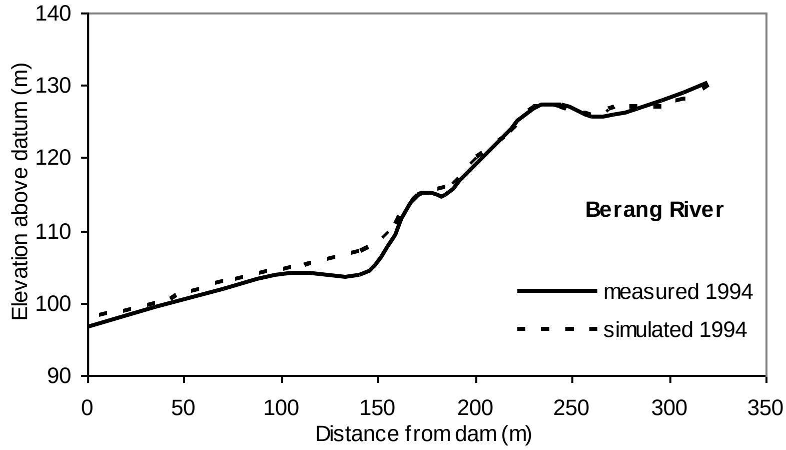


Fig. 12: Calibration of the Thalweg of the Berang River.

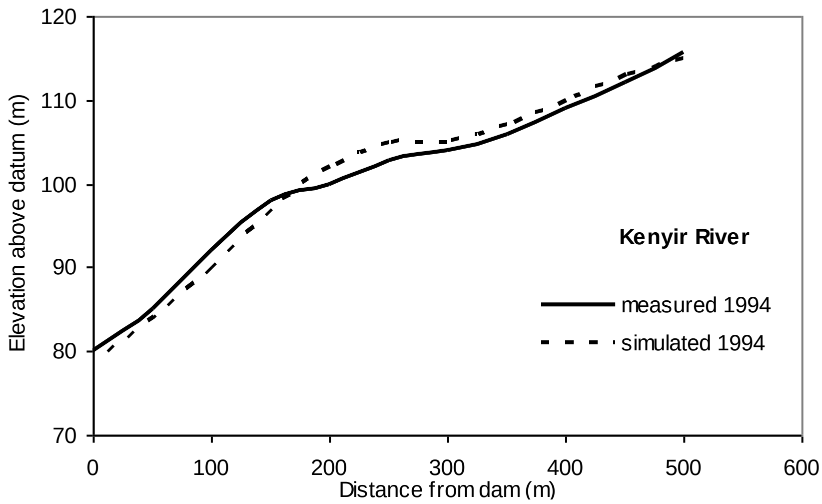


Fig. 13: Calibration of the Thalweg of the Kenyir River.

GSTARS3 Validation:

The GSTARS3 sediment transport model was run successfully to simulate the thalweg elevations for the periods outside the domain of the calibration period, by using the adjusted parameters obtained during the calibration process. Therefore, these adjusted parameters can explain the characteristic of the Kenyir Reservoir.

Based on these parameters, further simulations could be carried out to predict the sediment deposition for the reservoir in the future.

GSTARS3 model was validated to predict bed changes in the Kenyir Reservoir for sixteen years (1991-2006) at two locations, namely, the confluence of Berang river and confluence of Kenyir River. The simulation results for both thalweg and cross section at the two above location are shown in Figures 14, 15, 16 and 17.

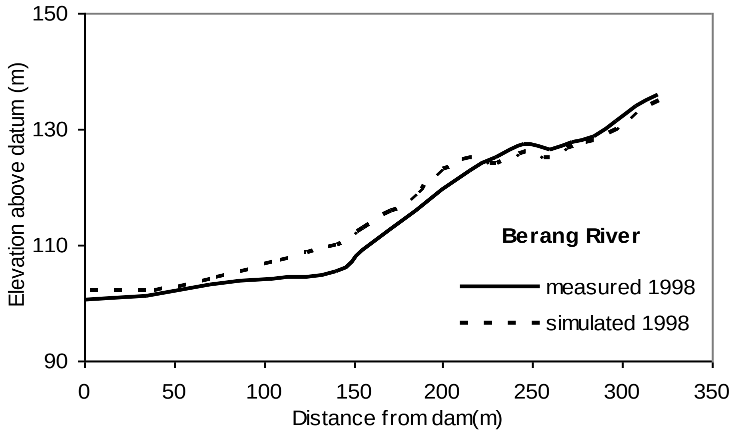


Fig. 14: Comparison between measured and computed thalweg profile for GSTARS3 simulation of Berang river 1998

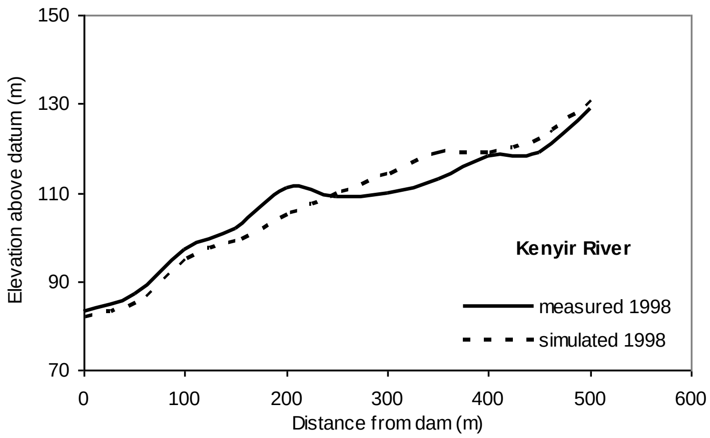


Fig. 15: Comparison between measured and computed thalweg profile for GSTARS3 simulation of Kenyir river 1998.

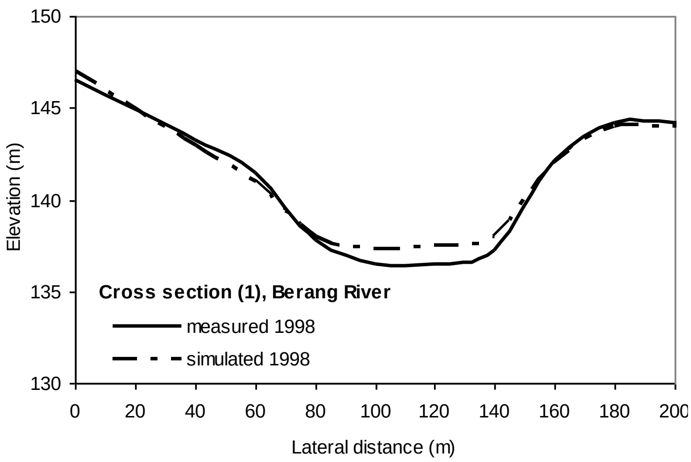


Fig. 16: Comparison between measured and simulated elevation at cross section (1) for GSTARS3 simulation of Berang river 1998.

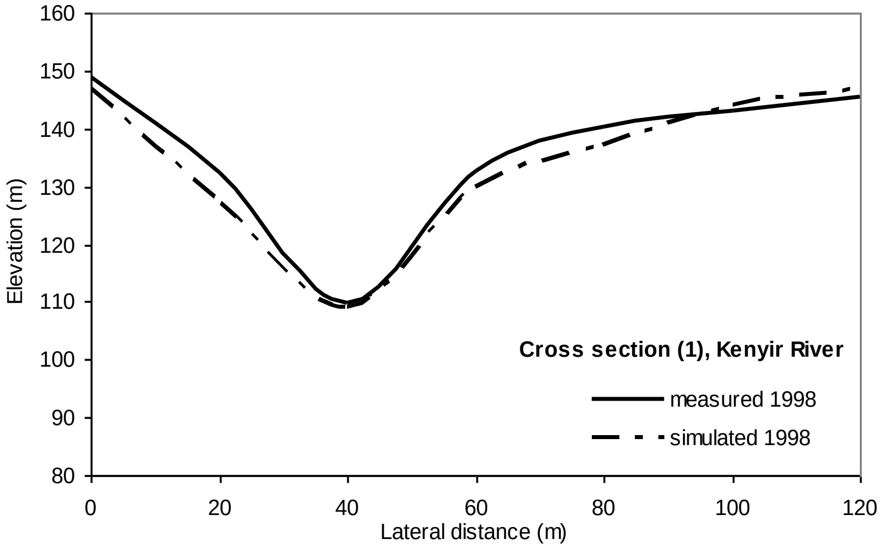


Fig. 17: Comparison between measured and simulated elevation at cross section (1) for GSTARS3 simulation of Kenyir river 1998.

The performance of GSTARS3 program was tested using MSE, MAPE and R^2 for the thalweg profiles and cross sections at the two locations in study area, first at Berang river confluence with the reservoir and second at Kenyir river confluence with the reservoir. The results are shown in Table 3.

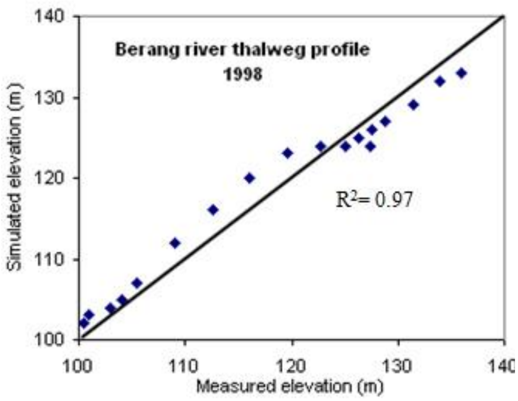
Table 3: Statistical Analysis for the GSTARS3 Model .

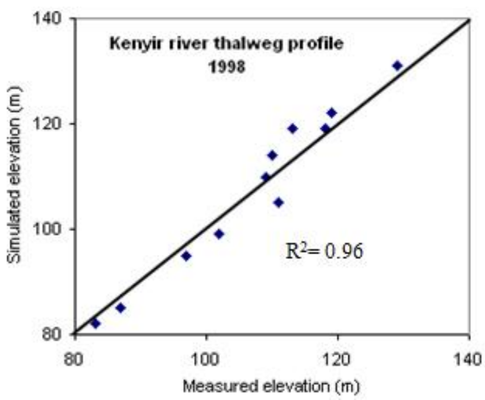
Location	MSE (m)	MAPE (%)	R^2
Berang River Thalweg	0.51	5.5	0.97
Berang Cross Section	0.91	7.5	0.97
Kenyir River Thalweg	0.55	6.2	0.96
Kenyir Cross Section	1.13	7.6	0.96

.

The results show that the error in simulation of the thalweg by GSTARS3 was low for Berang river compared with Kenyir river. For the thalweg simulation of Berang river the MSE is 0.51 m, MAPE is 5.5 % and coefficient of determination (R^2) is 0.97. For the thalweg simulation of the Kenyir river the MSE is 0.55 m, MAPE is 6.2 % and coefficient of determination (R^2) is 0.97. Although the simulation results for the lateral distance (cross section) has higher values for MSE and MAPE (Table 3), the model output is found to be in a good agreement with measured record in all location (thalweg and lateral distance) with an average error not exceed 10 %, less than 20 % was accepted by Yang (2002) when he simulated sediment deposition at Terbela reservoir in Pakistan for 22 years.

A graphical comparison that permit visualization of the performance of GSTARS3 in a form of scatter plot are shown in Figure 18 (a ,b, c and d). These plots demonstrate the accuracy of GSTARS3 model in predicting both thalweg and cross sections due to the sedimentation carried by Berang and Kenyir river.





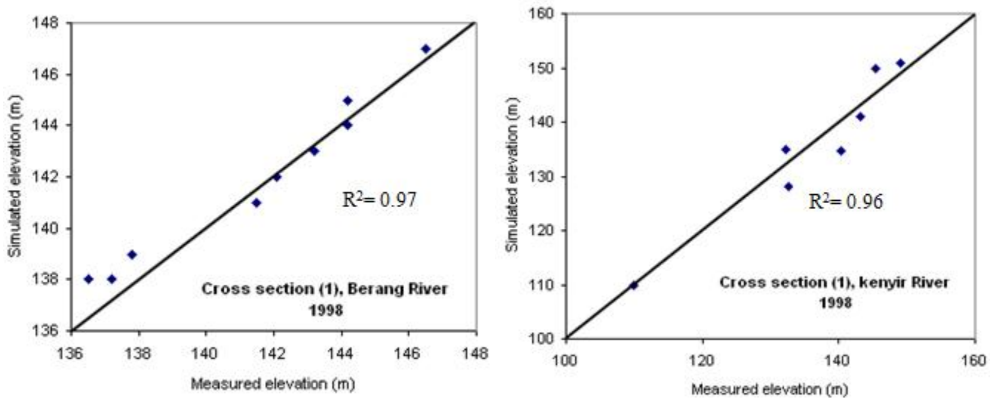


Fig. 18: Scattering for GSTARS model simulation, (a) Kenyir river thalweg, (b)Berang river thalweg, (c) Berang cross section, (d) Kenyir cross section.

Conclusion:

In this study, two models are combined, HEC-HMS and GSTARS3 to simulate the hydrological and sedimentation in the Kenyir reservoir, Terengganu, Malaysia. The variables and data used for the HEC-HMS to simulate the hydrograph are the rainfall data, soil type, land use, and stream flow. The results for HEC-HMS are used in the GSTARS3 model in addition to another data like grain size distribution, bed material, channel geometry, and roughness coefficient to simulate the sedimentation in Kenyir reservoir.

Figure 6 and Figure 7 show that the HEC HMS can be used to simulate the hydrograph for a gauged catchment with limited hydrological data. Table 2 gives the results of adjusting model parameters to achieve the best match between predicted and observed hydrographs.

Various statistical measures (MSE, MAPE and R^2) were used to test the simulated elevation by using GSTARS3 model. The results show a good agreement between the simulated and measured data with mean absolute percentage error (MAPE) ranges from 5.5 % to 7.5 %, mean square error (MSE) range from 0.51 m to 0.91 m, and coefficient of determination R^2 equal to 0.97 for Berang thalweg profile and main cross section, while for Kenyir river, (MAPE) ranges from 6.2 % to 7.6 %, mean square error (MSE) range from 0.55 m to 1.13 m, and coefficient of determination R^2 equal to 0.96 for thalweg profile and main cross section.

The data utilized are all from Department of irrigation and drainage, Ministry of Agriculture and Tenaga research Department. The calibration and validation for both stages of modeling were good and plausible.

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