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Modeling Sediment Accumulation at Kenyir Reservoir Using GSTARS3

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ABSTRACT
An attempt was made in this study to predict the Kenyir reservoir sedimentation deposition processes at Terengganu, Malaysia. The purpose of this study is to determine the amount and location of sediment accumulated since the start of the Kenyir dam operation. The assessment was undertaken using GSTARS3 sediment transport model, which was integrated with GIS to display the output as sequences of grids. ArcView was used to convert the GSTARS3 model output to Arc View GIS grid format. The study successfully integrated GSTARS3 and ArcView models. The study demonstrates the ability of the adopted methodology to visualize the accumulated sedimentation during the operation period of the Kenyir dam.

KEYWORDS: *Modeling, Sediment deposition, Reservoir, GSTARS3, ArcView.*

I. INTRODUCTION

Reservoir sedimentation can be a serious problem with many disadvantages. The control of reservoir sedimentation needs good instrumentations, trained man power and financial support (Simons and Sentürk, 1992). Sedimentation in a reservoir may affect hydropower generation due to the abrasion of turbines and other dam components (Morris and Fan, 1998). The efficiency of a turbine is largely depends upon the hydraulic properties of its blades. The erosion and cracking of the tips of turbine blades by water-borne sand and silt can reduces their generating efficiency and causing expensive repairs. Reservoir sedimentation also affects the benefits of navigation, water supply, and flood mitigation (Patrick, 1996).

Predicting the amount of sediment coming into a reservoir, its deposition, and its accumulation throughout the years are important for hydraulic engineering. Despite the advances made in understanding factors involved in reservoir sedimentation, predicting the accumulation of sediment in a reservoir is still a complex problem. Empirical models, based on surveys and field observations, have been developed and applied to estimate annual reservoir sedimentation load, accumulated reservoir sedimentation load, and accumulated reservoir sedimentation volume after a given number of years of reservoir operation (Morris and Fan 1998). Several mathematical models for predicting reservoir sedimentation have been developed based on the equations of motion and continuity for water and sediment such as those proposed by Thomas and Prashum (1977), Chang (1984), Molinas and Yang (1986), Hamrick (2001), Toniolo and Parker (2003), Andualem and Yonas (2008). Some of these 1D models have additional specific features such as the GSTARS which is developed Molinas and Yang (1986) based on the theory of minimum stream power (Yang and Song, 1986). GSTARS and it's modified and further improved GSTARS3 (Yang and Simöes, 2002) and GSTARS4 (Yang and Ahn, 2011) can be applied for the determination of optimum channel width and geometry for a given set of hydraulic and sediment conditions.

GSTARS3 sediment transport model was used in this study to predict sediment load from the watershed discharged to a reservoir. GSTARS3 and its modified versions were developed as generalized water and sediment-routing computer models for solving complicated river and reservoir engineering problems.GSTARS3 was applied by Yang and Simöes (2001) to simulate delta formation in a laboratory channel. GSTARS3 was also used to simulate sedimentation processes in the Rio Grand Reservoir, New Mexico, USA. The results for both applications show good agreements between simulated and measured results. Yang and Simöes (2002) also successfully applied the GSTARS3 model to simulate sedimentation and delta movement in the Terbela Reservoir in Pakistan. However, GSTARS3 has never been applied to simulate sediment movement in a reservoir located in tropical region.

Geographical information system (GIS) applications in water resources modeling have been increased in recent year to take advantage of the spatial data representation capabilities, (Molnar and Julien 1997), (Millward and Mersey 1999, (Baigorria and Consuelo 2006), (Fu. et al. 2004) and (Chen et al. 2005). In this study, GSTARS3 sediment transport model is integrated with Arc View to predict and visualize the pattern of sedimentation accumulation in the Kenyir Reservoir, Terengganu, Malaysia.

The Study Area

Kenyir Reservoir is the largest man-made lake in Southeast Asia. Kenyir dam and reservoir are designed for hydroelectric power generation and flood mitigation purposes. The dam is located at 50 km south west of Kuala Terengganu Malaysia, on the Terengganu River. The dam construction started in 1978 and completed in 1986. The dam operation started in 1987. One operational problem is the increase of sedimentation accomulation in front of the intake structure. This can be observed during extremely low water level. Murky water has been discharged from the turbines during the rainy seasons. At the same time, inflow of river waters from the Berang and Kenyir Rivers were observed to be high sediment load. There is a concern that in a few years sediments will start flowing into the turbines causing damages and outages which may be require expensive dredging (TNB Research, Malaysia, 2006).

II. METHODOLOGY

This study includes data collection, data preprocessing and model selection. The model selected for the catchment is calibrated and verified before any flow and sediment transport simulation is carried out.
The study demonstrates that GSTARS3 can be used to estimate sediment transport in rivers and inflow to the Kenyir Reservoir.

GSTARS3 model (Generalized Sediment Transport model for Alluvial River Simulation) has been used to address several specific issues in reservoir sedimentation. GSTARS has the ability to simulate and predict the hydraulic and sediment variation in both the longitudinal and transverse directions. GSTARS3 also has the ability to simulate and predict the change of alluvial channel profile and cross sectional geometry, regardless whether the channel width is variable or fixed.

III. DATA REQUIRED

Application of GSTARS3 computer model requires the use of appropriate data. The data has to be processed into ASCII data files so they can be recognized by GSTARS3. Figure 1 shows a flow chart for the application of GSTARS3 sediment model and its integration with ArcView.

3-1 Channel Geometry

The first step to model a river system using GSTARS3 involves the approximation of channels bed and geometry in a semi-two-dimensional manner. Channel cross sections are described by X-Y coordinate pairs, i.e., by pairs with lateral location (X) and bed elevation (Y). In this study, 18 cross sections were used to represent the Berang reach above the Kenyir Reservoir and 16 cross sections were used to represent the Kenyir reach above the Kenyir reservoir.

3-2 Hydrologic Data

The second step in GSTARS3 simulation is to incorporate hydrology data which are mainly the river reach and water stage. The hydrograph and rating curve can be used for this purpose. In this study, the model was run to simulate the progress of sediment accumulation in the Kenyir reservoir for 16 years (1991-2006). Sediment discharge from the Berang River and Kenyir River are included in the simulation. The selected period of simulation was divided into four 4- year intervals. Figures 2 and 3 show the hydrographs for Berang and Kenyir Rivers, respectively.

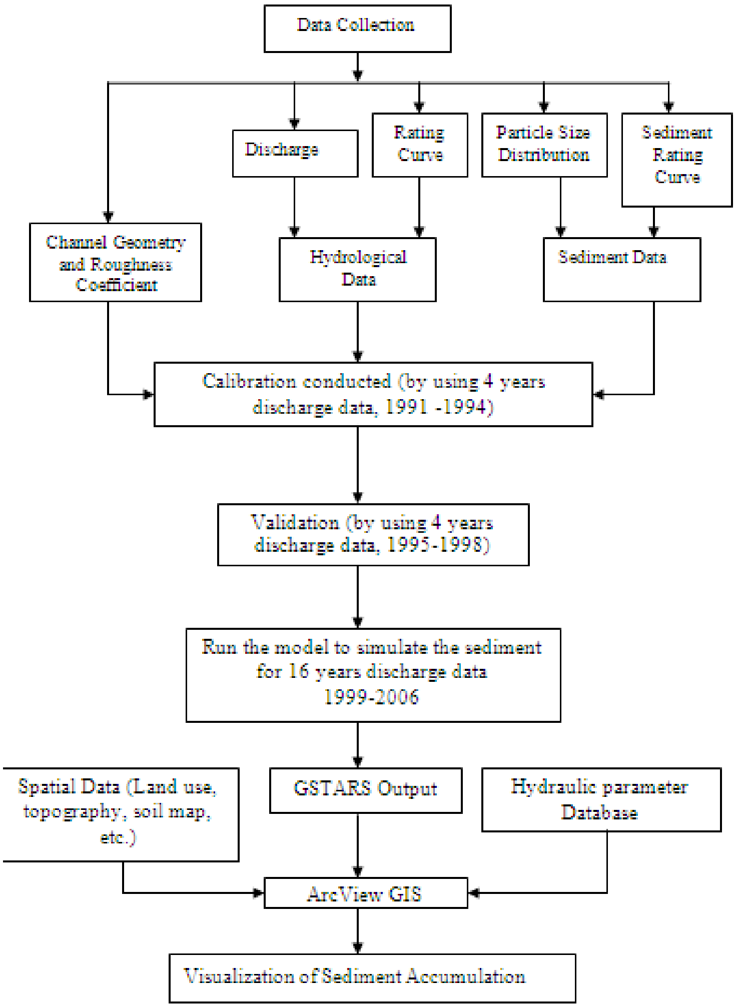


Figure 1: Flow chart for GSTARS3 sediment transport model integrating with ArcView

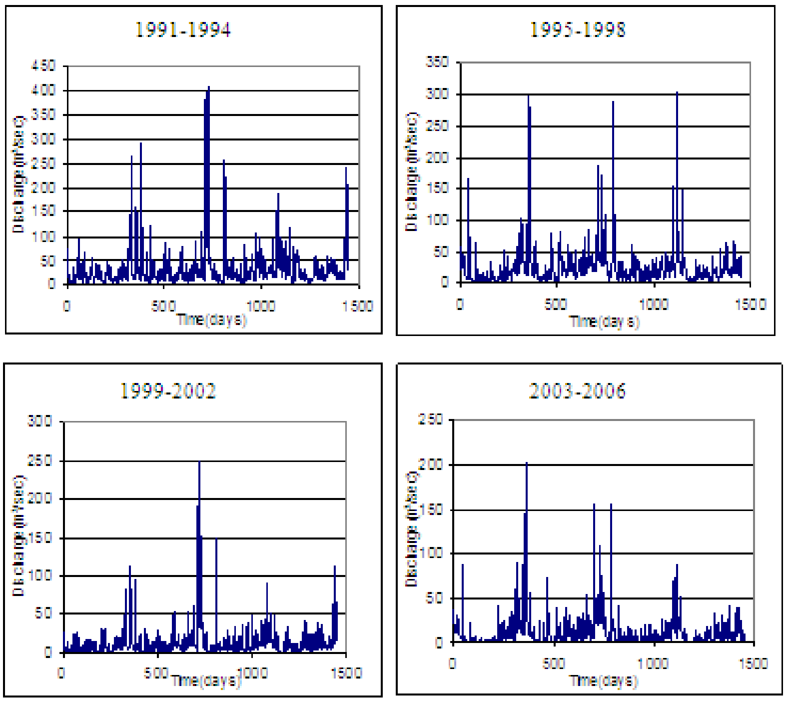


Figure 2: Discharge data of the Berang River for different periods

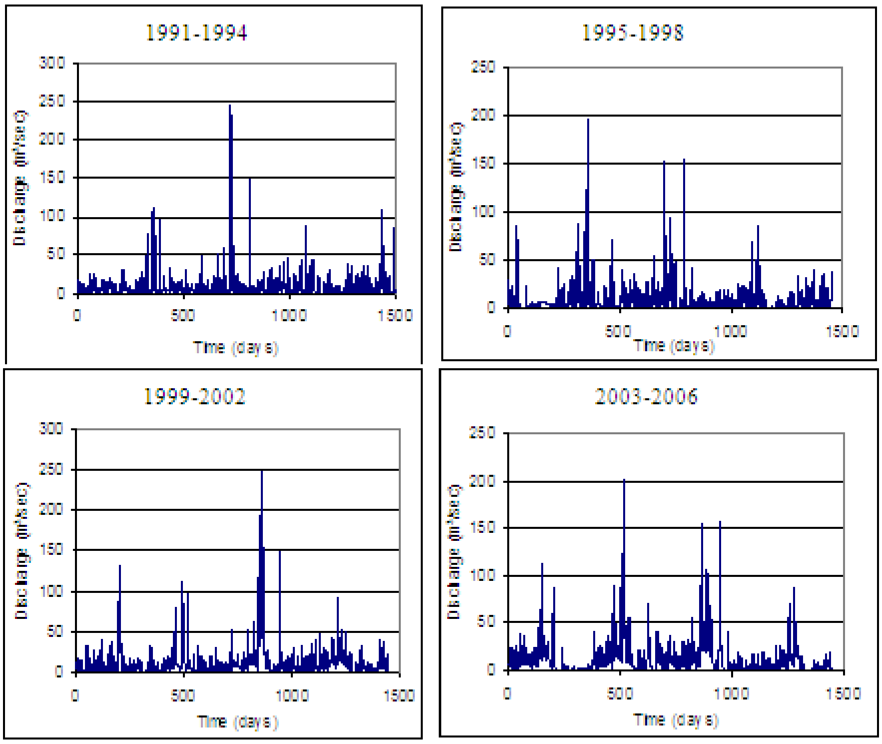


Figure 3: Discharge data of the Kenyir River for different periods

3-3 Sediment Data and Laboratory Work

Sediment data includes bed material size distribution for the reach of study and the sediment inflow hydrograph entering the reach. Sediment mixtures are characterized by gradation curves. Usually, bed graduation curve is used to define the nature of bed material. In this study, samples of sediment were collected from both Kenyir river and Berang river and the samples were taken to the laboratory in order to conduct grain size analysis.

Procedure for standard sieve analyses was followed in order to get the particle graduation. The retained sample fraction in each sieve is taken and weighted. The weighted fractions can be represented by a cumulative frequency curve that is made by plotting the sieve opening (grain size) versus a cumulative percent finer or coarser. Figures 4 and 5 show the grain size distributions for Berang and Kenyir basins, respectively.

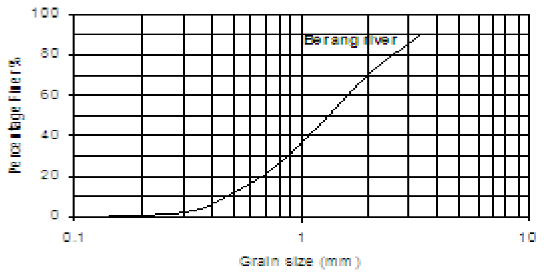


Figure 4: Grain size Distribution Curve for Berang basin

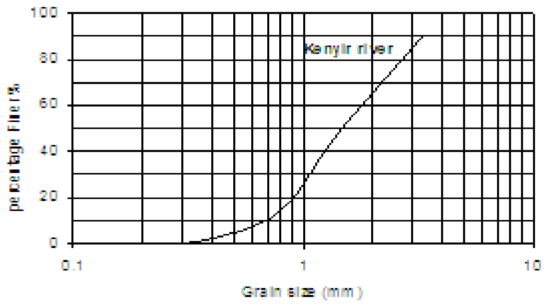


Figure 5: Grain size Distribution Curve for Kenyir basin

The incoming sediment discharge of Berang river and Kenyir river is specified as a function of water discharge described by the following relationship:

$$Q_s = 0.648\ Q \qquad \text{for Berang river} \qquad (1)$$

$$Qs = 0.4104\ Q \qquad \text{for Kenyir river} \qquad (2)$$

Sediment transport is computed using the Yang's sand (1973) and gravel (1984) transport Equations, respectively.

3- Calibration and Validation

GSTARS3 model was calibrated by employing the bathymetry data for the period from 1991 to 1994. For model calibration, a reasonable value for the Manning's roughness coefficient was selected. Figures 6 and 7 show the calibration for the Berang River thalweg profile and Kenyir River thalweg profile, respectively. The model was validated to evaluate its performance. This was achieved by using the parameters that were adjusted during the calibration. The bathymetry data from 1995 to 1998 was used for validation. Figures 8 and 9 show the validation for the Berang River and Kenyir River, respectively.

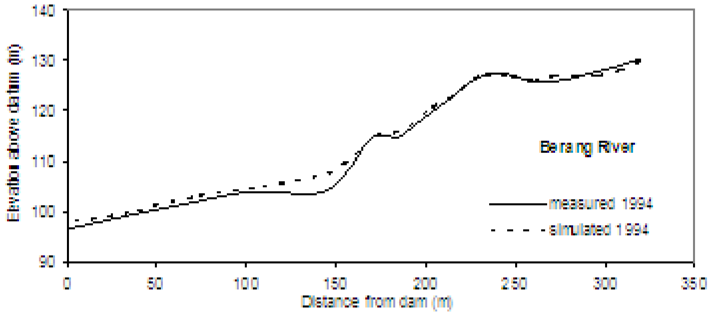


Figure 6: Calibration of the Thalweg for Berang River

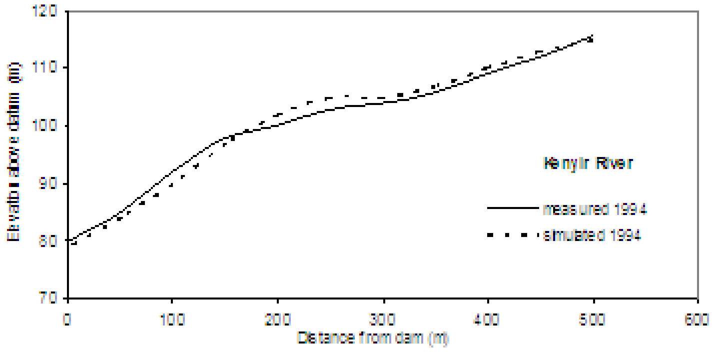


Figure 7: Calibration of the Thalweg for Kenyir River

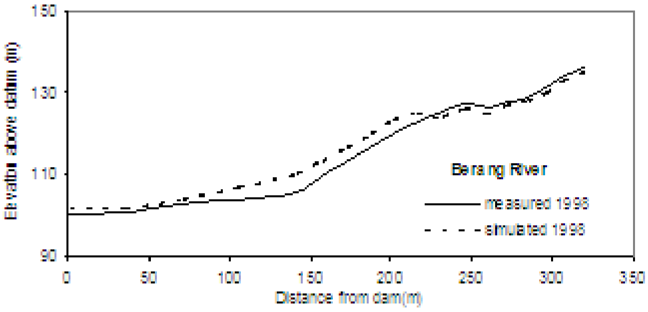


Figure 8: Validation of the Thalweg for Berang River

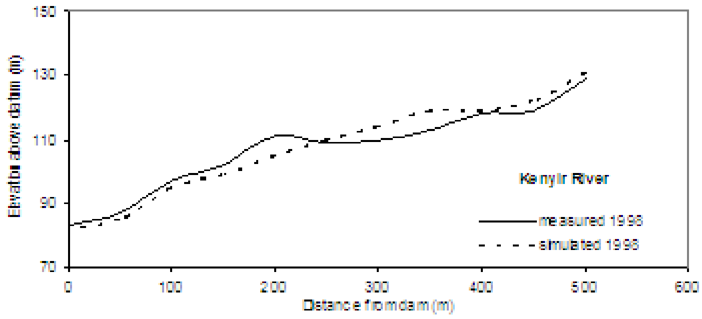


Figure 9: Validation of the Thalweg for Kenyir River

IV. STATISTICAL ANALYSES

Performance of the GSTARS 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 the use of MSE and MAPE for model assessment. MSE was used to measure the error in the model prediction while MAPE was used to measure the error in percentage. MSE and MAPE are defined as:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(Eli_{measured} - Eli_{simulated}\right)^2 \quad (3)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|Eli_{measured} - Eli_{simulated}\right|100 \quad (4)$$

where $Eli_{measured}$ is the measured bed elevation (m) obtained from the survey, $Eli_{simulated}$ is the simulated bed elevation (m) obtained from the model output, and N is number of data sets used.

V. RESULTS AND DISCUSSION

5-1 GSTARS Results

The performance of GSTARS3 sediment model was tested using MSE, MAPE, and R^2 for the Berang River and Kenyir River. For Berang river, the results show that the GSTARS3 sediment model gave a better fit and the same results were obtained for the Kenyir river. Tests for Berang river simulation results show that the value of the MSE is 0.51 m, MAPE is 5.5 %, and coefficient of determination (R^2) is 0.97. Also tests for the Kenyir River simulation results show that the values of the MSE is 0.55 m, MAPE is 6.2 % and coefficient of determination (R^2) is 0.96, as shown in Table 1. GSTARS3 simulation results show good agreement with the historical records of thalweg profile for both Berang and Kenyir rivers. The error between predicted and recorded thalweg was found to be less than 10 %. Error less than 20 % was acceptable by Yang (2000) when he compared the simulation results with historical record of Terbela reservoir in Pakistan. The simulations of bed elevation in both locations are shown in Figure 10 and Figure 11. The simulated and measured results were found in agreement.

Table 1: Statistical Analysis for the GSTARS3 Model

Location	MSE (m)	MAPE (%)	R^2
Berang River	0.51	5.5	0.97
Kenyir River	0.55	6.2	0.96

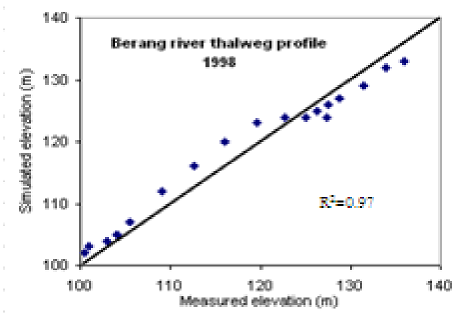


Figure 10: Comparison between the GSTARS3 model simulated and measured results along the Berang River thalweg

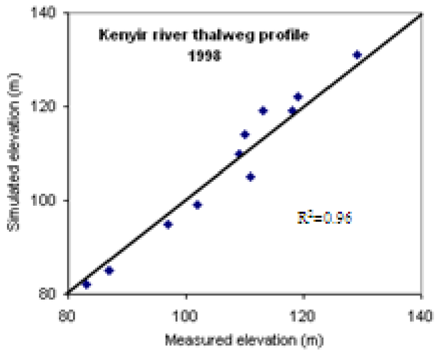


Figure 11: Comparison between the GSTARS3 model simulated and measured results along the Kenyir River thalweg

GSTARS3 program has the ability to determine the amount of sediment that exit the river reach and also to determine the sediment accumulation by size fraction. Based on GSTARS3 capabilities, amounts of sediment were simulated for every four years as shown in Figure 12. The sediment accumulation by particle size fraction for each reach was determined and shown in Table 2. It is noted that the amount of sediment exit from Berang river is greater than that exit from Kenyir river. The simulation results show that sediment rate was increased 62 % for Berang river and 38 % for kenyir river during sixteen years. However it is reasonable to compare it with Terbela reservoir in Pakistan, the sediment amounts that enter Terbela reservoir from 1976 until 1994 were equal to 1.01 $\times 10^{10}$ tons but Tapu reservoir in Thailand received 2.3×10^{6} tons of sediment from 1987 to 1990. Notably, these two reservoirs (Terbela in Pakistan and Tapu in Thailand) were modeled using GSTARS3 program

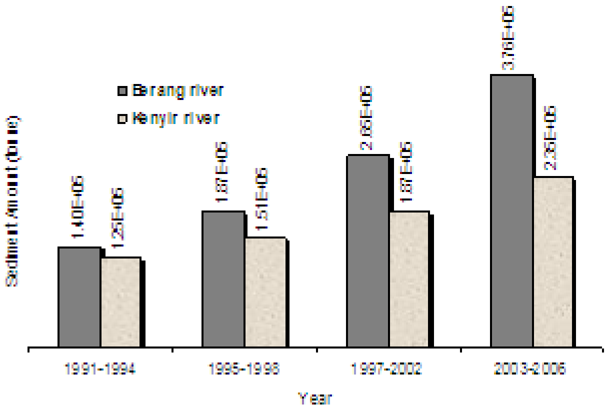


Figure 12: Sediment amount enter the reservoir from two rivers (Tonne)

Table 2: Sediment accumulation exit the reach by size fraction

Location	Year	Accumulative sediment exit the reach by size fraction (Ton)				
		Fine –Medium sand (0.12-0.24) mm	**Coarse sand (0.42-0.85) mm**	**Very coarse sand (0.85-2.0)mm**	**Very fine gravel (2.0-3.35) mm**	**Total**
Berang	1994	2.1×10^4	4.9×10^4	8.78×10^4	4.2×10^3	1.4×10^5
	1998	2.8×10^4	6.55×10^4	8.78×10^4	5.6×10^3	1.87×10^5
	2002	3.8×10^4	9.27×10^4	1.24×10^5	7.8×10^3	2.65×10^5
	2006	6.54×10^4	1.28×10^5	1.76×10^5	1.1×10^4	3.76×10^5
					Total	9.68×10^5
Kenyir	1994	8.75×10^3	5.0×10^4	4.0×10^4	2.6×10^4	1.25×10^5
	1998	1.06×10^4	6.04×10^4	4.83×10^4	3.17×10^4	1.51×10^5
	2002	1.3×10^4	7.48×10^4	6.0×10^4	4.0×10^4	1.87×10^5
	2006	1.64×10^4	9.4×10^4	7.52×10^4	4.93×10^4	2.35×10^5
					Total	6.98×10^5

4-2 Results of Integrating GSTARS with ArcView GIS

The important step in modeling process is to source out computed sediment and cross section geometry output generated from GSTARS3 model. Once the parameters shown in Figure 13 are imported into ArcView database format, various relationships can be established. Figure 13 shows the relationship between the control point in each cross section and the ArcView parameter table. Each point in the cross section has its coordinate (X-Y), distance from the dam location (Dis) and elevation (Ele).

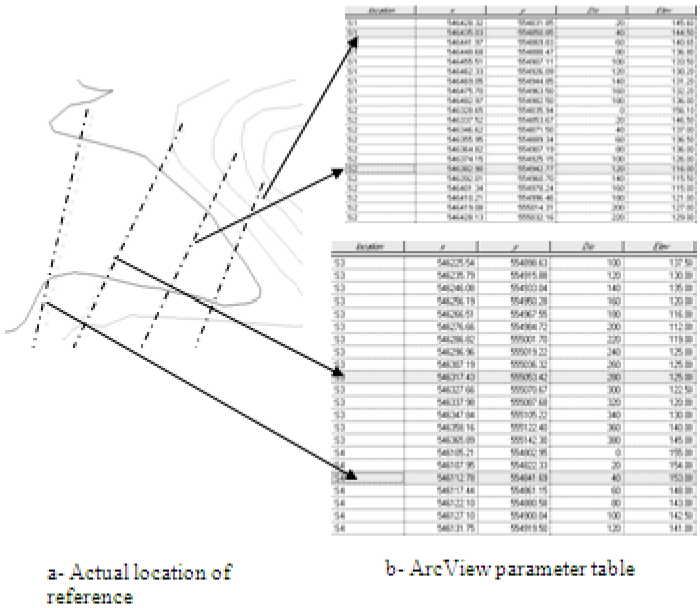


Figure 13: Relationship between map and imported parameter from GSTARS3 model at Kenyir Reservoir intersection with Berang River

An Integrated Triangular Irregular Network (ITIN) model was created by combining geometry information from GSTARS3 program with the extended contour line from outside modeling area. Figure 14 and Figure 15 show the changes in elevation with time for both Berang river and Kenyir river respectively. The elevation was made up of square cells which contain 250 rows and 350 columns and 54,518 cells and each cell represent an area of 14.45 m^2.

Figures 14 and 15 show that most of the sediment from Berang river was found deposited at the distance between 350 m to 210 m from the dam and that from Kenyir river was found at the distance between 500 m to 380 m from the dam. This may be related to the large amount of un-submerged and submerged vegetation that are exist at these two locations.

Figure 14 for Berang river show that the elevations of points at section (1) in the year 1991 range between 112 m to 146 m, this elevation started to increase to be range between 122 m to 146 m in the year of 2006, while the elevation of points at cross section (6) started to increase from the range between 112 m to 146 m in the year 1991 to be range between 132 m to 146 m in the year of 2006. The Figure also shows the change in the shape of cross sections according to the change of elevations. This will help in making the decision about the locations that are needed to be dredged.

Figure 15 shows that the elevation of points at cross section (1), Kenyir river, ranged between 109 m to 130 m in the year of 1991, then increased to be rang between 131 m to 146 m in the year of 2006. Cross section (8) has the same changes of elevation range. The Figure also shows the movement of sediment towards the dam starting from 1991 until 2006, this movement led to change the depth and shape of all section within the study area. It is also shown that the simulation of sediment deposition can be improved using Geographic Information System, and the sediment movement was successfully visualized within the channel boundary.

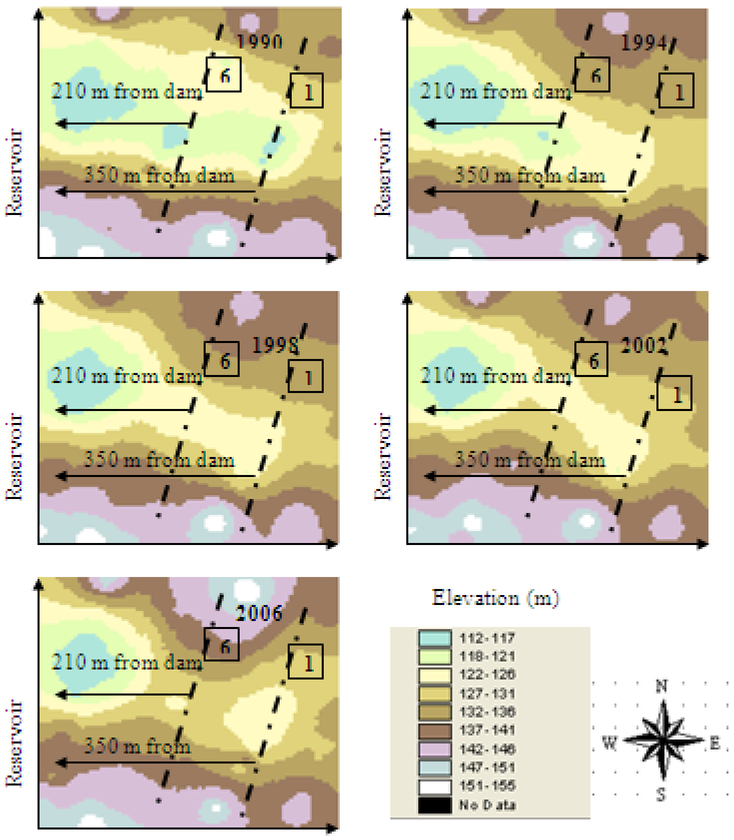
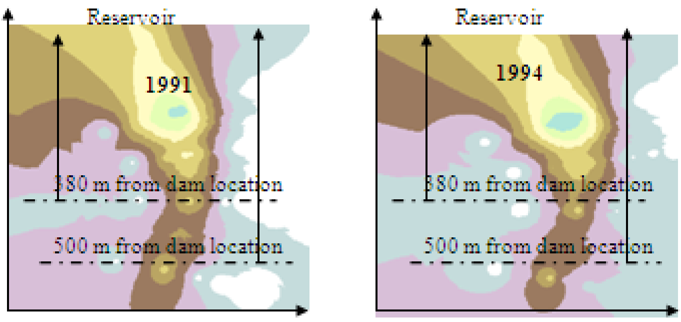


Figure 14: Elevation for Berang River at confluence point with Kenyir reservoir



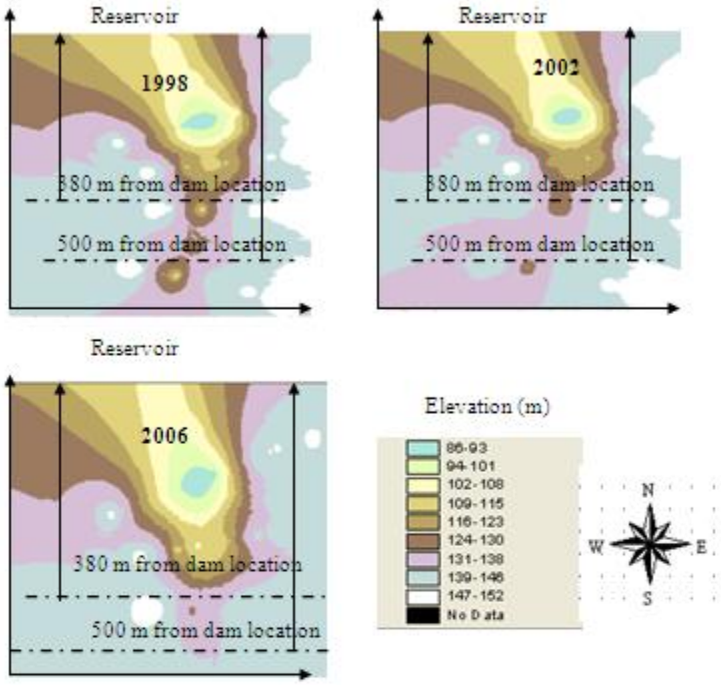


Figure 15: Elevation for Kenyir River at confluence point with Kenyir reservoir

VI. CONCLUSIONS

The main purposes of this study are:

(1) To simulate sediment inflow to the Kenyir Reservoir from Berang River and Kenyir River using GSTARS3 sediment transport model. Various statistical parameters (MSE, MAPE and R^2) were used to test the performance of GSTARS3 in simulating the amount of sediment accumulation. The results show that the simulation using GSTARS3 model were in agreements and the computed error was found to be 5.5 % for the case of Berang River and 6.2 % for the case of Kenyir River.

(2) To visualize the sediment accumulation in the Kenyir Reservoir and to identify the amount and location of sediment accumulation since the operation of Kenyir dam. GSTARS3 model was integrated with ArcView. It shows that the simulation of sediment accumulation can be improved using Geographic Information System. The sediment movement was successfully visualized within the channel boundary. Integrating GSTARS3 model with ArcView is a new technique for the management of reservoir sedimentation processes.

Two locations in Kenyir Reservoir were selected to demonstrate the success of integrating the GSTARS3 model with ArcView. These locations are at the confluences of Berang river and Kenyir river with Kenyir reservoir. GSTARS3 model was carried out separately to simulate the sediment deposition in Kenyir reservoir for the period from 1991 to 2006. The sedimentation rates from the two rivers are shown in Table 2.

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