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Sediment Transport in Kulim River, Kedah, Malaysia

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1. Introduction

Rivers are dynamic by nature; they adjust their characteristics in response to any change in the environment. These environmental changes may occur naturally, as in the case of climatic variation or changes in vegetative cover, or may be a result of human activities. Human factors influence channel changes, both directly by engineering projects including channelization, dredging, snag removals, dam construction and bridge construction, and indirectly through altering floodplain landuse such that erosion is more likely to occur during flood events more likely to occur during flood events (Ab. Ghani et al., 2010). These changes to river hydrology and sedimentation will in turn modify the channel morphology, which include changes to channel cross section, stability and capacity. Otherwise, hazard flood increases with the sedimentation and damages exceeded with muddy water. Consequently, it is necessary to study river channel behaviour and evaluate the river channel stability for its natural state and response to human modification due to the existing and future developments.

2. Study site

Kulim River catchment (Figure 1) is located in the southern part of the state of Kedah and in the northwestern corner of Peninsular Malaysia. Kulim River is a natural stream in Kedah state, Malaysia. Kulim River drains 130 km^2 of the surface area of southern part of the state of Kedah, is in the northwestern corner of Peninsular Malaysia. Kulim River emanates from the western slopes on Gunung Bangsu Range and flows in a north-westerly direction. The river slopes are steep and channel elevations drop from 500 meter to 20 meter above mean sea level (AMSL) over a distance of 9 kilometer. The central area of the catchment is undulating with elevation ranging from 100 meter down to 18 meter above mean sea level.
The study area has a tropical climate influenced by the movement of Inter-Tropical Convergence Zone. Its passage over the area results in two wet periods during the year which occur from April to May and from September to November. There is a transitional period of moderate rainfall during June to August and dry during December to March. Rainfall is generally convective and increase from around 2000 mm a year at the downstream to over 3200 mm a year on the mountainous area.
The Kulim River has experienced severe environmental damages, mostly related to significant erosion and sedimentation. Anthropogenic activities and natural events cause

changes in river morphology and stability of Kulim River. The human activity include the development to the year 2010 of Kulim district based on the Kulim Structure Plan, 1990-2010 (MDK, 1993), rapid urbanization at Kulim River catchment especially construction for housing state, the on-going 145 km² Malaysia's first and fully integrated Kulim Hi-Tech Industrial Park and river sand mining activities which may maximize the disturbance to river equilibrium and environment. Frequent flood occurrences in Kulim River catchment have significantly affected the community because of extensive damage in built up and agriculture areas especially the flood event in October 2003, which is an event slightly lower than the 100-year ARI based on the frequency analysis. Finally, these changes to the river hydrology and sedimentation will in turn alter the channel morphology, which can include changes to channel cross section, stability and capacity (Chang et al., 2005). The study reach covers about 14.4 km of Kulim River, from the upstream (CH 14390) to the state boundary between Kedah and Penang (CH 1900) and further downstream at the Ara Kuda gauging station (CH 0).

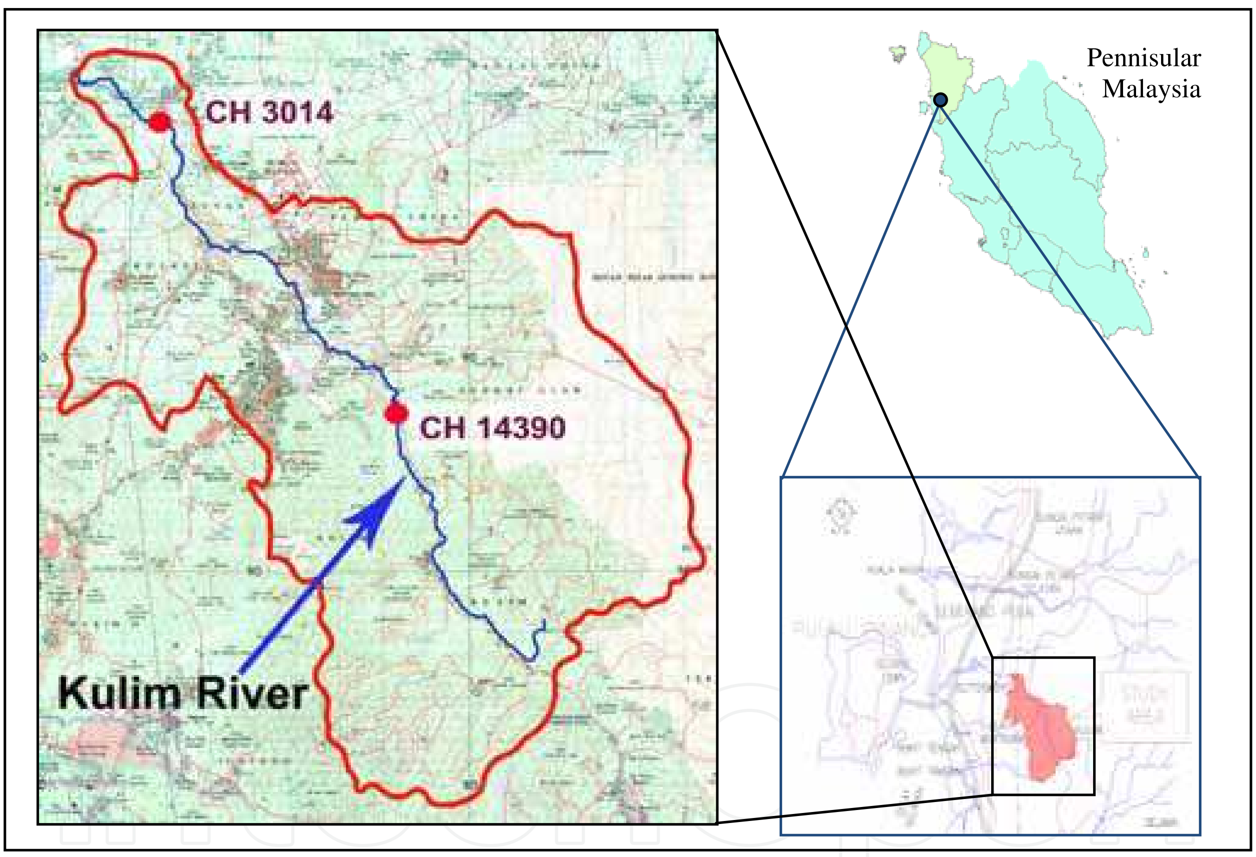


Fig. 1. Delineated Kulim River Catchment and Study Reach

3. Flood frequency analysis

The Kulim River benefited from 46-year period (1960–2005) of daily discharge measurements at Ara Kuda streamflow station, which include two major floods have occurred in 2001 and 2003 within the period. The annual peak discharges ranked in Table 1 indicate that the ten largest floods have been measured since 1961. This can be considered that the discharge of 92.90 m³/ s measured in 5 October 2003 is the highest during that period of record.

Rank	Discharge, Q (m^3/s)	Year	Date
1	92.90	2003	05-Oct
2	89.90	2001	22-Jan
3	67.90	1998	16-Nov
4	65.00	2000	22-Sep
5	62.30	1963	13-Nov
6	61.20	1999	05-Sep
7	58.50	2004	23-Sep
8	57.90	1962	21-Oct
9	56.90	1964	26-Sep
10	55.10	1987	09-Nov

Table 1. Flood Ranking for Kulim River at Ara Kuda

A flood frequency analysis was carried out for the 42-year period of streamflow data using Gumbel Extremal Type I. It was found that the result shows the better agreement to the measured streamflow data (Figure 2). The flood frequency analysis provided by the present study is also given in Table 2. It is therefore concluded that the 2003 flood discharge of 92.90 m^3/s is slightly lower than the 100-year peak discharge.

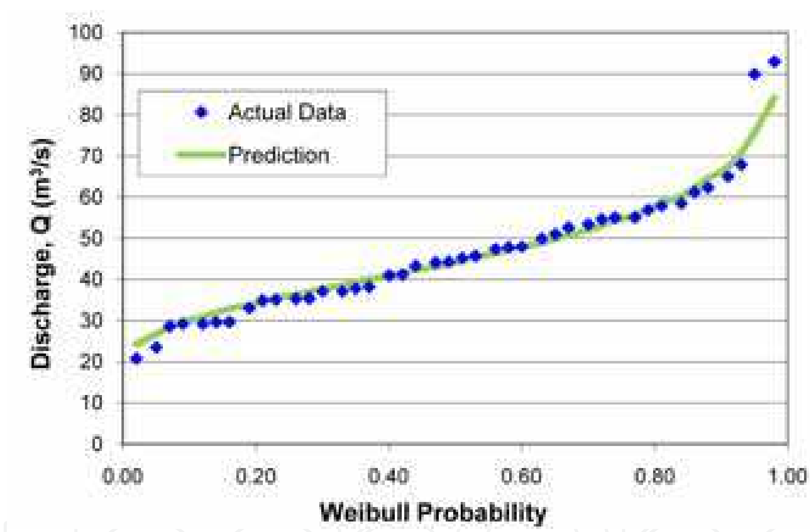


Fig. 2. Flood Frequency Analyses Using Gumbel Extremal Type I Distribution

Return Period	Discharge (m^3/s)
200	102.27
100	94.08
50	85.86
25	77.58
10	66.42
5	57.59
3	50.58
2	44.25

Table 2. Summary of Flood Frequency Analyses using Gumbel Extremal Type I

4. Sediment data collection and analysis

4.1 Field measurement

River surveys, flow measurement and field data collection provide the basic physical information such as sediment characteristics, discharge, water surface slope; which is needed for the planning and design of river engineering. In addition to the data needed for sediment transport studies, use of a sediment transport model also requires field data such as channel configuration before and after the changes, a flow record and sediment characteristics, which are generally used for test and calibration of a model. Field measurements were obtained at the selected cross sections (CH 14390 and CH 3014) from October 2004 to November 2006 along Kulim River by using Hydrological Procedure (DID, 1976; DID, 1977) and recent manuals (Yuqian, 1989; USACE, 1995; Edwards & Glysson, 1999; Lagasse et al., 2001; Richardson et al., 2001). The data collection includes flow discharge (Q), suspended load (T_s), bed load (T_b) and water surface slope (S_o). The water-surface slopes of the study reaches were determined by taking measurements of water levels over a distance of 200 m where the cross section was located (FISRWG, 2001). Besides that, bed elevation, water surface and thalweg (the minimum bed elevation for a cross section) measurement were also carried out at the selected cross sections. Details and examples of the measurement methodology for rivers in Malaysia can be found in Ab. Ghani et al. (2003) and DID (2009).

In this study, the water-surface slopes were found to be mild, where the average slope, S_o for CH 14390 and CH 3014 is 0.001 m/ m. Bed material samples were also collected at the selected cross sections including bank samples. This data were analyzed to determine the distributions of the mean sediment size or d_{50} and used to characterize the physical characteristics of the sediment responsible for sediment transport, which determines the river response in terms of erosion and deposition. Low sediment transport rate for Kulim River occurred during the field measurements. The mean sediment sizes show that Kulim River is sand-bed streams where d_{50} ranges from 1.00 to 2.40 mm.

A summary with ranges for hydraulics and sediment data collection is shown in Table 3 (Chang et al., 2008). The surveyed cross sections for the Kulim River show that it is a single

Study Site	CH 14390	CH 3014
No. of Sample	10	12
Discharge, Q (m^3/ s)	0.73 – 3.14	3.73 - 9.98
Bankfull width, TW (m)	25.0	50.0
Water surface width, B (m)	9.0 - 13.0	13.0 - 19.0
Flow depth, y_o (m)	0.20 - 0.54	0.36 - 0.58
Hydraulic radius, R (m)	0.23 - 0.57	0.40 - 0.63
Water surface slope, S_o	0.001	0.001
Mean sediment size, d_{50} (mm)	1.00 – 2.40	1.10 - 2.00
Manning *n*	0.029 - 0.072	0.024 - 0.037
B/ y_o	23.4 - 44.8	26.0 - 52.5
y_o/ d_{50}	126.9 - 369.01	240.0 - 550.9
R/ d_{50}	141.4 - 406.6	266.5 - 570.9
Bed load, T_b (kg/ s)	0.06 - 0.33	0.11 - 0.36
Suspended load, T_s (kg/ s)	0.02 - 0.27	0.03 - 1.21
Total load, T_j (kg/ s)	0.09 - 0.56	0.27 - 1.35

Table 3. Range of Field Data for Kulim River Catchment (Chang et al., 2008)

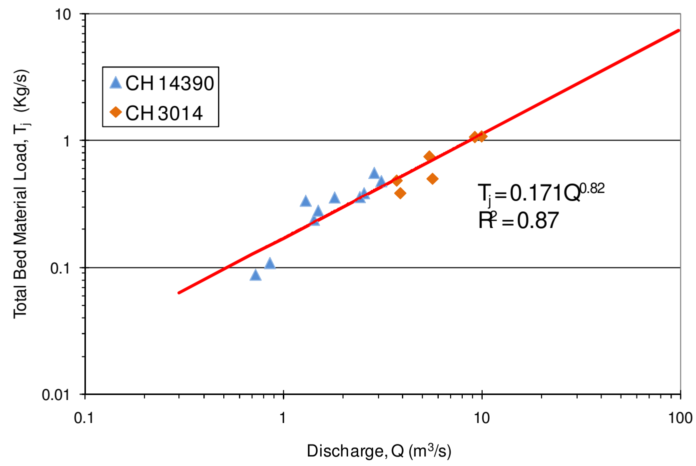


Fig. 3. Sediment Rating Curve along Kulim River

thread channel with the bankfull width ranging between 25 and 50 m, and aspect ratio (B/y_o) was between 23 and 53 indicating that it is a moderate-size channel. The total bed material load (T_j) is composed of the suspended load and bed load, representing the ability of the river to replenish the sediment and it must be specified for sediment transport, scour and deposition analysis. The measured total bed material load rating curves for these two sites at the Kulim River are illustrated in Figure 3. A mild curve is obtained for Kulim River indicating that a longer time is required for the replenishment before it is viable for sand extraction purpose. Therefore it is recommended that deposition should be allowed to occur first after a major flood before any river sand mining activity is allowed between these two sites. Based on the Table 1 and Figure 3, it is estimated that the 2003 flood with a discharge of 93 m^3/s will transport 7 kg/s of sand during the flood.

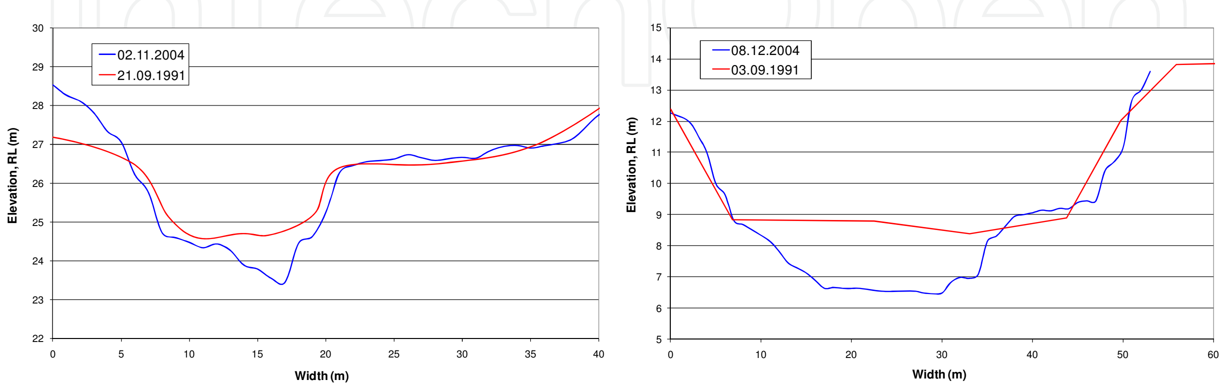
4.2 Channel morphology

Water and sediment transport through the Kulim River increase with time due to the reduction of river capacity that resulted from reclamation and sedimentation along the river. River bank erosion, river bed degradation, river buffer zone encroachment and deterioration of river water quality cause a serious and regular hazard in urban settlements at Kulim town. The powerful water currents wear away at the edges of these settlements during the wet periods and sometimes entire settlements established near the bank are washed away.
Figure 4 shows the channel planform modification along Kulim River due to an event slightly lower than the 100-year ARI flood during October 2003 at two urbanized areas of Kulim town and its surrounding areas. The main and most urbanized area of Kulim River pass the Kulim town and its surrounding. The channel widening can be observed in many locations along the Kulim River such as CH 10000, CH 12000 and CH 13500. The depositional areas are mainly located at the outer banks of meanders, while the erosion areas are at the opposite banks. These changes in channel river planform may cause extensive damages and inconvenience to the community (Sirdari, 2009).
Field measurements results including bed elevation, thalweg and water surface were carried out at several cross sections were compared to the river survey geometry data in September 1991. However, the comparison between cross sections provided by Department of Irrigation and Drainage (DID) and field measurement after October 2003 flood shows that there has been a change in cross section. The channel bed profile has gradually reduced

(a) CH 9000 – CH 11000 (b) CH 13000 – CH 14000

Fig. 4. Channel Planform of Kulim River (Sirdari, 2009)

within 13 years period, which proves that channel degradation occurred at most cross sections at Kulim River after the flood event (Chang et al., 2005). Thalweg at the CH 14390 has changed from 24.58 m to 23.50 ± 0.5 m and thalweg at the CH 3014 has changed from 8.38 m to 6.45 ± 0.5 m (Figure 5). From these results of cross section changes, it's shown that steep slope in Kulim River has induced higher discharge, and it was associated with the spatial variation in sediment transport and sediment size. The changes in river bed profile may be attributed to the erosion or deposition along the banks or the channel width. As a result, the study of changes in channel-bed profile, width variation and changes in bed topography, bank erosion, changes in channel degradation and aggradation, changes in channel curvature and river meandering were also carried out using sediment transport model.



(a) CH 14390 (b) CH 3014

Fig. 5. Cross Section Changes

4.3 Sediment transport equation assessment

The analysis for a total of 22 sets of data based on averaged size of sediment (d_{50}) have been obtained for nine sediment transport equations including five bed load equations namely Einstein bed load function (Einstein, 1942, 1950), Einstein-Brown's equation (Brown, 1950), Meyer-Peter-Muller's equation (1948), Shields' equation (1936), Duboys' equation (1879) and four total load equations namely Yang's equation (1972), Engelund-Hansen's equation (1967), Ackers-White's equation (1973) and Graf's equation (1971). The performances of the equations were measured using the discrepancy ratio (DR), which is the ratio of the predicted load to measured load (DR=predicted/ measured). In this study, a discrepancy ratio of 0.5 to 2.0 (DR = 0.5-2.0) was used as a criterion in the evaluation of the selected equations. However, the evaluation of these equations shows that all the existing equations, in most cases, over-predicted the measured values, as shown in Table 4. The result shows that Engelund & Hansen equations gives better prediction of measured data and yielded the highest percentage of data sets within discrepancy ratio of 0.5 to 2.0 at CH 14390 (50 %) and CH 3014 (41.67 %). The analysis also shows that all of the bed load equations gave unsatisfactory performance to predict the sediment load compared to total load equations.

Sediment Transport Equations	CH 14390		CH 3014	
	Total of Data	Total of Data Falls within 0.5-2.0	Total of Data	Total of Data Falls within 0.5-2.0
Einstein Bed Load Function (1942, 1950)	12	0	10	0
Einstein-Brown Equation (1950)		0		0
Meyer-Peter-Müller Equation (1948)		0		0
Shields Equation (1936)		0		0
Duboys' equation (1879)		0		0
Yang's equation (1972)		3		5
Engelund-Hansen equation (1967)		6		5
Ackers-White's equation (1973)		0		1
Graf equation (1971)		4		2

Table 4. Summary of Sediment Transport Assessment (Chang, 2006b; Ab. Ghani et al., 2007)

5. Sediment transport modeling

5.1 Software used

Studies of sediment transport, scour and fill, aggradation and deposition analyses can be performed by computer model simulation. The rapid pace of computer technology has been a milestone for mathematical models in sediment transport. As a result, the high demand on the models resulted in development of many models and the selection of the right model under certain constraints requires a comprehensive knowledge of the capabilities and features of available models. Recently, wide acceptance of a community sediment transport model would make the model a more effective tool for research, planning and design of river engineering, therefore numerous sediment models are available in the study of hydraulic and sediment transport modeling.

The review of capabilities and performance of sediment transport models has been discussed by the National Research Council (1983), Fan (1988), American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment (ASCE, 1998), Federal Interagency Stream Restoration Working Group (FISRWG, 2001) and Department of Water Resources, Resource Agency State of California (DWR, 2004). In addition, applications of the several commonly used sediment transport models have been described by Ab. Ghani et al. (2003) and Chang (2006b). These applications illustrate various capabilities of different models and each sediment transport model has its own limitations. The selection of the right model under certain constraints requires a comprehensive knowledge of the capabilities and features of available models.

The sediment transport model, FLUVIAL-12 (Chang 1982, 1984, 1988), which was first developed in 1972, has been selected for the Kulim River study. FLUVIAL-12 is developed for water and sediment routing in natural and man-made channels. The combined effects of flow hydraulics, sediment transport and river geomorphic changes are simulated for a given flow period. FLUVIAL-12 model is an erodible-boundary model that includes the width adjustment component, which simulates inter-related changes in channel-bed profile, width variation and changes in bed topography induced by the channel curvature effect. Besides that, bank erosion, changes in channel curvature and river meandering can also be modeled (Chang, 2006a).

The applicability of the FLUVIAL-12 model for the river channel responses under its existing conditions and proposed conditions in response to human intervention and the environmental impacts has confirmed by Chang et al. (2002), where FLUVIAL-12 simulations were made based on a 100-year flood as well as a long-term flood series. Besides that, several case studies of FLUVIAL-12 model applications as discussed by Chang (2006b) and Chang et al. (2008) also showed that FLUVIAL-12 was capable to predict river changes caused by nature and human activities, including general scour at bridge crossings, sediment delivery, channel responses to sand and gravel mining and channelization. Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time (Chang, 2006a).

5.2 Model input and output

The study reach covers approximately 14.5 km of Kulim River, from the upstream (CH 14390) to the Ara Kuda streamflow station (CH 0). The inputs to the FLUVIAL-12 model are described in detail in FLUVIAL-12 Users Manual (Chang, 2006a).

The geometry data consists of existing survey cross-sections in September 1991 between CH 1900 to CH 14390 at the upstream of Kulim River. However, the survey of CH 0 cross section in December 1995 was provided by DID Hydrology Division for the FLUVIAL-12 modeling requirement. In this study, a total of 120 existing survey cross sections were selected along the study reach to define the channel geometry as the input for FLUVIAL-12 model. FLUVIAL-12 has been used to simulate the channel geometry, lateral and vertical elevation changes for the flood events from 1991 to 2006.

The input hydrograph at Ara Kuda for year 1991 (Figure 6) was used for model sensitivity analysis whilst model calibration and validation was using the hydrograph from year 1991 to June 2006 (Figure 7). The rating curve which is used to define discharge variation of stage (water surface elevation) for the downstream boundary condition is shown in Figure 8; the

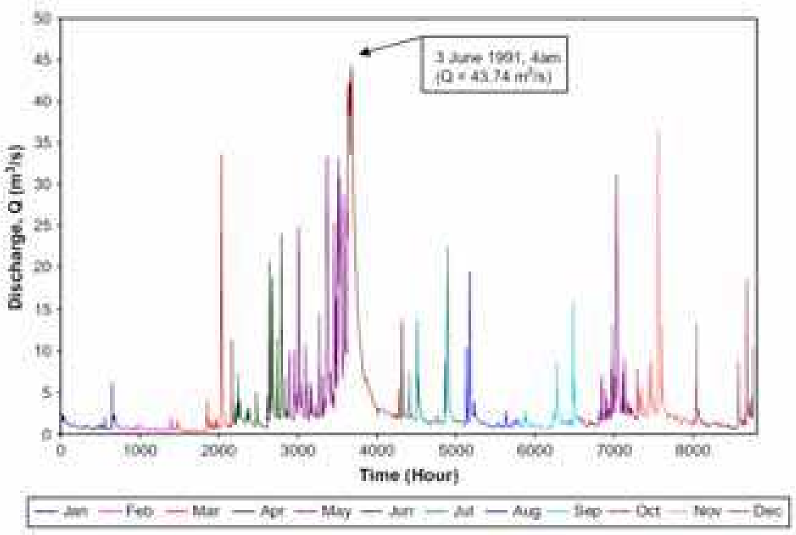


Fig. 6. Input Hydrograph for Year 1991

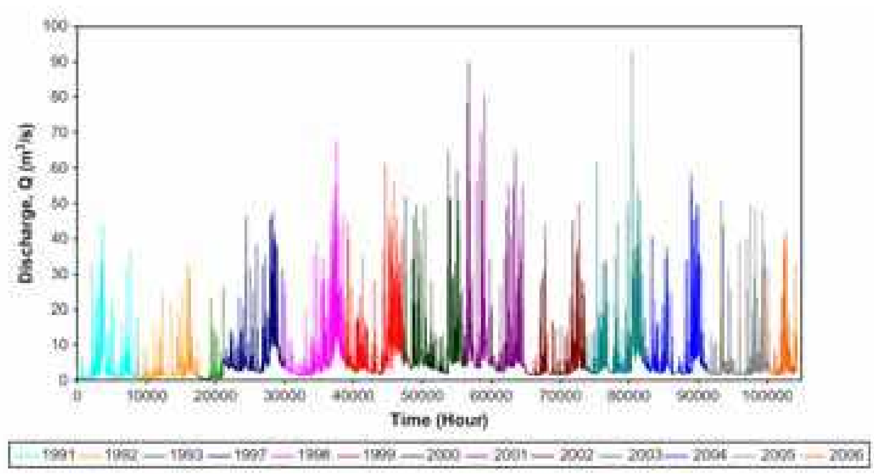


Fig. 7. Input Hydrograph for Year 1991 to June 1993, 1997 to June 2006

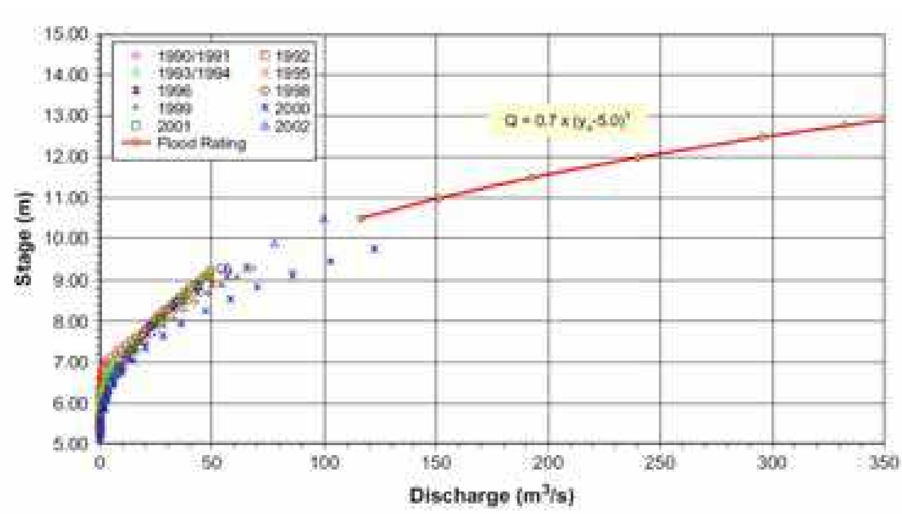
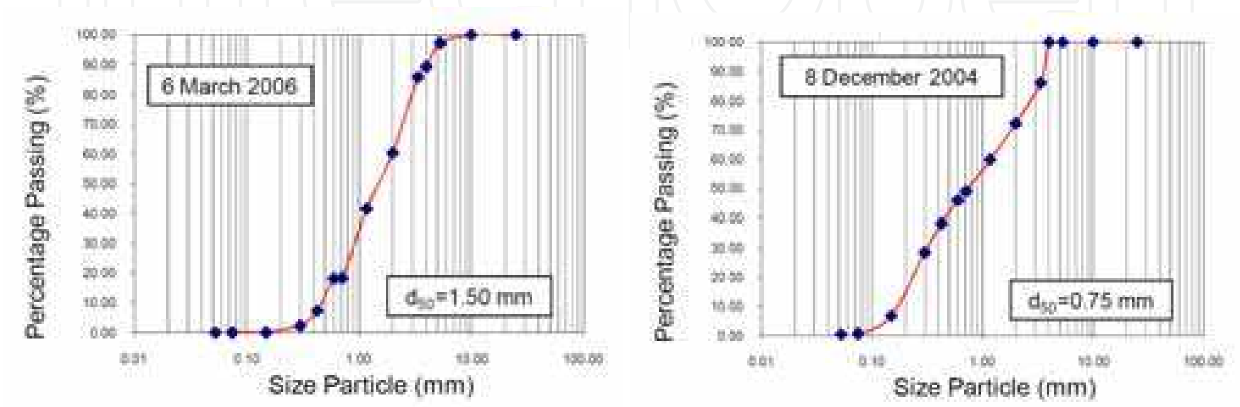


Fig. 8. Flood Rating Curve at Ara Kuda (CH 0)

shifts in stagedischarge relationships reflect the variability at Ara Kuda streamflow station derived from the past 12-year rating curve for Kulim River. The geometric mean of the bed material size fractions is adequately described from the sediment size distribution. Two sediment size distributions of such samples based on sieve analysis are required at the upstream (d_{50} = 1.50 mm) and downstream (d_{50} = 0.75 mm) cross sections to specify initial bed material compositions in the river bed (Figure 9). These input data, can be grouped into the categories of geometry, sediment and hydrology. A summary of the input and output parameter for each category is shown in Table 5.



(a) Upstream (CH 14390) (b) Downstream (CH 3014)

Fig. 9. Initial Bed Material Size Distributions

Category	Category	Parameter	Value	Source
Input Parameter	Geometry	Cross section	per section (Total of cross sections = 120)	CH 1900 – CH 14390 (DID 1991 Survey) CH 0 (DID 1995 Survey)
		Reach lengths	per section (Total length = 14.4km)	1991 (DID 1991 Survey)
		Roughness coefficient	Same by cross section (n = 0.020, 0.025, 0.030, 0.035, 0.040 were evaluated during the sensitivity analysis)	Values static at all levels of flow.
		Radius of curvature	per section	1991 (DID 1991 Survey)
	Sediment	Sediment samples	2 sediment size distributions of such samples are required (upstream and downstream section)	Data sampling at CH 14390 (Year 2006) and CH 0 (Year 2004)
		Regular non-erodible bank	Generally fix at left and right bank, varies by cross section	DID 1991 Survey
		Sediment transport formula	Seven sediment transport formulas were evaluated during the sensitivity analysis	Graf's sediment formula (1971) Yang's unit stream power formula (1972) Engelund-Hansen sediment

				formula (1967) Parker gravel formula (1982) Ackers-White sediment formula (1973) Meyer-Peter Muller formula (1948) Singer-Dunne formula (2004)
		Specific Gravity	2.65	Default (Soulsby, 1997)
	Hydrology	Discharge hydrograph	Varies by hydrograph	Historical hydrograph for Kulim River at Ara Kuda streamflow station Design Hydrograph from past study (DID, 1996)
		Rating Curve	Year 1991 to Year 2002	Developed by DID Hydrology Division
Output parameter	Geometry	Width	Changes over time in water surface, bed elevation and thalweg profiles. Simulation of curvature induced aggradation and deposition.	
		Depth		
		Cross-sectional area		
		Slope		
	Sediment	Mean sediment size (d_{50})	Changes over time in sediment transport, channel scour and fill, aggradation and degradation	
		Bed material size fractions		
		Sediment concentration	Sediment delivery or the total bed material yield during the study period	
		Sediment yield		
	Hydraulic	Water surface	Simulated water surface based on input hydrograph	
		Mean velocity	Flow data sets for representative cross sections in the study reach	
		Froude number		

Table 5. Summary of Input and Output Parameter for FLUVIAL-12 in Present Study (Chang et al., 2008)

5.3 Sensitivity analysis

An analysis was conducted to evaluate the sensitivity of the modelling results to changes in input parameters. To determine the sensitivity of FLUVIAL-12, which including flow, sediment transport and the channel geomorphic changes caused by the variation of each parameter, different values of the parameter were used in simulation runs and the results obtained are compared. Sensitivity analysis is an important step to be taken for more effective use of a model. Major items that required sensitivity test include roughness coefficient, sediment transport equations, channel curvature and number of cross section (reach length between two sections). This sensitivity analysis was carried out using the existing survey cross section and hydrograph for the year of 1991. However, the accuracy of the model is limited to the quality and quantity of the input data. Therefore, using available hydraulic and hydrology data including cross section spacing will affect the quality of the output data. Besides that, selection of the sediment transport formula and model calibration for roughness coefficient are also essential. Table 6 shows the summary of the sensitivity analysis for Sungai Kulim using FLUVIAL-12.

Parameter	Values Tested	Comments
Roughness Coefficient	Range: 0.020 – 0.050	Started out with values recommended in the 0.020. Some values were then changed. Water Surface is increasing when roughness coefficient increasing.
Sediment Transport Equation	7 sediment transport equations	All equations were tested due to field observation. Selection of the proper and applicable sediment transport formula is essential.
Channel Curvature	Zero curvature and curvature	Simulation of curvature induced aggradation and deposition in the model based on the flow curvature.
Number of Cross Sections	120, 62 and 32	Shortened distance between cross section or closely spaced along a reach produce more accuracy result in channel geometry changes.

Table 6. Summary of Sensitivity Analysis

5.4 Model calibration and validation

The simulation of the FLUVIAL-12 was obtained using 1991 cross section survey and hydrograph. Based on measured water levels, predictions using both roughness coefficients are close to the observed data during low flow. However, as the field data was not available from year 1991 to 2003, a long-term simulation has been carried out to calibrate and validate the model based on the recent measured water level and bed level data that were obtained from 2004 to 2006. Therefore, the calibration of the roughness coefficient using measured water level and bed level in November 2004 is done. As a part of the calibration procedure, the model was run for 12-year period between 1991 to 1992 and 1997 to 2006.

The results of the model simulation during the calibration period agree very well (Table 7 and Figure 10), and it can be concluded that prediction using roughness coefficient n = 0.030 and Engelund-Hansen formula were in good agreement with measured water levels and bed profiles and used for model validation. As a part of validation, measured water levels and bed profiles, during September 1991, January 2005 and March 2006 was compared to the predicted water levels and bed profiles by FLUVIAL-12 (Table 8). Longterm simulations including of the historical flood events showed very good results for both calibration and validation. Good agreements were obtained for both water level and bed levels between the measured and predicted by FLUVIAL-12 model.

Roughness coefficient *n*	Location	Water Level (m)					Thalweg Level (m)				
		Measured	Yang fomula		Engelund-Hansen fomula		Measured	Yang fomula		Engelund-Hansen fomula	
			Predicted	Difference	Predicted	Difference		Predicted	Difference	Predicted	Difference
0.025	CH 0	7.45	7.80	+0.35	7.80	+0.35	5.05	5.34	+0.29	5.29	+0.24
	CH 3014	8.61	8.14	-0.47	8.13	-0.48	6.66	6.79	+0.13	6.96	+0.30
	CH 8185	13.55	12.47	-1.08	13.67	+0.12	12.27	11.68	-0.59	12.85	+0.58
	CH 14390	25.61	26.00	+0.39	25.99	+0.38	23.45	24.58	+1.13	24.58	+1.13
0.030	CH 0	7.45	7.80	+0.35	7.82	+0.37	5.05	5.40	+0.35	5.27	+0.22
	CH 3014	8.61	8.36	-0.25	8.29	-0.32	6.66	6.57	-0.09	6.69	+0.03
	CH 8185	13.55	13.00	-0.55	13.36	-0.19	12.27	11.87	-0.40	12.16	-0.11
	CH 14390	25.61	26.17	+0.56	26.14	-0.53	23.45	24.58	+1.13	24.58	0.00
0.035	CH 0	7.45	7.80	+0.35	7.93	+0.48	5.05	5.33	+0.28	5.26	+0.21
	CH 3014	8.61	8.59	+0.02	8.52	-0.09	6.66	7.30	+0.64	7.53	+0.87
	CH 8185	13.55	13.55	0.00	13.45	-0.10	12.27	12.26	-0.01	12.31	+0.04
	CH 14390	25.61	26.20	+0.59	26.29	+0.68	22.85	24.58	+1.73	24.58	+1.73

Table 7. Comparison of Simulated Water Level and Bed Profile with Measured Data during 2 Nov 2004 for Roughness Coefficient n = 0.025, 0.030 and 0.035 (Chang et al., 2008)

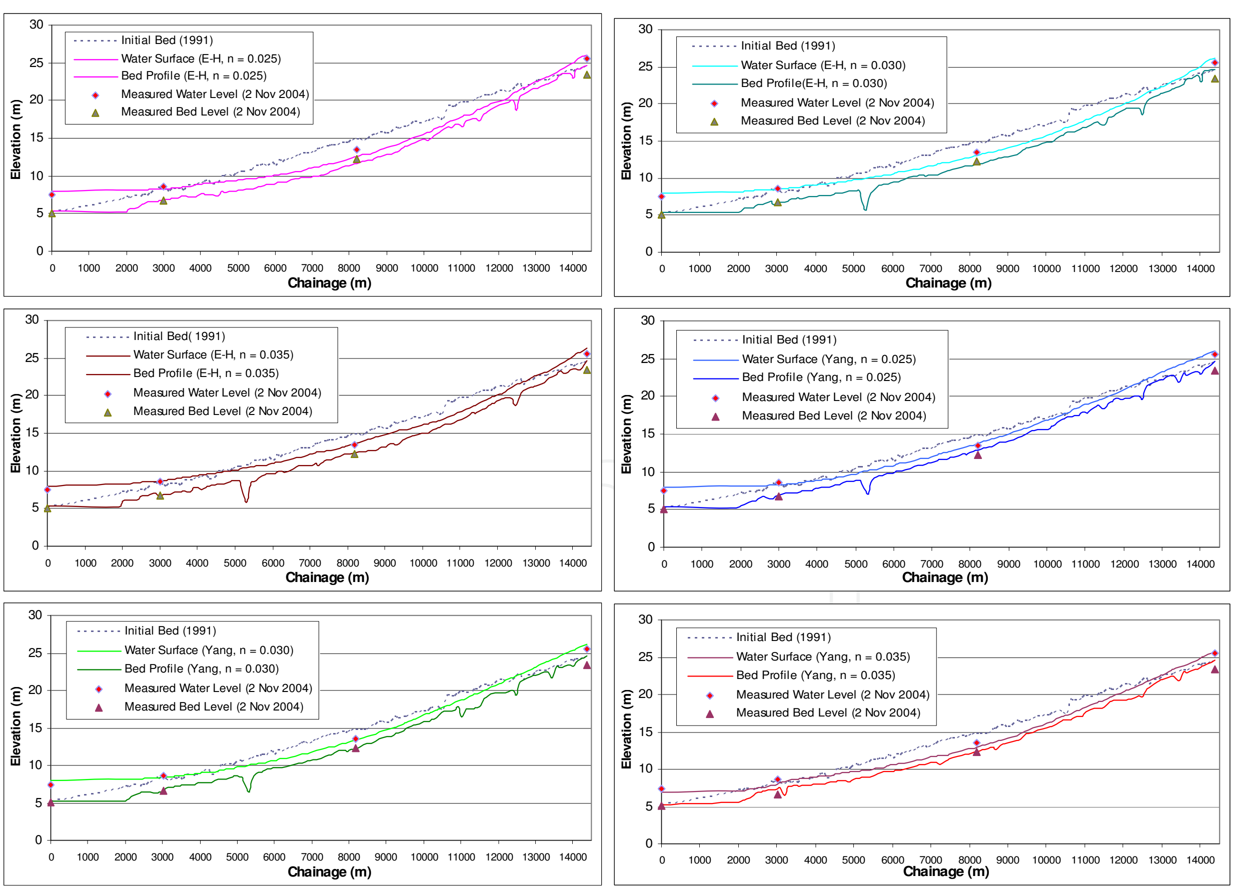


Fig. 10. Comparison of Water Level and Bed Profile for Roughness Coefficient n = 0.025, 0.030 and 0.035 (2 Nov 2004)

Date	Location	Water Level (m)			Thalweg Level (m)		
		Measured	Predicted	Difference	Measured	Predicted	Difference
20 September 1991	CH 0	6.40	6.00	-0.40	5.05	5.34	+0.29
	CH 10195	18.25	18.07	-0.18	6.66	6.79	+0.13
	CH 10438	18.53	18.39	-0.14	12.27	11.68	-0.59
	CH 14091	24.84	24.67	-0.17	23.45	24.58	+1.13
	CH 14206	24.86	24.80	-0.06	N/ A	N/ A	N/ A
11 January 2005	CH 0	6.10	6.09	-0.01	5.20	5.26	+0.06
	CH 10195	7.03	7.19	+0.16	6.50	6.59	+0.09
	CH 10438	17.32	17.14	-0.18	16.81	16.91	+0.10
	CH 14091	24.52	25.09	+0.57	23.42	24.58	+1.16
8 March 2006	CH 0	5.90	5.96	+0.06	5.20	5.27	+0.07
	CH 10195	7.38	7.05	-0.33	6.48	6.46	-0.02
	CH 10438	24.36	24.99	+0.63	24.04	24.58	+0.54
	CH 14390	25.61	26.20	+0.59	22.85	24.58	+1.73

Table 8. Comparison of Simulated Water Level and Bed Profile with Measured Data

5.5 Model simulation

Engelund-Hansen formula and roughness coefficient n = 0.030 were found to be the best combination to represent the sediment transport activity in the study reach throughout the model calibration and validation. The sediment transport modeling was conducted based on three scenarios. These include the existing condition modeling using October 2003 flood hydrograph, future condition modeling by using the design flood hydrograph for the Kulim River based on 2010 landuse (DID, 1996) and long-term modeling by relicensing the time frame using hydrograph for year 1991-1992 and 1997-2006 to predict future ongoing changes for the next 10 years.

The peak discharge of 92.90 m^3/s measured on 5 October 2003, which was the highest discharge measured in a 42-year period since 1960 is adopted as the design peak discharge for existing condition. Consequently, sediment transport modeling was carried out for this flood event (3 to 19 October 2003) as shown in Figure 11. Spatial variations of the sediment delivery during the October 2003 flood are shown in Figure 12. Sediment delivery generally decreased towards downstream especially near to the river sand mining site at CH 5064. This pattern indicated that erosion occurred at upstream and more sediment deposited at downstream of Kulim River.

Peak water surface and changes of the channel geometry due to scour and fill were depicted by the simulated changes in channel bed profile as illustrated in Figure 13. From the simulation results, flood level was higher at the downstream compare to the upstream of Kulim River. Whilst, the results also show that scour of the bed occurred at upstream and the cross sections near to the sand mining area (CH 5064) were subjected to greater changes than other cross sections. Commonly, channel degradation was predicted at most cross sections at Kulim River after the flood event.

Figure 14 shows the sediment transport rates at peak discharge during 2003 flood along the river. Figure 15 shows the example of cross section changes for several locations along Kulim River. In general, the river is stable at most locations after October 2003 flood with the exception of CH 5306 and CH 12490 where lateral migration is predicted at these two locations.

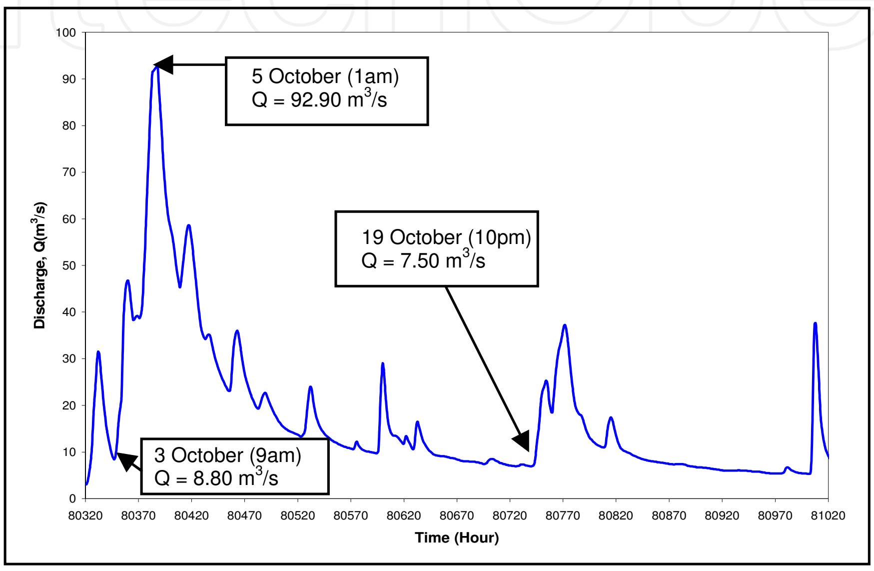


Fig. 11. Hydrograph of the October 2003 Flood at Ara Kuda (CH 0)

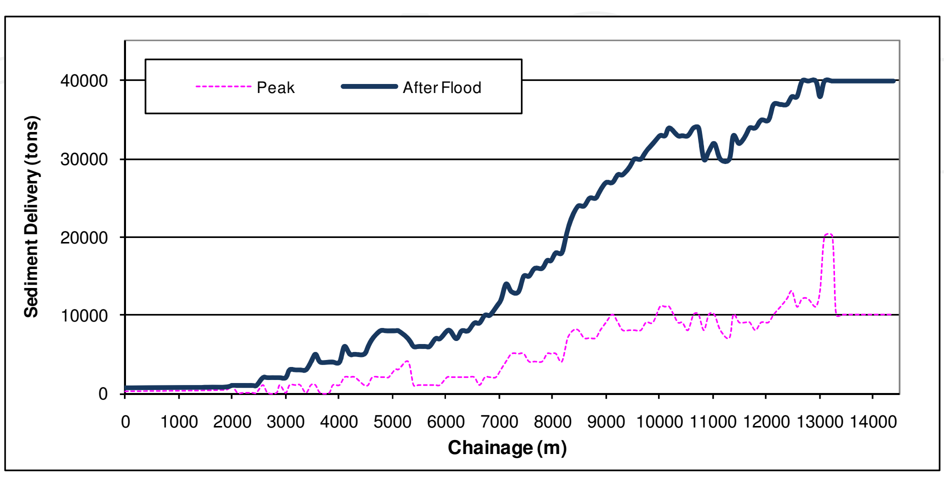


Fig. 12. Spatial Variations of the Sediment Delivery during the October 2003 Flood

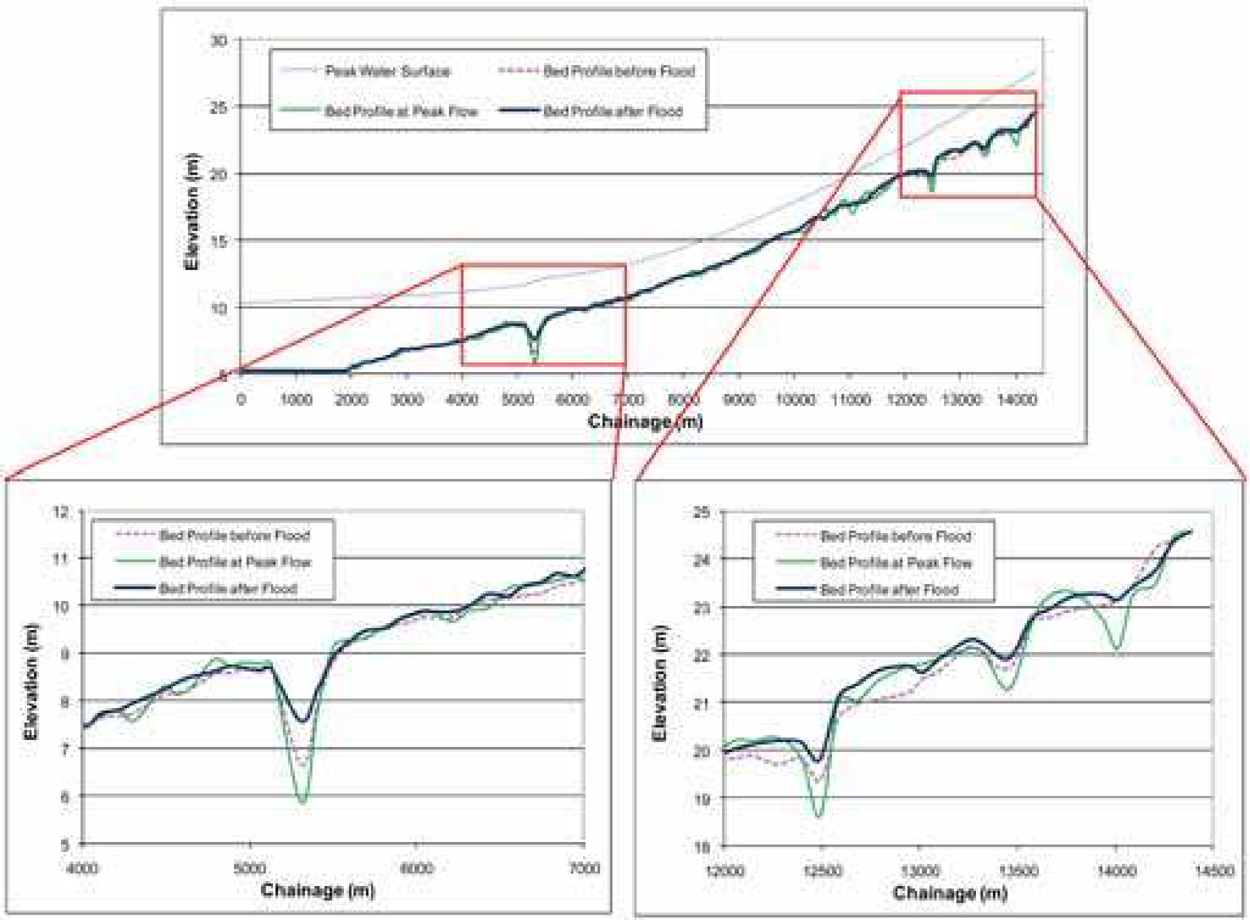


Fig. 13. Prediction of Water surface and Bed Profile Changes during October 2003 Flood

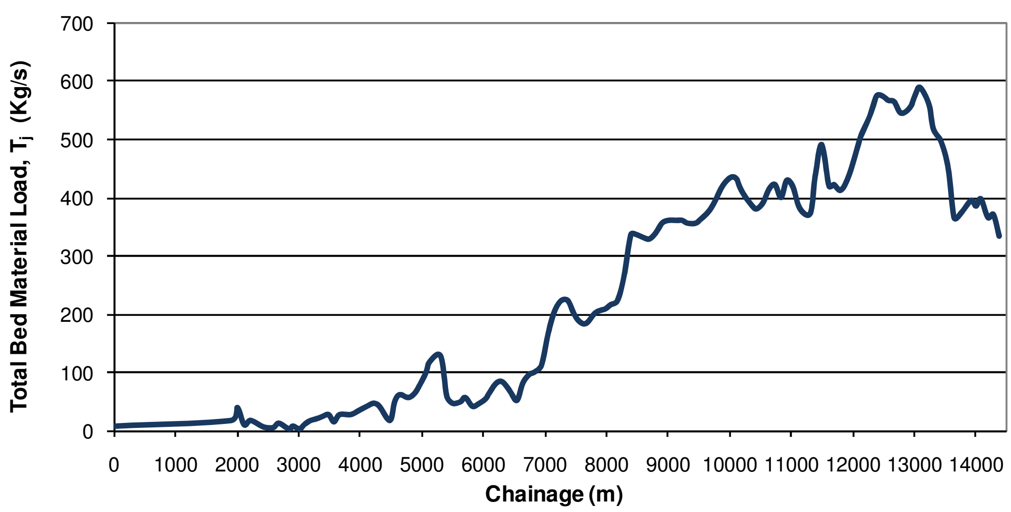


Fig. 14. Sediment Transport Rate at Peak during October 2003 Flood

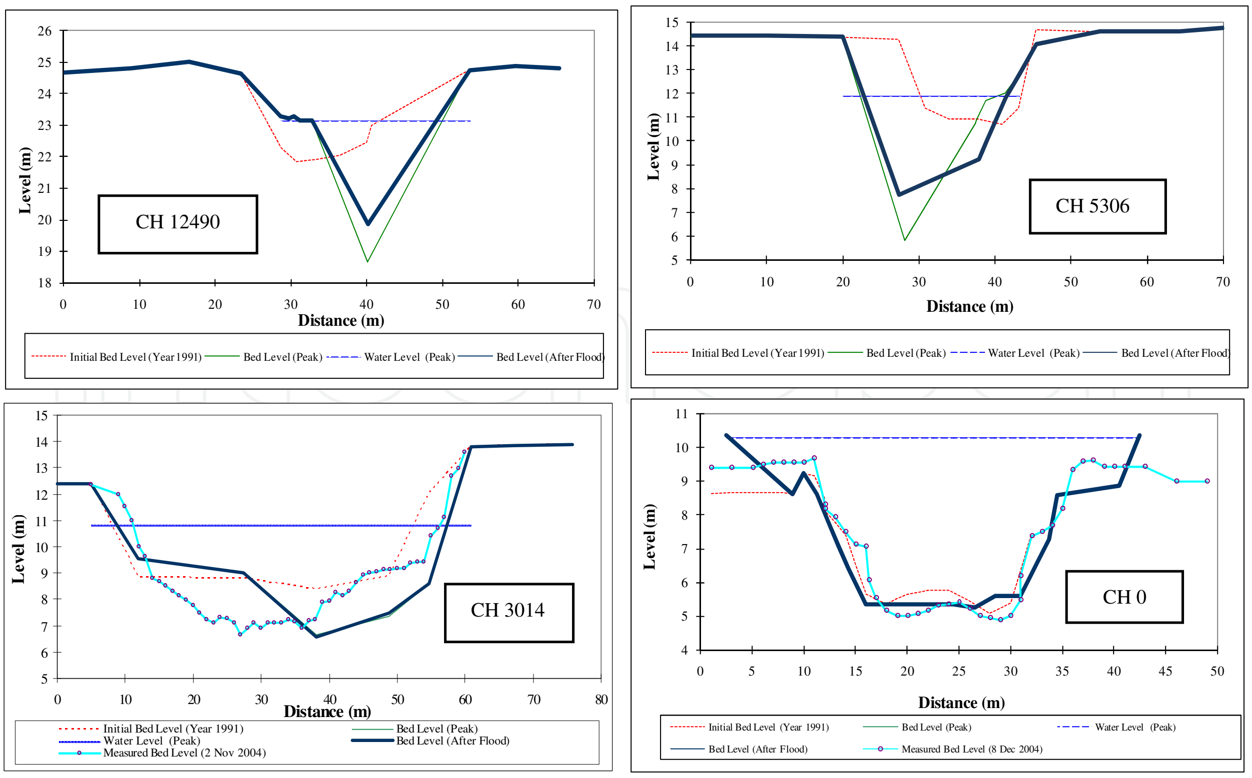


Fig. 15. Modeled Cross Section Changes before and after October 2003 Flood

The design flood hydrograph for the Kulim River based on 2010 landuse (DID, 1996) is shown in Figure 16. The critical peak flow of the event is 306.6 m^3/s (18-hour rainfall duration). Simulated peak water surface and channel bed changes for Kulim River based on design hydrograph are shown in Figure 17. The cross sections especially near to the sand mining area and few cross sections especially CH 10000 to CH 14390 were subjected to greater changes than other cross sections. In spite of this, channel degradation was predicted at most cross sections after the peak. Figure 18 shows the cross section changes for two selected locations along Kulim River.

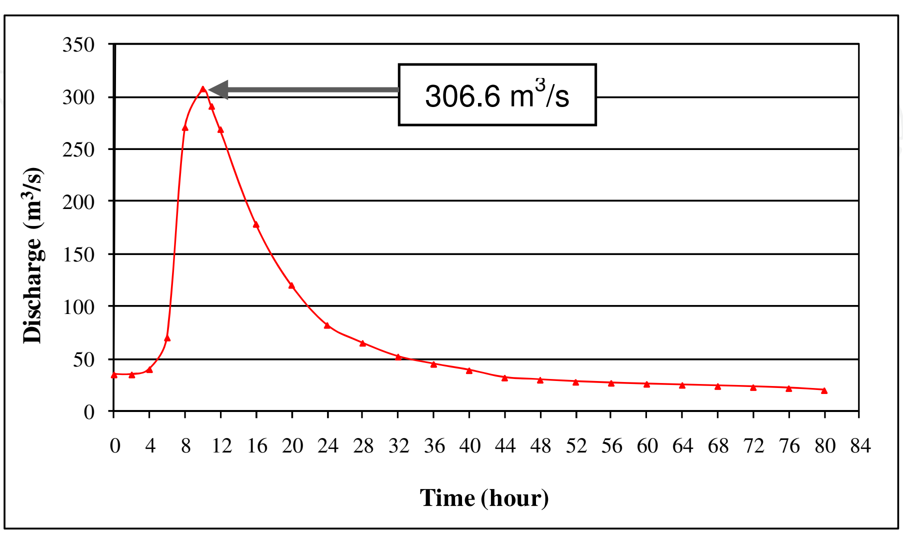


Fig. 16. Design Hydrograph for 2010 Landuse (DID, 1996)

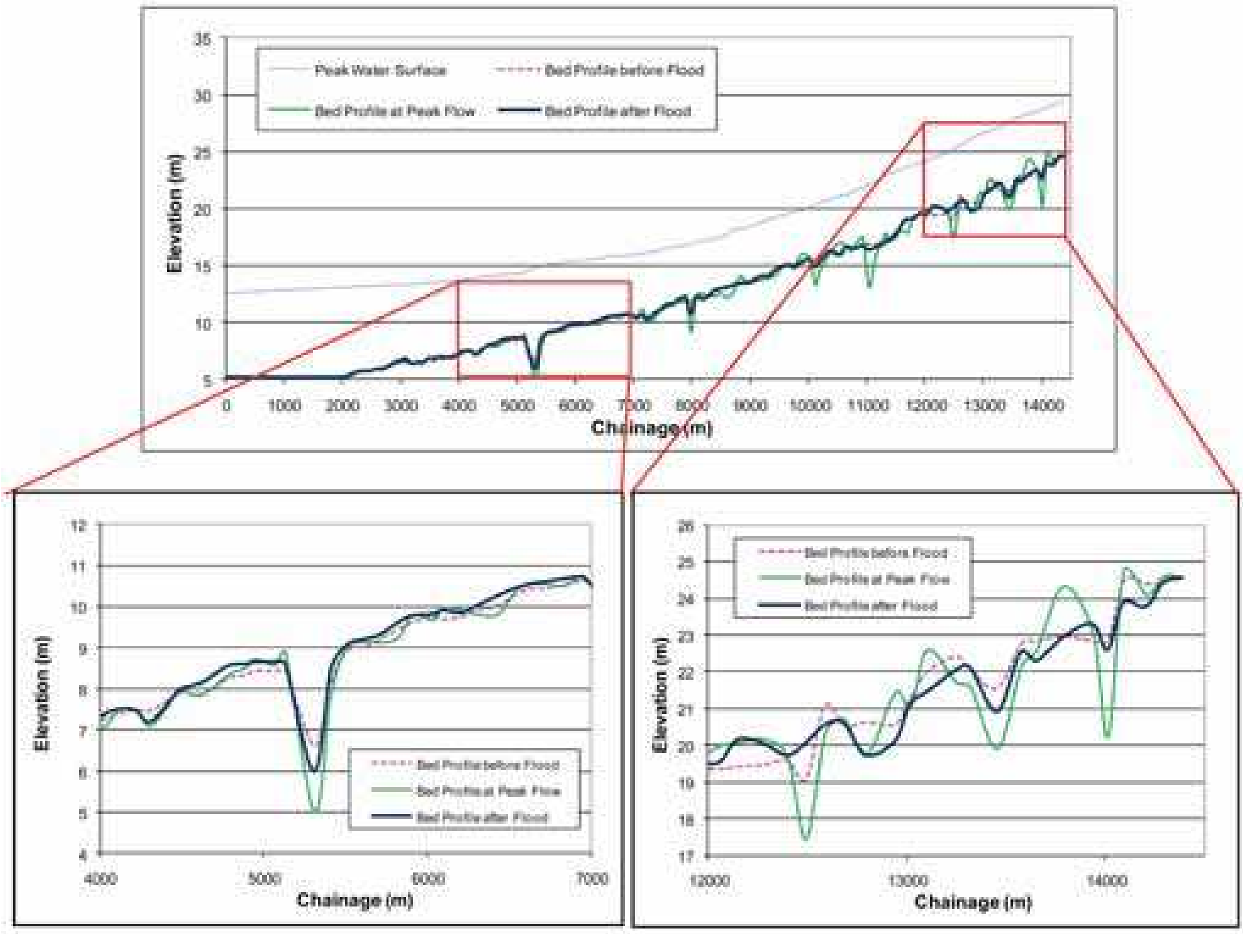


Fig. 17. Water Surface and Bed Profile Changes based on Design Hydrograph

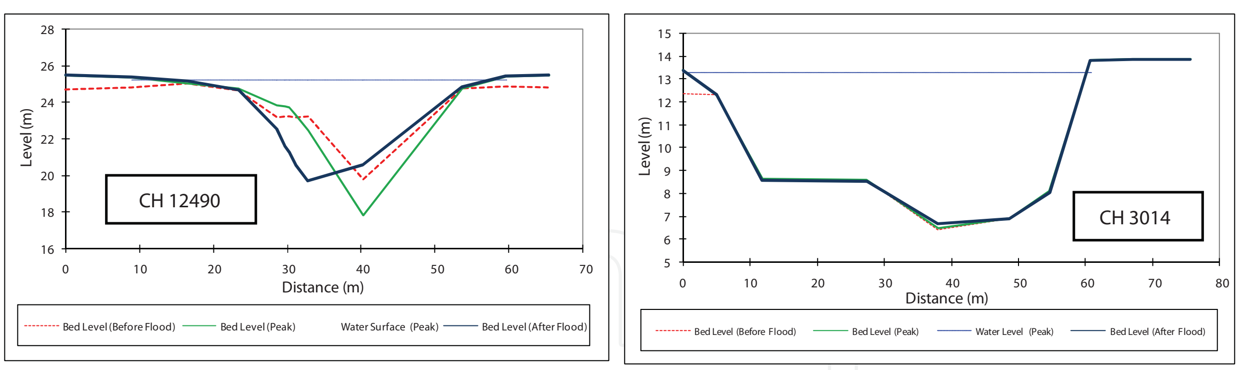


Fig. 18. Modeled Cross Section Changes before and after Design Flood

FLUVIAL-12 model was run to predict the channel geometry changes and sediment delivery for the next 10 years. Future changes for the next 10 years were simulated by using hydrograph as shown in Figure 7, which consists of 50-year ARI and 100-year ARI flood events. Sediment delivery or the amounts of sediment moving past each cross section predicted for the next 10 years (Year 2016) is shown in Figure 19. The simulation results show that the amount of sediment delivery was twice for year 2016 compared to the year 2006, but lesser sediment delivery at the downstream of Kulim River. The decreasing trend of sediment delivery indicates long-term sediment deposition at the downstream of Kulim River.

Simulation for Kulim River based on the time series illustrated the changes of the channel geometry as shown in Figure 20. The cross sections especially CH 10000 to CH 14000 are subjected to change with sediment aggradation, whilst sediment deposition occur at CH 6000 to CH 10000. Figure 21 shows the spatial variations of the predicted median grain size in year 2006 and 2016. The model run shows a large decrease in the sediment size at middle reach of Kulim River between years 2006 to 2016; where the reach-mean sediment size

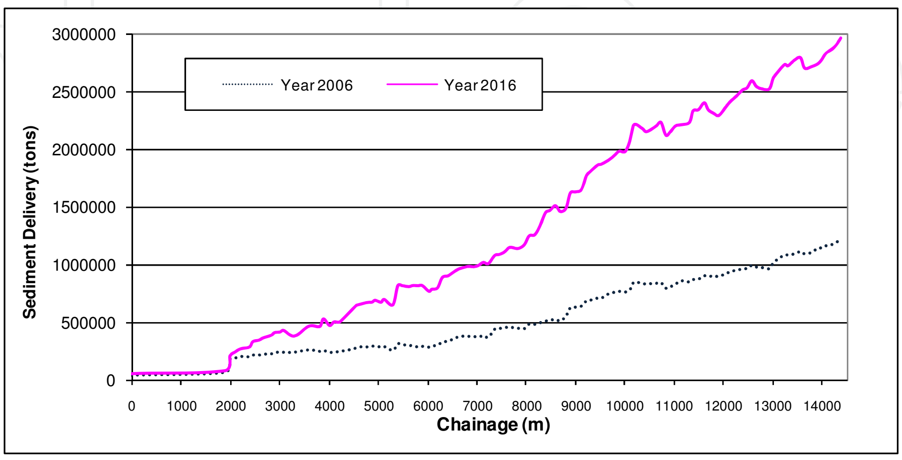


Fig. 19. Spatial Variations of the Predicted Sediment Delivery

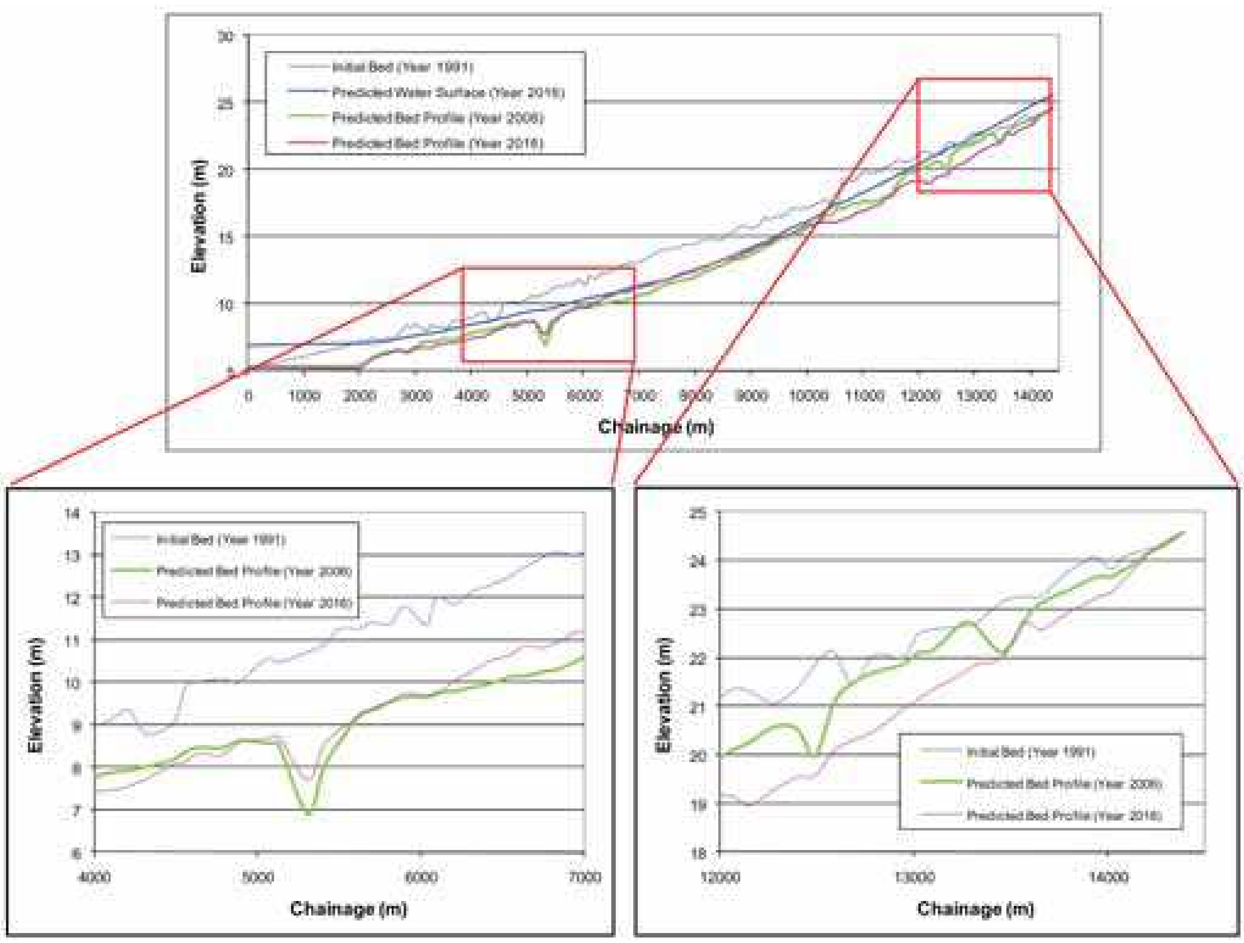


Fig. 20. Water Surface and Bed Profile Changes based on Design Hydrograph

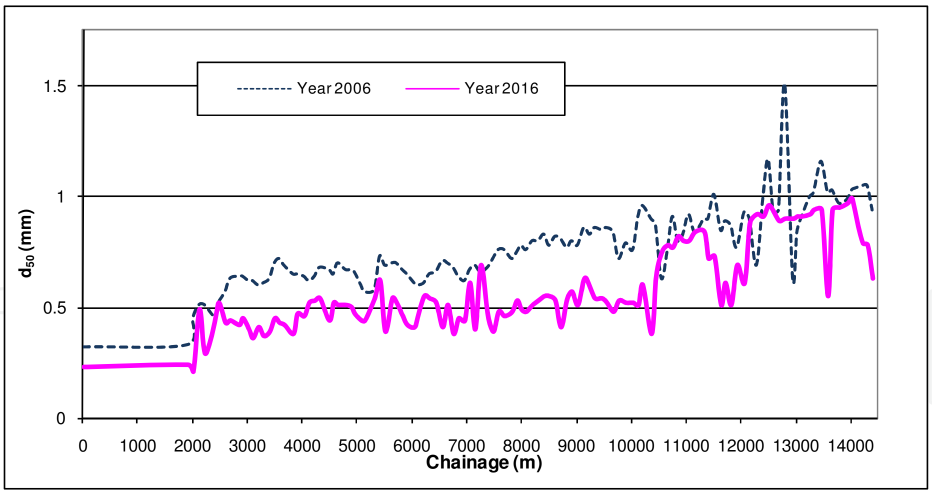


Fig. 21. Spatial Variations of the Predicted Median Grain Size for Year 2006 and 2016

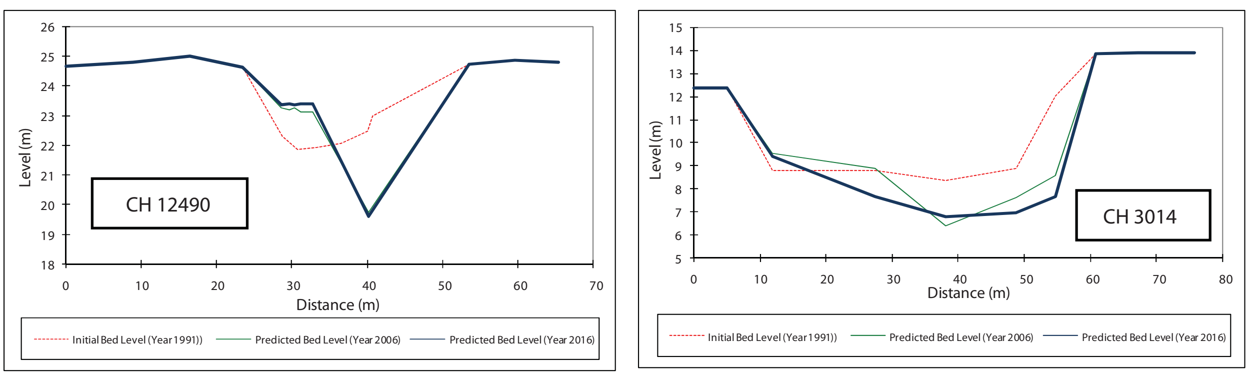


Fig. 22. Predicted Cross Section Changes for Year 2006 and 2016

decrease from 0.77 mm to 0.58 mm. As the channel bed became finer, more sediment was removed by erosion. Figure 22 shows the example of cross section changes for three locations along Kulim River.

In general, it is found that Kulim River will be in equilibrium conditions with slight degradation or erosion which deepen the river. The modeled results show that future changes in cross sectional geometry will generally be limited and erosion along the reach will be slowed down in the simulation period from 2006 to 2016. Thus, Kulim River was predicted to be stable at most locations.

6. Conclusion

Flooding in Kulim River is found to affect channel geometry, cross sectional geometry, sediment size and sediment delivery, which consists of scour and fill. Three scenarios was evaluated for Kulim River; the model simulation results for existing conditions, future conditions and long-term modeling show that the sediment size and channel geometry in Kulim River changed significantly and the amount of sediment delivery trend decrease with time indicates that long term sediment aggradation occurred at upstream and deposition occurred at downstream of Kulim River. However, modeled results show that future changes in cross sectional geometry will be limited and erosion along the reach will slow down from 2006 to 2016. The results based on the water surface profile simulated from the model should also be considered that the proposed bund level and bank protection should stay above the predicted water surface to avoid overtopping and reduce the flooding impact. The present study provides an estimate of sediment transport in moderate sandy stream and serves as a reference for sediment transport modeling of sandy streams in Malaysia and overseas.

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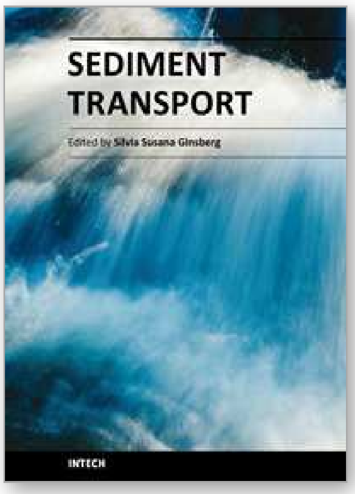

Sediment Transport

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Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.

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