Case Study: Flood Mitigation of the Muda River, Malaysia

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Abstract: The 2003 flood of the Muda River reached $1,340\ \mathrm{m^3/s}$ at Ladang Victoria and adversely impacted 45,000 people in Malaysia. A flood control remediation plan proposed a levee height based on a 50-year discharge of $1,815\ \mathrm{m^3/s}$ obtained from hydrologic models. This design discharge falls outside the 95% confidence intervals of the flood frequency analysis based on field measurements. Instream sand and gravel mining operations also caused excessive riverbed degradation, which largely off sets apparent benefits for flood control. Pumping stations have been systematically required at irrigation canal intakes. Several bridge piers have also been severely undermined and emergency abutment protection works were needed in several places. Instream sand and gravel mining activities should be replaced with offstream mining in the future.

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Introduction

Southeast Asia has long experienced a monsoon climate with dry and wet seasons. With mean annual rainfall precipitation locally in excess of 5,000 mm, the very intense rainstorms in the steep mountains of Malaysia have caused frequent and devastating flash floods. In the valleys, floodwaters spread over very wide flood plains developed for agriculture, predominantly, rice paddies and oil palm. For centuries, residents of Malaysia have built houses on stilts to cope with frequent floods, and longhouses were built along the main rivers. Over the years, a large number of inhabitants have encroached into the flood plain; nowadays, many dwellings are built on the river banks (Fig. 1). More recent industrial developments and rapid urbanization foster lifestyle changes. With cars and housing closer to the ground, flood control is subject to drastic changes. Urbanization also exacerbates flooding problems due to the increased runoff from impervious areas. As a result, the sediment transporting capacity of rivers also increases, thus causing major perturbations to river equilibrium (Ab. Ghani et al. 2003; Chang et al. 2005).

The Muda River in Malaysia experiences floods every year, and the floods of 1996, 1998, and 1999 were particularly high (Table 1). The Department of Irrigation and Drainage in Malaysia (Jabatan Pengairan dan Saliran Malaysia, also known as JPS or DID) enacted a Flood Control Remediation Plan with the assistance of consultants such as Jurutera Perunding Zaaba (JPZ) (2000). On October 6, 2003, flooding reached catastrophic proportions with a peak discharge of $1,340\ \mathrm{m^3/s}$, as shown on the flood hydrograph in Fig. 2. Fig. 3 illustrates the aerial extent of this flood, which adversely impacted 45,000 people in the State of Kedah.

The objectives of this paper are to review important issues relative to flood control in Southeast Asia and to specifically use the Muda River Flood as an example highlighting key aspects of hydraulic engineering design. The paper covers issues relative to comparisons of hydrologic and hydraulic models. There is also a specific focus on the impact of instream sand and gravel mining

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Fig. 1. Riparian communities impacted by the Muda flood

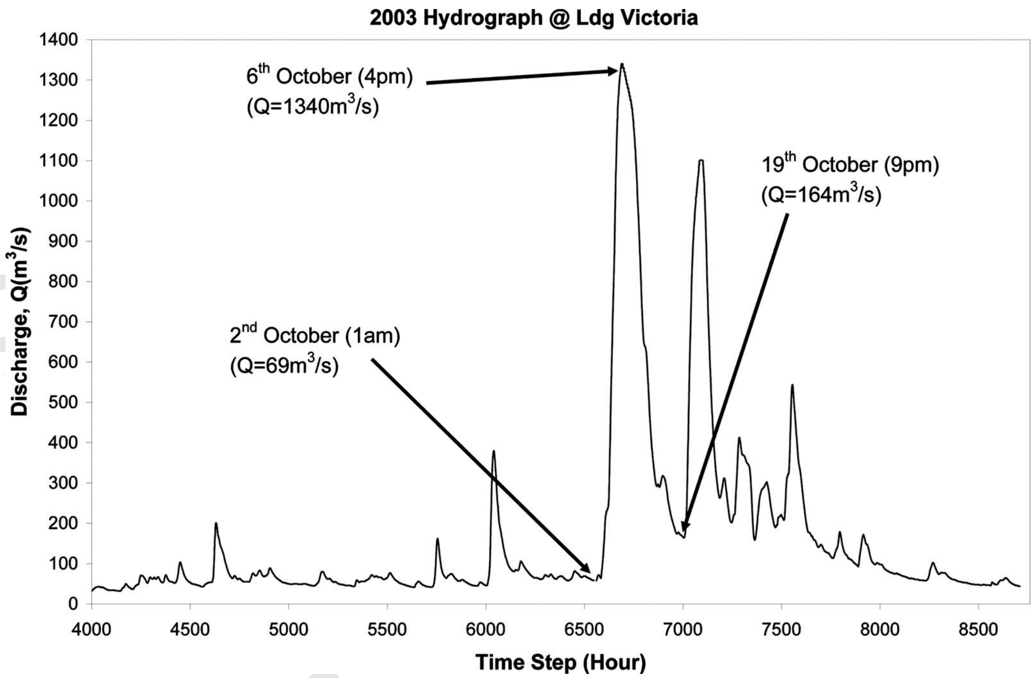

Fig. 2. Measured 2003 flood hydrograph of the Muda River at Ladang Victoria

activities in relation to flood protection and lateral and vertical channel stability of the Muda River.

Muda River Study Reach and Database

The Muda River drains mountainous areas of the State of Kedah and the topography of the region is shown in Fig. 4. The watershed is adjacent to Thailand and covers a drainage area of 4,210 km^2. At the upstream end of the Muda River is Muda Dam, which provides water storage for the Muda irrigation scheme. The upper and middle reaches of the Muda River belong to the State of Kedah, while the lower 30 km of the river delineates the boundary between the States of Kedah and Pulau Pinang. There are three major tributaries of the Muda River system, namely, the Ketil River with a drainage area of 868 km^2, the Sedim River with 626 km^2, and the Chepir River covering 335 km^2.

Table 1. Flood Ranking of the Muda River at Ladang Victoria

Rank	Year	Q (m^3/s)	Rank	Year	Q (m^3/s)
1	2003	1,340	23	1977	542
2	1988	1,225	24	2001	539
3	1999	1,200	25	1963	516
4	1996	1,100	26	1984	500
5	1998	980	27	1980	480
6	1967	912	28	1979	450
7	1965	861	29	1985	449
8	1971	789	30	1981	436
9	1973	781	31	1990	433
10	1972	706	32	1982	399
11	1966	661	33	1983	393
12	1964	640	34	1991	382
13	1997	626	35	1987	377
14	2000	626	36	1978	375
15	2002	612	37	1961	374
16	1970	602	38	2004	340
17	1960	572	39	1989	332
18	1968	572	40	1993	326
19	1975	565	41	1992	319
20	2005	565	42	1986	315
21	1976	549	43	1962	268
22	1969	546	44	1974	264

The study area has two typical monsoons, namely, the northeast monsoon and southwest monsoon. The northeast monsoon usually occurs from November to February. The southwest monsoon usually reaches the west coast of Peninsular Malaysia from the Indian Ocean and prevails over Peninsular Malaysia from May to August. In the transition period between the above two monsoons, westerly winds prevail from September to November and cause the heaviest annual rainfall precipitation in the study area. Thus, the study area tends to have two rainy seasons in a year: one from April to May and another from September to November. The annual rainfall depth in the study area is about 2,000–3,000 mm, while the average air temperature is about 27°C. Heavy annual rainfall in excess of 5,000 mm is observed locally around the central mountain of Gunung Jerai and the southern mountainous areas. There are four reference points within the Muda watershed representing the average design rain-

Fig. 3. Extent of flooding during the 2003 Muda River flood

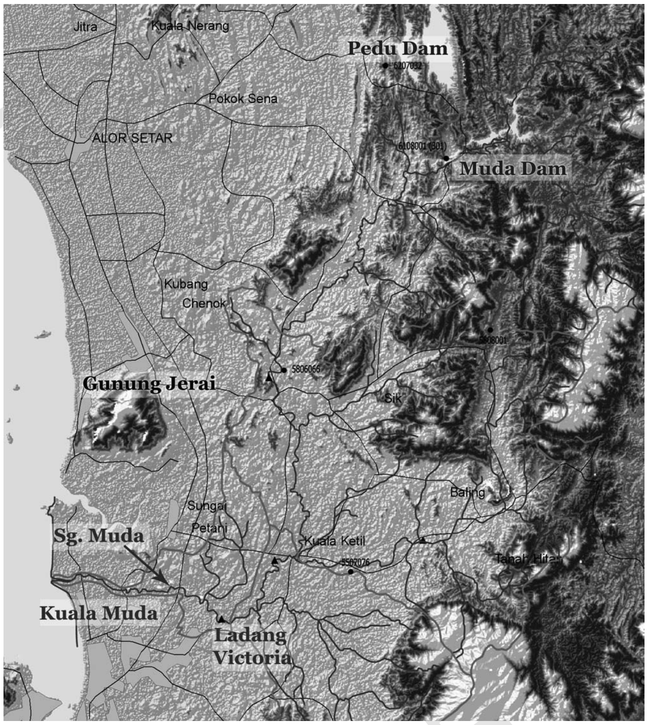

Fig. 4. Topography of the Muda River basin

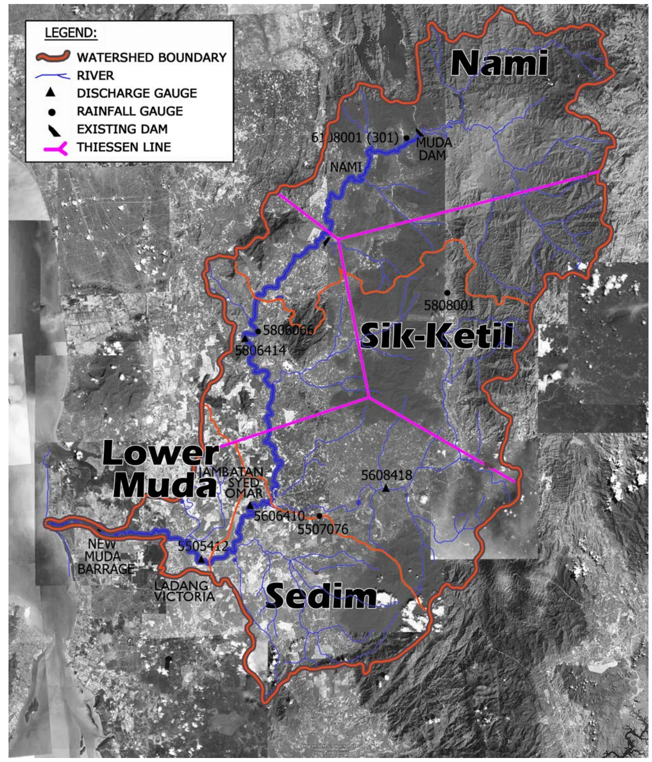

Fig. 5. Main stations and Thiessen polygons

fall: Jeniang Gage Station (for the Nami watershed), Jambatan Syed Omar Gage Station (for the Sik-Ketil watershed), and Ladang Victoria Gage Station (for the Sedim watershed).

Almost all of the northeastern part of the catchment is mountainous, fringed by hilly lands with elevations higher than 76 m. Most of the watershed upstream of Muda Dam is forested, with several areas designated as forest reserves. In these equatorial forest reserve areas, the dominant species identified are Kedondong, Kelat, Kerwing, Periang, and Nyatoh. Natural vegetation along the Muda River is however quite limited. The dominant vegetation along the river includes plantations of rubber trees, oil palm trees, fruit/garden trees, and nippa palms. Rice is also widely cultivated in many paddies along the floodplains of the river basin. The soils of the river basin are primarily composed of alluvium, sedentary soils, and lithosols. The lower reach of the Muda River is alluvial from the river mouth to the confluence with the Ketil River. The plain areas in the middle and upper reaches are covered with sedentary soil. Lithosols are dominant in the upper mountainous area [Japan International Cooperation Agency (JICA) 1995].

Hydrologic Modeling

In Malaysia, the design of flood mitigation projects is based on the 50-year flood. As a precautionary measure, a free board is usually added to pass the 100-year flood. For the determination of the 50-year and 100-year floods, the Flood Control Remediation Plan (JPZ 2000) considered several hydrologic models. Fig. 5 shows the delineation of four subwatersheds for the hydrologic modeling analysis, namely, the Nami, Sik-Ketil, Sedim, and the lower portion of the Muda River. There are four automatic rainfall stations shown in Table 2.

The hydrologic model calibration and validation went through two processes: (1) calculation of the average rainfall on the watershed from the weighted Thiessen Polygon method and (2) determination of parameters including losses, watershed and channel routing, and baseflow discharge. The weighted rainfall factors of the Thiessen Polygon method are listed in Table 2. The

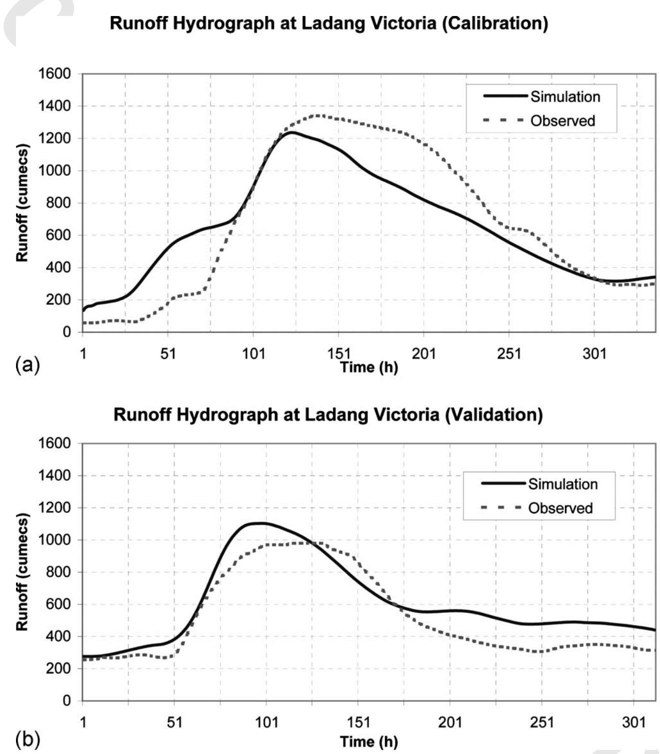

Fig. 6. Hydrologic model calibration and validation at Ladang Victoria

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Table 2. Weighted Rainfall Factors for Hydrologic Modeling

Subwatershed	Area (km^2)	Weighted rainfall stations			
		6108001	5808001	5806066	5507076
Nami	1,661	0.61	0.27	0.12	—
Sik-Ketil	1,718	—	0.34	0.25	0.41
Sedim	616	—	—	—	1.00
Lower Muda	215	—	—	0.07	0.93

observed discharge data recorded at Jambatan Syed Omar and Ladang Victoria were used in the calibration and validation. The calibrated parameters from the HEC-HMS model [United States Army Corps of Engineers (USACE), unpublished report, 2001] for the Muda watershed at Ladang Victoria are given in Table 3. The hourly rainfall data from October 1, 2003 (00:00 time) to October 14, 2003 (23:00 time) was used for the calibration. The calibrated model parameters were then validated with the hourly rainfall from November 14, 1998 (00:00 time) to November 26, 1998 (23:00 time).

Table 3. Calibrated Watershed Parameters

Watershed parameters	Nami	Sik-Ketil	Sedim	Lower Muda
Losses (Exponential)				
Initial range (mm)	15	15	15	15
Initial coef. $(mm/h)^{\wedge}(1-x)$	1.65	1.85	1.75	1.75
Coef. Ratio	1.0	1.0	1.0	1.0
Exponent	0.22	0.22	0.22	0.22
Imperviousness (%)	10	10	10	10
Transform (Clark UH)				
Time of concentration (h)	48	36	38	10
Storage coefficient (h)	45	60	45	45
Baseflow (constant monthly)				
November baseflow (cms)	92	92	92	92

The model calibration and validation results are shown in Fig. 6 for the discharge station at Ladang Victoria. A relatively high level of uncertainty was noticeable in the calibration and validation of these results. Indeed, there are several hundred m^3/s of difference between the calibration and validation results obtained by the same model when applied at Ladang Victoria. The reason for these discrepancies is not obvious, but the analysis is based on only four rain gauges and this seems to be a limiting factor in the representation of spatial variability of rainfall precipitation on this large watershed.

The design flood hydrograph (Fig. 7) was estimated using the calibrated HEC-HMS model [United States Army Corps of Engineers (USACE), unpublished report, 2001] on the basis of the design rainfall from the 50-year and 100-year isohyethal map which has been produced by JPZ (2000). The 3-day rainfall precipitation data of 260 mm (Jeniang), 300 mm (Jambatan Syed Omar), and 350 mm (Ladang Victoria) were used to determine the peak discharges. The 50-year and 100-year peak discharges were then determined from the calibrated model with the hourly precipitation of the Hydrological Procedure No.1 (HP.1) covering the three-day rainstorms, following the standard procedure in Malay-

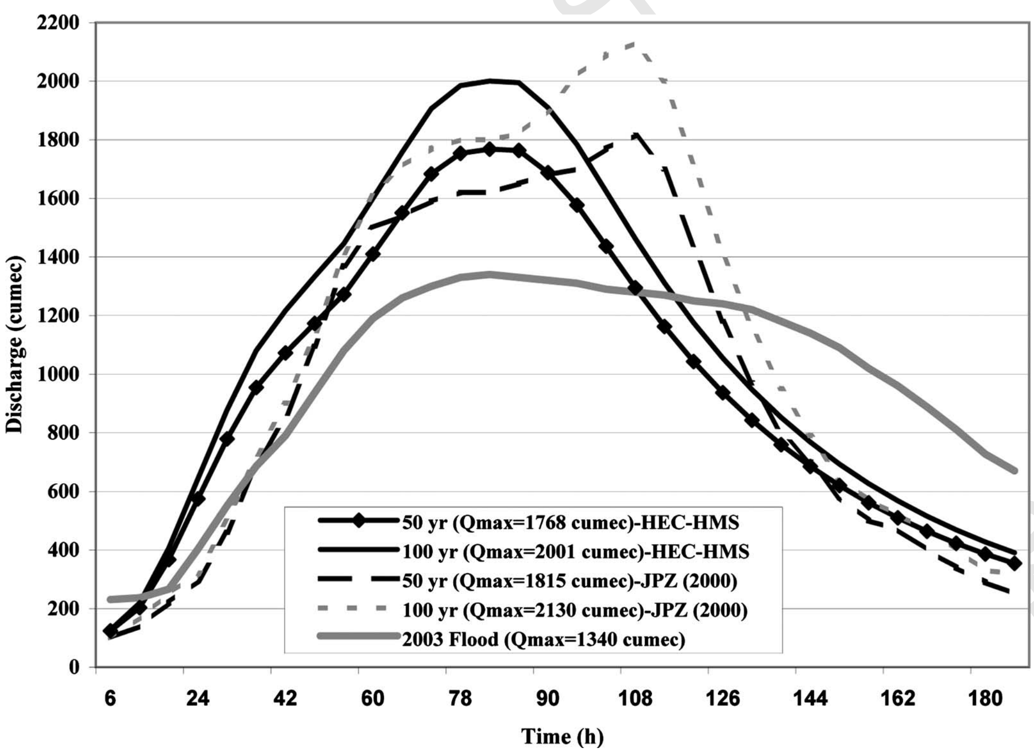

Fig. 7. Design hydrographs at Ladang Victoria

Table 4. Design Peak Discharge Comparison

Location	Area (km^2)	Mean annual rainfall (mm)	Tc (hour)	Rainfall (mm) 50 year	Rainfall (mm) 100 year	Design flood hydrograph (m^3/s) JICA 50 year	JICA 100 year	NWRS 50 year	NWRS 100 year	RAFTS-XP 50 year	RAFTS-XP 100 year	HP-4 50 year	HP-4 100 year	HP-11 50 year	HP-11 100 year	HEC-HMS 50 year	HEC-HMS 100 year	Observed historical flood 2003 (m^3/s)
Jeniang G.S	1,740	2,300	48	**260**	**290**	986	1,118	1,125	1,397	1,527	1,858	595	660	1,109	1,286	667	767	—
Jambatan Syed Omar G.S	3,330	2,300	72	**300**	**330**	1,275	1,403	1,890	2,348	1,936	2,396	994	1,102	1,951	2,114	1,386	1,579	831
Ladang Victoria G.S	4,010	2,300	84	**350**	**380**	1,338	1,477	2,180	2,709	1,815	2,130	1,151	1,276	2,120	2,358	1,768	2,000	1340
River Mouth (Outlet)	4,210	2,325	96	**385**	**415**	—	—	2,274	2,825	2,030	2,510	1,199	1,330	2,028	2,170	1,910	2,100	—

sia [Department of Irrigation and Drainage Malaysia (DID) 2000].

The HEC-HMS results are fairly consistent with the design hydrographs of JPZ (2000). In summary, the 50-year peak discharge obtained from HEC-HMS was $1,768\ m^3/s$ and compares well with the peak discharge of $1,815\ m^3/s$ obtained by JPZ with the model RAFTS-XP. On the other hand, Table 4 shows a wide variability in the 50-year flood predictions at Ladang Victoria obtained from different models compiled by Julien et al. (2006). For instance, the 50-year discharge varies from $1,151\ m^3/s$ for the model HP-4 to $2,180\ m^3/s$ for the NWRS model. A comparison of the discharge hydrographs obtained by the retained hydrologic models with the 2003 flood in Fig. 7 shows major discrepancies between the results obtained from hydrologic models and the largest flood recorded.

Flood Frequency Analysis

The Muda River benefited from a complete 44-year period (1960–2005) of daily discharge measurements at Ladang Victoria. The annual peak discharges ranked in Table 1 indicate that the five largest floods have been measured since 1988. The 2003 flood at Ladang Victoria was the highest discharge measured during the 44-year period and reached a peak discharge of $1,340\ m^3/s$. A flood frequency analysis was carried out (Table 5) and Fig. 8 shows the Gumbel plot with 95% confidence intervals. The results are also summarized in Table 5 for comparison with the results obtained by the DID, and an earlier study by JICA (1995). The results of the flood frequency analysis are consistent with 50-year flood peaks ranging between 1,254 and $1,275\ m^3/s$ at Ladang Victoria. It is therefore concluded that the 2003 flood discharge of $1,340\ m^3/s$ is slightly larger than the 50-year peak discharge.

In comparison with field measurements, the 50-year peak discharge of $1,815\ m^3/s$ obtained from hydrologic models falls outside the 95% confidence intervals ($1,006$–$1,529\ m^3/s$) of the flood frequency analysis shown in Fig. 8. A 50-year design discharge of $1,815\ m^3/s$ thus clearly overpredicts the field measurements. A more realistic 50-year peak discharge may be obtained from the 2003 flood with a peak discharge of $1,340\ m^3/s$. The large variability and tendency to overpredict of the hydrologic modeling results is a source of concern for river engineering applications.

River Modeling

The main channel of the Muda River has a length of about 180 km with a slope of 1/2,300 (or 0.00043) from the river mouth to Muda Dam. The channel is typically around 100-m wide and widens up to about 300 m near the river mouth. The bathymetric surveys in 2000 indicate that the shallowest point in the river is located 2.5-km upstream of the river mouth, which impedes navigation during low tides. A riverbed material survey shows a predominance of sands and gravels on the main stream and tributaries. Bed load transport is the dominant mode of sediment transport in the Muda River. The mean annual bed load discharge of the Muda River was estimated by JICA (1995) about $10,000\ m^3/year$. Significant scour of the channel bed is attributed to sand and gravel mining operations, aggravating bank erosion and causing riverbed degradation.

The study reach covers 41.2 km between the river mouth at CH 0 and Ladang Victoria at CH 41.2. This is the area that was

Table 5. Flood Frequency Analysis at Ladang Victoria

Return period (year)	DID	Japan International Cooperation Agency (JICA) (1995)	Present study Gumbel extremal type I (discharge data from 1960 to 2005)
	Discharge (m^3/s)		
2	517		552
5	760	810	776
10	916	950	926
25	1,125		1,114
50	1,275	1,260	1,254
100	1,423	1,340	1,393
200	1,572		1,531

heavily flooded in 2003 (e.g., Fig. 3). The hydraulic analysis using the HEC-RAS model [United States Army Corps of Engineers (USACE) 2002] provides information on the variations in river stages, discharges, and velocities for the design flood (Julien et al. 2006). The HEC-RAS model for this study generates the water surface elevation based on the 2000 survey of the existing cross section (Fig. 9) from CH 0 to CH 41.2 of the Muda River. The 2000 survey extends 50 m on the flood plain on both banks based on the recommendation by JICA (1995) study that the bunds should be constructed 50 m from the banks. The unsteady flow analysis in the HEC-RAS model was used to replicate the hydrograph data for October 2003. The hourly tidal level data at the Kedah Pier were also used as a downstream boundary condition at the river mouth (CH 0). The hydrograph at Ladang Victoria from October 2nd to October 19th was used to simulate the 2003 flood. The peak discharge took place on October 6, 2003 at 4 p.m. with a value of $1,340\ m^3/s$. Fig. 10 shows a few of the 215 cross sections used for the simulation. Hourly water level records at three locations (Ladang Victoria, Bumbong Lima, and River Mouth) were used to check the predicted water level by the HEC-RAS model. Different values of Manning n (0.025, 0.030, and 0.035) were tried for calibration, as shown in Fig. 11, and the best results were obtained with Manning n of 0.03 and 0.05 for the main channel and floodplains, respectively. Theses results corroborate the calibration done by an earlier study (JICA 1995). The model results are therefore considered sufficiently accurate for the determination of levee heights.

Proposed Mitigation Design of Flood Protection Works

Design Discharge and Levee Height

The proposed levee height (also called bund height by JPZ) was based on a 50-year average recurrence interval (ARI) design discharge of $1,815\ m^3/s$ plus freeboard. As a consequence, over 85% of the 41.2-km reach required a levee with height between 1.0 and 5.5 m. Table 6 shows the comparison between the predicted water levels at a discharge of $1,815\ m^3/s$ in comparison to the HEC-RAS simulation of the 2003 flood at a maximum discharge of $1,340\ m^3/s$. The corresponding difference in stage

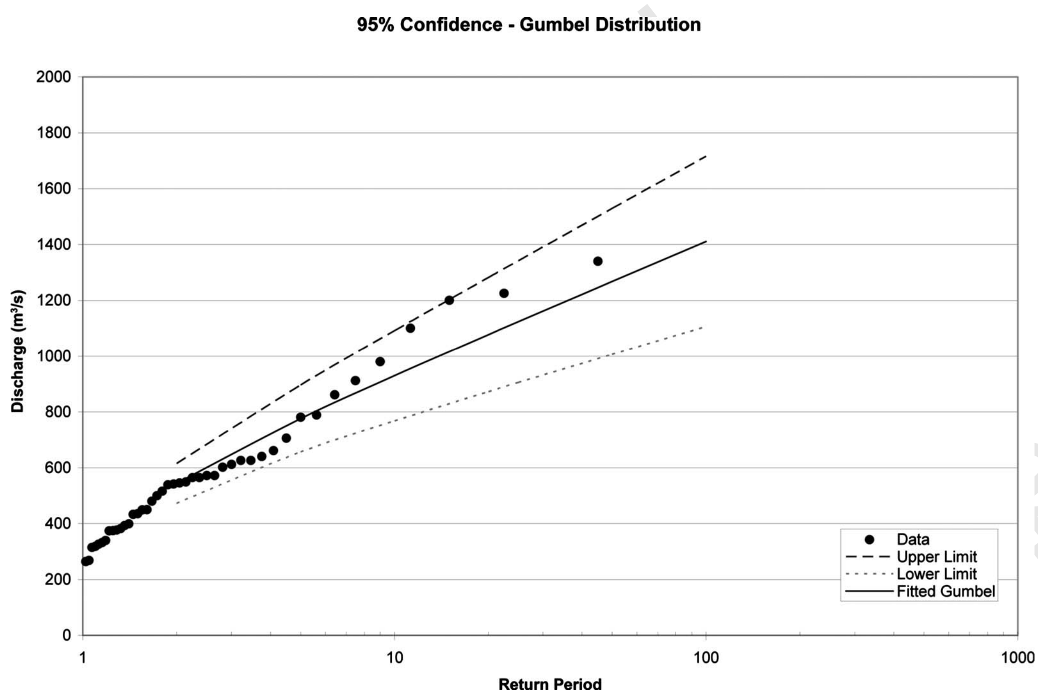

Fig. 8. Flood frequency and 95% confidence intervals at Ladang Victoria

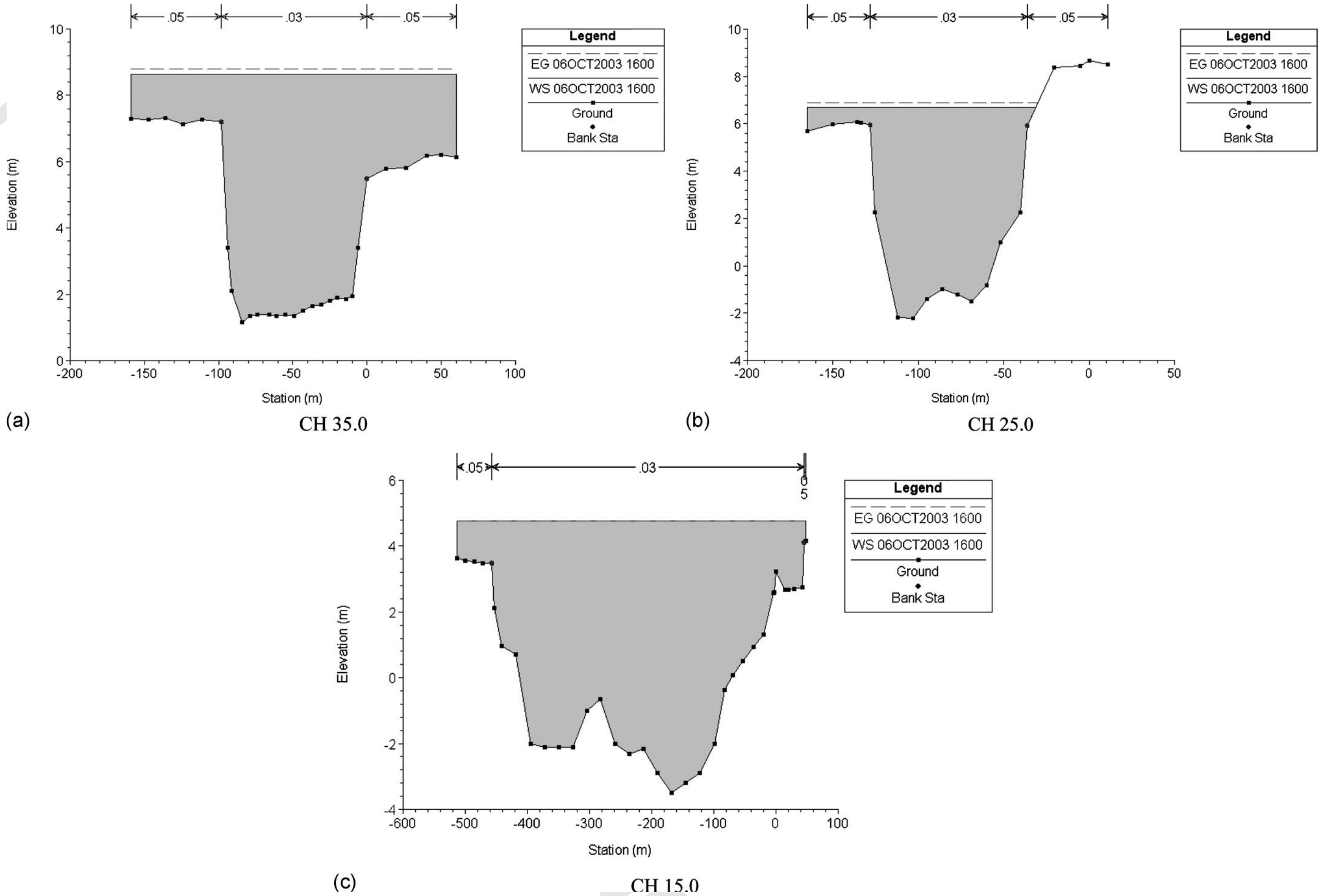

Fig. 9. Typical cross sections of the Muda River

elevation is as high as two meters in the upper reach of the Muda River. The comparisons between the bund height determined by JPZ and the water level of the 2003 flood without channel widening indicate that the proposed bund height is typically 1–2 m higher than the 2003 flood level. The resulting levee elevation based on field discharge measurements should be lower than proposed in a design based on hydrologic models. The recommended levee height for this flood control remediation plan could have been determined from the flood stage corresponding to the design peak discharge of $1{,}340\ \mathrm{m^3/s}$ plus a 1-m freeboard.

Lateral Migration and Floodplain Width

This section gives the results of additional river modeling of the Muda River based on the mobile boundary model FLUVIAL-12 (Chang 1988, 1997, 2006). The modeling involves simulation of

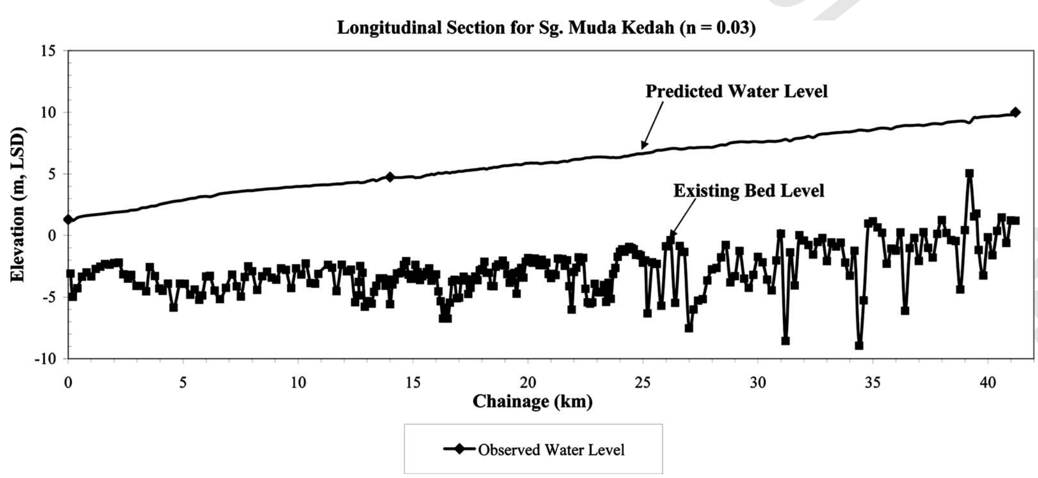

Fig. 10. Predicted water levels of the Muda River by the HEC-RAS model

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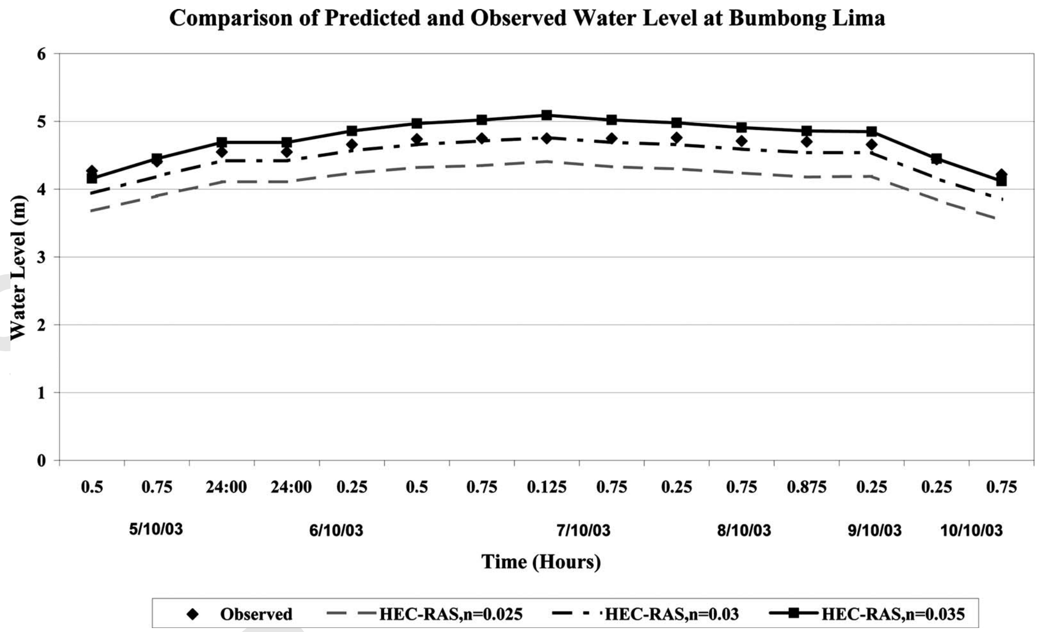

Fig. 11. Predicted and observed water levels of the Muda River at Bumbong Lima

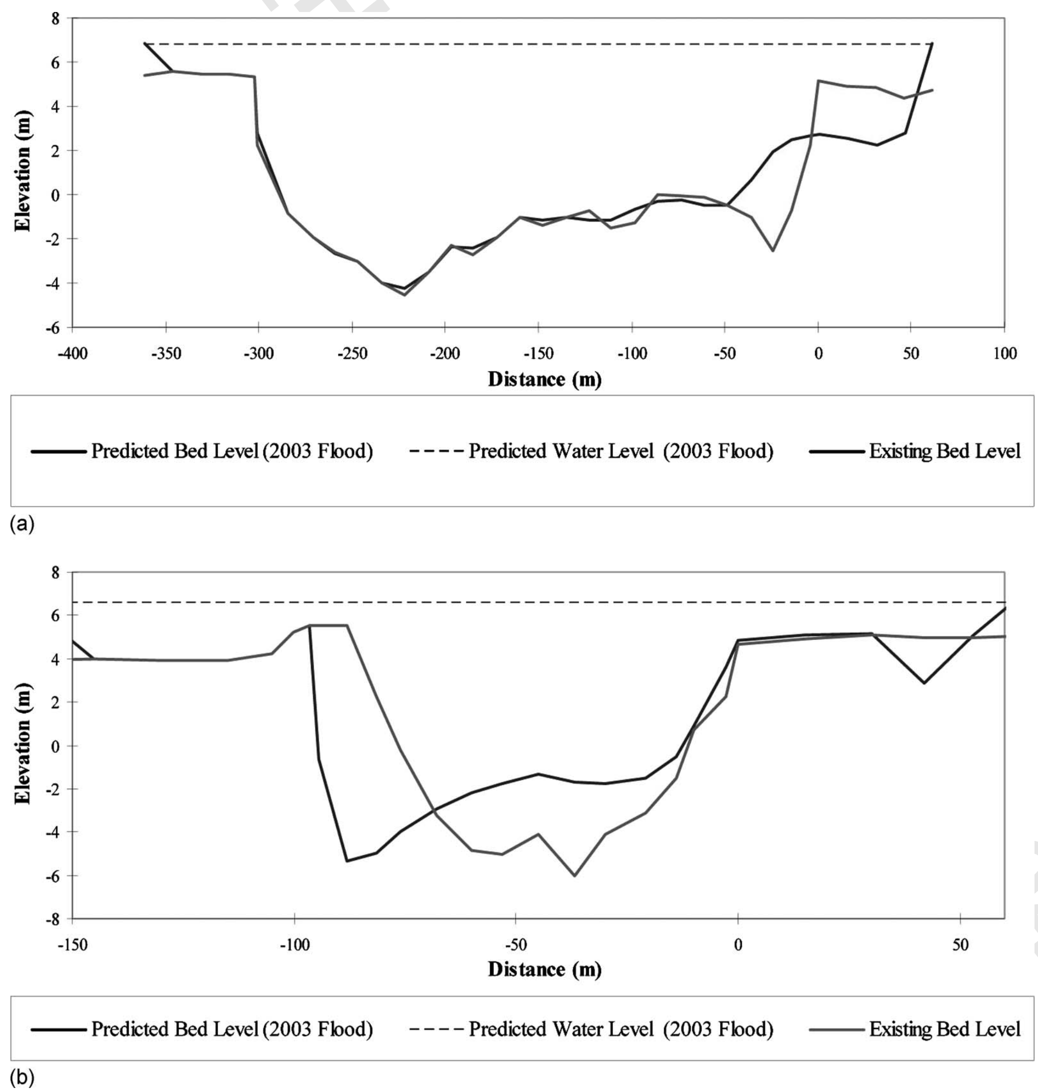

Fig. 12. Lateral migration of the Muda River at Lahar Tiang

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Table 6. Comparison of Flood Levels using Existing Cross Sections

Node	Cumulative distance	Existing invert (m)	50-year ARI level (m)	Flood 2003 level (m)	Bund level (m)	Difference between 2003 flood and design flood levels (m)	Difference between Bund and 50-year ARI levels (m)
CH41	40,275	1.09	11.46	9.79	11.01	1.67	0.45
CH40	39,589	0.81	11.32	9.65	10.95	1.67	0.37
CH39	38,535	1.18	11.12	9.26	10.83	1.86	0.29
CH38	37,382	−1.34	10.95	9.05	10.62	1.90	0.33
CH37	36,361	−1.10	10.85	8.96	10.45	1.89	0.40
CH36	35,223	0.97	10.71	8.81	10.26	1.90	0.45
CH35	34,344	−2.91	10.50	8.58	10.11	1.92	0.39
CH34	33,248	0.57	10.32	8.41	9.95	1.91	0.37
CH33	32,214	−4.48	10.19	8.26	9.74	1.93	0.45
CH32	31,459	−3.66	9.92	7.95	9.58	1.97	0.34
CH31	30,414	−4.09	9.75	7.70	9.37	2.05	0.38
CH30	29,447	−5.30	9.67	7.60	9.04	2.07	0.63
CH29	28,374	−1.82	9.63	7.56	8.79	2.07	0.84
CH28	27,460	−2.78	8.39	7.15	8.57	1.24	−0.18
CH27	26,541	−2.29	8.35	7.12	8.39	1.23	−0.04
CH26	25,853	−0.34	8.21	6.98	8.25	1.23	−0.04
CH25	24,821	0.17	7.83	6.64	8.02	1.19	−0.19
CH24	23,879	−3.83	7.49	6.33	7.81	1.16	−0.32
CH23	21,901	−1.48	7.56	6.37	7.41	1.19	0.15
CH22	21,039	−2.65	7.33	6.17	7.25	1.16	0.08
CH21	19,806	−3.16	7.05	5.93	6.98	1.12	0.07
CH20	18,951	−2.53	6.97	5.86	6.79	1.11	0.18
CH19	17,946	−2.92	6.73	5.67	6.55	1.06	0.18
CH18	16,946	−5.19	6.42	5.41	6.33	1.01	0.09
CH17	15,801	−3.01	6.16	5.21	6.07	0.95	0.09
PLUS2	15,771	−3.50	5.98	5.07	6.07	0.91	−0.09
CH16	14,944	−3.76	5.90	5.00	5.77	0.90	0.13
CH15	14,097	−3.80	5.61	4.76	5.63	0.85	−0.02
CH14	13,142	−2.47	5.56	4.71	5.50	0.85	0.06
MB2	13,112	−2.55	5.30	4.52	5.49	0.78	−0.19
CH13	12,123	−2.62	5.15	4.40	5.34	0.75	−0.19
CH12	10,665	−2.84	5.02	4.19	5.15	0.83	−0.13
CH11	10,354	−1.57	4.86	4.11	5.11	0.75	−0.25
BARR2	10,324	−1.57	4.74	4.01	5.14	0.73	−0.40
CH10	10,028	−1.67	4.71	3.98	4.95	0.73	−0.24
CH9	9,314	−3.47	4.55	3.82	4.68	0.73	−0.13
CH8	8,344	−2.66	4.36	3.64	4.45	0.72	−0.09
CH7	7,108	−2.56	4.21	3.50	4.16	0.71	0.05
CH6	6,184	−3.18	3.82	3.17	3.99	0.65	−0.17
CH5	5,298	−3.12	3.53	2.91	3.79	0.62	−0.26
CH4	4,299	−2.56	3.07	2.53	3.62	0.54	−0.55
CH3	3,413	−3.46	2.56	2.09	3.46	0.47	−0.90
CH2	2,152	−2.28	2.49	1.87	3.17	0.62	−0.68
CH1	1,294	−2.09	2.49	1.65	2.84	0.84	−0.35
River mouth		−7.80	2.50	1.30	2.39	1.20	0.11

the riverbed and cross sections for the 2003 flood based on the Yang sediment transport equation. The model results identify stretches prone to meandering and lateral migration, hence, needing extra protection. Changes in alluvial river geometry in terms of aggradation and degradation can also be modeled for this 41-km reach of the Muda River. The analysis of the river sinuosity has been explored to avoid excessive lateral migration of the channel.

Most of the reach seems relatively stable and has a proven record to sustain large floods since 1996. However, two main areas have been identified and channel relocation should be considered at Lahar Tiang and Bumbong Lima, where lateral migration is expected to be significant (Fig. 12). It is clear from the river model results that these two sharp bends are subject to large riverbed deformations that could potentially lead to lateral migration and more serious structural instabilities of the river reaches. It is proposed to consider straightening these two river reaches to improve the conveyance of the river during floods.

The location of the levee proposed by JPZ (2000) is shown in Fig. 13. Its design considers the flood carrying capacity of a nar-

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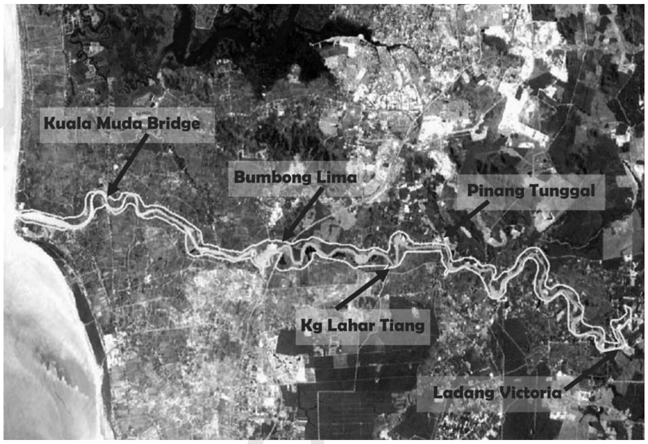


Fig. 13. Proposed location of the levee [by Jurutera Perunding Zaaba (JPZ) 2000]

row flood plain corridor as well as the possible impact on the communities living in proximity of the river. The lower reach of the Muda River has sustained major floods in recent years without apparent major lateral shifting in its river course. The fact that the banks are resilient to lateral mobility despite major floods and excessive degradation from sand and gravel mining is an indication that a narrow floodplain corridor from Ladang Victoria to Kuala Muda may be viable for this flood control remediation plan.

Sand and Gravel Mining

The Muda River is also a major source of construction material (sand and gravel) for the region [Japan International Cooperation Agency (JICA) 1995; Abdullah 2002]. The sediment size distribution curves for the main river channel between Sidam Kanan (CH 36) and Merdeka Bridge (CH 12) in Table 7 show that the mean sediment sizes d_{50} are between 1.0 and 2.0 mm, indicating the riverbed is made up of very coarse sand. A study by Japan International Cooperation Agency (JICA) (1995) showed that total sand being excavated from the river at more than hundred mining locations is about 100 times larger than the total sediment yield of the river. As a result, the riverbed had severely degraded throughout its length with many stretches of river banks also badly degraded. Fig. 10 shows that the bed elevation can remain below sea level at a distance as far up as 40-km upstream of the mouth of the Muda River.

In terms of flood control, the effects of sand and gravel mining have been viewed quite favorably in that deeper cross sections allow rivers to stay in the main channel during floods and this effectively reduces the flooding frequency. However, there have been adverse impacts of lowering the riverbed elevation. Lower river stages caused major difficulties supplying water to irrigation canals. Large pumping stations have been required to supply water at irrigation canal intakes.

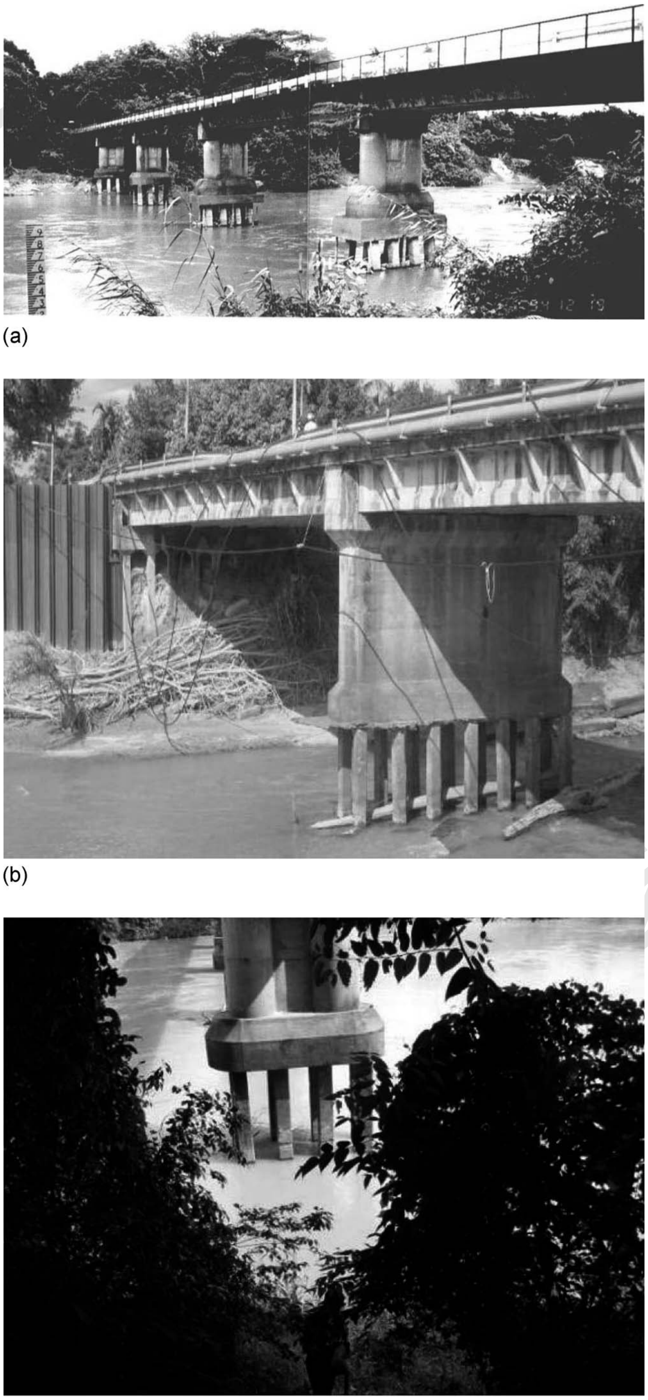
Bridge Piers and Bridge Crossings

Finally, bridge pier footings have been exposed as a result of the riverbed degradation from sand and gravel mining operations on the Muda River. The main concern is at Ladang Victoria where the bridge pier footings have become exposed far above the water surface, as shown in Fig. 14. These bridge piers need retrofitting to ensure the structural stability of the bridges. At some locations, bridge abutments have also failed, which required emergency protection works with sheet piles and back filling. In other locations, woody debris has accumulated around and between the piles, which can exert significant undesirable forces on bridge piers during floods. Two types of structures can be considered as countermeasures: (1) grade control structures downstream of bridge crossings that would maintain the riverbed elevation at an elevation higher than the bridge pier footings or (2) a strengthening of the bridge piers through caissons, sheet piles with grouting that would consolidate the interconnection of the bridge piers footing and piles. The new footing depth should be set at an elevation below the current bed elevation.

Headcutting and nick points are well known to develop and

Table 7. Median Sediment Size of the Bed Material

			d_{50} (mm)		
Chainage number	Site number	Name of location	Left bank	Main channel	Right bank
CH 0.20	M1	River Mouth 1	0.900	0.425	—
CH 0.80	M2	River Mouth 2	0.216	0.063	0.600
CH 1.40	M3	Kg. Sg Deraka	0.063	0.150	0.040
CH 2.97	M4	Kg. Pulau Mertajam	0.300	0.300	0.040
CH 4.86	M5	Kuala Muda Bridge	0.150	0.150	0.063
CH 12.64	M6	Merdeka Bridge	0.090	1.000	0.050
CH 21.90	M17	Kg Lahar Tiang	0.036	0.212	0.070
CH 23.10	M16	Kg Matang Berangan	0.036	0.036	0.036
CH 23.60	M9	Kuari 1	—	1.180	—
CH 25.20	M7	Pinang Tunggal Bridge	0.212	0.425	0.063
CH 25.60	M10	Kuari 2	—	1.000	—
CH 30.80	M15	Kg Pantai Perai	0.050	0.050	2.000
CH 31.00	M11	Kuari Kg Pantai Perai	—	1.500	—
CH 33.40	M12	Kuari Kg Terat Batu	—	1.800	—
CH 33.80	M14	Kg Lubok Ekor	0.014	0.036	0.020
CH 36.80	M13	Kg Sidam Kanan	0.040	1.180	0.036
CH 39.50	M8	Ladang Victoria Bridge	0.212	1.800	0.050



(a)

(b)

(c)

Fig. 14. Bridge piers along the Muda River

migrate upstream (Julien 2002). For instance, it has been noticed that the bridge at CH-25 of the Ketil River has also experienced similar problems. This systematic bed degradation caused by sand and gravel mining endangers the stability of upstream bridges and hence poses a potential threat to all vehicles crossing bridges on the Muda River and its upstream tributaries. It is recommended to shift instream sand and gravel mining operations to offstream sites within the floodplain corridor of the Muda River.

Conclusions

This review of the flood control remediation plan for the Muda River highlights several important points in the design of flood remediation countermeasures against the frequent and intense floods during the monsoons of southeast Asia. Some of the main conclusions include (1) the analysis of measured daily discharge records can produce a more reliable 50-year peak discharge than hydrologic models, i.e., there is a 25% difference between the flood frequency analysis of field measurements ($1{,}340\ m^3/s$) and hydrologic model results ($1{,}815\ m^3/s$); (2) various hydrologic models in Table 4 can result in 100% variability in the prediction of peak discharges and design hydrographs; (3) the proposed levee height of the Muda River could have been based on the 2003 flood plus a 1-m freeboard; (4) the sand and gravel mining operations caused major problems associated with riverbed degradation including pumping requirements at irrigation canal intakes and structural instability problems at bridge crossings; and (5) it is recommended to replace instream sand and gravel mining operations with offstream mining operations within the flood plain corridor at a minimum distance of 50 m from the river banks.

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