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Environmental Modelling & Software 18 (2003) 119–130
Environmental Modelling & Software
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Flood risk mapping for Pari River incorporating sediment transport

Shanker Kumar Sinnakaudan *, Aminuddin Ab Ghani, Mohd. Sanusi S. Ahmad, Nor Azazi Zakaria

[a] *River Engineering and Urban Drainage Research Center (REDAC), USM Engineering Campus, University of Science Malaysia, 14300 Nibong Tebal, Penang, Malaysia*

Received 18 October 2001; received in revised form 26 March 2002; accepted 12 August 2002

Abstract

Geographic Information Systems (GIS) are an efficient and interactive spatial decision support tool for flood risk analysis. This paper describes the development of ArcView GIS extension — namely AVHEC-6.avx — to integrate the HEC-6 hydraulic model within GIS environment. The extension was written in an Avenue Script language and Dialog Designer with a series of '*point and click*' options. It has the capability of analyzing the computed water surface profiles generated from HEC-6 model and producing a related flood map for the Pari River in the ArcView GIS. The user-friendly menu interface guides the user to understand, visualize, build query, conduct repetitious and multiple analytical tasks with HEC-6 outputs. The flood risk model was tested using the hydraulic and hydrological data from the Pari River catchment area. The required sediment input parameters were obtained from field sampling. The results of this study clearly show that GIS provides an effective environment for flood risk analysis and mapping. The present study only concentrates on the flood risk within the boundary of the bunds.

Keywords: GIS; River; Flood Risk Mapping; Sediment Transport; System Integration

1. Introduction

Flood-prone areas in Malaysia are still under heavy development because there are no proper guidelines for development in floodplains even though several major floods occured in recent years (both as localized flash floods and as basin-wide floods). Some of the badly affected areas are situated at the river basins in Perak (Kinta River Basin) (DID, 1994) and Penang (Juru River Basin) (MPSP, 1999a; 1999b). By their nature, floods are generated by the random coincidence of several meteorological factors, but man's use of the river catchment also has an impact upon the severity and consequences of the events. A flood can be treated as a hazard if it has the potential threat to humans and their welfare, and the risk of floods treated as the probability of the specific hazard occurrence (Smith, 1996). Thus the flood risk maps preferably should depict the extent and the probability of a specific flood with a certain average recurrence interval (ARI).

It is also clear that there is no holistic attempt to produce flood risk maps that could determine the platform level suitable for development. Thus, field measurements need to be done to verify the areas that are most vulnerable to flooding. The flood mitigation plans can be developed and managed efficiently if there are flood risk maps in digital form which could be updated to contain the flood depth information that are directly related to the spatial variation of the flood.

There is no particular attempt yet in Malaysia to provide accurate flood risk maps taking into account sediment movement along the river channel. Ab Ghani et al. (1998a) attempted to quantify the effects of sediment movement and corresponding cross-sectional changes in producing the flood levels. Successful applications of several sediment transport models such as HEC-6 and FLUVIAL-12 indicate the possibility of extending the obtained results in mapping the flood-prone areas by incorporating sediment transport, bearing in mind the physical aspects of the ability of rivers to change their boundaries (Abu Hassan, 1998; Ab Ghani et al., 1999;

* Corresponding Author. Tel.: + 604-5941035; fax: +604-5941036.
E-mail address: redac04@eng.usm.my (S.K. Sinnakaudan).

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doi:10.1016/S1364-8152(02)00068-3

Yahaya, 1999; Tan, 2000). These sediment transport models give detailed results on water surface elevation, erosion and sedimentation, riverbed changes, and other hydraulic characteristics in huge text files. However, a great amount of time, expertise, and cost are needed for validating and visualizing the model results in presentable formats so that they can be easily used by engineers, planners, and decision makers (Ab Ghani et al., 1998b). The results also cannot show the actual flooded locations and possible risk to structures such as buildings and roads in the area.

In recent years, efforts have been made to integrate hydraulic models and Geographic Information System (GIS) to facilitate the manipulation of the model output. Three possible ways of system integration may be identified as (i) loose coupling, (ii) tight coupling and (iii) fully integrated (Mcdonnell, 1996; Pullar and Springer, 2000). Loose coupling, which integrates GIS systems and hydraulic models with common file exchange usually in ASCII format, has been a very popular approach among hydrology or hydraulic engineers. However, tight coupling shows a more prominent trend in system design, input and output control. It can be defined as a system that provides a graphic user interface (GUI) for viewing and controlling the application which may also link to different sub-routines or component programs (Pullar and Springer, 2000). Recent modeling trends move towards the fully integrated approach, which requires a model to be programmed and act as a component of the GIS core program using resident programming languages such as Avenue Script in ArcView GIS, and Arc Macro language in Arc/INFO.

Sinnakaudan et al. (1998) and Sinnakaudan (1999) show the possibilities in incorporating the hydrologic models and Geographic Information Systems (GIS) to map the spatial variation in sediment movement patterns. Ab Ghani et al. (1999) suggest the fundamental concepts and the importance of flood risk analysis with a special emphasis given to spatial element in hydraulic analysis. Tate et al. (1999) introduce some of the flood risk analyzing methods by integrating the HEC-RAS model with ArcView GIS. Similar attempts were also made by Anrysiak (2000), EPA (1997), FEMA (1997) and Jones et al. (1998). Unfortunately, these attempts miss the important element in river modeling — the sediment transport processes. The use of a hydraulic model that caters for sediment transport processes in rivers may yield better results. One of the available and calibrated sediment transport models for rivers in Malaysia is HEC-6 — Scour and Deposition in Rivers and Reservoirs Model. HEC-6 differs from other hydraulic models in terms of the capability to simulate the sediment transport mechanism in the river channel.

The Urban Stormwater Management Manual for Malaysia, which was introduced by the Department of Irrigation and Drainage Malaysia (DID) in the year 2000 requires all drainage designs to consider risk factors. Non-structural measures such as setting of minimum floor levels and/or platform levels may also be used to mitigate the effects of floods larger than the design event (DID, 2000). They should be considered within the design process as possible alternative or complementary components of the overall design (DID, 2000; DID, 2001). A typical example of risk associated with the design storm selections for different average recurrence intervals (ARI) is shown in Fig. 1. The present study only concentrates on the flood risk within the boundary of the bunds. The results of the study could then be used for the evaluation of the design of the Pari River Flood Mitigation Project in terms of the required height of the bund levels.

2. Study site

Pari River basin as shown in Fig. 2 was chosen to quantify the flooding scenarios to meet the objectives specified in this study. Pari River is a subcatchment of Kinta River and has a drainage area of approximately 284 km^2 (above Kinta River confluence) and receives an average mean annual rainfall of 2250 mm. The main stream length is 39.78 km with a time of concentration (Tc) value of 14.4 minutes (DID, 2000a). This study will be focused on a reach length about 3.5 km long which experiences frequent floods and has a wealth of detailed data for modeling. About 45% of the Pari River drainage area is fully developed and the remaining is forest and agriculture areas (DID, 1994). Previously, the flooding problems in Pari River basin has happened more frequently due to high sedimentation in the river channel caused by tin mining activities. However, the siltation from the mining has reduced appreciably since the mid 1980s. In more recent times, construction and rapid development in the floodplains and the surrounding areas has again elevated sedimentation to very high levels (DID, 2000a). Fig. 3 shows the dredging activity in various parts of Pari River confirming excessive sedimentation. A study conducted by DID (2000) which considers two future development scenarios in the years 2020 and 2060 with a nominated flood standard as 100 year ARI clearly shows that the flooding will be more extensive in the near future. For ARI 100 year flood, the discharge at Pari River above the Kinta River confluence will be 263 m/s^3 for the year 2020 and is predicted to increase to 328 m/s^3 by the year 2060 (DID, 2000). The effects of the 1997 flood on the bed of the river can be seen in Fig. 4. During the flood of 19th November 1997, significant erosion occurs compared to conditions before and after the flood. Fig. 3 and Fig. 4 show the need to include sediment transport in mapping the flooding scenarios along Pari River due to significant erosion and deposition trends during the flood event.

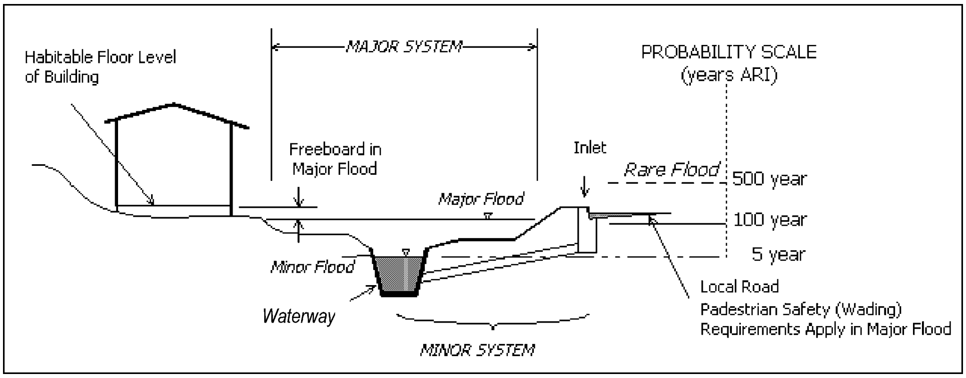


Fig. 1. Risk as the basis of design storm selection (DID, 2000b).

Some of the areas badly affected by flooding are Buntong New Village, Tengku Hussein Village, Datuk Ahmad Said Village, Manjoi Village, Kati River Village, and the housing areas such as Pari Garden, Merdeka Garden, Hock Aun Garden, Lim Garden, Cherry Park, and Sungai Pari Tower (DID, 1994; Ab Ghani et al., 1999). The Department of Irrigation and Drainage Malaysia (DID) have the burden of applying flood mitigation practices such as deepening, widening, and raising the existing bans. The flood mitigation project for Pari River originating from Meru River at the upstream down to Kuala Pari Village at the downstream for a length of about 8 kilometers (Ab Ghani et al., 1999) was launched in 1992 (Yahaya, 1999). The design channels are rectangular in shape with a width of 18 meters at the downstream of Tapah River and 16 meters for the rest. However, the width for certain sections — especially meandering sections — varies depending on the site conditions. The design discharge is based on 50 years ARI and varies from 112 m^3/s at the downstream to 86 m^3/s at the upstream. The typical cross-sections of the design channel are shown in Fig. 5.

Flooding in the year 1996 (Sinnakaudan, 1996) and year 1997 (Abu Hasan, 1998) proves that flood mitigation that has been carried out fails to control the floodwater. The damages to the properties within floodplains and the flood mitigation measures implemented by DID caused by the flood are shown in Fig. 6. Fig. 6 b shows that the bunds were breached during the 1997 flood causing the water to overflow to surrounding areas. Recently, the existing bund was upgraded with stone pitching at the river bend and the level has been raised (Fig. 7) to cater for the flood discharge, which is increasing due to rapid development. However, this creates an internal drainage problem such as back-water flow at the drain outlets to Pari River. In spite of serious flood problems, floodplain dwellers have their own way of adaptation to face the flood problems such as sealing house entrances with ion bars to a height of about 0.5 meters and they continue to stay in the flood-prone areas.

The subsequent formation of a research center known as the "River Engineering and Urban Drainage Research Center (REDAC) at University Science Malaysia", further enhances the capability for evaluating flooding problems in Malaysia. Some of the significant problems that were identified related to severe flooding are as follows:

1. High sedimentation rate
2. Development in the river-reserved land
3. Back-water phenomena

By considering the deficiencies in the existing flood plain development practices, the objective of this study has been set as follows.

3. Objectives

The objective of this study is to develop a user-friendly and menu-driven graphic user interface (GUI) called AVHEC6 for manipulating the output of the HEC-6 model to produce flood maps for different flood events in ArcView GIS 3.2. These can provide a better tool for identifying areas of flood inundation, depth-of-flood details, spatial variation in flood risk mapping and sediment transport based on hydrological, hydraulic, and socio-economic factors for Pari River catchment area. The end product is digital flood-risk maps that can be updated easily and can be analyzed with other digital data from Pari River catchment area.

4. The software used

HEC-6 hydraulic model and the ArcView GIS 3.2 with Spatial Analyst, 3D Analyst extensions were used in this study. HEC-6 is a one-dimensional movable boundary open channel flow numerical model designed to simulate and predict changes in river profiles resulting from scour and/or deposition over moderate time periods (USACE, 1993). It uses a sequence of steady flows to

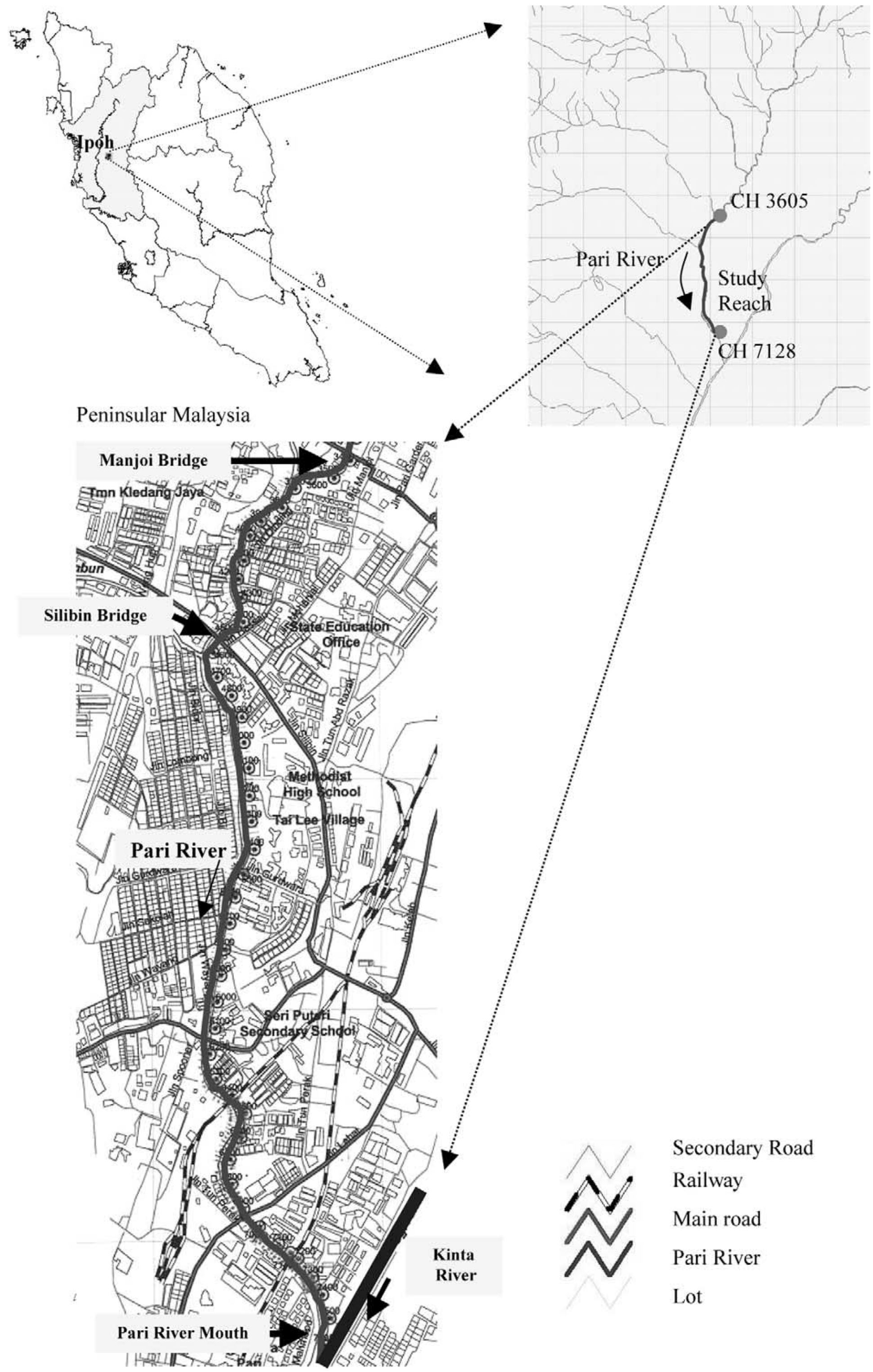


Fig. 2. Study area — Pari River reach.

represent discharge hydrographs. The movable bed is constrained within the limits of the wetted perimeter and the entire wetted part of the cross section is normally moved uniformly up or down (USACE, 1993). Abu Hassan (1998) and Tan (2000) had tested the HEC-6 model for Pari River to predict water levels based on the 1997 flood and obtained satisfying agreements with observed water levels (Fig. 8).

ArcView has become the preferred desktop GIS software. All the modeling processes within ArcView

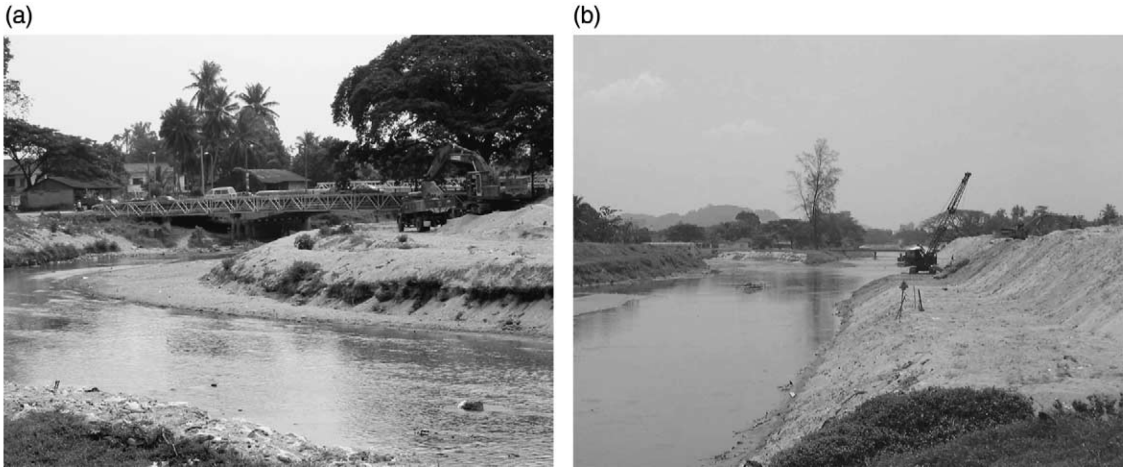


Fig. 3. Sand dredging at Pari River (July, 2002).

are organized with a project, which may consist of a number of views, tables, charts, layouts, and Scripts (ESRI, 1996a). While ArcView GIS 3.2 is treated as the core module, ArcView GIS Spatial Analyst and ArcView GIS 3D Analyst are used as specialized extensions for creating, querying, mapping, and analyzing raster and TIN data (ESRI 1996a, 1996b, 1999). The avenue programming language that is embedded in ArcView GIS and Dialog Designer was manipulated for customization and interface design to perform modeling tasks in this study (ESRI, 1996c, 1997).

Stream definition in the HEC-6 model is done by referring any point along the river reach by a series of stations (lateral coordinate) and elevation (Z- coordinate) (USACE, 1993). In contrast, ArcView GIS 3.2 structures the real world coordinate system based on its easting (x-coordinate), northing (y-coordinate) and elevation (z-coordinate) (ESRI, 1996b). In order to map the hydraulic output from the HEC-6 model in ArcView GIS 3.2, the differences in the coordinate system must be considered, which has been resolved in this study.

5. Methodology

This study provides an approach for processing output of the HEC-6 model to produce automated digital floodplain mapping for Pari River in Arc View GIS taking into account the river's ability to transport sediments. There were three important phases in this study: field data collection, river modeling using the HEC-6 model, and flood plain mapping by integrating the HEC-6 model output with ArcView GIS.

5.1. Hydraulics

The water surface elevation computational procedure in HEC-6 is based upon the solution of the one-dimensional energy and continuity equations using a standard step algorithm. Back-water computations proceed in the upstream direction for sub-critical flow, and in the downstream direction for supercritical flow (USACE, 1993). The data needed to perform these computations include: flow regime, starting elevation, discharge, loss coefficients, Manning's roughness, cross-section geometry, and reach lengths.

5.2. Sediment routing

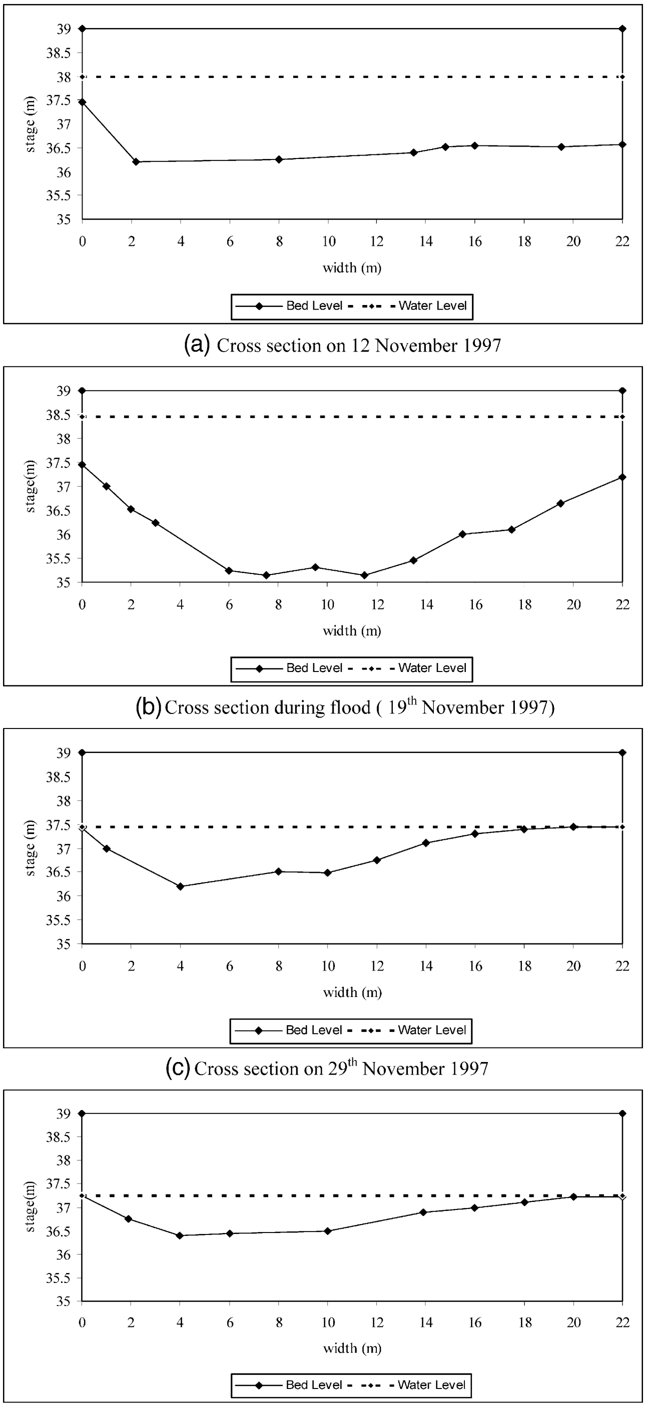
In the HEC-6, the sediment transport rates are calculated for grain sizes up to 2048 mm. There are twelve bed material load transport functions available in HEC-6 and it also has the flexibility to allow the user to specify his own equation. Inflowing sediment loads are related to water discharge by sediment discharge curves for the upstream boundaries of the stream. Transport potential is calculated at each cross section using hydraulic information from the water surface profile calculation and the gradation of bed material. Sediment is routed downstream after the backwater computations are made for each successive discharge (times step). The basis for adjusting bed elevations for scour or deposition is the continuity equation for sediment material or the Exner equation,

$$\frac{\partial G}{\partial \mathrm{X}} + B_o \bullet \frac{\partial Y_s}{\partial t} = 0 \tag{1}$$

where: B_o = width of movable bed, t = time, G = average sediment discharge (ft^3/sec) rate during time step Δt, X = distance along the channel, Y_s= depth of sediment in control volume

5.3. Calibration of HEC-6 for Pari River

Extensive field data samplings on sediment transport in Pari River were carried out to obtain sediment distri-



(a) Cross section on 12 November 1997

(b) Cross section during flood (19th November 1997)

(c) Cross section on 29th November 1997

(d) Cross section on 3rd December 1997

Fig. 4. Cross section measured before and after the 19th November 1997 flood at Manjoi Bridge, Pari River.

bution size and sediment load. Yahaya (1999) conducted an assessment on several existing sediment transport equations for the data collected at Merdeka Garden Station at Pari River. The discrepancy ratio is used to indicate the goodness of fit between the computed and measured results, i.e.,

$$R_i = \frac{Q_{ci}}{Q_{mi}} \tag{2}$$

$$\overline{R} = \frac{\sum_{i=1}^{J} R_i}{J} \tag{3}$$

where: R_i = discrepancy ratio; Q_{ci} and Q_{mi} = computed and measured bed-material loads, respectively; $\overline{R}$ = mean value of the discrepancy ratios; J = total number of data used in the comparison.Among the available eleven sediment transport equations in HEC-6, the unit stream power equation recommended by Yang (1996), namely

$$\log C_{ts} = 5.435 - 0.286\log\frac{\omega d}{v} - 0.457\log\left(\frac{U_*}{\omega}\right) + \left(1.799 - 0.409\log\frac{\omega d}{v} - 0.314\log\frac{U_*}{\omega}\right) \times \log\left(\frac{VS}{\omega} - 0.314\log\frac{V_{cr}S}{\omega}\right) \tag{4}$$

where: C_{ts} = total land concentration (in ppm by weight), ω = terminal fall velocity, d = median sieve diameter of sediment particles, v = kinematics viscosity, VS = unit stream power, and$V_{cr}S$= critical unit stream power required at incipient motion gives the best overall estimation of the observed sediment transport rate with 70% of the prediction within acceptable discrepancy ratios of 0.5 and 2.0 as shown in Fig. 9. The result indicates that, on average, Eq. (4) can be used to accurately compute sediment transport rate for Pari River as confirmed by calibration done on HEC-6 (Abu Hassan, 1998; Tan, 2000) as shown in Fig. 8.

The elevation mass points, cross section, bed forms, and other physical characteristic of the river were obtained from the river survey provided by the Department of Irrigation and Drainage Malaysia (DID). These survey data were then used to form channel geometry information in HEC-6, and rainfall hydrographs between August and November 1997 (Fig. 10) were used to represent the hydrological characteristic and simulate water levels for the 1997 flood. A steady-state approach has been applied where a continuous flow record is partitioned into series of steady flows of variable discharge durations (USACE, 1993). For each flow a water surface profile is calculated using step back-water method (USACE, 1993). Fig. 8 shows the results of the calibration of HEC-6 using the Yang equation (Tan, 2000), which depicts a good agreement between the observed and simulated water levels.

5.4. ArcView extension (AVHEC-6.avx)

A loose-coupling integration procedure which produces an ArcView extension, namely AVHEC-6.avx,

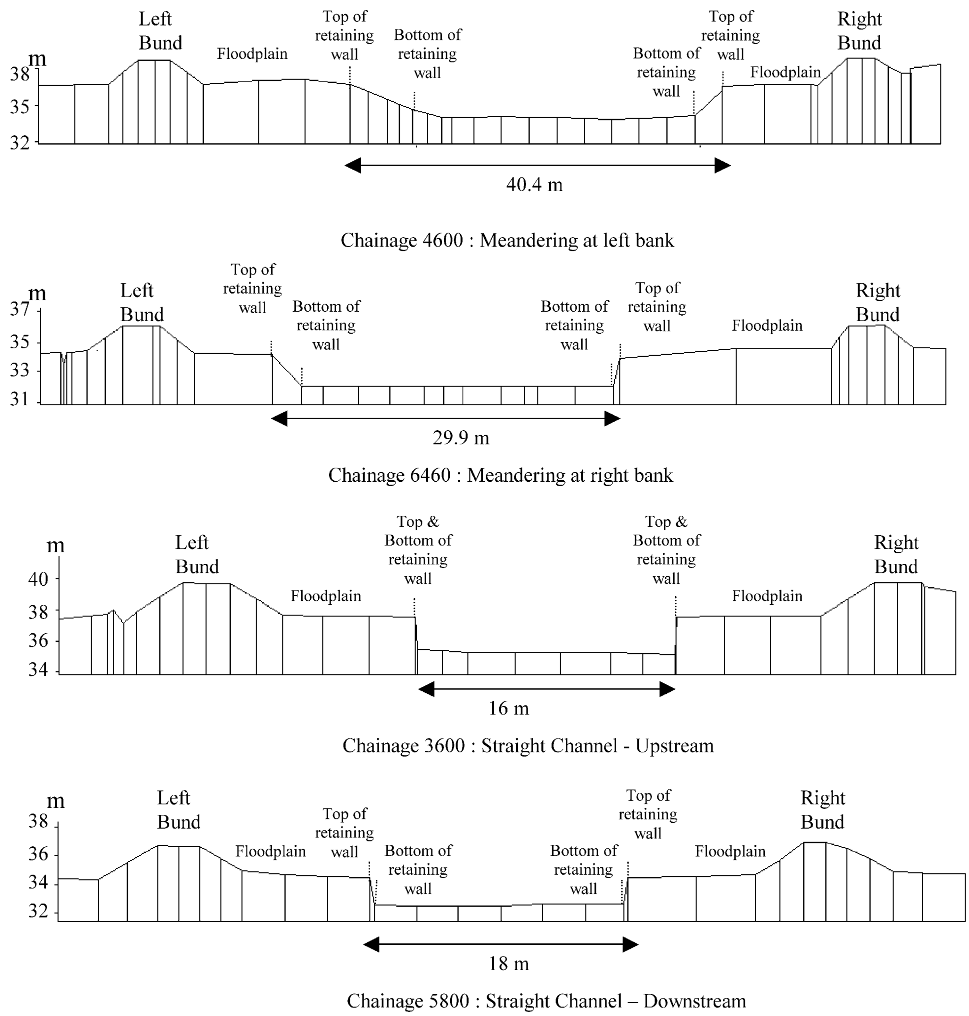


Fig. 5. Typical cross-section for Pari River.

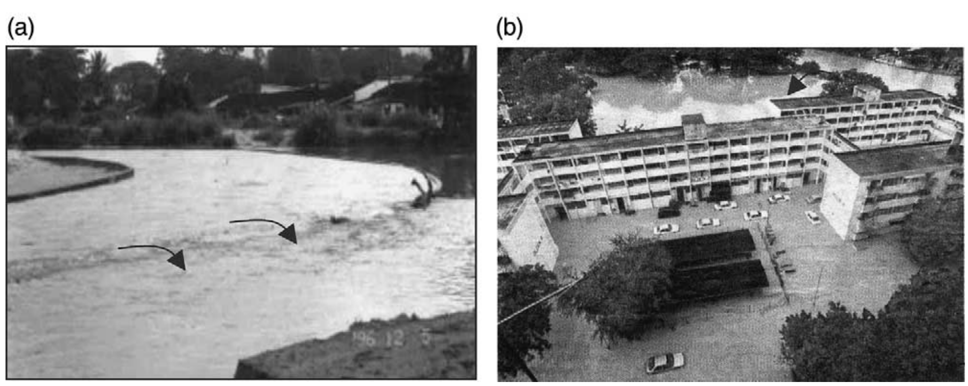


Fig. 6. Flood conditions in Pari River.

was developed to source out computed water surface profiles and cross section geometry output generated from the HEC-6 model and reproduce them in the cross-section parameter table in ArcView GIS. The Graphic User Interface for the AVHEC6 extension comprises two main menus, namely the AVHEC-6 and the AVHEC-6—Tools as shown in Fig. 11 a and b. Each menu item is connected with an avenue script to perform special tasks in flood-plain mapping. A sample GUI for cross section mapping and an avenue sub-routine for geometry coordinate calculation are shown in Fig. 11 c and d.

Cross sections were first mapped along the thalweg of the Pari River. The node at every cross section contains channel geometry information, which was used to create

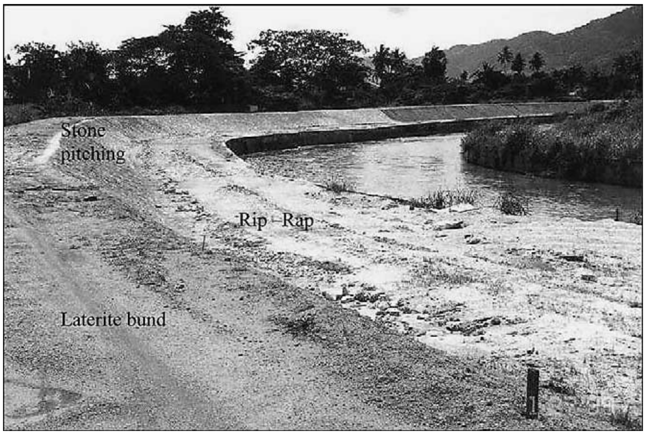


Fig. 7. Stabilization of Pari River after 1997 flood.

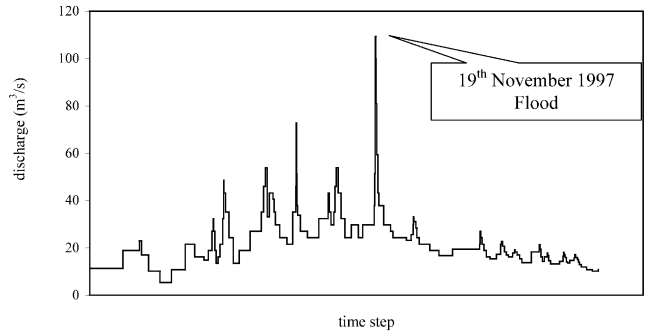


Fig. 10. Input hydrograph for HEC-6: August 1997–November 1997 (Tan, 2000).

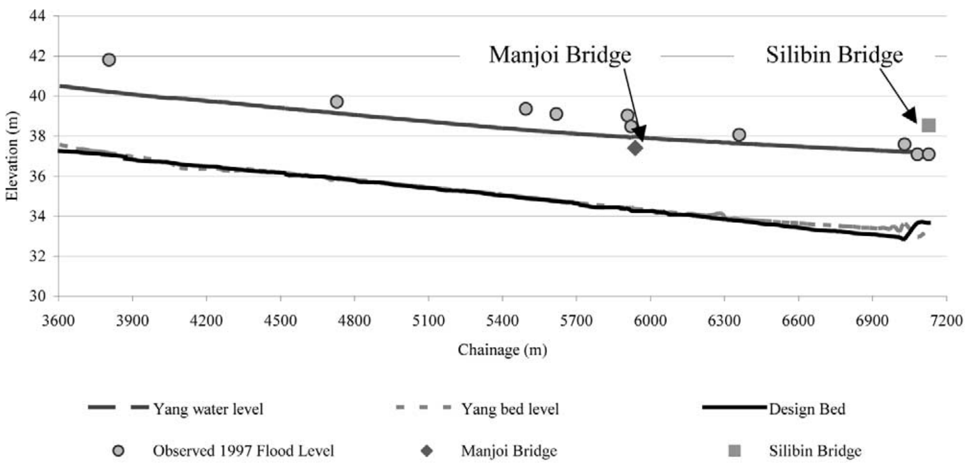


Fig. 8. The results of the calibration of HEC-6 using Yang equation (Tan, 2000).

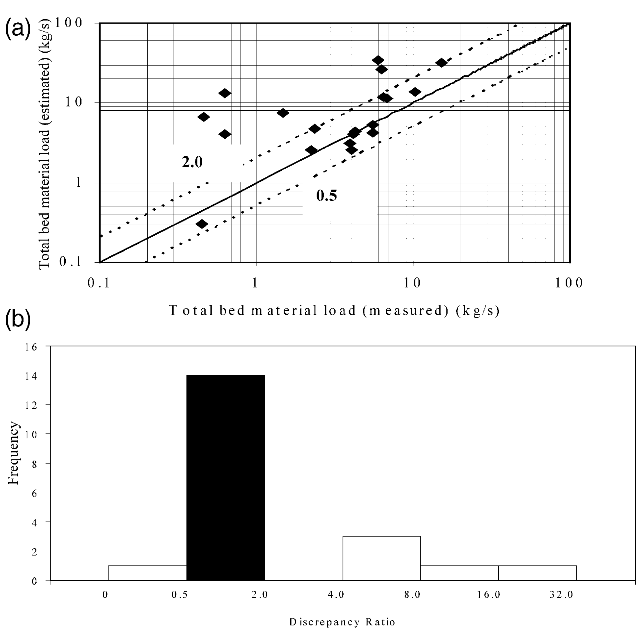
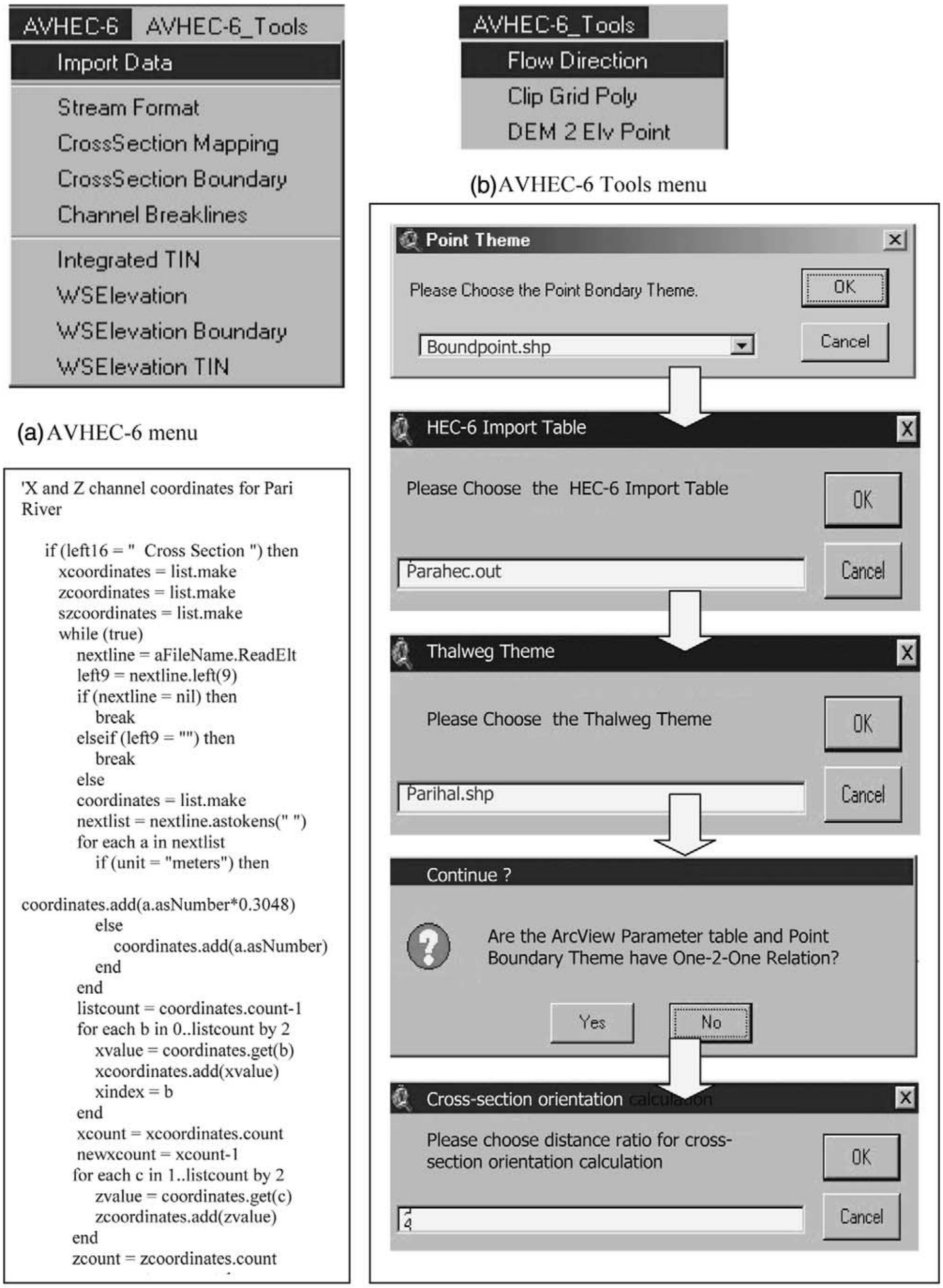


Fig. 9. Discrepancy ratio for sediment discharge at Pari River using Yang Equation (Yahaya, 1999).

a Triangulated Irregular Network (TIN) surface model for the river channel. In TINs, areal features such as lakes and islands are represented by a closed set of triangle edges. Linear features such as ridges are represented by a connected set of triangle edges. Triangle nodes represent peaks and pits (Anrysiak, 2000). Spot heights and contour elevation were then used to create a Digital Elevation Model (DEM) to represent the continuous surface where the survey data is not available (Leenaers and Okx, 1989; Sinnakaudan and Rainis, 1999). The grid (DEM) is the standard data model used for small-scale representation of the general land surface. In order to create a comprehensive TIN, a method to integrate relatively low-resolution digital elevation model (DEM) data with comparatively higher-resolution vector floodplain data were applied (Tate et al., 1999). By combining the vector and raster data to form a TIN, the intended result is a continuous three-dimensional landscape surface (integrated TIN) that contains additional detail in stream channels and surrounding areas for the study reach (Fig. 12).

The resulting floodplain and flood risk maps can then be digitally drawn by integrating the results from the



(c) An Avenue sub-routine to read the channel cross-section coordinates

(d) An example of sub-menus: cross section mapping

Fig. 11. Operation menus for AVHEC6 extension.

HEC-6 model. A water surface elevation TIN was created and draped over Pari River integrated surface TIN to draw a two-dimensional floodplain (Fig. 13). In order to get a good visualization of the resulting floodplain, the 3D Analyst extension in ArcView GIS was used to get a 3D view of inundated areas. Floodplain areas corresponding to water levels for low and high flow during the 19th November 1997 flood with the Yang equation is shown in Fig. 14. Although Fig. 14 clearly shows that the water surface profile may exit the left and right bund of Pari, the visualizing of this phenomenon was limited by the geometrical information provided in the HEC-6 model. The definition of a wider floodplain in the HEC-6 model needs considerable effort in surveying and other photo-grametric spatial data processing. The modeling and visualizing limitations identified would be of great importance in future research.

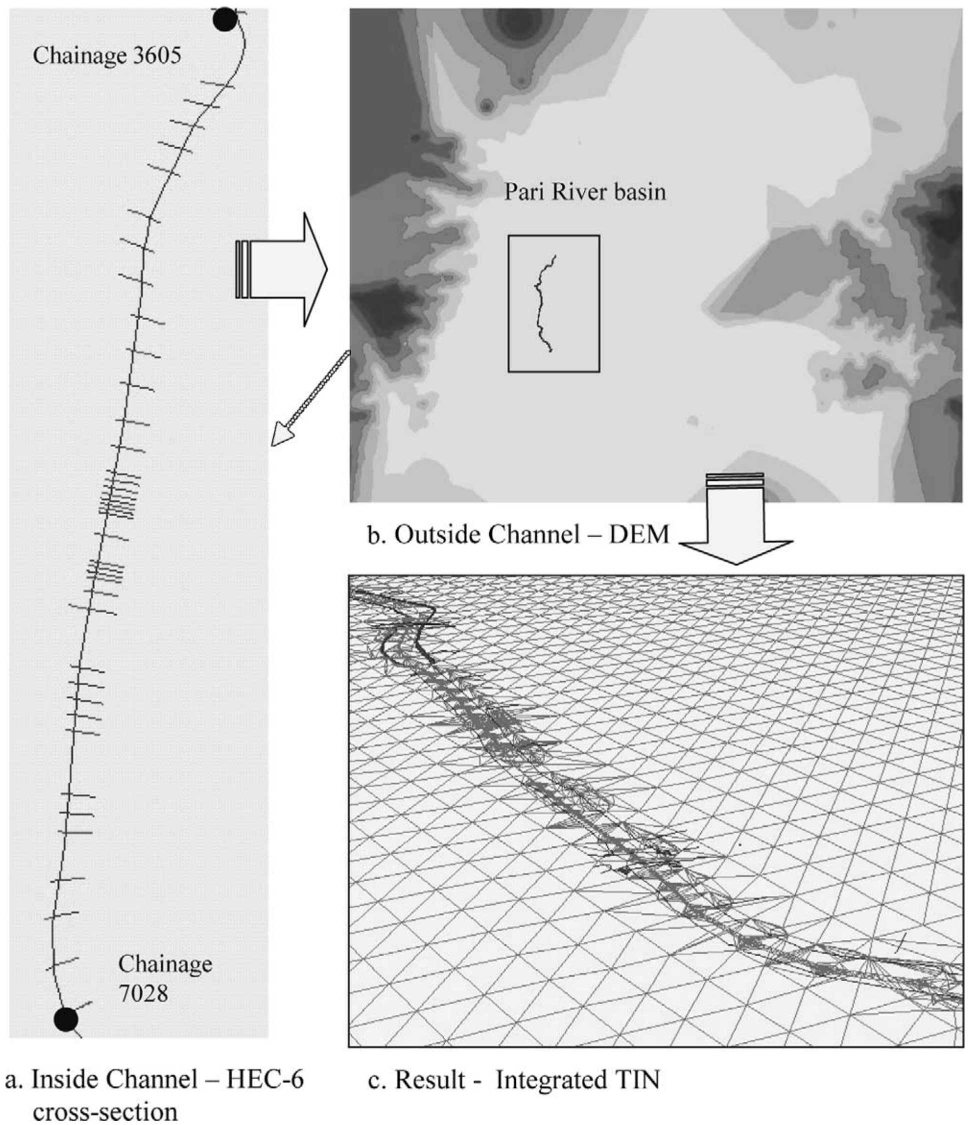


Fig. 12. Three-dimensional TIN terrain modeling approach.

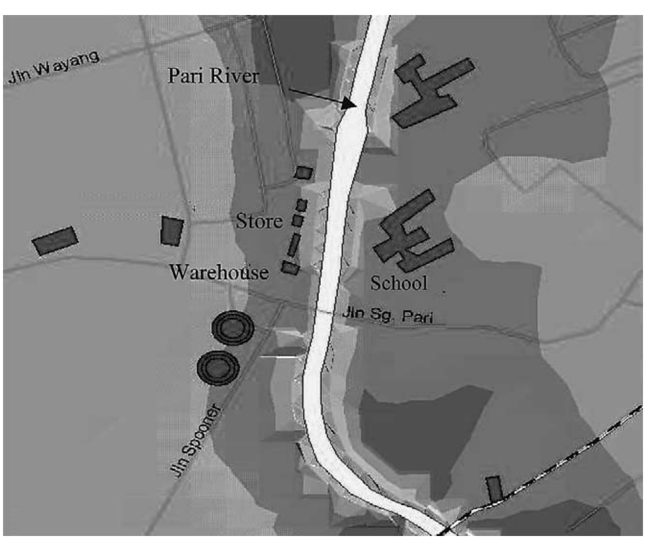


Fig. 13. Two-dimensional flood risk map for Pari River.

6. Future work

The proposed methodology has yielded a better dissemination of floodplain information management compared to paper maps in terms of consistency, efficiency, and accuracy. However, the loose coupling integration procedure developed is found to be still prone to errors and bugs when applied to other rivers having different hydraulic and geometric properties. It acts as a partly automated floodplain mapping procedure and the preprocessing part, which included geometric data generation and hydraulic parameter representation for hydraulic simulation, still has to be done manually. The geometric model formation for river channel and floodplain in the HEC-6 will be a tedious and time-consuming task since hundreds and thousands of points have to be keyed in manually each time if there is a small change in the study area in the model. This method will be error prone and will only be advanced with the introduction

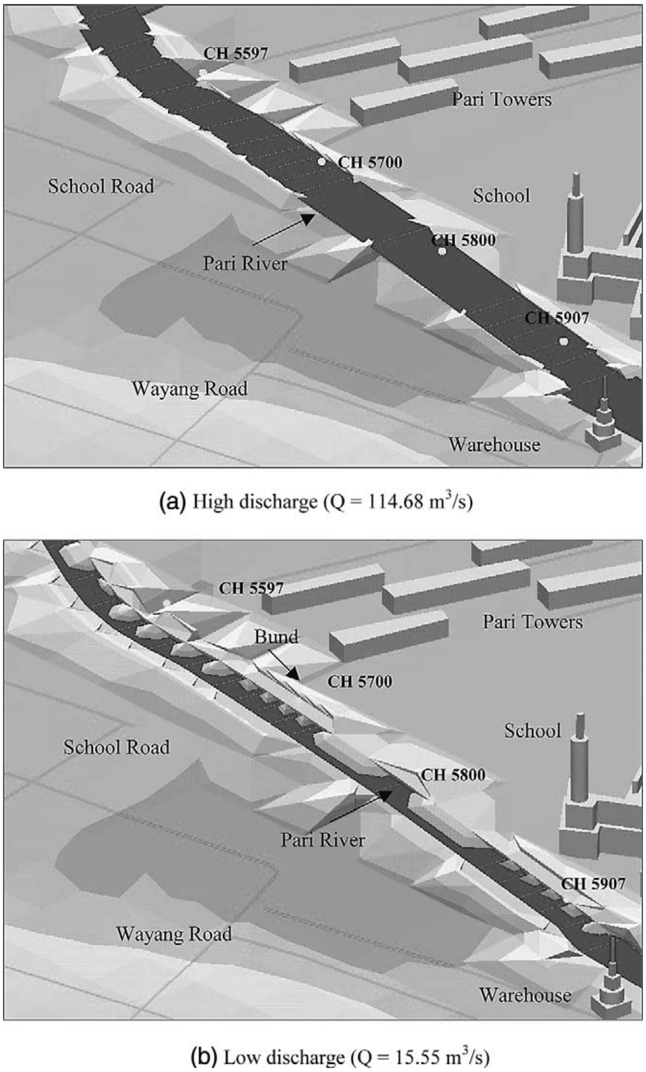


Fig. 14. Three-dimensional flood risk maps for Pari River using Yang equation during the 19th November 1997 flood.

of fully automated floodplain modeling techniques conducted within a GIS Environment. This will also ease the focus on the development of flood risk maps for different return periods. Flood plains along Pari River will then be classified according to risk zones for future development.

By bringing in object linking and embedding (OLE) and object-oriented programming (OOP) technology, it is possible to integrate maps and their attributes with the hydraulic data derived from the HEC-6 hydraulic model. Future study will include development of a hydraulic model that operates within the ArcView GIS environment. The methodology used can save time and resources when conducting flood studies. The integrated spatial database, sediment routing and water routing procedures will be developed in ArcView GIS to get a fully functioned GIS-based hydraulic model. However, this is no easy task since GIS is prone to many problems in handling dynamic modeling needs. The channel survey will be expanded outside the channel boundary using electronic distance measurement (EDM) techniques to get more accurate flood plain visualization.

7. Conclusions

This research has suggested the possibilities of using a loose coupling method within Arc View GIS and HEC-6 hydraulic model for flood risk analysis. The methodology followed here is suitable for any geometrically defined river channel. The AVHEC6 extension created was successfully applied in flood risk analysis for Pari River. However, more fine tuning and possible bug fixes are needed before it can be made a common modeling extension for ArcView GIS and used as a visualizing tool for various flood phenomena for different catchment areas. In this study, the flood profile was successfully visualized within the channel boundary. Here, it is recommended that more emphasis be given to the development of an embedded flood risk analysis model within the GIS environment.

Acknowledgements

The authors would like to acknowledge the Intensified Research in Prioritised Area Grant (IRPA–08-02-05-6006) provided by the Ministry of Science, Technology & Environment, Malaysia that has resulted in this paper. Many thanks are also due to the Department of Irrigation and Drainage, Kinta Batang Padang, Perak for providing the required data on Pari River. The authors would also like to thank Ir. Eric Tate from Center for Research in Water Resources (CRWR), The University of Texas at Austin for his comments throughout this research. An appreciation also goes to Mr. Tan Boon Huat, Mr. Lau Tze Liang, Mr. Lee Chee Beng and Mr. Paker Mohamad Abdul Hamid for assistance in sediment data collection and analysis. Finally, many thanks to the members of River Engineering and Urban Drainage Research Center (REDAC) at the University of Science, Malaysia for their support, advice and encouragement.

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