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Hydraulic Simulation of Flood Occurrences in a Tropical River System: the Case of Linggi River System

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ABSTRAK

Ramalan banjir adalah penting kerana ianya dapat menolong mengurangkan kerosakan akibat banjir terutamanya di kawasan hilir sungai. Peningkatan dalam kaedah-kaedah numerikal dan teknologi komputer telah menghasilkan banyak model matematik yang boleh digunakan untuk simulasi hidraulik banjir. Simulasi hidraulik banjir dalam satu sistem sungai kebiasaannya termasuk ramalan luas dan kedalaman banjir di sepanjang sungai tersebut. Maklumat sedemikian adalah penting kerana ianya dapat membantu jurutera untuk memberi perhatian yang lebih ke atas reka bentuk bagi mengurangkan kerosakan oleh banjir. Model hidraulik yang digunakan bagi mensimulasikan aliran sungai boleh diklasifikasikan kepada model hidraulik dinamik dan model hidraulik statik. Model HEC-2 statik telah digunakan untuk membuat ramalan hidraulik aliran Sungai Linggi di kawasan Seremban, Malaysia. Model HEC-2 adalah berdasarkan kepada penyelesaian numerikal bagi persamaan tenaga satu dimensi. Kalibrasi dan verifikasi tentang profil permukaan air telah diperolehi dengan menggunakan data rekod bagi Sungai Linggi. Selepas kalibrasi, model HEC-2 telah digunakan untuk meramalkan profil permukaan air untuk Q_2, Q_{10} dan Q_{100} di sepanjang sistem Sungai Linggi. Hasil perbandingan tersebut menunjukkan tiada perbezaan ketara, dengan ralat absolut maksimum adalah 100 mm dan ralat absolut minimum adalah 20 mm sahaja.Bacaan-bacaan ini menunjukkan perbezaan yang kurang daripada 5%.

ABSTRACT

Flood forecasting is important because it can help in reducing the consequences of flood damage especially at the downstream end. Advances in numerical methods and computer technologies, have resulted in the development of many mathematical models which can be used for hydraulic simulation of flood. These simulations usually include the prediction of the extent of flood and its depth along a river system. Information obtained from the simulated models are essential because it can help engineers to take precautionary measures in designing their hydraulic structures. Hydraulic models that are used in the simulation can be classified into dynamic hydraulic models and static hydraulic models. The HEC-2 static hydraulic model was used to predict the flow of Linggi river in the vicinity of Seremban town. HEC-2 model is based on the numerical solution of a one-dimensional energy equation of the steady gradually varied flow using an iteration technique. Calibration and verification of the HEC-2 model were conducted using the recorded data for the Linggi river. After calibration, the model was used to predict the water surface profiles for Q_2, Q_{10}, and Q_{100} along the watercourse of the Linggi river. The predicted water surface profiles were found to be in agreement with the recorded water surface profiles, whereby the maximum computed value of the absolute error in the predicted water surface profile was found to be 100 mm while the minimum absolute error was found to be 20 mm only. In term of percentage, these errors represent a difference of less than 5% between the readings of the computed simulation to the actual field records. Testing process showed that HEC-2 model is sensitive to value of Manning coefficient of roughness and the intervals of cross sections long studied river system.

Keywords: Simulation, modelling, flood, tropical river system, water surface profile

INTRODUCTION

A flood is any abnormally high water-stage or flow over land, in a stream, floodway, lake, or coastal areas that can cause detrimental effects to life and property. Flooding in the river system of a tropical region is mainly due to excessive rainfall in the upper catchment of the river system. This is made worse if the catchment area is infringed with development. The worst flood in Malaysia was recorded in 1926 which had been described as having caused the most extensive damage to the natural environment. Subsequent major floods were recorded in 1931, 1947, 1954, 1957, 1967, and 1971. Floods of lesser magnitude also occurred in 1973, 1979 and 1983 (Ann 1994). As a result of advances in numerical methods and computer technologies, many mathematical models have been developed and used for hydraulic simulation of the flood. The hydraulic simulation of the flood in a river system usually includes the prediction of the extent of flood and its depth along a river course. This type of information is essential because it will help engineers to take precautionary measures in their design so as to minimize the potential flood damage especially at the downstream end. Hydraulic models that are used in the simulation can be classified into dynamic hydraulic models and static hydraulic models. This classification was based on the concept and the approach used in the formulation of these models. An example of a recent work on the static hydraulic model for computing water surface profile in prismatic and non-prismatic channels was developed by Ishikawa (1984). Examples of dynamic hydraulic models were those developed by Lyness and Myers (1994), Molls and Chaudhary (1995), and Sturm and Sadiq (1996). Nik (1996) applied both HEC-2 static hydraulic model and MIKE 11 dynamic hydraulic model to predict the water surface elevation of the Klang River, and found that there was a difference of about 5% in the results obtained. In the present study, the HEC-2 static hydraulic model was calibrated, verified and then applied to predict the water surface profiles along the watercourse of the Linggi river and its tributaries.

MODEL FORMULATION

The hydraulic simulation of the flow in a river, stream or a drain is useful for many water resources projects. Knowledge about the water surface profile in nonprismatic channels is important specifically for flood plain management, flood mitigation and for analysis and design of the river crossing. In this study, the flow along nonprismatic channel was hydraulically simulated and a final form of the mathematical model was used to predict the water surface profile of the Linggi river watercourse. A hydraulic model known as HEC-2, developed by the Hydrologic Engineering Center, USA was used to simulate the flow. The model is based on the numerical solution of a one-dimensional energy equation that can be applied for the flow between two sections of a river reach. In the HEC-2 model, both major and minor losses in energy occurred in a river reach, were considered since these two types of energy losses are effective. Thus, the total energy loss for the flow in a river is due to the friction loss, eddy loss and any other possible minor losses. To explain the mathematical algorithm, it is convenient to refer to the water surface for a natural channel above a datum at the two sections as shown in *Fig. 1.* When the energy principles are applied for the two sections, the following equations were obtained:

$$h_f = \left(\frac{L_l Q_l + L_c Q_c + L_r Q_r}{Q_l + Q_c + Q_r} \right) \left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}} \right) \tag{1}$$

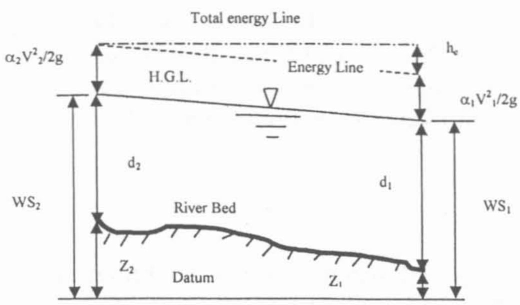

Fig. 1: Natural river reach used in the derivation of HEC-2 model

and $WS_1 = d_1 + z_1$ (2)

$$WS_2 = d_2 + z_1 \tag{3}$$

Substituting Equation (2) and Equation (3) into Equation (1) results in the following equation:

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_2 V_1^2}{2g} \tag{4}$$

Where WS_1, WS_2 are water surface elevations from a datum for section 1 and section 2 respectively, d_1, d_2 are water depths at section 1 and section 2 respectively, z_1 , z_2 are the channel bed elevations above a datum at section 1 and section 2 respectively, V_1 , V_2 are average velocities (total discharge per total area of the flow) at section 1 and section 2 respectively , α_1, α_2 are velocity weighting coefficients at section 1 and section 2 respectively, g is the acceleration due to gravity, and he is the energy loss in the reach.

Chow (1959) defined the energy loss in the reach of a river as a combination of the friction loss and eddy loss:

$$h_e = h_f + h_l \tag{5}$$

where h_f is the friction loss and h_l is the eddy loss.

The eddy loss h_l is appreciable in nonprismatic channels and there is no available rational method of evaluating this loss. The eddy loss depends mainly on the velocity head change and may be expressed as shown below:

$$h_l = \theta\left(\alpha_2 \frac{V_2^2}{2g} - \alpha_1 \frac{V_1^2}{2g}\right) \tag{6}$$

where θ is the eddy loss coefficient.

For a gradually converging reach, θ varies from 0 to 0.1, and for a gradually diverging reach θ varies from 0 to 0.2. For abrupt expansions and contractions, θ is about 0.5. For prismatic and regular channels, the eddy loss is practically zero, ($\theta = 0$). For nonprismatic channel, friction loss can be described by the following formula:

$$h_f = L\bar{S}f \tag{7}$$

The discharge-weighted reach length L in Equation (7) is computed by proper proportioning the length of left overbank, the main channel, and right overbank with their respective flows at the end of the reach as given by the following equation :

$$L = \frac{L_l\overline{Q}_l + L_c\overline{Q}_c + L_r\overline{Q}_r}{\overline{Q}_l + \overline{Q}_c + \overline{Q}_r} \tag{8}$$

A representative friction slope S is expressed as follows:

$$\bar{S}f = \left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}}\right)^2 \tag{9}$$

where L_l, L_c, L_r are reach lengths specified for flow in left over bank, main channel and right overbank, respectively, Q_l, Q_c, Q_r are arithmetic average of the flows at the ends of the reach for left overbank, main channel, and right overbank respectively, Q_{T1}, Q_{T2} are the values of the total discharge at section 1 and 2 respectively, K_{T1}, K_{T2} are the composite or total conveyance for section 1 and 2 respectively.

By substituting Equation (8) and Equation (9) into Equation (7), the following equation is obtained:

$$h_f = \left(\frac{L_l Q_l + L_c Q_c + L_r Q_r}{Q_l + Q_c + Q_r}\right)\left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}}\right) \qquad (10)$$

Total energy loss in a river reach h_e can be obtained by substituting Equation (10) and Equation (6) into Equation (5):

$$h_f = \left(\frac{L_l Q_l + L_c Q_c + L_r Q_r}{Q_l + Q_c + Q_r}\right)\left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}}\right)^2 + \theta\left(\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right) \qquad (11)$$

The total conveyance of a river section can be described as below:

$$K_{Ti} = \frac{Q_{Ti}}{\sqrt{S_i}} \qquad (\mathrm{i} = 1, 2, 3, ..., \mathrm{N}) \qquad (12)$$

If the river section is divided into N number of subsections, the total conveyance is the sum of the conveyance for each subsection as shown below:

$$K_{Ti} = k_1 + k_2 + k_3 + ... + k\mathrm{N} \qquad (13)$$

where k_1, k_2, k_3, ..., k_N are the conveyance for the subsection number 1, 2, 3, ..., N

To simplify the calculation, natural channel is divided into three main subsections namely the right bank, the central reach and the left bank as shown in *Fig. 2.*

Equation (13) can be simplified into the following form:

$$K_{Ti} = k_l + k_c + k_r \qquad (14)$$

where k_l, k_c and k_r are the conveyance of the left subsection, central channel, and right subsection respectively.

From the Manning formula, the conveyance of each subsection can be written as:

$$k_j = \frac{1}{nj} A_j R_j^{2/3} \qquad (\mathrm{j} = \mathrm{l, c, r}) \qquad (15)$$

where l, c, and r denote the left subsection, central subsection and right subsection

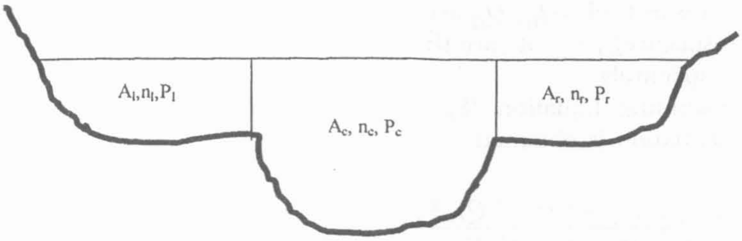

Fig. 2: Division of the flooded natural cross section into discrete elements

By substituting Equation (15) into Equation (14), the following equation is obtained:

$$h_f = \left(\frac{L_l Q_l + L_c Q_c + L_r Q_r}{Q_l + Q_c + Q_r} \right) \left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}} \right) \tag{16}$$

where n_l, n_c, and n_r is Manning coefficient of roughness for left overbank, central channel, and right overbank respectively.

The velocity coefficient α at any river section can be written as:

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_2 V_1^2}{2g} \tag{17}$$

where A_T is the total area of cross section, Al, Ac, Ar are flow area of left overbank, main channel and right overbank, respectively.

In Equation (17), the difference in velocity head between the main channel and the overbank sections is taken into consideration. The average velocity at a section can be described by:

$$V_i = \frac{Q_{Ti}}{A_{Ti}} \tag{18}$$

By substituting Equation (18), Equation (17) and Equation (11) into Equation (4) and after simplifying, the following equation is obtained:

$$\begin{aligned} \mathrm{WS}_2 = \mathrm{WS}_1 &+ \left(\frac{1-\theta}{2g} \right) \left[\left(\frac{Q_{T1}{}^2}{K_{T1}{}^3} \right) \left(\frac{k_{l1}{}^3}{A_{l1}{}^2} + \frac{k_{c1}{}^3}{A_{c1}{}^2} + \frac{k_{r1}{}^3}{A_{r1}{}^2} \right) - \left(\frac{Q_{T2}{}^2}{K_{T2}{}^3} \right) \left(\frac{k_{l2}{}^3}{A_{l2}{}^2} + \frac{k_{c2}{}^3}{A_{c2}{}^2} + \frac{k_{r2}{}^3}{A_{r2}{}^2} \right) \right] \\ &+ \left(\frac{L_l \overline{Q}_l + L_c \overline{Q}_c + L_r \overline{Q}_r}{\overline{Q}_l + \overline{Q}_c + \overline{Q}_r} \right) \left(\frac{Q_{T1} + Q_{T2}}{K_{T1} + K_{T2}} \right)^2 \end{aligned} \tag{19}$$

COMPUTATIONAL METHOD

Equation (19) describes the HEC-2 model that can be used to predict the water surface profile of a river for known values of discharge and the Manning coefficient of roughness. On the other hand the section geometry along the river must be defined in the model computation. Numerical computation of Equation (19) can be performed manually, but it is rather cumbersome and time consuming. The HEC-2 program has been developed to perform the numerical computation of Equation (19). The numerical implementation of Equation (19) can be explained as follows:

1. Assume a water surface elevation at the upstream cross section WS2 for subcritical flow in the river channel while the SW_1 is known.
2. Based on the assumed water surface elevation, determine the corresponding total conveyance. The determinations of the areas and the conveyance for subsections are important for model application.
3. Solve Equation (19) for SW_2 and compare the computed value of SW_2 with the value assumed in step 1; repeat steps 1 to 3 until the value agree within 0.01m accuracy. The calculated SW_2 will be used as SW_1 for the computation of the water surface elevation to the next upstream section.

Linggi River

The Linggi river is a major river system in the state of Negeri Sembilan, Malaysia. The river discharges its water to the sea (The Straits of Malacca) through the river mouth at Port Dickson, which is located approximately 53 km downstream from Seremban town, the capital of the state. Seremban is located approximately 70 km south of Kuala Lumpur at Latitude 2.750 North and Longitude 101.90 East. Simulation of water surface profile of the Linggi river was carried out for the river system in the vicinity of the Seremban town. *Fig. 3* shows the upstream Linggi River basin and the Seremban town occupies the lower portion of the basin. The Linggi river system passes through residential, commercial, industrial and agricultural areas. There are several areas within the township that experience flooding due to the high flows of the Linggi river during the rainy season. It is important to control flooding in the town centre by increasing the carrying capacity of the linggi river. According to a survey data, the average slope of the Linggi river is 1/500 while the measured length up to the control point (Station 2619401) is 5688 m (Mohammed 1998).

Data Acquisition

The data needed for this study was obtained from the Hydrology Section of the Drainage and Irrigation Department (DID) in Kuala Lumpur. The data acquired can be categorized as: (a) the streamflow records, (b) the stage records, (c) the longitudinal section of the river and (d) the cross sections of the river at 50 m interval.

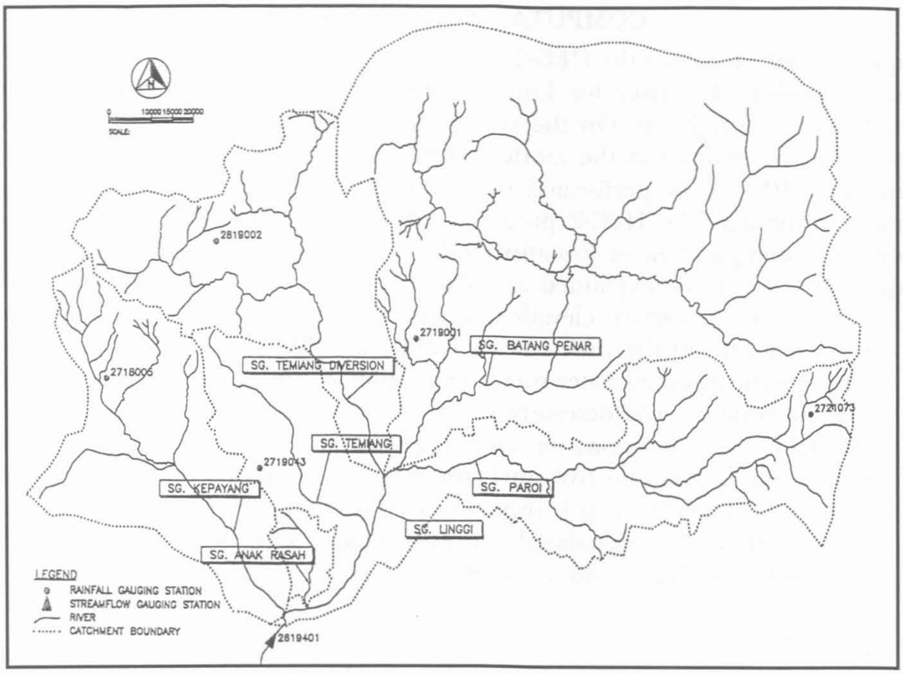

Fig. 3: Upstream basin of Linggi River system

Model Calibration and Verification

The calibration of HEC-2 model involves accurate estimation of the empirical hydraulic coefficients so that the flow events simulated by the model can produce flows of actual events as closely as possible. However, it is necessary to use the actual boundary conditions of the watercourse in the model. For backwater computation of the subcritical flow, the water level at a downstream control section is considered as a boundary condition in the HEC-2 model. This can be achieved by using the rating curve at this section. The other boundary condition that is involved is the tributary inflows to the main river. In the calibration process, consideration of various values of the incoming flow from tributaries to the main river will help the modeler to get accurate estimation for the roughness coefficients along the main watercourse. For the Linggi river, the eddy loss coefficient, θ and Manning coefficient of roughness, n were estimated based on field measurement of the water surface profile of the Linggi river for a stretch of 600 m using different discharges which include discharges of the tributaries. Applying the energy equation, values of the eddy loss coefficients for Linggi river were found to be within the range of values given by Chow (1959). The Manning formula was used to estimate the Manning coefficient of roughness, n along the stretch of the watercourse where the study was conducted, using various water levels.

To study the effect of the variation in values of Manning coefficient of roughness, the n values were varied from 0.03 to 0.032 for the central channel only. For the left and right banks which are grown with grass, the value of the Manning roughness coefficient were varied from 0.032 to 0.04 depending on the conditions of the banks. Field measurement for water surface profile for the Linggi river was used in the verification process of HEC-2 model. Using an actual flow of 36.2 m^3/s and a value of the Manning coefficient of roughness equal to 0.032, the HEC-2 model was used to predict the water surface profile for the 600 m stretch of the Linggi river. The simulated water surface profile was then compared to the actual measured water surface profile as shown in *Fig. 4*. The maximum and minimum absolute errors in the predicted water surface profile for Linggi river were computed and found to be 100 mm and 20 mm respectively (Mohammed 1998). The deviations were less than 5%.

SENSITIVITY ANALYSIS

Accuracy of the computed water surface profiles for a river using HEC-2 model is dependent on many factors such as the accuracy of the stream geometry, accurate estimation of the Manning coefficient of roughness and interval between stations along a river. It is premised that modern survey technologies can give good accuracy in determining cross-sectional geometry of the river, so the sensitivity analysis was limited to the impact of Manning coefficient of roughness and the intervals between the cross sections or stations on the accuracy of the predicted water surface profile for Linggi river using HEC-2 model. Using constant interval of 50 m between stations along the Linggi river,

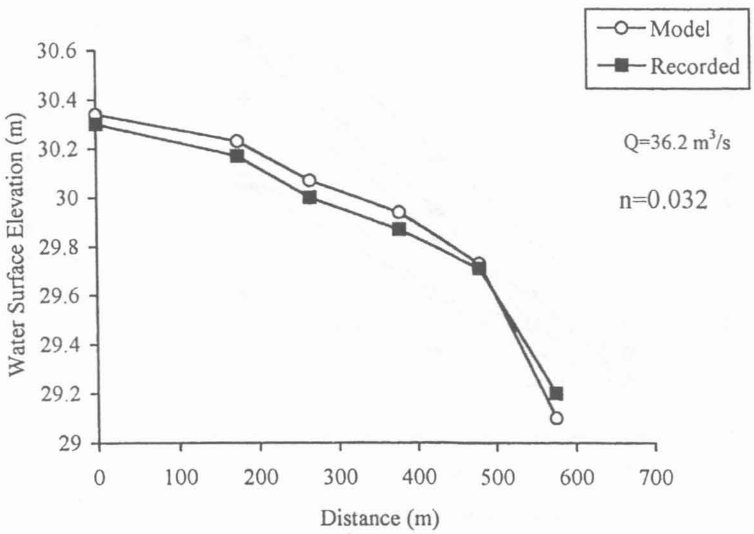

Fig. 4: Verification of the HEC-2 model using recorded water surface elevation of the Linggi river

a variation of 0.001 in the value of Manning coefficient of roughness was associated with an average variation of 2.5 cm in the prediction water surface elevation (Mohammed 1998). *Fig. 5* shows the impact of the variation in Manning coefficient of roughness on the predicted water surface elevation at 1 km interval along the stretch of the Linggi river. A difference of 51 cm, 37 cm, 7 cm, 3 cm in the predicted water surface elevation at the most upstream section were obtained by running the HEC-2 computer package for a stretch of 5688 m from Linggi river using intervals of 1000 m, 500 m, 200 m, and 100 m receptively. These differences were computed using the predicted water surface elevation for 50 m interval. The bigger errors in the longer interval predictions may be attributed to the accumulated errors in misrepresenting the real features of the stream geometry and alignment.

Model Application

The model was used to predict the water surface profile of the Linggi river for flood occurrences of Q_2, Q_{10}, and Q_{100}. The values obtained were 100 m^3/s for 100-year return period, 57.2 m^3/s for 10-year return period and 32.7 m^3/s for 2-year return period. Cross sections at 50 m interval along the watercourse of the Linggi River for a reach of 5.688 km were used as the input data to the HEC-2 model. The value of Manning coefficient of roughness being used for central channel was 0.030 while a value of 0.035 was used for both the right overbank and left overbank. *Fig. 6* shows the predicted water surface profiles for Linggi river for different flood magnitudes (Mohammed 1998).

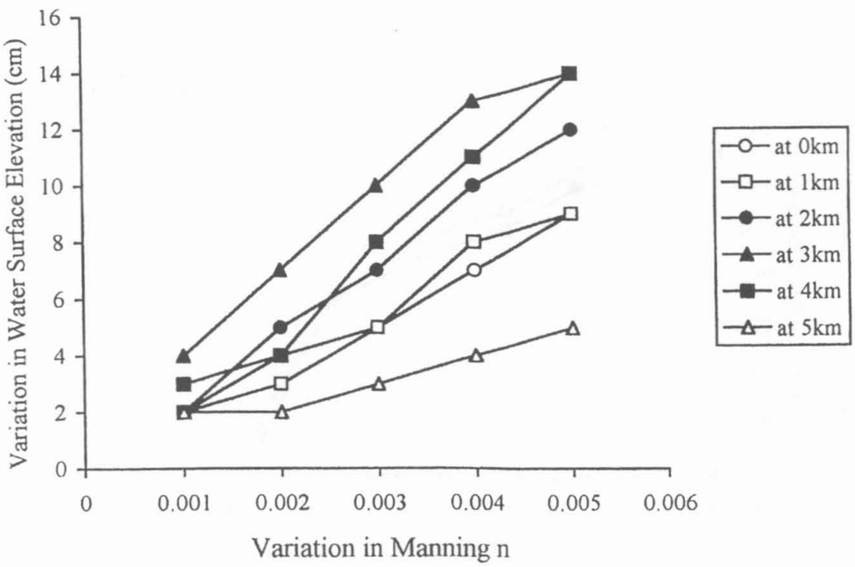

Fig. 5: Effect of Manning roughness on the predicted water surface elevation along the Linggi River

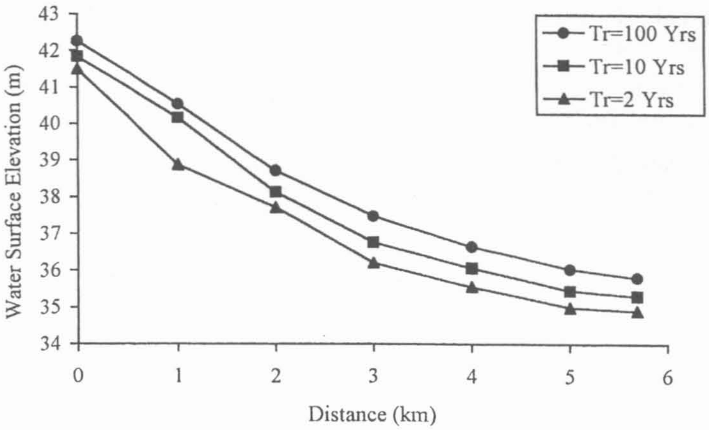

Fig. 6: Predicted water surface elevation for the Linggi River

CONCLUSION

The application of the HEC-2 model to the Linggi river system in the vicinity of Seremban, showed a good agreement between the predicted water surface profile and the recorded water surface profile. The maximum absolute error in the predicted water surface profile for Linggi river was found to be 100 mm while the minimum absolute error was only 20 mm only. These errors are less than 5% of the recorded data). Model testing showed that HEC-2 is sensitive to value of Manning coefficient of roughness and the intervals of cross sections long the studied river system. Tacking into consideration model sensitivity, HEC-2 model can be applied to simulate the water surface profile of a tropical river system with reasonable accuracy.

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