[ENV11] Sediment transport modeling and flood risk mapping in Geographic Information System (GIS)

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Introduction

Most computer models used in the flood risk analysis of rivers have inadequate functions in its spatial analytical capabilities and without sediment transport simulation capacity or suitable equations to represents correctly in-situ hydraulic processes (Sinnakaudan et al., 2001, Sinnakaudan, 2003). Further more, the consistent deficiencies of these models are their inability to connect the information describing the water profiles with their physical locations on the land surface. This is where a Geographic Information System (GIS) becomes a valuable tool in spatial modeling for engineers, planners and geoscientist (Burrough, 1998; Sinnakaudan et.al, 2003).

In recent years, efforts have been made to integrate hydraulic models and GIS to facilitate the manipulation of the model output for flood risk analysis. Tate (1999) introduces some of the flood risk analyzing methods by integrating HEC-RAS model with ArcView GIS. Similar attempts were also made by Jones *et al.* (1998) and Anrysiak (2000). Unfortunately, these attempts miss the important element in river modeling that is the sediment transport processes. Due to this, Sinnakaudan et al (2003) had loosely coupled ArcView GIS and HEC-6 sediment transport model by writing an integrator tool namely AVHEC6 (Sinnakaudan et al., 2002[b])

The requirement for risk base analysis and risk mapping become more prominent since the Urban Stormwater Management Manual for Malaysia (MASMA), which was introduced by Department of Irrigation and Drainage Malaysia (DID) in year 2000. The manual 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). A typical example of risk associated with the design storm selections for different ARIs is shown in Figure 1.

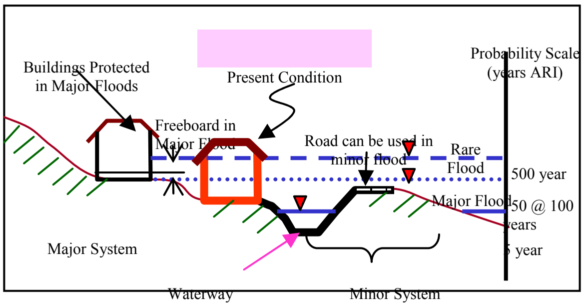

FIGURE 1. Risk as the basis of design storm selection (DID, 2000)

As a result, the current research presents the development of a new total bed material load equation using multiple linear regression analyses that is applicable for flood risk analysis in Malaysian rivers. It was developed and embedded as a modified version of HEC-6 model (USACE, 1991) and named SEDFlood model (Sinnakaudan, 2003).

Pari River, which is one of the main tributary of Kinta River located in Ipoh, Perak, Malaysia (Figure 2) has been chosen to quantify the flooding scenarios to meet the tasks specified in this study. A 3.0 km stretch between the gauging stations at Silibin Bridge (upstream) and Kinta River Confluence (downstream) is chosen (Figure 2). The design main channels are rectangular in shape with an average width of 18 meter at the downstream of Tapah River and 16 meters for the rest.

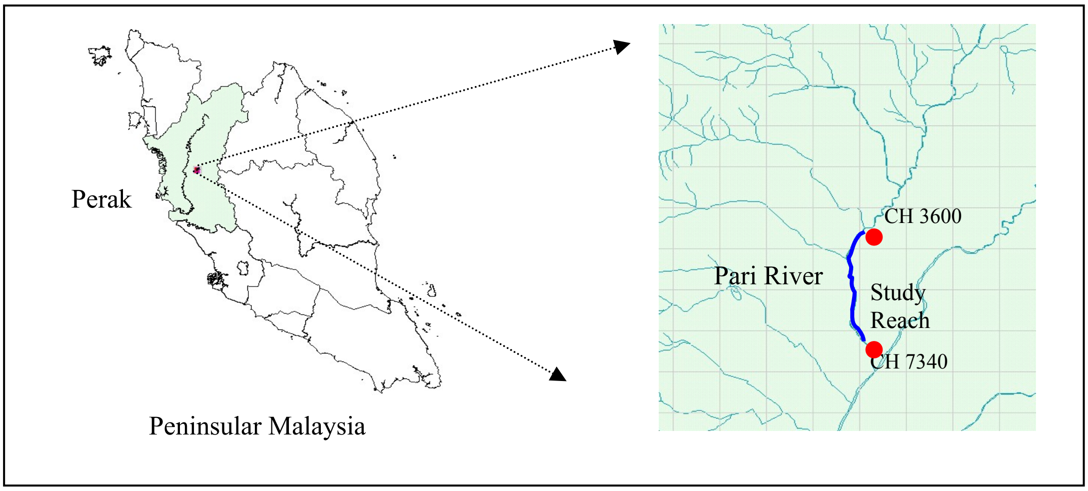

FIGURE 2 Study Area

Materials and Methods

This study was carried out in four stages. This includes field sampling, spatial and non-spatial data collection and processing, total bed material load equation development, customization and modification of the HEC-6 model source codes using Compaq Visual FORTRAN to create SEDFlood model. The modeling tool was compiled with an ArcView GIS extension and is named as *SEDflood.avx.* The procedure is comprised of three elements, which are (1) a set of equations compiled in the form of SEDFlood geospatial model governing the hydraulic processes, (2) maps that define the study area and (3) database tables that numerically describe the study area and the model parameter. The GUI for the modeling system has been designed so that it perfectly integrates the three components as stated above.

A total of 346 reliable sediment and hydraulic database was established from recent studies (Ariffin *et al.*, 2001; Sinnakaudan *et al*., 2003; Sinnakaudan, 2003; DID, 2003). The data sets were then divided, in which 181 data were used for analyses process (equation development), and the balance of 165 data were utilized for model validation. The validation process was further extended using a total of 987 available sediment samples and hydraulic data from rivers in the United States and Pakistan (Brownlie, 1981).

The regression technique (Hair *et al.*, 1995) namely multiple linear regression was used to predict sediment discharge using selected flow and sediment discharge parameters. In the multiple linear regression technique, the *Fitting of all Possible Regression Equation Method* is preferred since all the possible test cases formed must represent one variable from each of the 5 hydraulic categories namely mobility, transport, sediment, conveyance shape and flow resistance.

Four criteria were used to select the best regression model namely coefficient of determination or R square values (models that has the highest R^2 value was chosen), mean square error (MSE_e) (models that has minimum value was chosen), statistical C_p (the C_p value approximates to number of variables ($C_p \approx p$) was chosen). The fourth criterion is based on the modifications of R_p^2 that accounts for the number of variables in the model. While the addition of predictor variables will always cause the coefficient of determination to rise, the adjusted coefficient of determination may fall if the added predictor variables have little explanatory power and are statistically insignificant. The *Analyses of Variance* (ANOVA) approach was used to test the statistical significance of the derived regression model. The outliers in the data were analyzed using Studentized Deleted Residuals and the degree of influential of the outlier's determined using the DFFITS test. The accuracy of the model has been evaluated also using the discrepancy ratio, which shows the deviation between the observed and the predicted total bed material load value. The acceptable range of the discrepancy ratio is 0.5 to 2.0.

The final regression equation derived is as follows:

$$C_v = 1.811 * 10^{-4} \left(\frac{VS_0}{\omega_s}\right)^{0.293} \left(\frac{R}{d_{50}}\right)^{1.390} \left(\frac{\sqrt{g(S_s - 1)d_{50}^{\,3}}}{VR}\right) \quad \text{(Eq. 1)}$$

*Equation 1 will be refered as Shanker's Equations in the following sections.

The Total Bed Material Load, T_j is derived using:

$$T_j = C_v * Q * \rho_s \quad \text{(Eq. 2)}$$

where,

C_v = volumetric concentration of Sediment
V = average velocity
ω_s = sediment fall velocity
S_0 = Energy slope
g = acceleration due to gravity
S_s = specific gravity of sediment
d_{50} = sediment diameter where 50% of bed material are finer
R = hydraulic radius
T_j = Total bed material load
Q = Discharge
ρ_s = Specific weight of sediment

Shanker's Equation accounts for 71.51 % of the variability in analyses data and 63.63 % in the validation data. FIGURE 3 show the comparison between measured and estimated total bed material load and validation of Shanker's Equation. FIGURE 4 show the derived sediment-rating curve using Shanker's Equation, which falls very closely to measured Malaysian river data. The model is best suited for rivers having uniform sediment size distribution with a d_{50} value within the range of 0.37 mm to 4.0 mm and performs better than the commonly used Yang, Graf and Ackers-White total bed material load equations.

Shanker's Equation was coded in FORTRAN 90 and embedded into the existing HEC-6 source codes. The modified codes of HEC-6 were compiled and named as SEDFlood.exe with the permission from Hydraulic Engineering Center (HEC) of United States Army Corps of Engineers (USACE) (Gee, 2003). The variable names in the new coding remained the same so that they will tally with the various existing subroutines hydraulic calculations in SEDFlood hydraulic model. The header information of the SEDFlood is shown in Figure 5. This model later used to simulate the effect of sediment transport mechanism on flood risk.

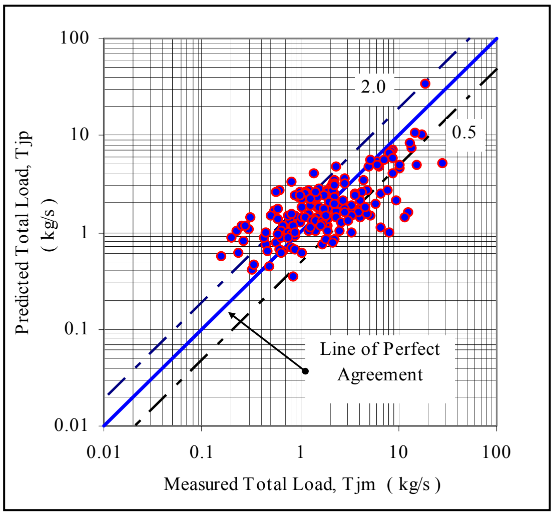

FIGURE 3 Validation of predicted total bed material load using Shanker's Equation

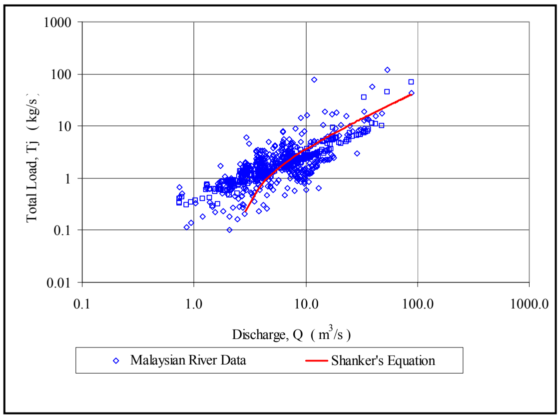

FIGURE 4 Sediment rating curve derived using Shanker's Equation

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*       Version: 4.2.00 -  JUNE 2003              *     *  U.S. ARMY CORPS OF ENGINEERS                        *
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*  OUTPUT FILE: d120ari100_1.out                  *     *  DAVIS, CALIFORNIA 95616-4687                        *
*  RUN DATE: 30 SEP 03    RUN TIME: 14:39:50      *     *  (916) 756-1104                                      *
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*  MODIFIED BY:
*  MR. SHANKER KUMAR SINNAKAUDAN                          DR.CHOONG KOK KEONG                                  *
*  RIVER ENG. & URBAN DRAINAGE RESEARCH CENTRE            SCHOOL OF CIVIL ENGINEERING                          *
*  ENGINEERING CAMPUS, UNIVERSITI SAINS MALAYSIA          UNIVERSITI SAINS MALAYSIA, SERI AMPANGAN             *
*  SERI AMPANGAN, 14300 NIBONG TEBAL, PENANG              MALAYSIA. TEL: 04-5937788 Ext.6225                   *
*  MALAYSIA. TEL: +604-5941035, FAX: +604-5941036
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   **********************************************************************
   *  MAXIMUM LIMITS FOR THIS VERSION ARE:                              *
   *       10  Stream Segments (Main Stem + Tributaries)                *
   *      500  Cross Sections                                           *
   *      200  Elevation/Station Points per Cross Section               *
   *       20  Grain Sizes                                              *
   *       10  Control Points                                           *
   * #### A NEW SED.TRANS EQS.FOR MALAYSIAN CONDITIONS                  *
   * #### RECIEVE SEDFLood GIS GENERATED INPUT FILE                    *
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FIGURE 5 Header information of the SEDFlood output File

The water surface profile through the reach was computed with SEDFlood for various set of discharge and geometry data configuration as shown in Table 1. 4th November 1997 flood was used to calibrate and validate the the simulation results (Figure 6).

TABLE 1 SEDFlood Simulation Configuration

Flood Scenarios	Storm Durations (minutes)
4 November 1997 Flood Hydrograph (Validation Data)	Measured data
Design Flood for ARI 10, 50 & 100 years	30, 60 & 120

A user-friendly, menu-driven GUI for two and three-dimensional (2D & 3D) digital floodplain delineation was developed through ArcView GIS and SEDFlood tight coupling procedure by utilizing Avenue Scripting Language and Dialog Designer. This version of the model comprises user-friendly interfaces for Pre-Processor, Post Processor, SEDFlood Tools and SEDFlood buttons (Figure 7 and Figure 8). It is capable to produce quick analysis (snapshots) at any desired discharge time steps in flood risk mapping procedure. Field measurements were carried out to validate the hydraulic setting and the accuracy of model outputs.

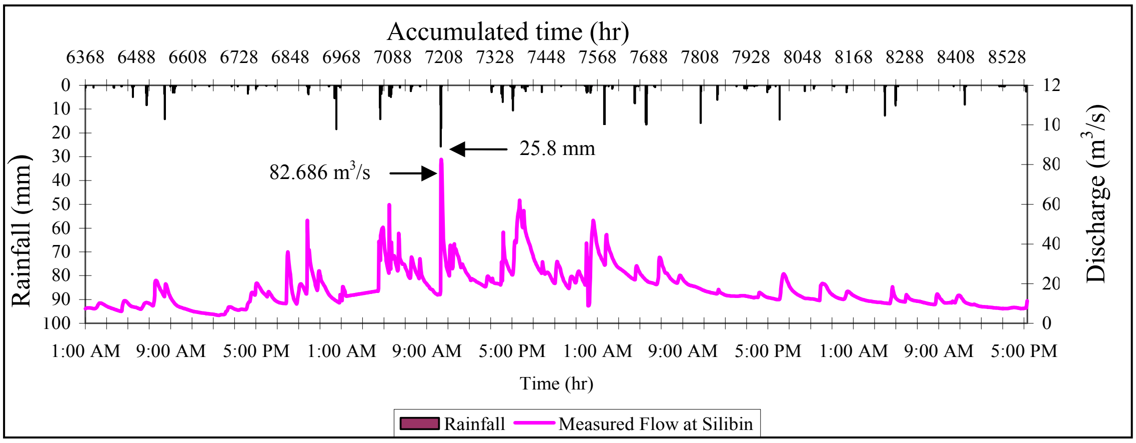

FIGURE 6. 29th October 1997 – 31st December 1997 rainfall (Station 4511111) and discharge hydrograph (Station 4610466) records

FIGURE 7 Graphic User Interface (GUI) of SEDFlood model

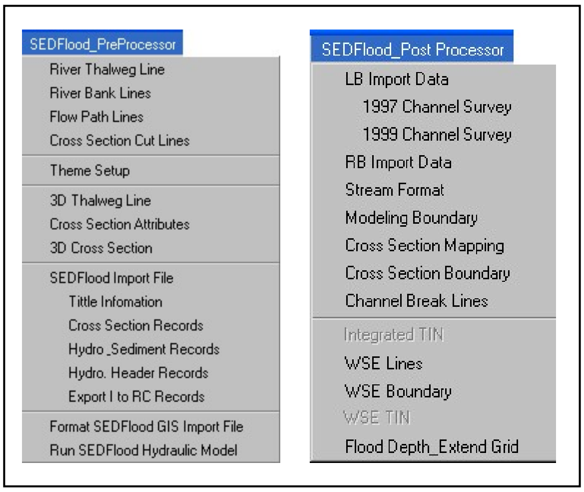

FIGURE 8 SEDFlood Pre-Processor and Post Processor Menus

Results and Discussion

The feasibility of simulating a flood event along a river channel and floodplain by using SEDFlood model was tested for Pari River catchment's area. The model calibration is focused mainly to high flows which cause floods and is related to the water level (WL) data obtained for 4th November 1997 flood (Figure 6 & 9). Flood risk analysis were conducted for the design flood events for 10, 50, 100-year Average Recurrence Interval (ARI). The design rainfall duration of 30, 60 and 120 minutes for the present and future land use conditions (year 2020) were considered in the simulation scenarios as summarized in Table 1.

The model simulation results between Silibin Bridge (upstream) and Lahat Bridge (downstream) were analyzed. The simulation results between Chainage 3600 - 4500 and 7020 – 7300 (downstream) were treated as model stabilization sections and not used for flood risk analysis and mapping. Wherever the flood level is greater than the bund surveyed in the year 1999, the areas are considered as flooded and validated with field observation, flood photographs and water level records as provided by DID Perak.

The predicted flood level for ARI 10, 50 and 100 years for present and future land use conditions were draped over an Integrated TIN (Sinnakaudan et al., 2002) (Figure 10) to derive the flood inundation and flood risk zone map.

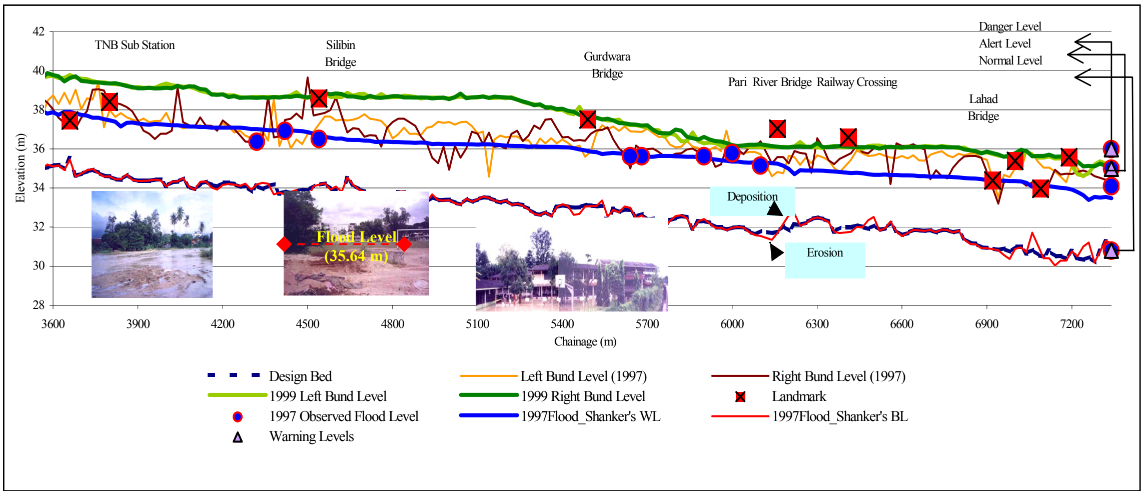

FIGURE 9 Calibration and Validation of SEDFlood Modeling results

Figure 11 and 12 shows the flood inundation map for present and future land use conditions respectively. Figure 13 and Figure 14 shows the delineated flood risk zones based on the probability of flood event for present and future land use (year 2020) conditions.

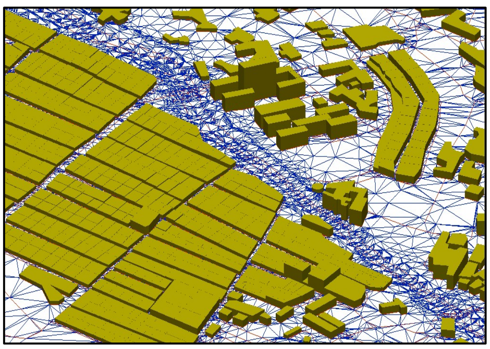

FIGURE 10 Sample 3D Mesh of Integrated TIN (ITIN) for study area

FIGURE 11 3D Flood risk map for D120, ARI 100 years ($Q = 220\ m^3/s$) - Present land use conditions

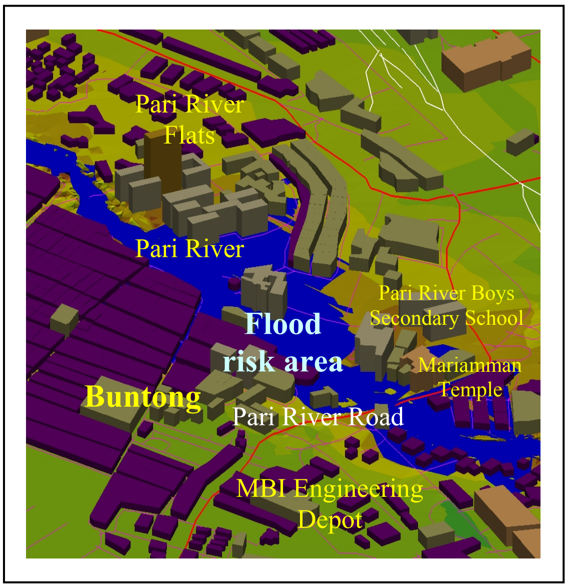

FIGURE 12 Flood risk map for D120, ARI 100 years ($Q = 343.0\ m^3/s$)- Year 2020 land use conditions

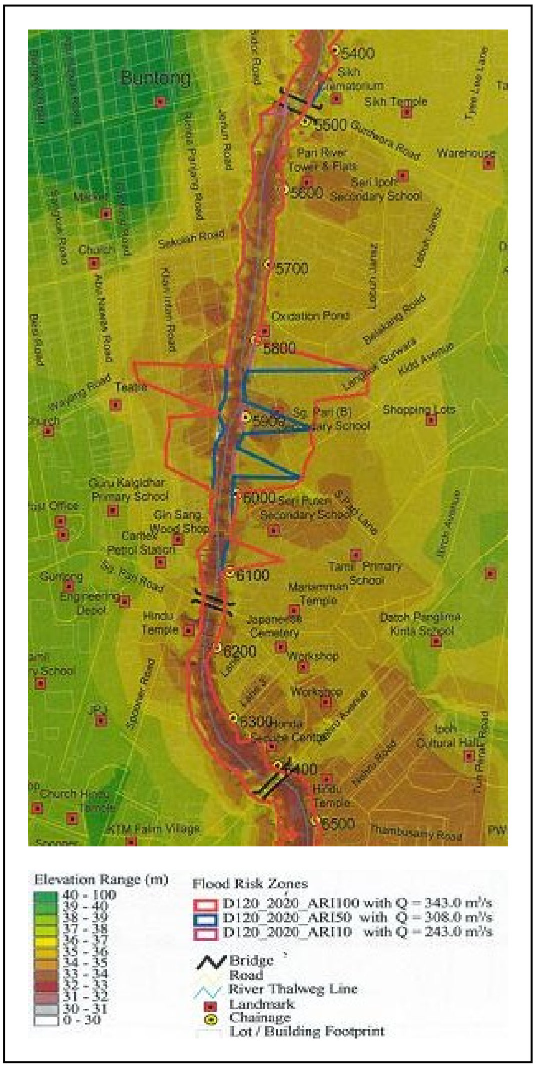

FIGURE 13 Delineated flood risk zones based on the probability of flood event for present land use conditions

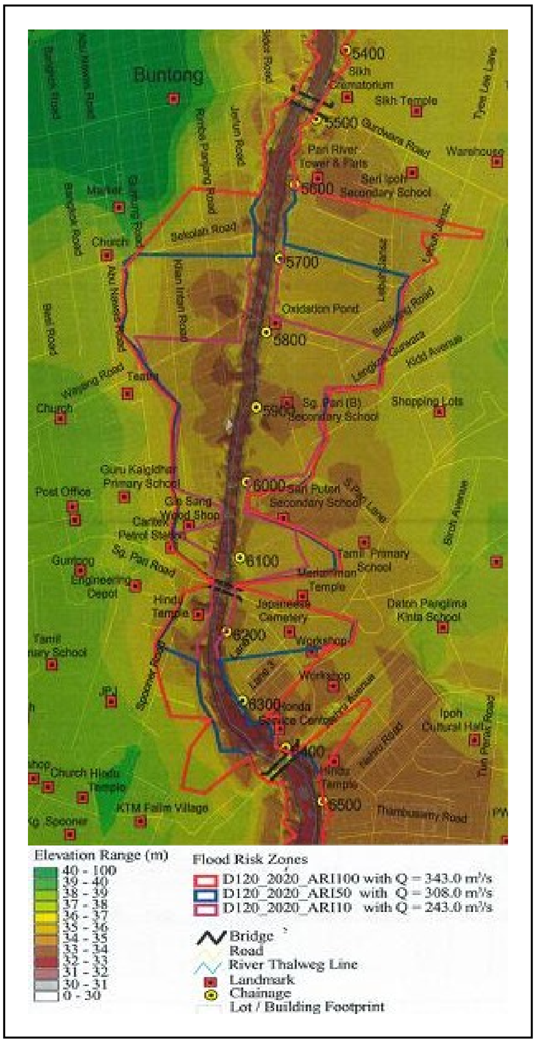

FIGURE 14 Delineated flood risk zones based on the probability of flood event for future land use (year 2020) conditions

The existing bund level is adequate to cater for 10 to 50 year flood for present land use conditions. However, for future land use conditions the Pari River is unable to convey the excess water at the Chainage 4120 to 4520 at the upstream of Silibin Bridge and Chainage 5240 to 7340 (Figure 14). Thus, flood-proofing measures may be considered such as raise up the existing bunding crest level above the predicted flood level (Figure 14) with an appropriate freeboard. The existing channel may be widening up by removing the compound channels.

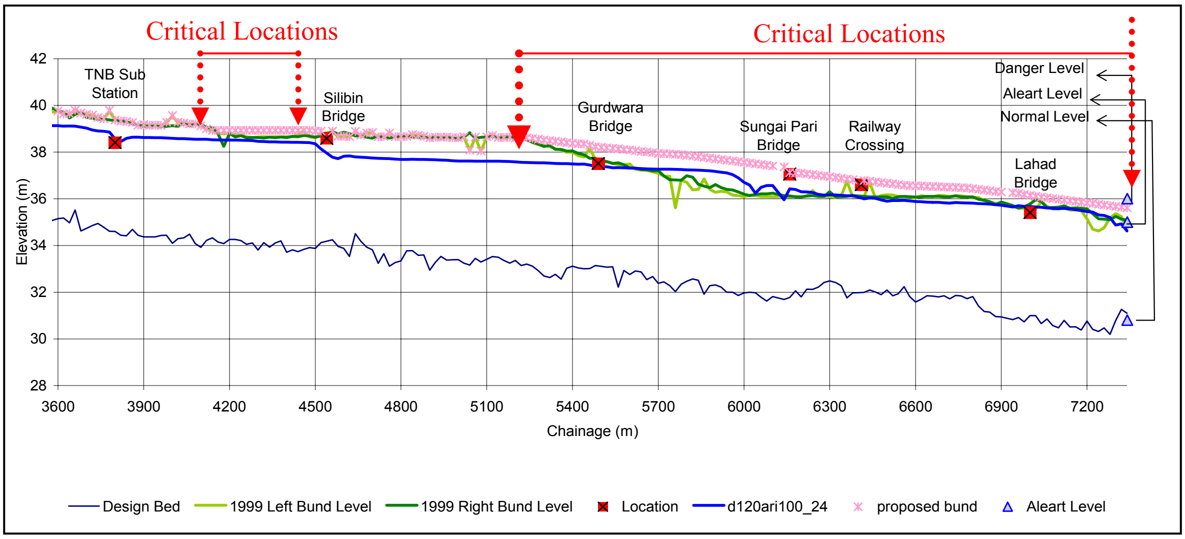

FIGURE 15 Proposed bund elevations and channel improvement locations (Sinnakaudan, 2003)

Conclusion

The principal purpose of this research to develop a new sediment transport equation applicable to rivers in Malaysia is achieved by the derivation of Shanker's equation. This equation successfully applied to simulate the effect of sediment transport mechanism on flood level and extend by developing SEDFlood modeling interface. The result of this research indicates that GIS is an effective environment for floodplain analysis and its integration with hydraulic model is not only feasible but also mutually beneficial for both GIS users and hydraulic modelers.

This alternative will provide more flood conveyance for Pari River at the affected chainages. The second alternative may be implemented with the relocation of the flood plain dwellers who are most vulnerable to flood according to the flood risk zones as shown in Figure 11, 12 and 13. The third alternative is to implement "source control" oriented designs based on the Urban Stormwater Management Manual for Malaysia (2000) for new development in the Pari River catchment area. The main aim is to delay the time of the excess runoff to reach the main conveyance channel.

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