Sensitivity Analysis on Water Surface Profiles Generated from Hydrodynamic Modelling with Respect to Inaccuracy of Cross-section Data

V.A.N. Soysa1, G.A.I.R.K. Galhena2

1Lecturer, Department of Civil Engineering, University of Moratuwa. Sri Lanka
2 Graduate Research Assistant, Victoria University of Technology, Australia

Abstract: Computer aided Hydrodynamic Modelling has become a convenient tool in modern-day with the development of separate hydraulic analysis components attached to multi-user networks with graphical user interfaces. Generated outputs from hydrodynamic models are used to predict engineering design parameters and to check hydraulic designs. Hence, model calibrations and verifications are performed, in order to assess and confirm the reliability of generated outputs. Accuracy of the input data significantly affects the model reliability. Although, the achievement of high degree of accuracy for hydraulic engineering parameters during data collection process is unlikely, careful scrutinisation and prompt attempt to identify the inaccuracies even in the order of magnitude can certainly enhance model performance and reliability. To study the influence of inaccurate input data to the model performance, inaccurate data were purposely included for previously calibrated and verified models. The said calibrated and verified models were developed by the authors for case studies of stormwater drainage analysis for Colombo-Katunayake Expressway at Kalu Oya intersection and for Southern Transportation Development Project at Welipenna intersection. The present work describes the sensitivity of generated outputs and specially the water surface profile with respect to inclusion of three inaccurate cross-sections for each model. Further, percentage errors of cross-sections were discreetly varied as +50%,+35%,+25%,–25%,–35% and –50% to study the influence. Additionally, individual effect for inaccurate cross-sections and combined effect for selected and amalgamated inaccurate cross-sections were studied. For the considered range in percentage error of input data, results indicate that water surface profile varies –15% to 30%.

Keywords: Hydrodynamic Modelling, Sensitivity Analysis, Model reliability, Input Data Accuracy

1. Introduction

During the last few decades, computer aided hydrodynamic models have been frequently used due to faster computation power, separate hydraulic analysis components with efficient numerical solvers, development of larger data acquisition and storage capabilities and more importantly availability of graphical user interfaces. Hence nowadays, lots of flood routing and simulations systems, flood plain delineation and insurance studies, flood hazard mitigations and investigations are based on the results generated from computer aided hydrodynamic models.

Moreover, added advantage is that, calibrated and validated models can be used to simulate extreme design conditions which may or may not happen in reality. Hence, it could enhance the effectiveness of controlling, and mitigating the flood inundations through comparing many design alternatives and demarcating the design with the highest effectiveness.However, uncertainties in hydrodynamic model calibration can lead to a significant deviation, thus in Hall(2005), uncertainty analysis involves quantification of uncertainties and their progression.

Model reliability can be reduced from either computational errors or uncertainties of the input data to the model. Since, governing flow equations such as momentum, energy and continuity equations are explicit, and with the ability of faster and accurate calculation with even small computational time increment, uncertainty of input data to the model plays a significant role. The physical properties of topography, roughness, discharge and slope of a natural stream are highly variable and spatially and temporally heterogeneous. Therefore, hydraulic variables are affected by the above mentioned physical parameters (Buenhan & Davis, 1986).

As mentioned in Alemseged T.H&Rientjec (2006), real world properties at grid element scale are assumed homogeneously distributed although, when compared to real world heterogeneity, system properties vary within the selected spatial scale of grid elements. It is emphasized in Gary (2010) that factors such as dramatic changes in channel cross-sectional properties, abrupt change in channel slope and complex hydraulic structures (bridges, culverts, weirs and levees) lead any model application to be accompanied by a sensitivity study, where the accuracy and the stability of the solution are tested with various time and distance intervals.

Although, the achievement of high degree of accuracy for hydraulic engineering parameters during the data collection process is unlikely, careful scrutinisation and prompt attempt to identify the inaccuracies even in the order of magnitude can certainly enhance both model performance and reliability.

2. Objectives

The objective of the research work was to study the influence of inaccurate cross-section data during the hydrodynamic model development towards the model performance, and the response to the generation of water surface profiles. Since, the achievement of high degree of accuracy for cross-sections during data collection is unlikely and seasonal variations of cross-sections are significant, the study is focused on quantifying the influence of inaccurate cross-section data over the generation of water surface profiles from a hydrodynamic model.

3. Methodology

For the research work, calibrated and verified hydrodynamic models which were developed by the authors for case studies of stormwater drainage analysis for Colombo-Katunayake Expressway at KaluOya intersection(Soysa & Wijesekera, 2010) and for Southern Transportation Development Project at Welipenna intersection(Galhena & Wijesekera, 2010) were utilised.

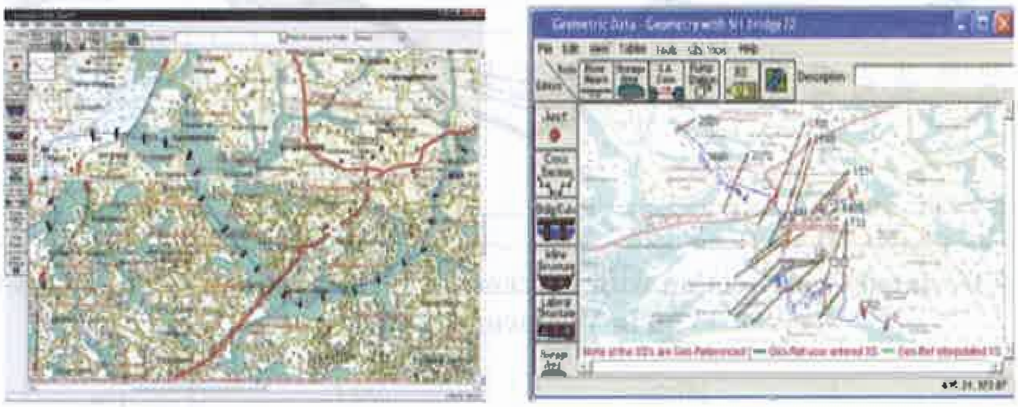

Figure 1 - Geometric Data View of KaluOyaand Welipennamodel (HEC RAS user interface)

HEC-RAS, (2009) – freely available software for hydrodynamic model simulation – was used to develop both above mentioned models for steady flow simulation.Figure 1 depicts the geometric data view for KaluOya and Welipenna models. 25 numbers of cross-sections were considered for stream section of 11.3 km in Kalu Oya model whereas 15 numbers of cross-sections for 2.6 km stream in Welipenna model.

To study the influence of inaccurate cross-section data to the model performance, three original cross-sections from each model were selected and purposely replaced by inaccurate cross-section data. In Kalu Oya model which has 25 numbers of cross-sections, 5th, 10th and 15th cross-sections were selected whereas in Welipenna model, which has 15 numbers of cross-sections, selected cross-sections were 4th, 8th and 12th. Above mentioned selected original cross-sections were systematically deviated. Coordinates of deviated cross-sections were calculated by discreetly varying the percentage of discrepancies as + 50%, + 35%, + 25%, – 25%, – 35% and – 50%.

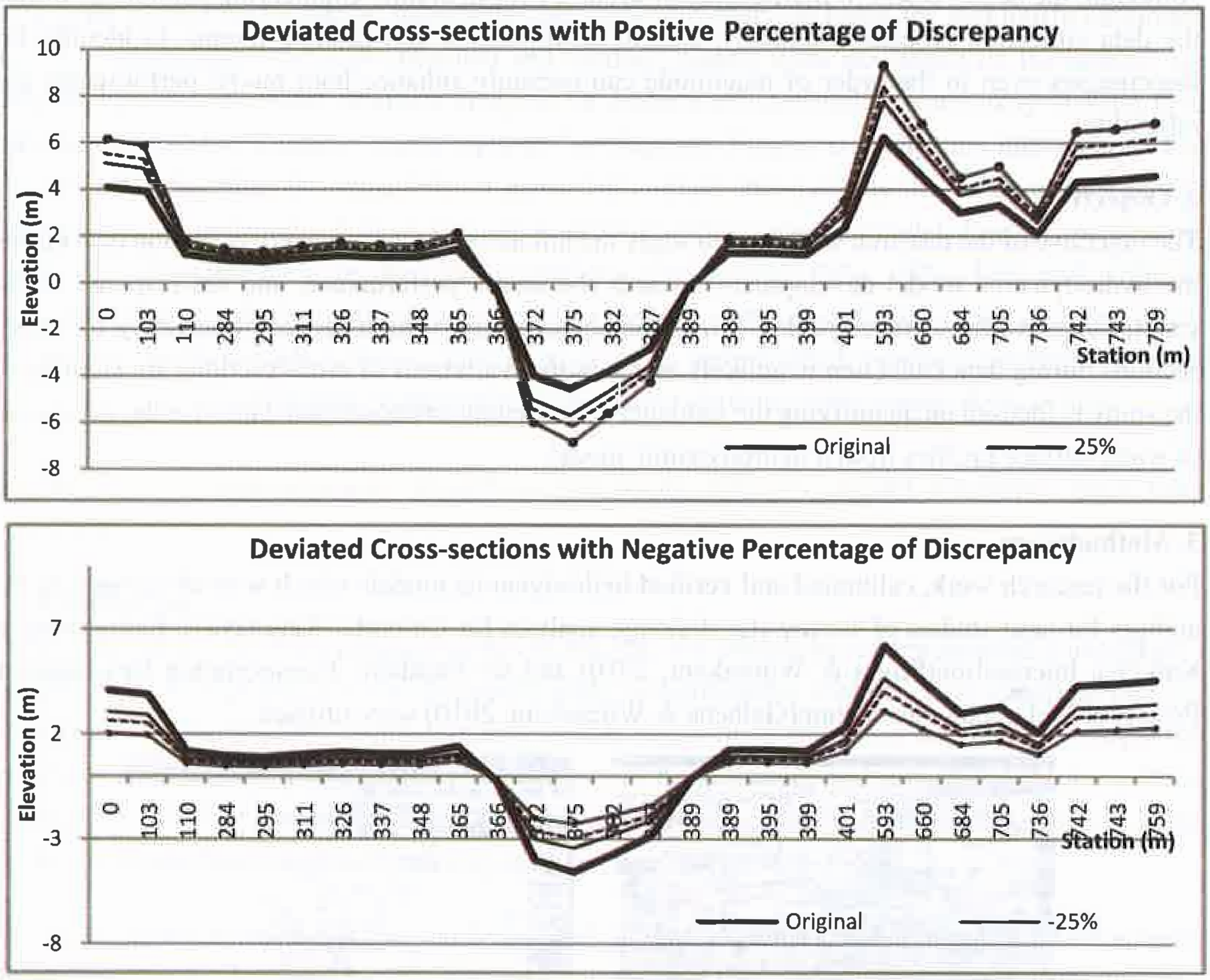

Figure 2 - Deviated Cross-section with Percentage of Discrepancy for the Cross-section #8 in Welipenna model

Figure 2 illustrates one such set of deviated cross-section for a location that was considered with different magnitude in percentage of discrepancy in Welipenna model. Since, datum of 0 m elevation wasselected as river bank station, positive discrepancy has deepened the cannel section and elevated the river banks. In contrast, cannel section is shallower with negative percentage of discrepancy. (Figure 2)

It is obvious that deviation of the cross-section affect the water surface profile locally. However, sometimes water surface profile can be affected not at the exact location of the deviated cross-section, but either downstream or upstream side. In order to trace the effect along the stream apart from the exact location,several combinations of deviated cross-sections (Table 1) were considered in both KaluOya and Welipenna models.Three main cases were concerned for Welipenna model analysis. In case i, only 12th cross-section was replaced with cross-sections with percentages of deviation by +50%, +35%, +25%, –25%, –35% and –50%. Hence, 6 numbers of scenarios were considered in case i.

Similarly, case ii and case iii comprised six numbers of scenarios each. Two cross-sections (12th and 8th) were replaced in case ii, whereas three cross-sections (12th, 8thand 4th) were replaced in case iii.Similarly, case iv, v and vi were concerned for KaluOya model with the consideration of 20th, 15th and 10th cross-sections. However, in KaluOya model, it was also focused to study influence due to combination of negative and positive percentage of deviation from the original cross-sections. Therefore,case vii and case viii were concerned with the effect due to replaced cross-section with positive percentage of deviation which was sandwiched in replaced cross-section with negative percentage of deviation and vice versa. For that, percentage deviation of +35% and –35% were selected.

4. Water Surface Profile Calculations

In HEC RAS models, water surface profiles are computed from one cross-section to the next by solving the energy equation (Equation 1) with an iterative procedure called the standard step method.(Gary, 2010).

Table 1 - Combinations of deviated cross-sections with percentage of discrepancy for the analysed cases

	Case	**Cross-section. #12**	**Cross-section. #08**	**Cross-section. #04**
Welipenna Model	i	+50%, +35%, +25%, –25%, –35%, –50%	-	-
	ii	+50%, +35%, +25%, –25%, –35%, –50%		-
	iii	+50%, +35%, +25%, –25%, –35%, –50%		
KaluOya Model	**Case**	**Cross-section. #20**	**Cross-section. #15**	**Cross-section. #10**
	iv	+50%, +35%, +25%, –25%, –35%, –50%		
	v	+50%, +35%, +25%,		
		–25%, –35%, –50%		
	vi	+50%, +35%, +25%, –25%, –35%, –50%		
	vii	–35%	+35%	–35%
	viii	+35%	–35%	+35%

$$\boldsymbol{Z_2 + Y_2 + \frac{\alpha_2 {V_2}^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 {V_1}^2}{2g} + h_e}$$

Equation [1]

Where,

Z_1, Z_2 = Elevation of the main channel inverts at section 1 and 2,

Y_1, Y_2 = Depth of water at cross-sections

V_1, V_2 = Average velocities

α_1, α_2 = Velocity weighting coefficients

g = Gravitational acceleration

h_e = Energy head loss

In order to calculate the energy head loss (h_e) in Equation [1], friction, expansion and contraction head losses are concerned as in Equation [2].

$$h_e = LS_f + C\left|\frac{\alpha_2 {V_2}^2}{2g} - \frac{\alpha_1 {V_1}^2}{2g}\right|$$

Equation [2]

Where,

L = Discharge weighted reach length

S_f = Friction slope between two sections

C = Expansion or contraction coefficient

Computation procedure for water surface in HEC – RAS includes the assumed water surface elevation at the upstream cross-section as the first step. Then, based on the assumed water surface elevation, the corresponding total conveyance and velocity head are determined as the second step. Friction slope between two cross-sections are computed and Equation [2] is solved for the energy head loss as the third step in the process. Next, utilising the resulted values in both second and third steps, Equation [1] is solved for the elevation at the second cross-section. Finally, computed value of water surface elevation at second cross-section will be compared with the assumed value in the first step, and intermediate steps are processed till the discrepancy reduces up to a user defined tolerance. (Gary, 2010)

5. Results

As mentioned inTable 1, three main cases were considered for each model for the sensitivity analysis. Following subsections will indicate the generated results and emphasize on the deviation of the results due to the percentage of discrepancies in cross section data.

In order to quantify the discrepancies, Percentage of Water Surface Increment (Equation [3]) and Mean Ratio of Absolute Errors (Equation [4]) which are defined below were calculated.

$$\text{PWSI} = \frac{\boldsymbol{H_{scenario}} - \boldsymbol{H_{original}}}{\boldsymbol{H_{original}}} \text{x } 100\%$$

Equation [3]

At locations that cross-section details were fed into the model, PWSI were calculated. $H_{original}$ refers to the water surface elevations that were generated from the original models (no deviations for the cross-section data are purposely included). $H_{scenario}$ refers to the water surface elevations that were generated from the scenario models simulated for the mentioned cases in Table 1

$$\text{MRAE} = \left(\frac{100\%}{K}\right)\sum_{n=1}^{K}\frac{\left|\boldsymbol{H_{original}} - \boldsymbol{H_{scenario}}\right|}{\boldsymbol{H_{original}}}$$

Equation [4] afterWijesekera & Abeynayaka, (2003)

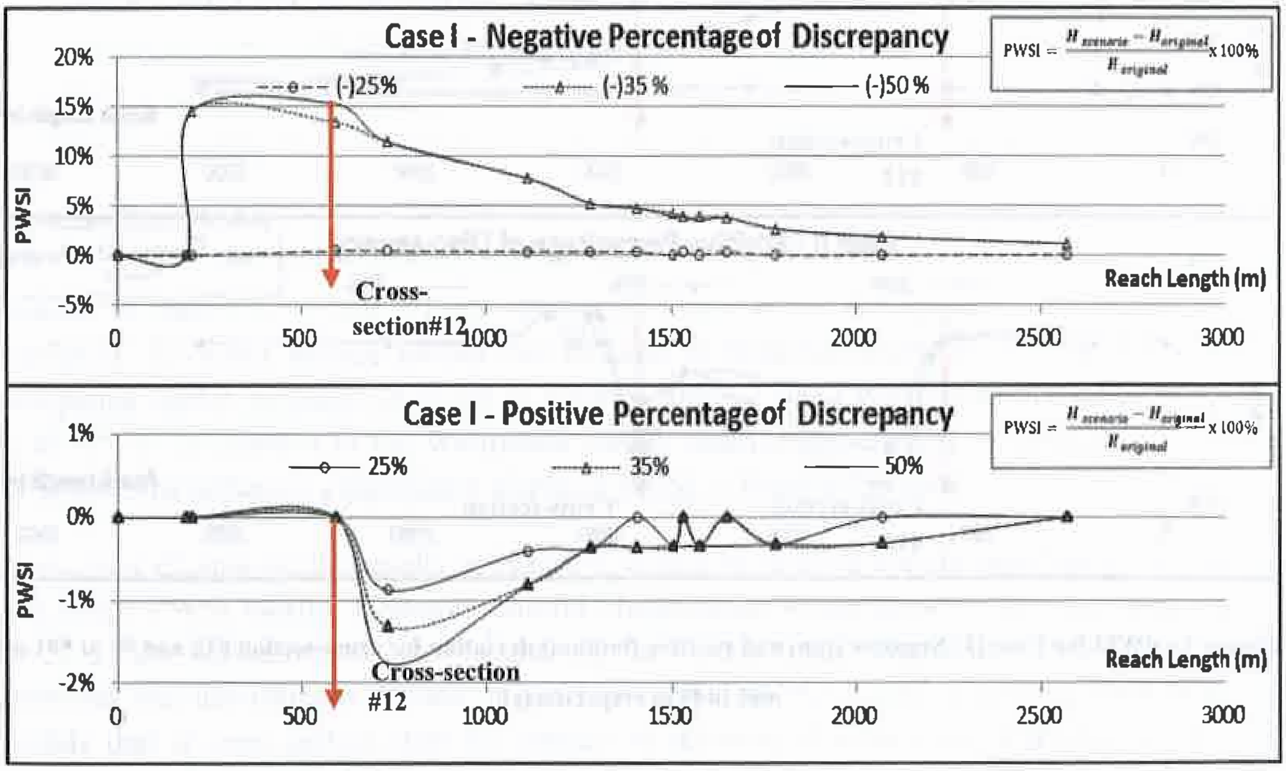

Figure 3 - PWSI for Case I [Negative (top) and positive (bottom) deviation for cross-section #12 at 591 m]

The indicator, Mean Ratio of Absolute Error MRAE [after Wijesekera & Abeynayaka, (2003)]is given in Equation [4]and is defined as the average modulus value of the difference between water surface elevations generated from the original ($H_{original}$) and scenario models ($H_{scenario}$) with respective to original model ($H_{original}$). K is the number of concerned water elevations at cross-sections that were fed into the model

5.1 Welipenna Model

Results of case I, II and III which were obtained from the Welipenna model are shown in Figure 3, Figure 4 and Figure 5 respectively.

It can be seen that percentage of water surface increment (PWSI) varies in a range of 16 % to -4 % for all three cases considered in Welipenna model. Case I, where only 12th cross-section details were altered, did not indicate significant variation with respect the case III where three cross-sections (12th, 8th and 4th) details were altered. Further, it is depicted that -25 % percentage of discrepancy for cross-section considered in all three cases resulted the minimum PWSI. Additionally, negative percentage of discrepancies of cross-sections show higher influence on PWSI over the positive percentage of discrepancies of cross-sections.

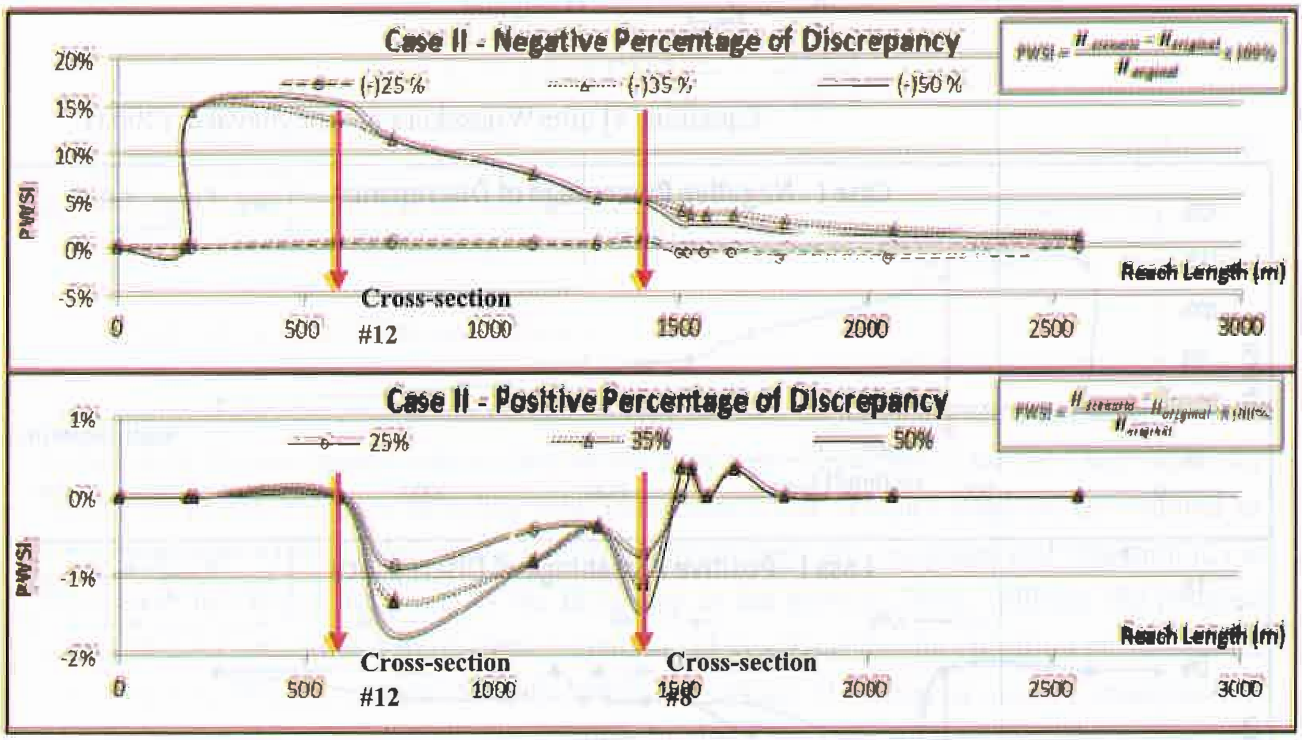

Figure 4 - PWSI for Case II [Negative (top) and positive (bottom) deviation for cross-section #12 and #8 at 591 m and 1405 m respectively]

As far as the influenced area along the reach is considered, it is shown that both negative and positive deviations created at the 12th cross-section affects for the whole reach length covered by the model.

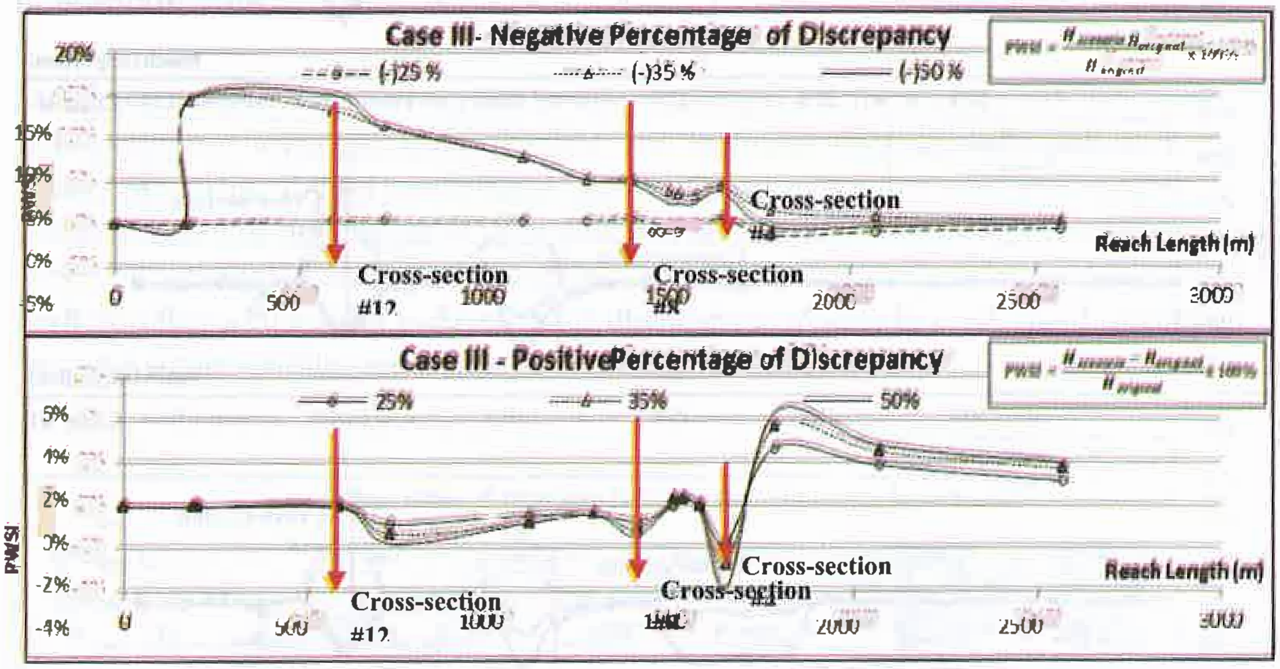

Figure 5- PWSI for Case III [Negative (top) and positive (bottom) deviation for cross-section #12 #8 and #4 at 591 m ,1405 m and 1649 m respectively]

5.2 KaluOya Model

Results of case IV, V and VI are shown in Figure 6 for the KaluOya model.Hgher sensitivity for water surface profile can be seen in KaluOya model in comparison with Welipenna model, as results depicted in Figure 6 indicate that PWSI varies in a range of 35 % to -15 %. In contrast to the Welipenna model, positive percentages of discrepancies in cross-sections influence a significant effect on PWSI in KaluOya model.

At the first glimpse on the results in Figure 6, it may be implied that deviated cross-section data affect PWSI locally. However, careful observations would pinpoint that influence on PWSI by the deviated cross-section data can be visible to an area at least 1 km in both upstream and downstream. Hence, it can be noted from the results generated from both models that if cross-section data are altered or deviated at a location, influence of that alteration can be identified along the river at both upstream and downstream up to a distance of three cross-sections fed locations in the model.

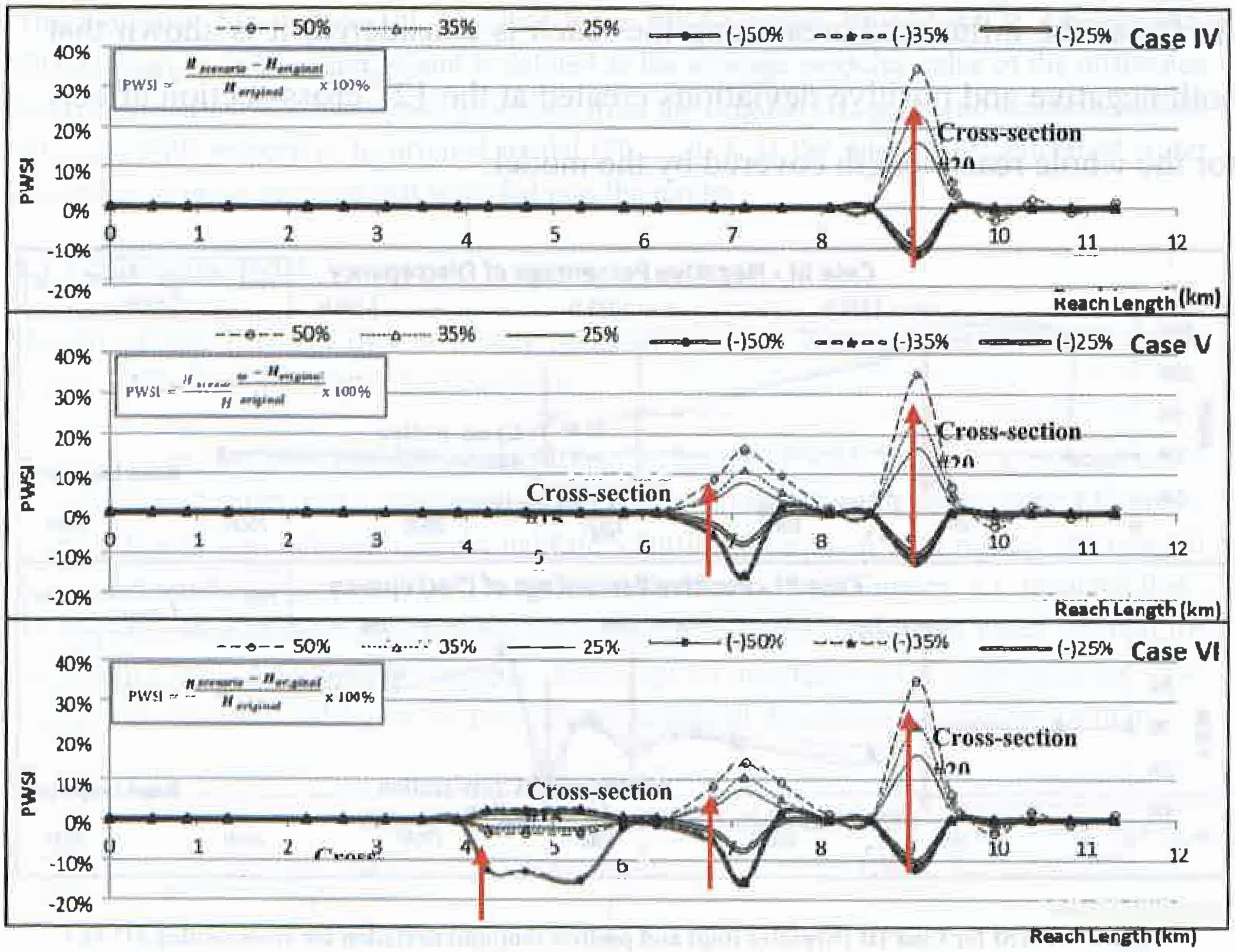

Figure 6- PWSI for Case IV,(top), Case V (middle) and Case VI (bottom) with deviation for cross-section #20 #15 and #10 at 9070 m , 6792 m and 4255 m respectively

As indicated in Figure 2, positive percentages of discrepancy of a cross-section data create deeper cross-sections than the actual and negative percentages of discrepancy of a cross-section data create shallower cross-sections. Therefore, combination of positive and negative percentages of discrepancies has reduced the magnitude of PWSI according to the Figure 7.

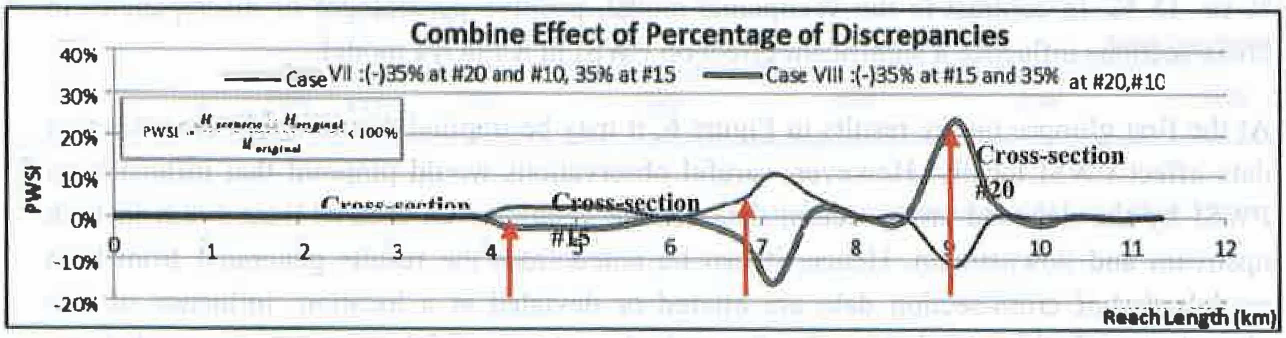

Figure 7 - PWSI for Case VII and Case VIII

Though the PWSI were in the range of 16 % to -4 % and 35 % to -15 % for Welipwnna and KaluOya models respectively, MRAE calculated according to Equation [4] shows that values for both models were in the range of 0.5% to 6 %. Tendency for increasing MRAE with the increment of either negative or positive percentage of deviations for cross sections is visible in the results shown in Figure 8

6. Conclusions

Sensitivity analyses for water surface profile with respect to the accuracy of cross-section were performed using previously verified and calibrated hydrodynamic models by the authors using HEC-RAS. Three selected cross-section of each model were purposely altered within a range that percentages of discrepancy of cross-section to the original cross-section vary – 50% to 50 %. Several cases were performed with various types of combinations of deviated cross-sections and percentages of discrepancy in order to study the sensitivity of the water surface profiles and it leads to following conclusions.

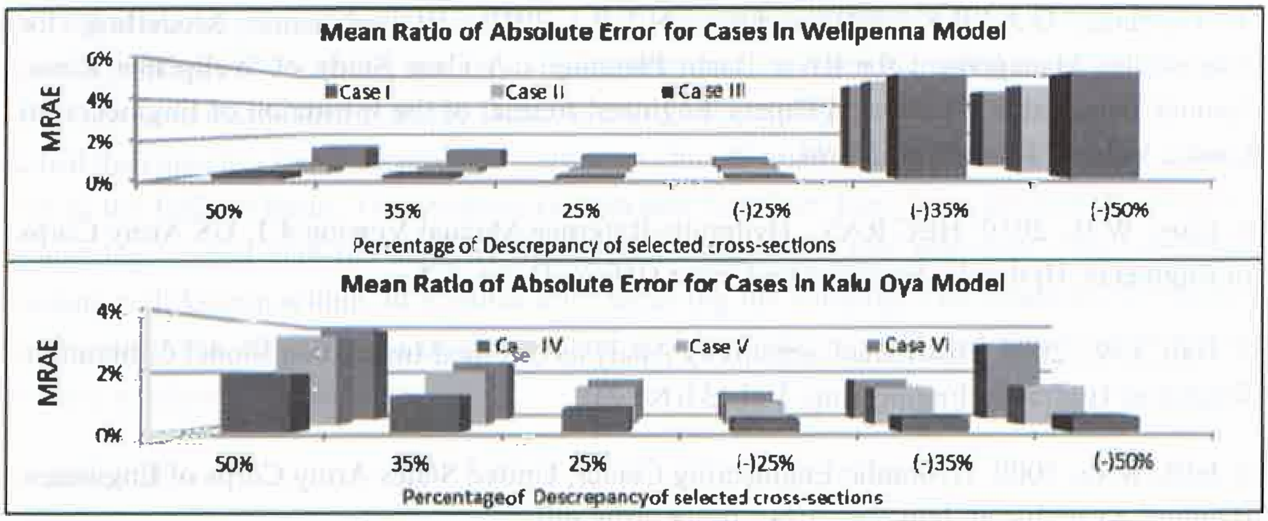

Figure8 - Mean Ratio of Absolute Error for scenario models

1. PWSI were in the range of 16 % to -4 % for Welipenna*(2.6 km stream section with 15 numbers of cross-sections)* and 35 % to -15 % for KaluOya*(11.3 km stream section with 25 numbers of cross-sections)* models when three number of randomly selected cross-section details were deviated by -50 % to 50 %.
2. The water surface profiles were influenced for a distance of 1 km in both upstream and downstream from the location which purposely deviated cross-sections were fed into the models.
3. However, water surface profile for the whole stream sections that were simulated in hydrodynamic models are considered, value for MARE is only 6 % for the case which three number of randomly selected cross-section details were deviated by 50 %.

Acknowledgement

Authors gratefully acknowledge the advice of Prof. N.T.S. Wijesekera regarding the water surface sensitivity analysis. The assistance provided by Sri Lanka Land Reclamation and Development Cooperation and department of Survey during the model development processes are kindly appreciated. Especially the support of additional General Manager Mr. P.P. Gnanapala and Engineer Mr. C.B. Amarasinghe are acknowledged. Further, availability of free Hydrodynamic software HEC-RAS was very valuable and those responsible are gratefully acknowledged.

References

1. Alemseged T.H &Rientjec, T.H.M., 2006. Uncertainty Issues in Hydrodynamic Flood Modelling. [Online] Available at: http://www.isprs.org/proceedings/XXXVI/2-C43/Session3/Paper%20Alemseged.pdf [Accessed 3 May 2012].

2. Buenhan, M. & Davis, D.W., 1986. Accuracy of Computer Water Surface Profile.US Army Corps of Engineers, Hydraulic Engineering Center (HEC), Davis, CA.

3. Galhena, G.A.I.R.K. &Wijesekera, N.T.S., 2010. Hydrodynamic Modelling for Stormwater Management for River Basin Planning - A Case Study of Welipenna River. Annual Transaction - Techincal Papers 'Engineer' Journal of the Institution of Engineers Sri Lanka, Volume I Part B, pp.87-94.

4. Gary, W.B., 2010. HEC RAS - Hydraulic Refernce Manual Version 4.1. US Army Corps of Engineers, Hydraulic Engineering Center (HEC), Davis, CA.

5. Hall, J.W., 2005. Distributed Sensitivity Analysis of Flood Inundation Model Calibration. Journal of Hydraulic Engineering, Vol.131(No.2).

6. HEC-RAS, 2009. Hydraulic Engineering Center, United States Army Corps of Engineers. [Online] Available at: http://www.hec.usace.army.mil.

7. Soysa, V.A.N. &Wijesekera, N.T.S., 2010. Stormwater Drainage in Expressway Design Analysis of Colombo-Katunayake Expressway at KaluOya. Annual Transaction - Techincal Papers 'Engineer' Journal of the Institution of Engineers Sri Lanka, Volume I Part B, pp.79-86.

8. Wijesekera, N.T.S. &Abeynayaka, J.C., 2003. Watershed similarity conditions for peak flow transportation - A case study of river basins in the wet zone of Sri Lanka. 'Engineer' Journal of the Institution of Engineers Sri Lanka.