FLOOD-FLOW CHARACTERISTICS OF EQUATORIAL NATURAL RIVERS IN SARAWAK, MALAYSIA

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ABSTRACT

A study on two natural rivers during flood events located in the outskirt of Kuching city, Sarawak is carried out. This paper presents the results obtained from the field measurements, including velocity distributions, stage discharge relationships, roughness behaviours and discharge estimation. These have illustrated a large difference in velocity between the main channel and floodplain under flood conditions, and the effects of momentum transfer between deep and shallow flow, which include reduction in main channel velocity and discharge capacity, leading to a reduction in compound section capacity at depth above bankfull. Another significant characteristic for flow in natural rivers is that the floodplain regions are found to behave as a storage reservoir instead of conveying excess water. Flow resistance relationships have been presented in terms of Manning's coefficient and Darcy-Weisbach friction factor, showing the complex nature of flow resistance in flooded natural rivers and further explaining the danger inherent in the conventional practices of extrapolating inbank data for the analysis of overbank flows. Results for discharge estimation have been shown for comparison with actual data, the errors incurred by applying empirical methods to compound channel flows have been quantified and found to depend on the particular method used.

Keywords: *Discharge Estimation, Flow Resistance, Natural River, Overbank Flow, Velocity Distribution*

1.0 INTRODUCTION

A large number of hydro-engineering problems are related to open flow in compound channels. An understanding of flow in compound channels or natural rivers with floodplains is essential in practical problems of flood mitigation and floodplain management. It is therefore important for flow simulation to be correct not only on the water surface elevation, but also the sectional discharge and velocity distribution, during the event of overbank flows. Unfortunately, most of the studies that have been carried out are based on idealised experimental laboratory investigations. Field study is rare, partly because compound channel flow conditions occur typically under flood conditions when acquisition of data is difficult and sometimes dangerous. In the work presented, an attempt was made to focus on natural rivers under flood conditions.

2.0 THEORETICAL CONSIDERATIONS

In open channel flow prediction, it is usually assumed that the flow is parallel and has a uniform velocity distribution (steady-uniform flow) and that the slope of the channel is small. Under such conditions, the convection acceleration is zero, and the streamlines are straight and parallel. Since velocity does not change, the velocity head will be constant; therefore, the energy grade line and water surface will have the same slope as the channel bottom.

Based on the above assumptions, a series of empirical methods of discharge estimation in open channels and rivers have been developed. The simplest of these are uniform flow equations attributed to Chezy and Manning, with parallel development in pipe flow leading to the Darcy-Weisbach equation. The uniform equations may be written as follow:

The Chezy equation gives

$$V = C(RS_o)^{1/2} \tag{1}$$

The Manning equation gives

$$V = (R^{2/3}S_o^{1/2}) / n \tag{2}$$

The Darcy-Weisbach equation for channel flow gives

$$V = [(8gRS_o) / f)]^{1/2} \tag{3}$$

where V is the average cross-sectional velocity, R is the hydraulic radius = A/P, A is the cross sectional area, P is the wetted perimeter, S_o is the bed slope, g is gravitational acceleration, C is the Chezy roughness coefficient, n is the Manning roughness coefficient and f is the Darcy-Weisbach friction factor [1].

In analysing the flow through open channels of regular sectional shape and hydraulic roughness, it is sufficient, in general, to use the overall hydraulic radius as the parameter, which characterises the properties of the cross section. It is then possible to calculate the discharge through the channel from one of a range of well-known uniform flow formulas in term of the channel roughness, slope and depth as given above.

However, if the cross-sectional shape is irregular, this could lead to considerable errors. One particularly important example of this occurs on the occasion of a compound section consisting of a deep main channel with associated shallow floodplains. In this case, a sudden change of depth would happen at the transition between the main channel and the floodplain. Moreover, the hydraulic roughness of the floodplain is often greater than that of the main channel. The combined effects of the greater depth of flow and smaller hydraulic roughness of the main channel can lead to significantly higher velocity than those occurring on the floodplain. This velocity difference inevitably results in a lateral mass and momentum transfer mechanism, which can greatly reduce the channel discharge capacity.

3.0 RELATED STUDIES

Since many rivers assumed a compound shape at flood flows, it is of considerable importance to have reliable methods of channel analysis. This has prompted a significant research effort in the area of compound channels, aimed at a fuller understanding of the structure of flow as well as the development of accurate method for discharge estimation. However most of these works have been laboratory based, usually considering smooth boundary straight channels. Early work by Sellin [2] and Zheleznyakov [3] identified the presence of a momentum transfer mechanism between the main channel and the floodplain flows. This takes the form of a bank of vortices having vertical axes, which formed along the main channel/floodplain interface. The effect of the mechanism is to reduce main channel discharge capacity while increasing the flow on the floodplains. However, since the main channel takes the majority of flow at depths just above bankfull, the net effect of the mechanism at such depth is to reduce the capacity of the compound section when compared with that of a simple section at the same depth.

A number of studies have been aimed at quantifying the mechanism in terms of an apparent shear force, which acts at the main channel/floodplain interface, the value of this apparent shear force has been shown to be many times greater than the averaged boundary shear force. Studies of this type included Myers [4], Wormleaton and Hadjipanos [5], Knight and Demetriou [6], Knight and Hamed [7], Christodolou and Myers [8]. A wide range of geometry and boundary roughness has been considered and empirical expressions have been developed. However none yet commands wide spread acceptance. The error incurred in applying conventional methods of discharge estimation to compound channels have been presented and discussed [5, 6, 9-14].

Laboratory studies have succeeded in uncovering the fundamental structure of flow in compound channels, but to be useful in providing guidance for river engineers, such data must be verified by comparison with those obtained from full-scale compound river channels. Such data is very scarce because of the difficulties of collecting measurements from river in flood. The study presented in this paper is aimed at remedying to some extent the paucity of data from full-scale compound river channels, thereby contributing to the understanding of flooding river channel hydraulics.

4.0 FIELD STUDY AND DATA COLLECTION

The study was carried out on two natural rivers namely River Senggai and River Batu located in Kuching, the capital city of Sarawak State, Malaysia. These rivers were selected due to serious floods occurrence during Monsoon season in the past few years. Extensive flood data from River Main [15] in Northern Ireland has also been obtained for comparison.

The selected rivers are shown in Figures 1 to 3. The rivers selected have almost straight and uniform cross section, free from backwater and tidal effect. Table 1 shows the geometrical properties and surface conditions of the rivers at the gauging stations for comparison. The typical cross sections of these rivers are shown in Figures 4 to 6.

Flow gauging of the rivers was carried out from an adjustable bridge built across the rivers, using the velocity-area method.

Figure 1: Morphological cross-section of River Senggai, Kuching

Figure 2: Morphological cross-section of River Batu, Kuching

Figure 3: Morphological cross-section of River Main, Northern Ireland

Table 1: Geometrical properties and surface conditions

Geometrical properties	River Senggai	River Batu	River Main
Bankfull depth, H_{bf} (m)	1.060	1.544	0.900
Top width, B (m)	5.285	5.150	13.700
Aspect ratio, B/H_{bf}	4.986	3.335	15.222
Bed slope - main channel, S_0	0.0010	0.0016	0.0030
Bed slope - left floodplain, S_L	0.0010	0.0013	0.0030
Bed slope - right floodplain, S_R	0.0010	0.0013	0.0030
Surface condition – main channel	Erodible soil	large boulder	large boulder
Surface condition – side bank	Erodible soil	Erodible soil	large boulder
Surface condition – floodplain	long vegetation	long vegetation	short vegetation

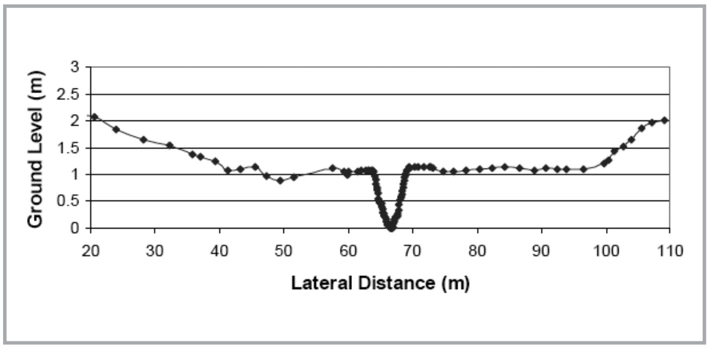

Figure 4: Lateral cross section of River Senggai

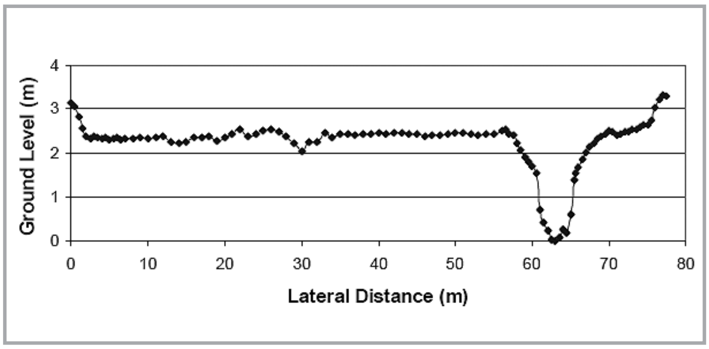

Figure 5: Lateral cross-sectional of River Batu

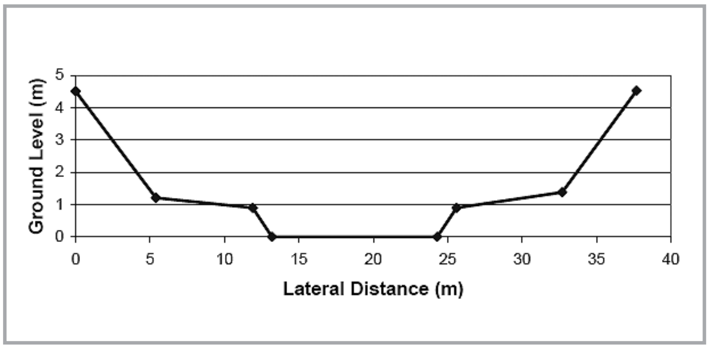

Figure 6: Lateral cross-sectional of River Main

A leveling staff has been used to measure the depth of flow, whereas an electromagnetic flow meter was used to measure point velocity at 20%, 40%, 60% and 80% of flow depth at up to 20 verticals across the sections. The flow depths and point velocities were measured to an accuracy of 0.0005m (0.5mm) and 0.0001m/s respectively. For each measuring pints, 3 to 5 reading were taken and averaged to give a mean point velocity to reduce the error due to variation in water flow. Some 20 discharges were recorded for each river, covering a wide range of inbank and overbank flows.

5.0 RESULTS AND ANALYSIS

5.1 Velocity Distribution

Velocity distributions at the gauging site of the rivers are shown in Figures 7 and 8. These figures clearly show that the maximum flow velocity occurs in the central of main channel region, which decreases towards the side banks and bottom directions, whereas, the flow velocity on the floodplains is found near to zero in all cases even at high overbank flow.

Figures 9 and 10 show the lateral distributions of averaged depth velocity for the same rivers. These figures further illustrated the increase of flow velocity with respect to flow depths. The large differences in velocity between the main channel and floodplain are due to the differences in depths and surface roughness.

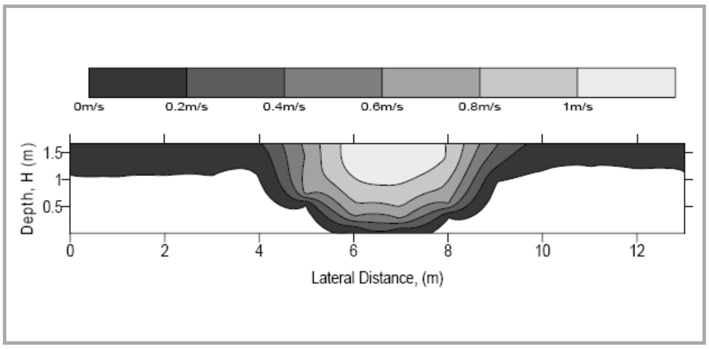

Figure 7: Velocity distribution for overbank flow of River Senggai, H = 1.658m

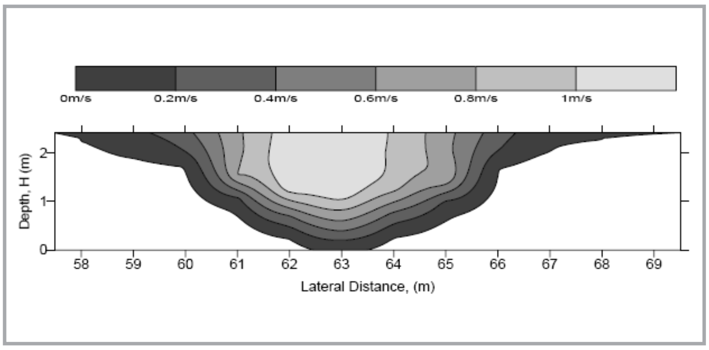

Figure 8: Velocity distribution for overbank flow in River Batu, H = 2.42m

At the interface region between the main channel and floodplain, the velocity is found to decrease rapidly, *i.e.* from very high main channel velocity to near or sometimes smaller than the floodplain velocity. This is due to the significant momentum transfer and apparent shear existed between the two zones characterised by a series of vortices (Vor1 – Vor5) as shown in Figure 11. These interactions tend to retard the flow at the interface region of main channel, while increasing the corresponding parameter on the floodplain.

On the floodplain region, flow velocity remained near to zero in all observations even though under very high overbank flow conditions. This is due to the very rough surface and floodplain vegetations, which prevent it from flowing. As a result, the floodplain regions were found to serve as storage reservoir at shallow overbank flow instead of conveying access water.

The main channel and the floodplain discharges obtained from field measurements are divided by the respective area subjective to flow, the mean velocity for the main channel and floodplain regions for each river, and shown in Figures 12 and 13. These results further show that there is a large difference in velocity between the flow in main channel and that on floodplain. For River Senggai and River Batu, the velocities in the main channel increased rapidly with depth due to the decreased of relative roughness in the main channels, *e.g.* the mean velocity for the main channel of River Senggai has increased from 0.277 m/s at bankfull depth ($H = 1.06$ m) to 0.749 m/s at depth, $H = 1.658$ m.

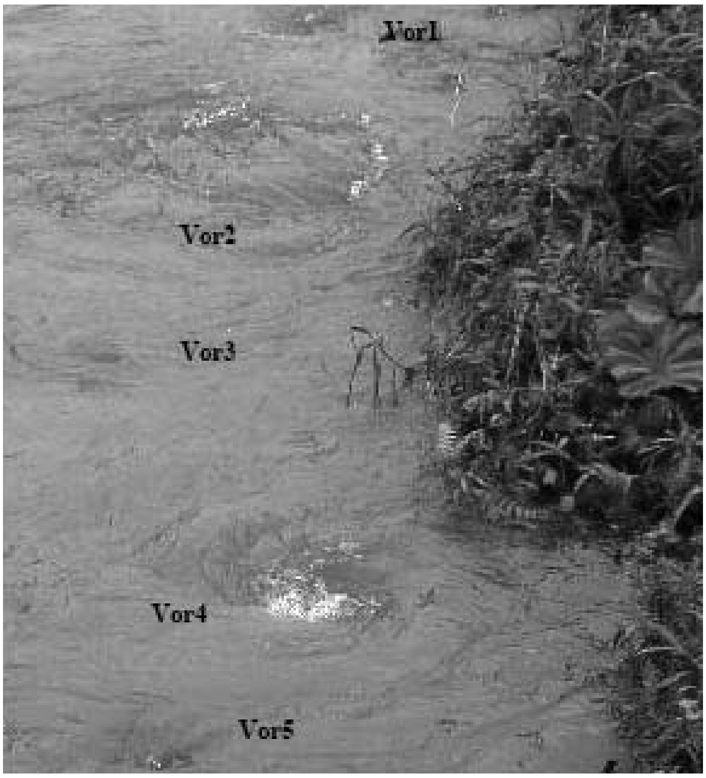

Figure 11: Series of vortices at the interface region of main channel and floodplain for River Batu

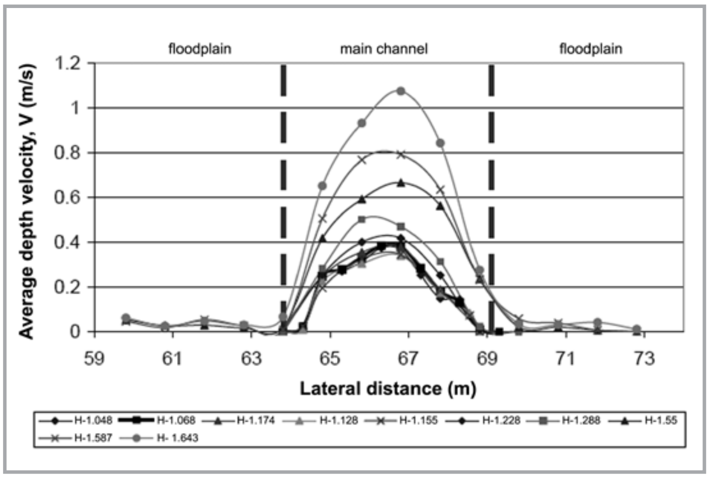

Figure 9: Averaged depth velocity for overbank flow of River Senggai

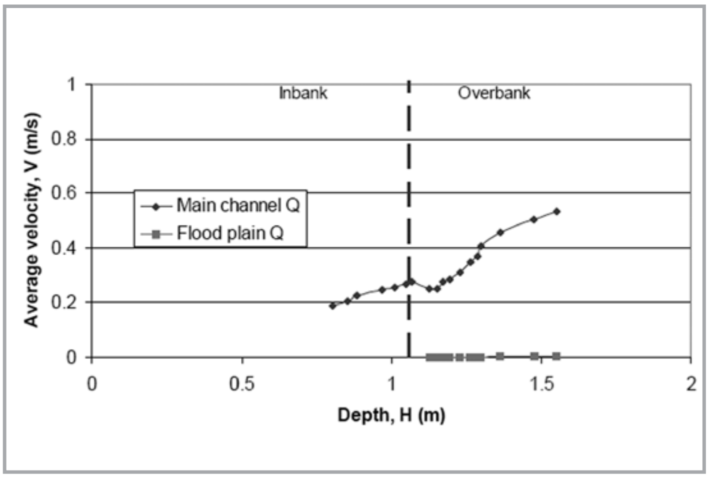

Figure 12: Average main channel and floodplain velocity for River Senggai

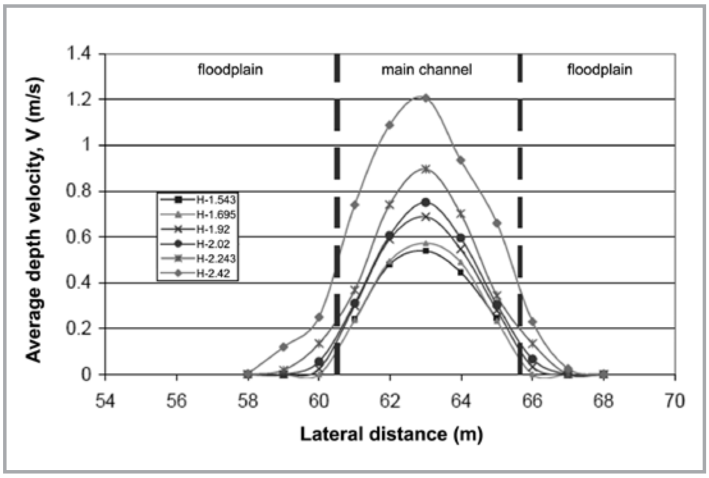

Figure 10: Averaged depth velocity for overbank flow in River Batu

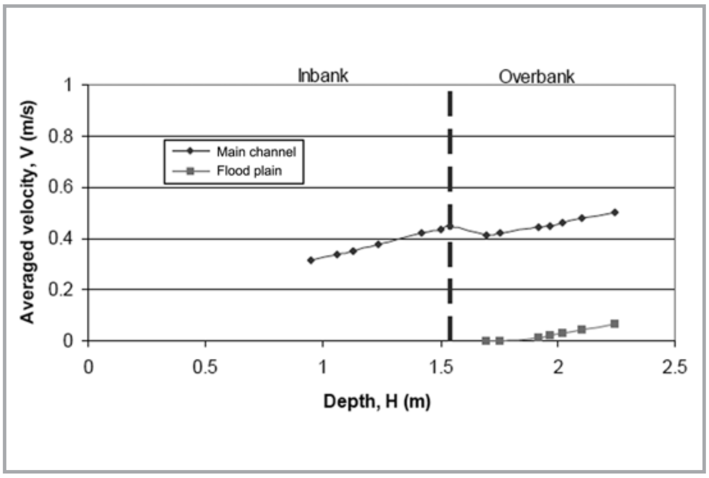

Figure 13: Average main channel and floodplain velocity for River Batu

On the other hand, the mean velocities for the floodplain regions are found to remain near to zero (< 0.1 m/s) in both cases due to the ponding effects of the floodplain vegetation. Under such conditions, the floodplain regions are found to have little contribution to flood flow conveyance capacity.

5.2 Stage-Discharge Relationship

When the discharge obtained from measurements is plotted against depth of flow as shown in Figures 14 to16, the graphs show that below bankfull level, the rating curves behave as expected, in which the discharge increases accordingly with depth of flow.

When the flow is overbank, all the plotted graphs have shown a discontinuity, *i.e.* reduction of discharge when the flow is overbank, due to the interaction between the main channel and floodplain, following by a more rapidly increase of discharge at larger depth due to larger areas subjected to flow. The interaction can significantly reduce the main channel velocity when the flow is overbank. For River Senggai (Figure 14) and River Batu (Figure 15) with very obvious roughness differences between the main channel and floodplain, the discontinuity starts at the bankfull level, in which the discharge at bankfull level is found larger than those for just overbank levels, even though it has a smaller flowing area. For example, the discharge for River Senggai at bankfull level (H = 1.06 m) is 0.903 m^3/s, whereas, the discharge for overbank flows of H = 1.128 m and 1.155 m are 0.855 and 0.898 m^3/s respectively.

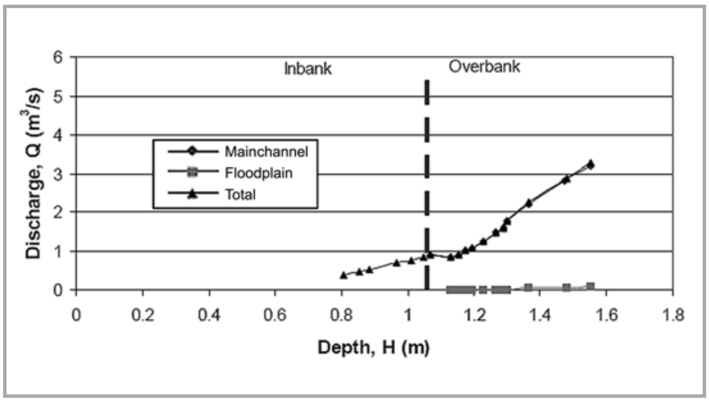

Figure 14: Stage and discharge relationship for River Senggai

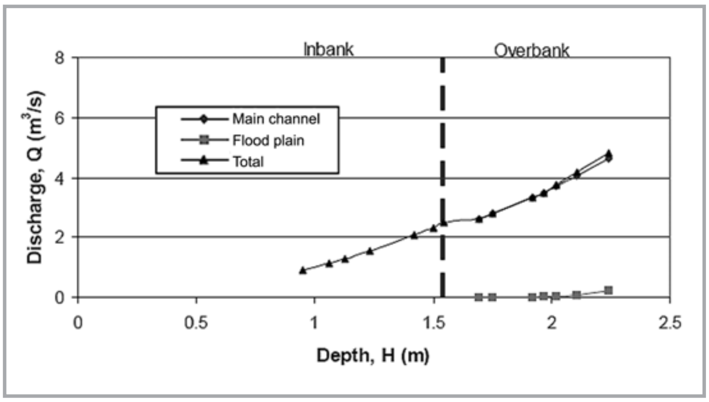

Figure 15: Stage and discharge relationship for River Batu

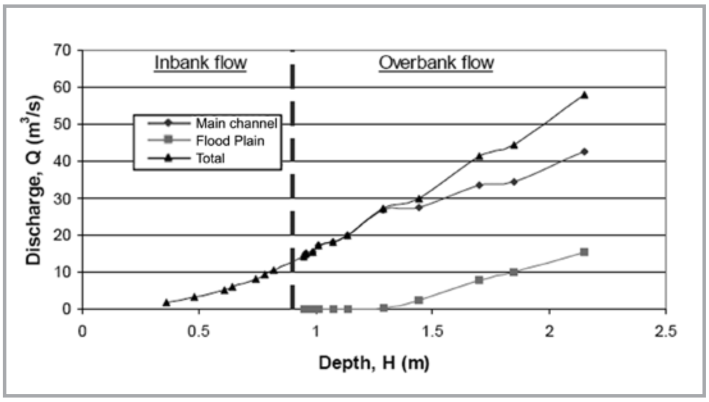

Figure 16: Stage and discharge relationship for River Main

For River Main (Figure 16) with similar roughness in the main channel and that on the floodplain, the reduction of discharge in main channel is not clearly seen at the bankfull level but after a certain stage of overbank flow, *i.e.* (H-h)/H ≈ 0.2. The main reason for this is that, when the flow is just overbank, the flow at both sides of the interface region is very slow moving due to the side bank vegetation and those on floodplain. When this happened, the difference in velocity is small at the interface region, and thus the interaction effect is not clearly seen.

Table 2: Contribution of main channel and floodplain in discharge capacity of flooding natural rivers

River Senggai			**River Batu**			**River Main**		
(H-h)/H	MC (%)	FP (%)	(H-h)/H	MC (%)	FP (%)	(H-h)/H	MC (%)	FP (%)
0.0075	100.00	0.00	0.0891	100	0.00	0.0526	100.00	0.00
0.0603	100.00	0.00	0.1192	100	0.00	0.0576	100.00	0.00
0.1130	100.00	0.00	0.1958	99.62	0.38	0.0625	100.00	0.00
0.1770	100.00	0.00	0.2142	99.29	0.71	0.0863	100.00	0.00
0.2234	97.94	2.06	0.2356	98.78	1.22	0.1089	100.00	0.00
0.2838	97.73	2.27	0.2665	97.81	2.19	0.1628	100.00	0.00
0.3161	97.32	2.68	0.3116	95.55	4.45	0.2077	100.00	0.00
0.3321	95.71	4.29	0.3382	94.10	5.90	0.3023	100.00	0.00
0.3607	92.12	7.88	0.3620	91.71	8.29	0.3750	91.10	8.90
						0.4000	88.55	11.45
						0.4706	81.01	18.99
						0.5135	77.11	22.89
						0.5814	73.27	26.73
Notes: MC – Main Channel ; FP – Floodplain								

When the flow in the main channel and on floodplains are considered separately, Figures 14 to 16 together with Table 2 further show that the main portion of discharge for overbank flow is carried by the main channel region, especially when the flow is just overbank, *e.g.* the discharge on floodplains equal to zero for flow depth (H-h)/H ≤ 0.15, and >90% of the discharge is carried by the main channel for depth ratio (H-h)/H ≤ 0.30.

The contribution of the floodplain regions in the total discharge is also varied from river to river, for example, for a depth ratio (H-h)/H of 0.35, Table 2 shows that the contributions from the floodplain regions of River Senggai, River Batu, and River Main are approximately 6.5%, 7.0% and 6.2%, respectively. These results show that for the rivers investigated, the contribution of flow from the floodplain is minimal.

5.3 Flow Resistance

The resistance to flow in the main channel region for each river has been calculated according to Equation 2 in terms of Manning roughness coefficient, *n* and Equation 3 in terms of Darcy-Weisbach friction factor, *f*. Selected graphs are shown in Figures 17 and 18. In each case, the plotted graphs are divided into two distinct zones:

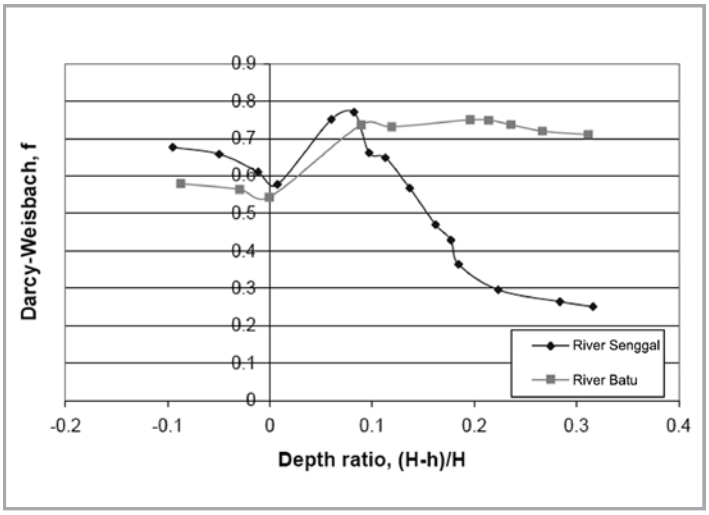

Figure 17: Variation of Darcy-Weisbach friction factor with depth of flow.

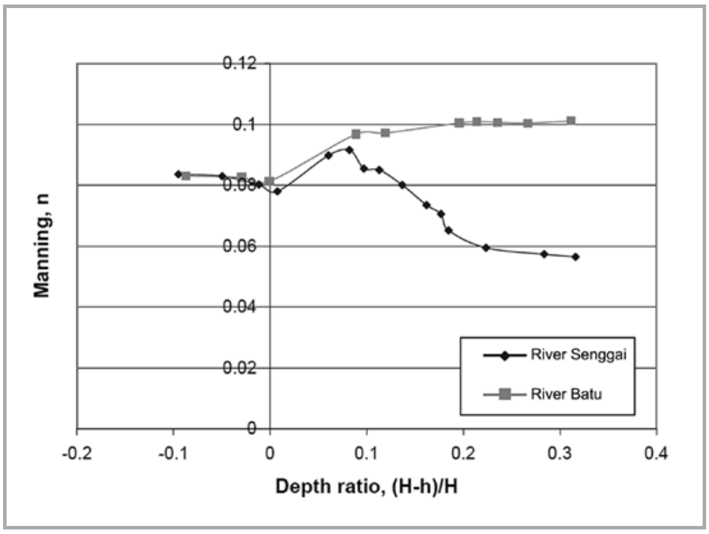

Figure 18: Variation of Manning coefficient, n with depth of flow

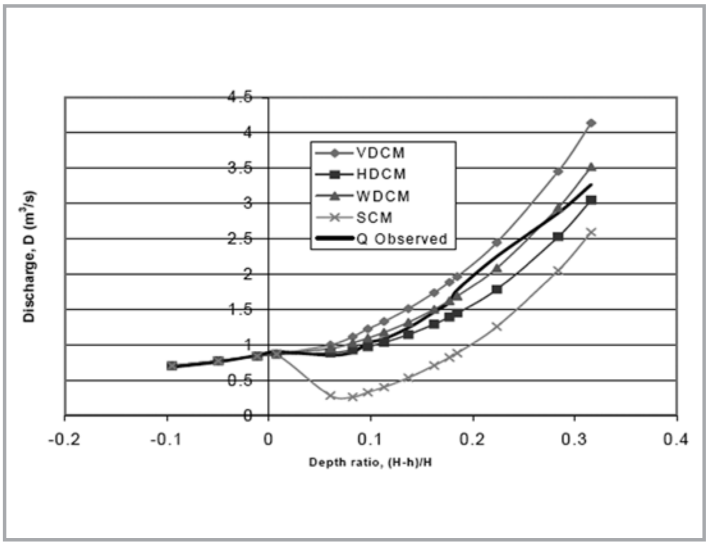

Figure 19: Comparison of observed and predicted discharge for River Senggai

The first zone is characterised by the inbank flow of natural rivers, in which the Manning coefficient and Darcy-Weisbach friction factor are decreasing linearly with flow depths due to the decreased of relative roughness in the main channel region. Generally, for the main channel regions, the Manning roughness coefficients are similar for the River Senggai and River Batu, with values ranges from 0.07 to 0.10, whereas the values of *f* calculated ranges from 0.54 to 0.89. This shows that the surface roughness for the main channel regions of the selected rivers are much higher than that of laboratory compound channels studied before, which normally have main channel roughness, $n \leq 0.01$.

The second zone is characterised by a sudden increased of roughness value when the flow is overbank. As the surface properties in the main channels remained the same, such an increment is considered due to the interaction mentioned previously, which slow down the flow in main channel. For example, the *n* and *f* values for River Senggai have increased from 0.078 and 0.577 at the bankfull level to 0.092 and 0.771 at (H-h)/H = 0.082, before they continue to reduce at higher depths.

For the floodplain regions, the value of *n* and *f* for each river has also been calculated. However, as the velocities on the floodplain are always very close to zero, so in this case, the value of roughness determined is very big and practically meaningless for floodplain analysis.

5.4 Discharge Estimation

The results above clearly show the complex nature of flow in flooded natural rivers, and to underline the danger of using inbank data as a guide to overbank flow behaviour, discharge estimation is carried out using the Manning equation and various divided channel method, *e.g.* single channel method (SCM), vertical divided channel method (VDCM), horizontal divided channel method (HDCM), and weighted divided channel method (WDCM). The roughness coefficient used for the main channel region is that at bankfull depth, which is likely to be the value chosen in the absence of data from overbank flow, whereas for the floodplain region, a recommended value by the Department of Irrigation and Drainage of Malaysia [16] of $n = 0.25$ has been used.

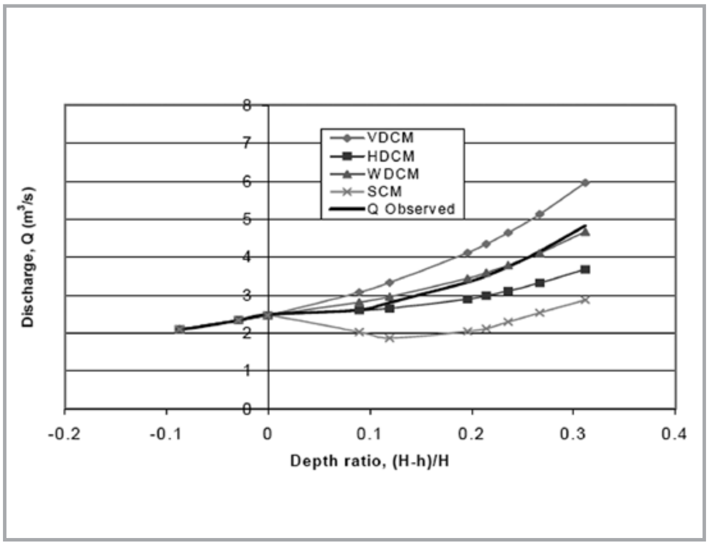

Figure 20: Comparison of observed and predicted discharge for River Batu

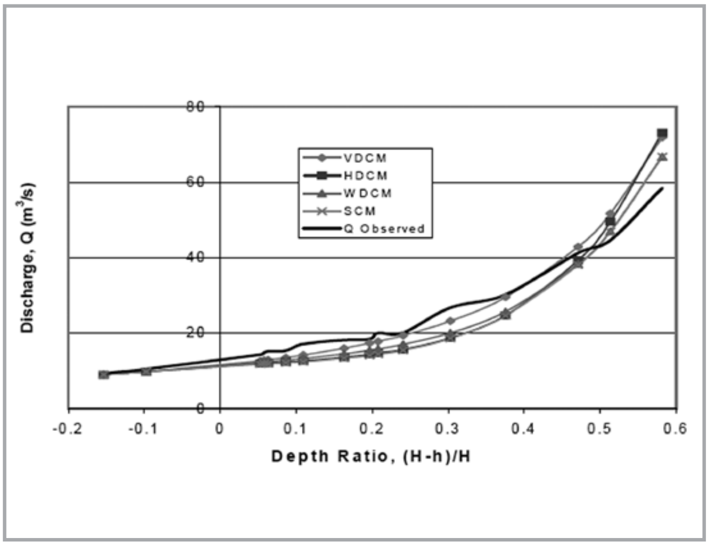

Figure 21: Comparison of observed and predicted discharge for River Main

Table 3: Discharge estimation for flooded natural rivers using conventional methods

Name of River	Method	Max. Error (%)	Ave. Error (%)	RMSE (%)
River Senggai	VDCM HDCM WDCM SCM	26.766 -20.781 7.821 -71.041	14.500 9.835 6.781 25.222	15.534 11.882 8.553 42.477
River Batu	VDCM HDCM WDCM SCM	26.749 -43.294 -22.980 -59.659	11.089 11.126 5.508 28.158	16.268 17.775 8.709 37.549
River Main	VDCM HDCM WDCM SCM	35.262 28.196 24.454 -22.385	7.337 8.835 5.043 9.154	12.372 11.809 7.889 11.765

The results obtained are plotted in Figures 19 to 21. The observed data are also plotted for comparison. These results show that for inbank flow, the estimated discharges match closely to the observed discharges, which imply that the inbank discharges are able to be estimated accurately using traditional method, provided that an accurate roughness coefficient is used.

When the flow is overbank, the discharges are over - or- under estimated depending on the method used. In most cases, the VDCM method is found to over-estimate the total discharge with average error of 7.34 - 15.94% and maximum errors of 26.77 - 46.84% depending on the river. On the other hand, the HDCM method is found to under-estimate the discharge with average errors of 7.94 - 11.12%, and maximum errors of 20.78 - 43.29%. Other methods such the SCM method is found to seriously under-estimate the discharge at low overbank flow, but becomes better at larger depth of flow. The WDCM method is found to be able to produce a significantly improved result, with average errors of 5.04 - 8.04%, and maximum errors of 7.82 - 24.45%. In general, as shown in Table 3, the conventional methods are seen to be rather inconsistent, with large differences in accuracies from river to river.

6.0 CONCLUSION

Results of field measurements have been presented for several flooded natural rivers, and the data has been analysed to illustrate the effects of momentum transfer on velocity, discharge capacity, and flow resistance coefficients.

Velocity distribution and stage discharge relationships confirm previous laboratory findings of a reduction in main channel parameters due to the interaction between main channel and floodplain, with a consequent reduction in compound section capacity when floodplains are inundated.

Flow resistance behaviour has been illustrated using Manning coefficient, and Darcy-Weisbach friction factor, thus showing the complex nature of resistance relationships under flood conditions, and the consequent danger of using inbank data to overbank flows.

The discharge in flooded natural river is either over-or-underestimated using the conventional methods, where the results obtained from SCM, VDCM, HDCM and WDCM are rather inconsistent. Therefore, further study has to be carried out in order to develop a reliable method for hydraulic analysis under overbank flow conditions. ■

REFERENCES

[1] W.R.C. Myers, D.W. Knight, J.F. Lyness, and J.B. Cassells, "Resistance coefficients for inbank and overbank flows", Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy, 136, pp 105-115, 1999.

[2] R.H.J. Sellin, "A laboratory investigation in the interaction between flow in the channel of a river and that of its floodplain", La Houille Blanche, No. 7, pp 793-801, 1964.

[3] G.V. Zheleznyakov, "Interaction of channel and floodplain streams", Proceedings, Fourteenth International Conference of the International Association for Hydraulic Research, Paris, France, 1971.

[4] W.R.C. Myers, "Momentum transfer in a compound channel", Journal of Hydraulic Research, ASCE, Vol. 16, pp 139-150, 1978.

[5] P.R. Wormleaton, and P. Hadjipanos, "Flow distribution in compound channels", Journal of Hydraulic Engineering, ASCE, Vol. 111, No. 2, pp 357-361, 1985.

[6] D.W. Knight, and J.D. Demetriou, "Floodplain and main channel flow interaction", Journal of Hydraulic Engineering, ASCE, Vol. 109, No. 8, pp 1073-1092, 1983.

[7] D.W. Knight, and M.E. Hamed, "Boundary shear in symmetric compound channels", Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 10, pp 1412-1430, 1984.

[8] G.C. Christodolou, and W.R.C. Myers, "Apparent Friction Factor on the FloodPlain-Main Channel Interface of Compound Channel Sections", Proceedings of 28th Congress of the International Association for Hydraulic Research, Craz, Austria, SE3, A379, 1999.http://www.iahr.org/membersonly/grazproceedings99/doz/000/000/367.htm [12 July 2004]

[9] P.R. Wormleaton, J. Allen, and P. Hadjipanos, "Discharge assessment in compound channel flow", Journal of Hydraulic Division, ASCE, Vol. 108, No. HY9, pp 975-994, 1982.

[10] P. Prinos and R. Townsend, "Comparison of methods for predicting discharge in compound open channels", Advance in Water Resources, Vol. 7, Dec, pp 180-187, 1984.

[11] W.R.C. Myers, "Velocity and discharge in compound channels", Journal of Hydraulic Engineering, ASCE, Vol. 113, pp 753-766, 1987.

[12] W.R.C. Myers, "Influence of geometry on discharge capacity of open channels", Journal of Hydraulic Engineering, ASCE, Vol. 117, pp 676-680, 1991.

[13] M.F. Lambert and W.R. Myers, "Estimating the discharge capacity in straight compound channels", Proceedings of the Institution of Civil Engineering, Water, Maritime and Energy, Vol. 130. pp 84-94, 1998.

[14] W.R.C. Myers, J.F. Lyness and J. Cassells, "Influence of boundary on velocity and discharge in compound channels", Journal of Hydraulic Research, Vol. 39, No. 3, pp 311-319, (2001).

[15] W.R.C. Myers, "River Main Data courtesy of WRC Myers", Department of Civil Engineering and Transport, University of Ulster at Jordanstown, 2002.

[16] Department of Irrigation and Drainage, Malaysia, "Urban Stormwater Management Manual for Malaysia", Vol. 5 - Runoff estimation, Kuala Lumpur, Malaysia, 2000.

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