Discharge estimation for equatorial natural rivers with overbank flow

LAI SAI HIN, *Lecturer, River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia. E-mail: redac lai@eng.usm.my*

NABIL BESSAIH, *Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kotta Samarahan, Sarawak, Malaysia*

LAW PUONG LING, *Department of Civil Engineering, Faculty of Engineering, UNIMAS, 94300 Kota Samarahan, Sarawak, Malaysia*

AMINUDDIN AB. GHANI, *Professor and Deputy Director, REDAC, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia. E-mail: redac02@eng.usm.my*

NOR AZAZI ZAKARIA, *Professor and Director, REDAC, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia. E-mail: redac01@eng.usm.my*

MAH YAU SENG, *Department of Civil Engineering, Faculty of Engineering, UNIMAS, 94300 Kota Samarahan, Sarawak, Malaysia*

ABSTRACT

The estimation of discharge capacity in river channels is complicated by variations in geometry and boundary roughness. Estimating flood flows is particularly difficult because of compound cross-sectional geometries and because of the difficulties of flow gauging. Results are presented of a field study including the stage-discharge relationships and surface roughness in term of the Darcy-Weisbach friction factor, f_a for several frequently flooded equatorial natural rivers. Equations are presented giving the apparent shear force acting on the vertical interface between the main channel and floodplain. The resulted apparent friction factor, f_a is shown to increase rapidly for low relative depth. A method for predicting the discharge of overbank flow of natural rivers is then presented, by means of a composite friction, f_c , which represents the actual resistance to flow due to the averaged boundary shear force and the apparent shear force. Equations are also presented giving the composite friction factor from easily calculated parameters for overbank flow of natural rivers. The results obtained using the methods proposed show that a significant improvement has been achieved compare to the discharge obtained using traditional methods, with an averaged error of 2.7%.

Keywords: Discharge estimation; flow resistance; friction factor; momentum transfer; natural river; overbank flow.

1 Introduction

Whether by nature or design, many rivers exhibit a compound or two-stage geometry, consisting of a deep central main channel flanked by one or two floodplains. For this type of channel geometry, previous research has shown that the use of conventional methods for overbank flow hydraulic calculation are incorrect, as they fail to allow for the loss in conveyance arising from interaction between main channel and floodplains (Zheleznyakov, 1965; Knight and Demetriou 1983, Wormleaton *et al.* 1982, Prinos and Townsend 1984, and Myers 1987, 1991, Acker, 1992, Lambert and Myers 1998, Myers *et al.* 2001). This has become the subject of considerable research in the past 30 years, covering various aspect of compound channel e.g. flow distribution, stage discharge relationship, surface roughness, apparent shear, and discharge estimation. Various methods as well as

empirical formulas have been proposed for discharge calculation of overbank flow, however none yet commands wide spread acceptance, due to most of the research carried out for overbank flow have been laboratory based with idealized conditions.

In natural rivers, the floodplains are often heavily wooded or vegetated with very complex configurations, the shapes are irregular, and the flow is usually turbulent with a considerable mixing. These leading to a completely different roughness conditions than that modeled in laboratory flumes. Thus, despite the extensive researches carried out, full-scale field experiments would be the best way to further understanding of overbank flow in compound river channels, as well as evolving accurate methods of overbank discharge prediction. At the present stage, field study is rare due to overbank flow conditions occur typically under flood conditions when acquisition of data is difficult and sometimes dangerous.

As many flood improvement schemes consist of a main channel with associated floodplains or berms. An overestimate of discharge capacity at the design stage may lead to flooding at more frequent intervals than contemplated in these cases. Moreover, in flood routing through complex river systems, it is essential that the interaction between the channel and floodplain sections be properly modeled. Therefore, the need for accurate and preferably simple methods of discharge calculation in compound sections is thus very important. Therefore, a field study on discharge estimation of overbank flow was carried out to derive a method for accurate discharge predictions during flood events and for a reliable stage-discharge relation for flood control measures and management schemes.

2 Review

In analyzing 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 characterizes 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 such as the Chezy, Manning, and Darcy-Weisbach equations, in term of the channel roughness, slope and hydraulic radius.

However, if the cross-sectional shape is irregular, this can lead to considerable errors. One particularly important example of this occurs when we encounter a compound cross-section consisting of a deep main channel with associated shallow floodplains or berms. In this case, there may be a sudden change of depth 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 gradient inevitably results in a lateral mass and momentum transfer mechanism as shown in Figure 1, which can greatly reduce the channel discharge capacity.

Sellin (1964), was the first to investigate the momentum transfer mechanism, which was manifested by a series of vortices having vertical axes, form along each channel-floodplain interface (Figure 2). Zheleznyakov (1965), (1971), confirmed the presence of the momentum transfer mechanism, which he called the “kinematic effect”, and he demonstrated, under laboratory conditions, the effects of the mechanism in decreasing the overall rate of discharge for floodplain depths just above bank-full. As the floodplain depth increased, the importance of the phenomenon diminished. Barishnikov and Ivanov (1971) reached similar conclusions and found a reduction in the section discharge capacity of up to 16%, due to momentum transfer effect.

Townsend (1968) undertook similar research in a channel with a single floodplain and studied the longitudinal and transverse characteristics of the flow. His results highlighted the tendency of the turbulence at the interface to disperse laterally across the floodplain. This illustrated the ability of the series of vortices

Figure 1 Mechanisms of overbank flow in a straight compound channel (after Shiono and Knight, 1991).

Figure 2 Vortices form at the interface of main channel and floodplain.

present in the mixing zone to transport the final sediment fractions from the fast flowing deep channels of rivers on to the floodplains in time of flooding. Based on the results, he concluded that for small floodplain depths, both the stream-wise and cross-stream turbulence intensities at the channel-floodplain interface were significantly higher under interacting (compound channel) flow conditions than the corresponding values obtained for the equivalent isolated (separate channels) conditions.

Myers & Brennan (1990) found that the mechanism retards channel velocity and discharge, while increasing the corresponding parameters on the floodplain. The most notable feature of

these relationships is the discontinuity at bankfull depth, with a reduction in discharge as depth rises just above the bankfull value. If flow depth continues to rise, the floodplain discharge and flow velocity will increase rapidly, to a point where main channel and floodplain are roughly equal in carrying capacity. This equalization of discharge and velocity results in a consequent decrease in momentum transfer from main channel to floodplain and may lead to a reversal in the direction of momentum transfer at larger depths.

Prinos and Townsend (1985) presented that when the flow in a river channel rises above the bankfull stage and inundates the adjacent floodplain areas, momentum is transferred across the junction regions separating the deep and shallow zones. If the velocity gradient across the junction region is large, this transfer mechanism will influence both velocity and boundary shear force distributions and also the turbulence characteristics of the junction regions. Under such conditions, the accuracy of most conventional discharge estimation methods is reduced. This is largely because conventional discharge estimation methods do not account for the appreciable apparent shear force occurring at the main channel-floodplain interfaces.

The studies of Wormleaton *et al.* (1982), Myers (1987) and Myers *et al.* (2001) illustrated the error encountered by various traditional calculation methods for discharge estimation in compound channels due to momentum transfer. The single channel method (SCM) is found seriously in error when the flow is just overbank. The divided channel method with horizontal (HDCM) and vertical (VDCM) division lines are either under or over-estimated the flow in compound channels, with errors of up to 45% in the rough floodplain case. Smooth main channel and floodplain are more accurately modeled by this method with 10% error. While the river discharge errors peak at almost 30%. It is clear that more reliable and preferably simple method of analysis is needed for discharge estimation in such rivers.

3 Field study and data collection

The study was carried out in three natural rivers namely River Senggai, River Senggi (B) 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 (2002) in North Ireland has also been obtained for comparison.

The selected rivers are shown in Figures 3–6. It presents that the rivers are almost straight and uniform in 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.

Flow gauging of the rivers was carried out from an adjustable bridge built across the rivers, using the velocity-area method, in which 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 0.0005 m (0.5 mm) and 0.0001 m/s respectively. For each measuring point, 3–6 reading

Figure 3 Morphological cross-section of River Senggai.

Figure 4 Morphological cross-section of River Senggi (B).

Figure 5 Morphological cross-section of River Batu.

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.

Figure 6 Morphological cross-section of River Main.

4 Theory considerations

The Darcy-Weisbach equation is commonly used to express flow in open channels, following the recommendation of the American Society of Civil Engineers (ASCE) in 1963. Therefore it has been adopted in this study, in which

$$V = \left[\frac{2gDS_0}{f} \right]^{1/2} \quad (1)$$

where V is the average cross-sectional velocity, D ($= \frac{P}{B}R$) is the hydraulic diameter, S_0 is the bed slope, g is gravitational acceleration, and f is the Darcy-Weisbach friction factor.

In applying the Darcy-Weisbach equation above, the greatest uncertainty lies in the determination of the Darcy-Weisbach friction factor, f ; for there is no exact method of selecting the f value, especially under overbank flow conditions of natural rivers, as limited published data is available and heterogeneous floodplains may be difficult to characterize. The picture is further complicated by the existent of an apparent shear due to the momentum transfer at the interface region as mentioned above.

In order to account for the increase of resistance due to momentum transfer in discharge calculation of overbank flow,

the invisible apparent shear can be quantified as shown below:

Assuming uniform flow in a simple channel section with trapezoidal shape,

Driving force = Resisting force

$$W \sin \theta = \tau_0 P \Delta x$$

but $\tau_0 = C_f \rho \frac{V^2}{2}$, $C_f = \frac{f}{4}$, $W = \rho g A$, and $\sin \theta = S_0$. For a unit distance,

$$fPV^2 = 8gAS_0$$

In the case of overbank flow with vertical interface, an additional resisting force due to apparent shear must be added in terms of an apparent friction factor, f_a , velocity gradient at the interface region of main channel and flood plain, ΔV^2 and the interface perimeter, y (Christodolou and Myers, 1999). Then, considering the balance of forces along the flow direction in the main channel leads to:

$$f_{am} = \frac{8gA_m S_0 - f_{mp} PV_m^2}{2y (\Delta V^2)} \quad (2)$$

Similarly, for the floodplain region,

$$f_{af} = \frac{f_{fp} PV_f^2 - 8gA_f S_0}{y (\Delta V^2)} \quad (3)$$

For Equations 2 and 3 above, the flow velocities V_m and V_f are from measured values, the channel slopes S_0 , the interface wetted perimeter y , the sub-sectional area A and the sub-sectional wetted perimeter P can be obtained easily from geometrical measurement. The boundary friction factors, f_{mp} and f_{fp} can be obtained by extrapolation using inbank data, assuming that no interaction existed between the main channel and floodplain. Since the measured velocities are strongly influenced by the floodplain and main channel interaction, the velocity differences (ΔV) between subsections were obtained, not from the measured values, but from estimated velocities for each sub-sections using the Darcy-Weisbach equation.

The values of f_{am} and f_{af} calculated using Equations 7 and 8 above should in principle have the same values ($= f_a$) but acting in opposite directions, and depend on the geometrical cross section (B, b), flow depth ($H, H-h$), geometrical relationships (M_f, M_m, R_f, R_m), and boundary roughness (f_{fp}, f_{mp}) of

Table 1 Geometrical properties and surface conditions.

Geometrical properties	River Senggai	River Senggi (B)	River Batu	River Main
Bankfull depth, h (m)	1.060	1.306	1.544	0.900
Top width, B (m)	5.285	5.500	5.150	13.700
Aspect ratio, B/h	4.986	4.211	3.335	15.222
Bed slope – main channel, S_0	0.0010	0.0010	0.0016	0.0030
Bed slope – left floodplain, S_L	0.0010	0.00085	0.0013	0.0030
Bed slope – right floodplain, S_R	0.0010	0.00085	0.0013	0.0030
Surface condition – main channel	Erodible soil	Erodible soil	large boulder	coarse gravel
Surface condition – side bank	Erodible soil	long vegetation	Erodible soil	large boulder
Surface condition – floodplain	long vegetation	long vegetation	long vegetation	short vegetation

the main channel and floodplain. In dimensionless form:

$$f_a \propto \left[\frac{B}{b}, \frac{H-h}{H}, \frac{M_f}{M_m}, \frac{R_f}{R_m}, \frac{f_{fp}}{f_{mp}} \right] \quad (4)$$

This relationship can be sorted using a multiple non-linear regression analysis approach to give the relationships on which f_a depends. This approach is preferred as it allows the evaluation of f_a in a predictive sense, i.e. without the need for measuring the velocities of the subsections.

5 Velocity distribution

The lateral distributions of averaged depth velocity at the gauging site of the rivers are shown in Figures 7–9. These figures clearly show that the maximum flow velocity occurs in the central of main channel region, which decreases towards the side banks direction, and increases with the increase of flow depth. Whereas, the flow velocity on the floodplains is found near to zero in all cases even at high overbank flow due to the retention effects of the floodplain vegetations. As a result, a large velocity gradient

Figure 7 Averaged depth velocity for overbank flow of River Senggai.

Figure 8 Averaged depth velocity for overbank flow of River Batu.

Figure 9 Averaged depth velocity for overbank flow of River Senggai (B).

is found between the main channel and floodplain, due to the different in depth and surface roughness.

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. These interactions tend to retard the flow at the interface region of main channel, and reduced the cross sectional discharge capacity.

6 Flow resistance results

By substituting $D = (P/B)R$ to Equation 1, the resistance to flow for the main channel region of the investigated rivers has been calculated in term of the Darcy-Weisbach friction factor, f_m as shown in Figure 10. For inbank flow, i.e. $(H-h)/H < 0$, the f value for the selected equatorial rivers was found to be in the range of ± 0.2 at low flow, and it decreases linearly with flow depths towards the bankfull level, due to the decrease in relative roughness in the main channel region. An exception to this is in River Senggai (B), which experienced a slight increment of f_m value due to the vegetation at the side banks. The respective values for River Main were found comparatively small with f_m values equal to ± 0.04 .

The overbank flow is characterized by an increased of roughness value. As the surface properties in the main channels remained the same, such an increment can be considered due to the apparent shear mentioned earlier, which slows down the flow in main channel. For River Senggai and River Batu with obvious roughness differences between the main channel and floodplain, the increase in roughness starts when the flow is just overbank. For example, the f values for River Senggai increased from 0.157 at the bankfull level to 0.208 at $(H-h)/H = 0.082$, before they continue to reduce at higher depths. For River Senggai (B) and River Main, the increase only starts after a certain stage of overbank flow, i.e. $(H-h)/H = 0.166$ for River Senggai (B) and $(H-h)/H = 0.302$ for River Main due to the bank vegetation and cross-sectional geometry which prevent the interaction occurring before the effective bankfull level.

For the floodplain regions, the velocities collected from field measurements during overbank flow are always close to zero, except under very high overbank flow depth. As a result, the f_f values obtained are very high. Such values are known to be

Figure 10 Variation of Darcy-Weisbach friction factor, f with depth of flow.

Figure 12 Apparent friction factor, f_a observed and predicted using Equation 6.

correlations between f_a and B/b , f_{fp}/f_{mp} , M_f/M_m would indicate that these variables will have lesser degree of influent to the values of f_a .

However, when the correlation is carried out with a combination of 2, 3, 4 and 5 variables, better results are obtained. This shows that all the variables are significant in the determination of an accurate value of f_a . Therefore, all the independent variables are retained, and the final regression equation obtained is:

$$f_a = 0.82 \left(\frac{H-h}{H} \right)^{-2} \left(\frac{M_f}{M_m} \right)^{-11.5} \left(\frac{B}{b} \right)^{0.55} \left(\frac{f_{fp}}{f_{mp}} \right)^{-0.85} \times \left(\frac{R_f}{R_m} \right)^{0.31} + 0.1255 \quad (6)$$

The coefficient of multiple correlations is found to be 0.995. The determination coefficient of 0.991 indicates that the preceding equation would explain 99.1% of the total deviation in f_a .

The values of f_a estimated by equation 6 are compared with the observed values in Figure 12. The close agreement of the data, from flooded natural rivers, and over a range of geometrical conditions, is encouraging.

8 Composite friction factor

Based on the estimated boundary shear stress, f_{mp} , and the apparent friction factor, f_a , the weighted ratio on how the composite (actual) friction factor, in the main channel, f_c depends on f_{mp} and f_a has been found in terms of the associated wetted perimeters P_m and y , as:

$$f_c = 1.03 \left[\left[0.117 \left(\frac{P_m}{P_t} \right)^{-7.06} f_{mp} + 0.507 \left(\frac{2y}{P_t} \right)^{1.08} f_a \right] - 0.008 \right] \quad (7)$$

in which P_t is the total wetted perimeter

The results obtained using Equation 7 are compared with the observed main channel friction factor in Figure 13. It can be seen that that most of the main channel friction factors can be calculated accurately, with a coefficient of determination of 0.994. However, as the data are based on only four natural rivers, only limited reliance can be placed on this. Additional data is needed

Figure 13 Observed and estimated composite friction factor using Eq. 7.

before more reliable relationships for calculating the apparent friction factor and composite friction factor can be found. Nevertheless, the writers consider that this analysis has helped to pinpoint the important causative factors in determining the friction factors, and at best provide a simple means of determining it from easily calculated parameters.

9 Discharge estimation

As mentioned above, the velocities on floodplain are close to zero in most cases, and it has little contribution to the overall discharge capacity. Therefore, the discharge estimation carried out was focused on the main channel region, to avoid the overestimation at the floodplain region, and to give a simple but reasonable estimate of discharge for such river channels. The results of obtained using the composite friction factor estimated, f_c were plotted in Figs. 14–17. Also plotted are the observed data and the discharge estimated using the conventional Manning equation with bank-full roughness for comparison. From the results, it can be seen that the discharges are significantly over-or-under estimated using the conventional method with an averaged error of 12.5%, 19.2%, 16.3%, 44.9% for River Senggai, River Senggai (B), River Batu, and River Main, respectively. In extreme case, the discharge estimated for River Main (i.e. $H-h/H = 0.58$) is almost twice of the observed discharge with a maximum error of 91.2%. These highlighted the danger inherent in the conventional practices of extrapolating inbank data for the analysis of overbank flows.

Figure 14 Comparison of observed and predicted main channel discharge for River Senggai.

Figure 15 Comparison of observed and predicted main channel discharge for River Senggi (B).

Figure 16 Comparison of observed and predicted main channel discharge for River Batu.

Figure 17 Comparison of observed and predicted main channel discharge for River Main.

From the graphs plotted, it can also be seen that the results are significantly improved using the estimated composite friction factor, compared to those estimated using traditional methods, in which all the discharge estimated using the composite friction is seen to match closely to the observed data. Table 3 further shows the significant improvement achieved using the proposed method in which the averaged error for River Senggai, River Senggi (B), River Batu and River Main have been reduced tremendously to

Table 3 Comparison between discharges estimated using traditional method, and composite friction factor, f_c .

Stat. Calc.	River Senggai		River Senggi (B)		River Batu		River Main	
	Trad.	f_c	Trad.	f_c	Trad.	f_c	Trad.	f_c
Max. Error (%)	28.44	8.82	56.16	12.55	24.88	5.93	91.21	8.83
Ave. Error (%)	12.52	2.37	19.20	3.60	14.15	1.38	44.91	3.38
RMSE (%)	15.49	3.54	26.00	4.77	16.95	2.12	49.43	4.38

2.37, 3.60, 1.38 and 3.38% only. Other statistical calculation such as the maximum error, and root mean square error (RMSE) carried out also supported positively the consistency and accuracy of the proposed method in discharge estimation of overbank flows.

10 Conclusions

Based on extensive data collected from four frequently flooded natural rivers and results obtained, it can be concluded that:

1. A very strong apparent shear is found at the interface region of main channel and floodplain. The apparent shear has been quantified in the form of apparent friction factor f_a , and it is found that the apparent shear is maximized when the flow is just overbank but reduced at higher depths.
2. The use of traditional method for overbank flow estimation was found to be significantly in error, with an averaged over-or-under estimation of 22.7%, due to the interaction between the main channel and floodplain flows.
3. A statistical method is able to provide a simple means of determining the apparent friction factor and composite friction factor from easily calculated parameters for overbank flow of natural rivers. The results obtained using the methods proposed show that a significant improvement has been achieved compare to those obtained using traditional methods, with an averaged error of 2.7%. However, more data is needed to further generalize and verify the equations.

Notation

ρ = Fluid density

τ_0 = Mean shear stress on the bottom

Δx = Flowing distance in streamwise direction

ΔV = Velocity gradient at the interface region of main channel and flood plain

A = Wetted area

A_m, A_f = Wetted areas for the main channel and flood plain

b = Bankfull width

B = Top width

C_f = Resistance coefficient

D = Hydraulic diameter

f = Darcy-Weisbach friction factor

f_a = Apparent friction factor

f_c = Composite friction factor

f_{am} , f_{af} = Apparent friction factors for the main channel and flood plain
 f_f , f_m = Observed Darcy-Weisbach friction factors for the main channel and flood plain
 f_{fp} , f_{mp} = Estimated Darcy-Weisbach friction factors for the main channel and flood plain
 h = Bankfull depth
 H = Depth of flow
 $HDCM$ = Horizontal Divided Channel Method
 M = A geometrical parameter ($= 2P/B$)
 M_f , M_m = Geometrical parameters, for flood plain and main channel
 P = Cross sectional wetted perimeter
 P_m = Main channel wetted perimeter
 R = Hydraulic radius
 R_f , R_m = Hydraulic radius for flood plain and main channel
 S_0 = Longitudinal bed slopes
 SCM = Single Channel Method
 V = Mean velocity
 V_m , V_f = Mean velocities for the main channel and flood plain
 $VDCM$ = Vertical Divided Channel Method
 W = Gravitational weight of fluid
 y = Interface wetted perimeter

Acknowledgement

The authors would like to express their gratitude to Dr. W. R. C. Myers, University of Ulster, U.K., for providing data from River Main in Northern Ireland.

References

1. ZHELEZNYAKOV, G.V. (1965). "Relative deficit of mean velocity of instable river flow; kinematic effect in river beds with floodplains," *Proceedings of the Eleventh International Conference of the International Association for Hydraulic Research*, Leningard, U.S.S.R.
2. KNIGHT, D.W. and DEMETRIOU, J.D. (1983). "Floodplain and Main Channel Flow Interaction," *Journal of Hydraulic Engineering, ASCE*, 109(8), 1073–1092.
3. WORMLEATON, P.R., ALLEN, J. and HADJIPANOS, P. (1982). "Discharge Assessment in Compound Channel Flow," *Journal of Hydraulic Division, ASCE*, 108(9), 975–994.
4. PRINOS, P. and TOWNSEND, R. (1984). "Comparison of Methods for Predicting Discharge in Compound Open Channels," *Advances in Water Resources*, 7(Dec), 180–187.
5. MYERS, W.R.C. (1987). "Velocity and Discharge in Compound Channels," *Journal of Hydraulic Engineering, ASCE*, 113, 753–766.
6. MYERS, W.R.C. (1991). "Influence of Geometry on Discharge Capacity of Open Channels," *Journal of Hydraulic Engineering, ASCE*, 117, 676–680.
7. ACKERS, P. (1992). "Hydraulic design of two-stage channels," *Proceedings of the Institution of Civil Engineering, Water, Maritime and Energy*, 96, 247–257.
8. LAMBERT, M.F. and MYERS, W.R. (1998). "Estimating the Discharge Capacity in Straight Compound Channels," *Proceedings of the Institution of Civil Engineering, Water, Maritime and Energy*, 130, 84–94.
9. MYERS, W.R., LYNESS, J.F. and CASSELLS, J. (2001). "Influence of Boundary on Velocity and Discharge in Compound Channels," *Journal of Hydraulic Research*, 39(3), 311–319.
10. SHIONO, K. and KNIGHT, D.W. (1991). "Turbulent Open Channel Flows with Variable Depth Across the Channel," *Journal of Fluid Mechanics*, 222, 617–646.
11. SELLIN, R.H.J. (1964). *A laboratory investigation in the interaction between flow in the channel of a river and that of its floodplain*, *La Houille Blanche*, No. 7, 793–801.
12. ZHELEZNYAKOV, G.V. (1971). *Interaction of channel and floodplain streams, proceedings, Fourteenth International Conference of the International Association for Hydraulic Research*, Paris, France.
13. BARISHNIKOV, N.B. and IVANOV, G.V. (1971). "Role of floodplain in flood discharge of a river channel," *Proceedings, 14th International Conference of the International Association of Hydraulic Research*, Paris, France.
14. TOWNSEND, D.R. (1968). "An investigation of turbulence characteristics in a river model of complex cross-section," *Proceedings of the Institute of Civil Engineers*, Vol. 40, 155–175.
15. MYERS, W.R.C. and BRENNAN, E.K. (1990). "Flow Resistance in Compound Channel," *Journal of Hydraulic Research*, 28(2), 141–155.
16. PRINOS, P. and TOWNSEND, R. (1985). Friction factor relationships for flow in compound channels. *Advances in water resources*, University of Birmingham (Tebbutt T.H.Y. (ed.)). Elsevier, London, 332–339.
17. MYERS, W.R.C. (2002). River Main Data courtesy of Myers WRC, Department of Civil Engineering and Transport, University of Ulster at Jordanstown.
18. TASK FORCE. (1963). "Friction Factor in Open Channels," Report of the ASCE Task Force," *Journal of Hydraulic Engineering, ASCE*, 89(2), 97–143.
19. CHRISTODOLOU, G.C. and MYERS, W.R.C. (1999). "Apparent friction factor on the floodplain-main channel interface of compound channel sections," *Proceedings of 28th Congress of the International Association for Hydraulic Research*, Graz, Austria, SE3, A379, <http://www.iahr.org/membersonly/grazproceedings99/doz/000/000/367.htm>.