Influence of boundary roughness on velocity and discharge in compound river channels

Influence de la rugosité des frontières sur la vitesse et le débit des rivières à lit composé

W.R.C. MYERS, J.F. LYNESS & J. CASSELLS, *School of the Built Environment, University of Ulster, Jordanstown, Newtownabbey, BT37 0QB, UK.*

ABSTRACT
Results are presented of an experimental compound channel research programme carried out at the UK Flood Channel Facility including fixed and mobile main channel boundaries together with two flood plain roughnesses. For comparison data from a natural compound river channel are also presented. Velocity and discharge relationships are explored illustrating the complex behaviour of compound river channels and calling attention in particular to the errors incurred in applying conventional methodologies to discharge assessment in overbank flows. Relationships are presented for velocity and discharge ratios which could form the basis of mathematical modelling of overbank flow estimation methods. The research also represents a step towards prototype conformity by the introduction of mobile boundaries.

RÉSUMÉ
L'article présente les résultats d'un programme expérimental de recherche sur les lits composés, mené au UK Flood Channel Facility, incluant des frontières fixes et mobiles du lit principal, ainsi que deux rugosités de lit majeur. A titre de comparaison, les données naturelles d'une rivière à lit composé sont aussi présentées. Les relations de vitesse et débit sont explorées, illustrant le comportement complexe des rivières à lit composé, et attirant particulièrement l'attention sur les erreurs encourues lorsqu'on applique les méthodes conventionnelles d'évaluation des débits aux écoulements avec débordement. Des relations sont présentées pour les rapports de vitesse et de débit, qui pourraient constituer la base de la modélisation mathématique des méthodes d'estimation des écoulements avec débordement. Cette recherche représente également une étape vers une conformité au prototype par l'introduction de frontières mobiles.

Introduction

Rivers represent one of mankind's most important environmental assets. River flows are often affected by man's activities and therefore require careful management for water supply, waste disposal, flood alleviation and power generation as well as amenity uses.

River engineering design and management has tended to be dominated by engineering concerns there is now an increasing recognition that the conflicting pressures of engineering and ecological objectives must be rationalised and harmonised to ensure optimum use of a valuable resource. Thus river design is becoming more environmentally sensitive seeking solutions which are sustainable and which enhance the ecological environment as well as ensuring flood protection.

Two-stage or compound river geometries (Fig 1) ensure reasonable depths at low flows, which provide a suitable habitat for fish and other wildlife, while the flood plains provide conveyance for floods There is however difficulty in estimating discharge capacity in rivers of a compound cross-sectional shape. Methods appropriate to simple cross-sectional shapes are not accurate when applied to overbank flows and may lead either to over-estimation of discharge capacity, which is dangerous, or to under-estimation of capacity which leads to over design and wastage of resources.

Review

Compound channel flow is complicated by the existence of a region of turbulent shear at the interface between main channel and flood plain flows, which takes the form of a momentum transfer mechanism, which retards channel velocity and discharge, while increasing the corresponding parameters on the flood plain. The effect is enhanced by the fact that flood plain roughness often significantly exceeds that in the main channel.

Conventional methods of computing conveyance are not applicable to compound channels. The Single Channel Method (SCM) treats the compound geometry as a single unit, assigning single values of roughness and hydraulic radius. The Divided Channel Method (DCM), divides the cross-section into main channel and flood plain zones, which are treated separately. Neither method takes account of momentum transfer across the interface between

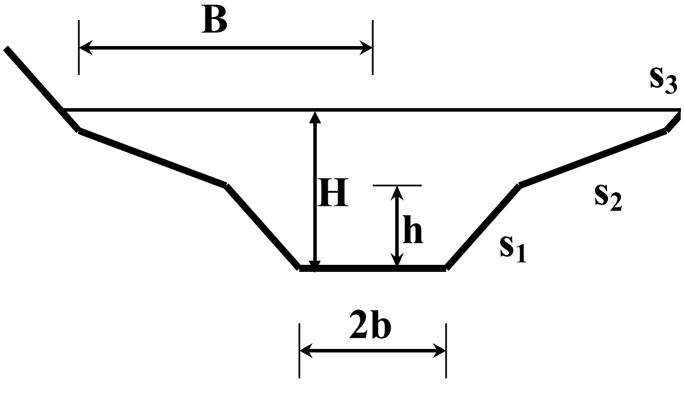

Fig 1. Compound channel geometry

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main channel and flood plain.

Early investigations by Sellin (1964) and Zheleznyakov (1971) demonstrated the presence of the vortices and their effect on velocity and discharge at over-bank flows. Myers (1975 & 1978), Knight & Demetriou (1983) and Wormleaton, Allen & Hadjipanos (1982) were able to quantify the momentum transfer mechanism by measuring boundary shear stress distributions and applying the momentum equation to channel and flood plain zones, showing that apparent shear stress on the channel flood plain interface is many times greater than the average shear stress around the solid boundaries.

Some field studies have been undertaken by Martin & Myers (1991) and Myers & Lyness (1994) which have proved valuable in indicating values of flow resistance parameters at prototype scale. Field data is difficult and often dangerous to measure, is site specific, and should be generalised only with extreme caution.

The United Kingdom Flood Channel Facility (FCF) was designed to bridge the gap between laboratory and prototype scales while also providing a flexible environment where a wide ranging generalised study of compound channel hydraulics could be undertaken, Knight & Sellin (1987).

Phase A of the FCF programme centred on straight and skewed fixed boundary compound channels, and the results of this have been presented by Myers & Brennan (1990), Knight & Shiono (1990), Wormleaton & Merritt (1990) and Elliott & Sellin (1990). Phase B explored meandering planforms having fixed boundaries and which has been reported by Sellin, Ervine & Willetts (1993), Ervine, Willetts, Sellin, & Lorena (1993), and Greenhill & Sellin (1993). The data from Phases A and B have been presented in the form of a design guide for river engineers by Wark, James and Ackers (1994). Preliminary results from Phase C have been presented by Myers et al (1999) and Knight et al (1999).

A promising development is the application of two-dimensional and three-dimensional turbulence models to compound channel flow as reported by Krishnappan and Lau (1986), Satish, Guo & Rahman (1991) and Tominaga & Nezu (1991). Wark, Slade & Ramsbottom (1991) have attempted to apply a turbulence model to the prediction of discharge in both field and laboratory contexts, and have compared their findings with experimental data.

Development of 2D and 3D turbulence models continues to represent a major thrust for compound channel research in the future. It presents the attractive prospect of a generalised methodology of compound channel analysis and design. To engender confidence in such approaches however there needs to be verification by comparison with extensive data from both laboratory and field. For any mathematical or computational model of compound channel flow to be valid it must represent the component flows of the compound cross-section as well as accurately reflecting the overall velocity and discharge values. The current study is aimed at interpreting FCF data covering fixed and mobile boundaries to further understanding of the distribution of velocity and discharge in compound channels

Experimental arrangement

The laboratory experiments were carried out in the UK Flood Channel Facility (FCF), which is a large scale compound channel facility located at the laboratories of HR Wallingford Ltd. The facility is some 50 m long by 10 m wide with associated recirculation arrangements capable of delivering flows of up to 1 m^3/s. The general arrangement of the FCF is shown in Fig 2. Since 1986 the FCF has been used for a major programme of compound channel research which is summarised in Table 1.

The current paper presents data from Phase A and Phase C to demonstrate the influence of mobile boundaries on the velocity and discharge characteristics of a compound channel. For the purposes of comparison almost similar geometries have been chosen for consideration and the values of relevant parameters are presented in Table 2, which also refers to Fig 1.

Flood plain roughness took the form of 25 mm diameter circular dowel bars which were distributed to give a density of 12 bars per square metre of flood plain bed area.

The mobile bed in Phase C consisted of sand of uniform size with a D_{50} of 0.8 mm.

The recirculation system consisted of four pipes conveying water from the downstream sump to an upstream header tank. Discharge was measured in each pipe by means of an orifice plate meter. Sediment was trapped in a sump at the downstream end of the channel and recirculated by means of a slurry pump and a separate pipe to a special arrangement upstream which then separated sand from water and sand mixture for re-entry into the main channel. This ensured equilibrium between sand input and output from the channel. Sand discharge was measured by means of an infra-red meter which had previously been calibrated. Velocities were measured using a miniature propeller meter. Bedforms were recorded using an automatic bed profiler linked to a PC. Typical bedforms at a relative depth of 0.3 are illustrated in Fig 3.

Water surface levels were measured using stilling wells connected to the sides of the main channel, and levelled in to datum. Water surface elevation could be controlled by a series of weirs at the extreme downstream end of the facility. For each discharge, a series of water surface elevations was investigated including M1 and M2 curves, until uniform flow was achieved. Fuller details of the experimental arrangements relating to Phases A and C of the FCF are presented by Myers and Brennan (1990), Brown (1997) and Knight et al (1998).

Also presented for comparison are field data from a compound river channel. The experimental programme leading to the acquisition of the field data is described by Martin & Myers (1991), while the relevant geometrical data are included in Table 2.

Absolute values of certain parameters are not necessarily directly

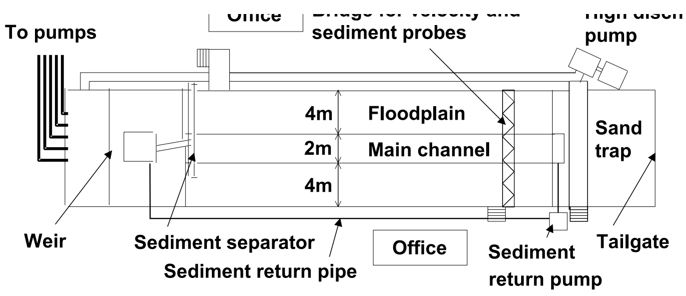

Fig 2. General arrangement of flood channel facility

Table 1. Flood channel facility research programmes

Flood Channel Facility	RESEARCH PROGRAMME	DATES
PHASE A	STRAIGHT AND SKEWED CHANNELS WITH FIXED BOUNDARIES	1986-1989
PHASE B	MEANDERING PLANFORMS WITH FIXED BOUNDARIES	1989-1991
PHASE C	STRAIGHT AND MEANDERING PLANFORMS WITH MOBILE BOUNDARIES	1994-present

Table 2. Geometrical & roughness parameters

	PHASE A Series 2	PHASE A Series 7	PHASE C Series 1	PHASE C Series 2	River Main
b	0.75 m	0.75 m	0.8 m	0.8 m	5.5 m
B	3.15 m	3.15 m	4.0 m	4.0 m	13.7 m
B/b	4.2	4.2	5.0	5.0	2.5
h	0.15 m	0.15 m	0.2 m	0.2 m	0.9 m
s_1	1 : 1	1 : 1	1 : 1	1 : 1	0.7v : 1h
s_2	0	0	0	0	0.06v : 1h
s_3	1 : 1	1 : 1	1 : 1	1 : 1	0.62v : 1h
So	1×10^{-3}	1×10^{-3}	1.83×10^{-3}	1.83×10^{-3}	3×10^{-3}
channel boundary	smooth concrete	smooth concrete	sand	sand	boulder banks & gravel bed
flood plain boundary	smooth concrete	rod roughness	smooth concrete	rod roughness	grass

comparable, the comparison of laboratory and field data is very useful in assessing the effectiveness of the smaller scale investigations in predicting trends and ranges of important parameters and relationships. Table 3 presents values of measure depth and discharge for the range of experiments analysed in this paper.

Interpretation of results

Velocity Profiles

Lateral depth averaged velocity profiles for both fixed and mobile main channel boundaries together with smooth and rough flood plains are shown in Fig 4. River data are also included for comparison. All data refer to a relative depth of 0.3, where relative depth is defined as the ratio of flood plain depth to total depth. The horizontal axis is the ratio of the distance from the main channel centreline to the main channel half top width. This allows direct comparison between the slightly different geometries. The vertical axis shows depth averaged velocities non-dimensionalised by ratioing with average cross-sectional velocity.

There is more scatter in the data in the main channel with mobile beds due to the presence of bedforms in the form of large scale dunes, and on the roughened flood plains. Fig 3 illustrates the nature and size of dune formation at the depth investigated. However the main trends are obvious in Fig 4 where it may be seen that velocity gradient at the main channel flood plain interface is partly governed by bed roughness differential, which is maximum when the main channel is smooth and the flood plains are rough and minimum when a mobile main channel boundary is combined with smooth flood plains. The river data exhibit sharp differences between channel and flood plain velocities due to differential roughness. Main channel values are well modelled by the smooth compound channel data, but the correspondence breaks down on the flood plain, partly due to the lateral inward slope on the river flood plain beds.

Ratios of average main channel and flood plain velocities to full cross-sectional values are shown in Figs 5 and 6. Fig 5, shows the effect of mobile main channel boundaries, which is to render the ratios closer to unity, at lower depths, although all cases converge to unity at large depths. This indicates a weakening of the momentum transfer mechanism with depth which has been well doc-

Table 3. Ranges of measured depths and discharges

DATA SOURCE	SERIES	DEPTH m	DISCHARGE m^3/s
FCF PHASE A	2	0.1565	0.2123
FCF PHASE A	2	0.1687	0.2483
FCF PHASE A	2	0.1778	0.2821
FCF PHASE A	2	0.1868	0.3237
FCF PHASE A	2	0.1979	0.3832
FCF PHASE A	2	0.2136	0.4800
FCF PHASE A	2	0.2486	0.7630
FCF PHASE A	2	0.2880	1.1140
FCF PHASE A	7	0.1559	0.2160
FCF PHASE A	7	0.1655	0.2332
FCF PHASE A	7	0.1765	0.2540
FCF PHASE A	7	0.1859	0.2717
FCF PHASE A	7	0.1995	0.2998
FCF PHASE A	7	0.2188	0.3429
FCF PHASE A	7	0.2498	0.4238
FCF PHASE A	7	0.3025	0.5434
FCF PHASE C	1	0.2249	0.2500
FCF PHASE C	1	0.2427	0.3488
FCF PHASE C	1	0.2593	0.4491
FCF PHASE C	1	0.2741	0.5981
FCF PHASE C	1	0.2935	0.7480
FCF PHASE C	2	0.2273	0.2476
FCF PHASE C	2	0.2581	0.3498
FCF PHASE C	2	0.2814	0.4495
FCF PHASE C	2	0.3202	0.5989
RIVER MAIN		0.95	14.82
RIVER MAIN		0.96	15.40
RIVER MAIN		0.99	15.17
RIVER MAIN		1.08	17.10
RIVER MAIN		1.12	19.99
RIVER MAIN		1.19	20.10
RIVER MAIN		1.29	27.24
RIVER MAIN		1.44	29.91
RIVER MAIN		1.50	36.05
RIVER MAIN		1.70	41.23
RIVER MAIN		1.85	44.38
RIVER MAIN		2.15	57.85

umented in previous studies.

The influence of flood plain roughness is illustrated in Fig 6, where the effect is to render the ratios much more divergent. Also shown in Fig 6 is the river data, which are seen to converge in similar fashion to the FCF smooth flood plain case. The reason for the difference in behaviour is due to the characteristics of surface penetrating roughness used on the FCF, which produces increasing roughness with depth. The natural roughness is submerged and leads to decreasing relative roughness as depth increases. It may be noted also that due to the lateral inward slope on the river flood plains full overbank flow is only achieved at a relative depth of 0.3. The natural trends therefore are better modelled by the smooth flood plain FCF data.

Fig 3. Bedform patterns for relative depth of 0.3

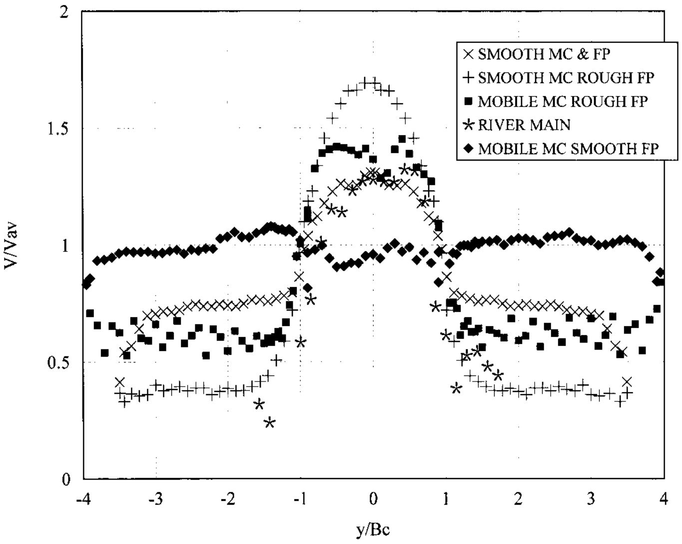

Fig 4. Lateral velocity profiles

Another representation of the velocity data is presented in Fig 7 where ratios of main channel to flood plain velocities are shown. In keeping with previous findings, see Myers (1987), the data are logarithmic, rendering such relationships amenable to easy mathematical description. The river data tend to diverge from the linear pattern at low depths when roughness height and flood plain depth converge in size. The ranges values of the ratios are clearly influenced by differential roughness with the river data falling in

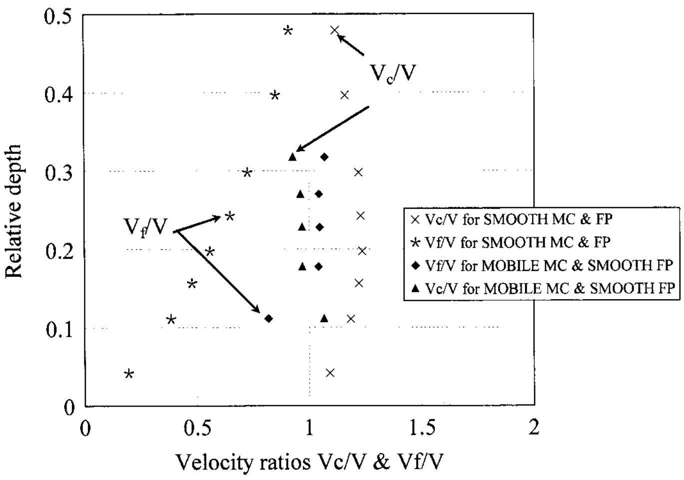

Fig 5. Ratios of channel and flood plain velocity to average cross-sectional values for smooth flood plains

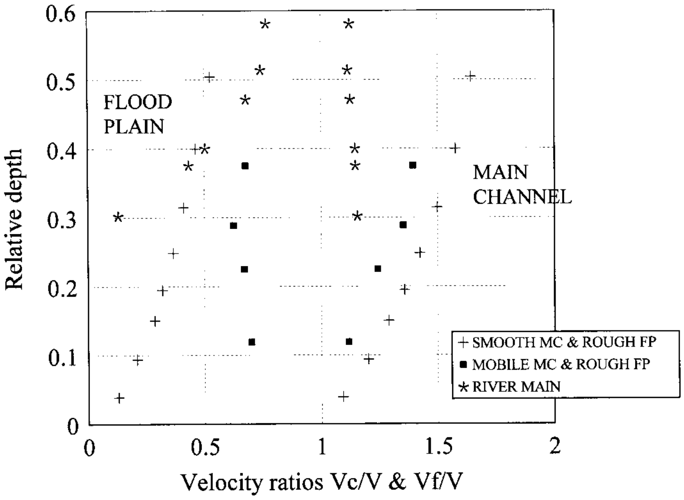

Fig 6. Ratios of channel and flood plain velocity to average cross-sectional values for rough flood plains

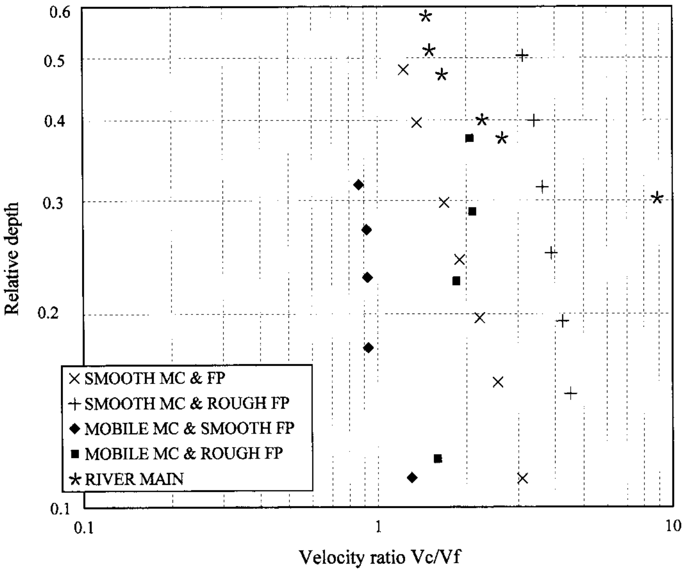

Fig 7. Ratios of channel to flood plain velocities

the middle of the laboratory data.

Such linear relationships are useful in numerical modelling approaches, Myers (1987) has shown that the parameters may be represented by a relationship of the form:

$$V_r = K(D_r)^k \qquad (1)$$

where

V_r = V_c/V_f
V_c = average main channel velocity
V_f = average flood plain velocity
D_r = relative depth = flood plain depth / total depth
K = coefficient
k = exponent

Table 4 presents values of K and k for each case considered as well as indicating closeness of linear fit by means of a correlation coefficient. The lowest value of correlation coefficient relates to Phase C Series 1 data shown in Fig 7. It may be noted that these data are represented by an almost vertical line indicating very little variation with depth. The equation however, despite the poor correlation, accurately predicts velocity ratio. The river data exhibits good linearity, but the lowest depth has been excluded from the analysis.

Discharge Relationships

The fundamental challenge in understanding compound channel flow remains the accurate prediction of discharge capacity. A number of methods is available but none yet commands widespread acceptance. One criterion of a satisfactory method of discharge estimation is that it must accurately account for zonal flows in main channel and flood plains as well as providing a good estimate of overall flow rate. A feasible method of doing this is by means of discharge ratios which show proportions of flow in channel and flood plain sub areas. Figs 8 and 9 present ratios of main channel and flood plain discharges to full compound section values. Fig 8 shows the effects of main channel bed material illustrating that the mobile boundary produces significantly closer values of ratio with cross over at the largest depth considered. Rough flood plains shown in Fig 9 display much more divergent ratios, which do not meet at the depths consid-

Table 4. Values of coefficient k & exponent k in equation (1) relating velocity ratios (v_c/v_f) to relative depth (d_r)

DATA SET	COEFFICIENT K	EXPONENT k	CORRELATION COEFFICIENT R^2
FCF Phase A Series 2	0.786175	-0.623305	0.99853
FCF Phase A Series 7	2.547025	-0.305454	0.99657
FCF Phase C Series 1	0.554083	-0.361242	0.83066
FCF Phase C Series 2	2.709741	0.246750	0.91643
River Main	0.622376	-1.414736	0.91849

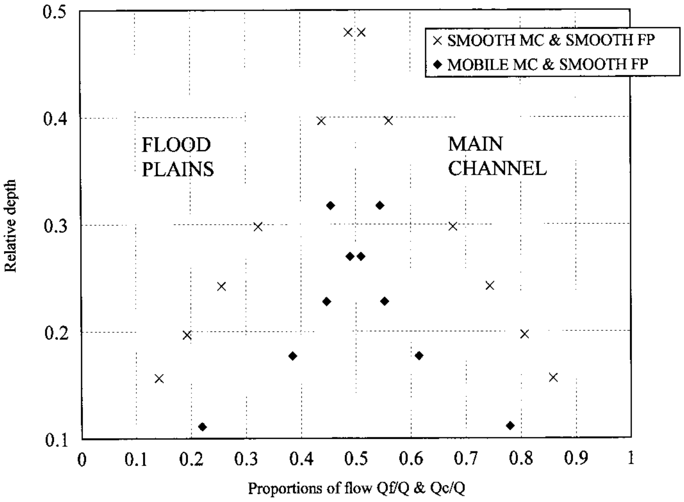

Fig 8. Proportions of flow in main channel and flood plains for smooth flood plains

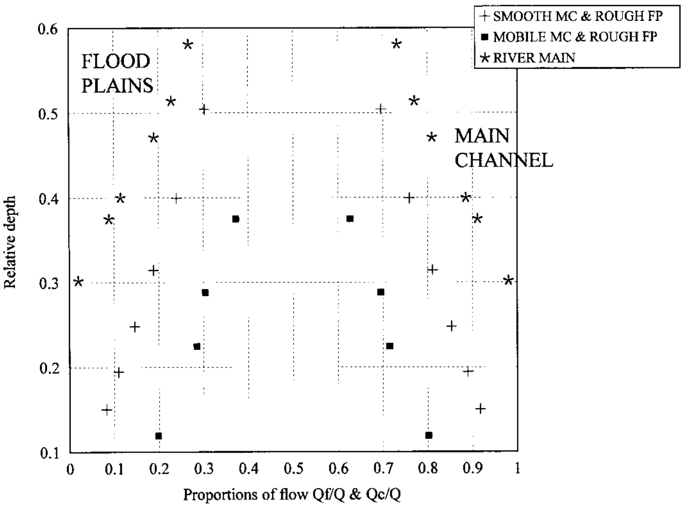

Fig 9. Proportions of flow in main channel and flood plains for rough flood plains

ered. Also shown in Fig 9 is the data for the prototype river scale which display even more divergence than the laboratory data, but with very similar tends.

The data are represented differently in Fig 10 showing ratios of channel to flood plain flows for all cases. All data including the river measurements display logarithmic relationships, with broadly similar trends but differing absolute values . Such representations can be easily modelled numerically and may point the way towards extrapolation of laboratory data as well as forming the basis of computational models of compound river channels. Myers (1987) has shown that the ratio of main channel to flood plain discharge may be represented by an equation of the form:

$$Q_r = G(D_r)^g \tag{2}$$

where

Q_r = Q_c/Q_f
Q_c = average main channel discharge
Q_f = average flood plain discharge

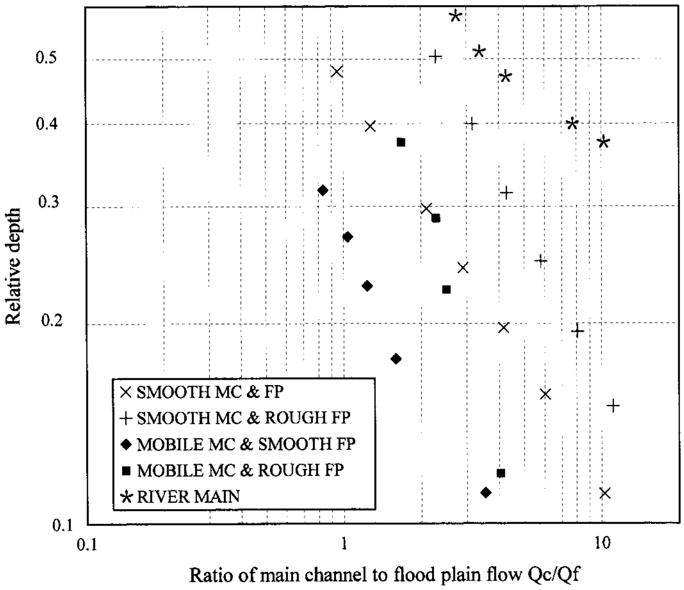

Fig 10. Ratios of main channel to flood plain discharge

D_r = relative depth = flood plain depth / total depth
G = coefficient
g = exponent

Table 5 presents values of coefficient G and exponent g for all cases considered, together with values of correlation coefficient. In analysing the river data the lowest value of depth was omitted from the regression.

It is instructive to compare the traditional methods of discharge estimation in compound channels in relation to their ability to model the effects of scale and boundary roughness as represented by the current data. Figs 11 and 12 show the errors incurred by applications of the divided channel method (DCM) to the current compound geometries. The DCM divides main channel from flood plain and assigns hydraulic radius and roughness values to each zone. The discharges from each zone are then summed to give the total value. Fig 11 illustrates the smooth main channel cases, with smooth and rough flood plains. For the smooth boundaries a value of Manning's roughness coefficient of 0.01 was

Table 5. Values of coefficient g & exponent g in equation (2) Relating discharge ratio (q_c/q_f) to relative depth (d_r)

DATA SET	COEFFICIENT G	EXPONENT g	CORRELATION COEFFICIENT R^2
FCF Phase A Series 2	0.293338	-1.618455	0.99978
FCF Phase A Series 7	0.865254	-1.379012	0.99907
FCF Phase C Series 1	0.171489	-1.350605	0.98550
FCF Phase C Series 2	0.838906	-0.742470	0.99001
River Main	0.466976	-3.070487	0.97422

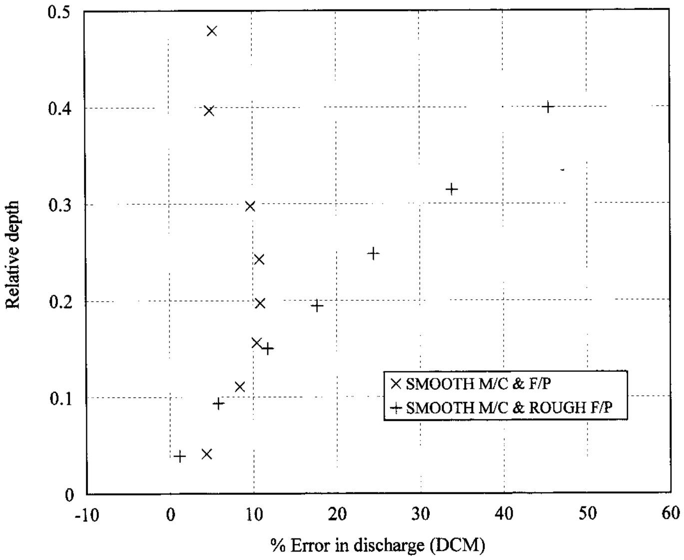

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Fig 11. Discharge errors using the divided channel method for smooth main channel data

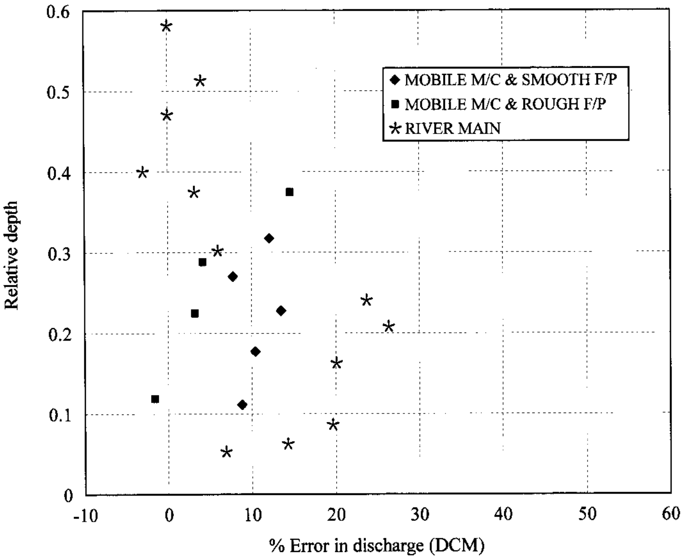

Fig 12. Discharge errors using the divided channel method for mobile main channel and river data

used, being the bankfull value as measured. To determine values of roughness coefficient for the rod roughness used on the flood plains, tests were carried out using the main channel only with the same dowel roughness pattern as used on the flood plains. Values of roughness coefficient were measured for a range of depths applicable to flood plain flow. The average of these values (0.027) was used in the DCM to estimate discharge on the roughened flood plains for both smooth and mobile main channels.

Fig 11 shows that the DCM overestimates compound discharge, with errors of up to 45% in the rough flood plain case, which also exhibits increasing error with depth. Smooth main channel and flood plains are more accurately modelled by this method with 10% errors. The DCM becomes more accurate with increasing depth.Fig 12 shows errors for the DCM applied to FCF data with mobile main channels and with river data for comparison. The value of roughness coefficient used for main channel calculations was that measured at bankfull depth, namely 0.03, (Knight & Brown 1998) while for the river calculations the bankfull value of "n" (0.038) was used for both main channel and flood plain estimations. There is more scatter in the data for these cases but the general level of discharge error is clearly seen. The laboratory data show maximum errors of around 15% for both flood plain roughnesses, while the river discharge errors peak at almost 30%, before converging to around zero at large flood plain depths. None of the laboratory data accurately model the river data behaviour, although the smooth compound channels data match the prototype trend.

Figs 13 and 14 show errors incurred by utilisation of the single channel method (SCM) to estimate compound channel flows. The SCM method treats the compound section as a single unit, with single hydraulic radius and roughness values for each depth. In each case the bankfull value of roughness coefficient has been

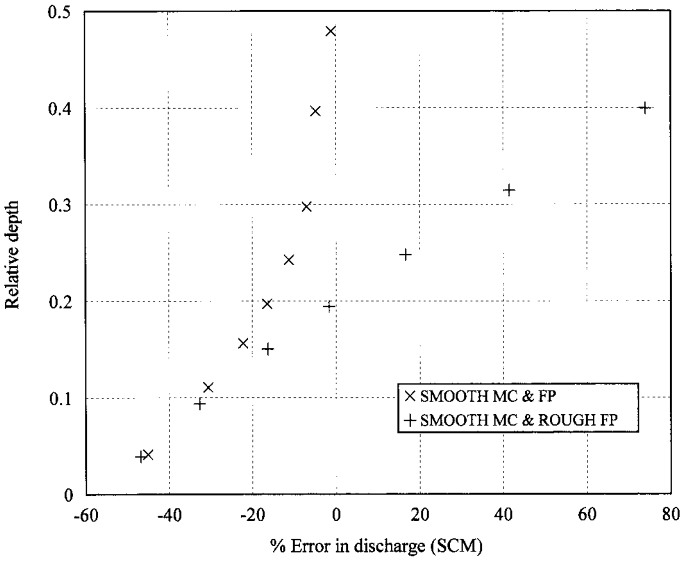

Fig 13. Discharge errors using the single channel method for smooth main channel data

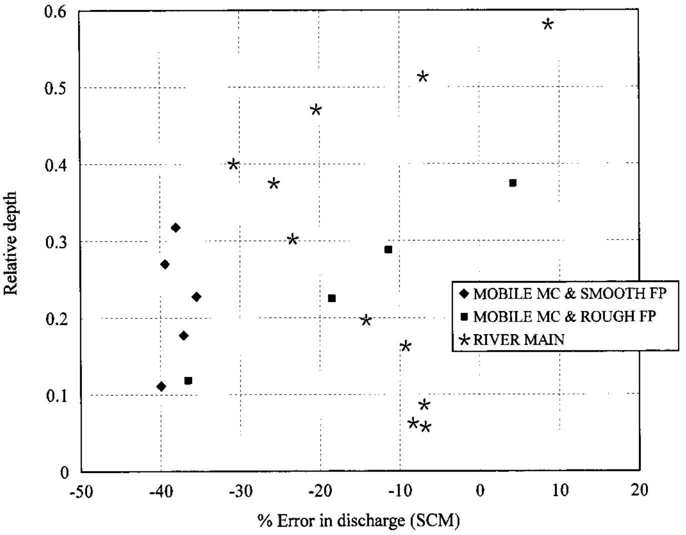

Fig 14. Discharge errors using the single channel method for mobile main channel and river data

used and this leads to generally negative errors indicating an underestimation of discharge capacity. Not surprisingly maximum errors occur in relation to cases with the largest roughness differential and in the cases of rod roughened flood plains the errors become positive at large depths and continue to increase. The river data exhibit maximum errors of around -30%, but return to near zero at large depths as the compound channel begins to act as single unit. Thereafter errors become positive. None of the laboratory relationships model the trend of the prototype data.

Conclusions

1. A comparison has been presented of the velocity and discharge characteristics of fixed and mobile bed compound laboratory channels with smooth and roughened flood plains, which have been compared with data from a prototype compound river channel.
2. Ratios of main channel to flood plain average velocities plot logarithmically for the laboratory data, but linearity is not as strongly evident in the natural river data. Equations have been fitted to the data and values of coefficient and exponent presented.
3. Values of velocity ratio for the river lie within the range found for the laboratory data.
4. Ratios of main channel to flood plain discharge plot logarithmically for the laboratory data, but linearity is not so strongly present in the river data. Equations have been fitted to the data and values of coefficient and exponent presented.
5. Values of discharge ratio for the river data lie outside the range found for the laboratory data, but this may be due to differences in geometry.
6. The divided channel method (DCM) of discharge estimation overestimates the compound channel discharge in all cases.
7. The divided channel method exhibits reasonable accuracy when applied to laboratory data with smooth flood plains, but shows significant errors of up to 35% for rough flood plain data, and up to 27% for river data.
8. The single channel method (SCM) significantly underestimates compound discharge for all cases for low flow depths, but becomes more accurate at larger depths for the smooth boundary laboratory data and the river data.

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List of symbols

b = half bottom width of main channel
B = half total width of compound channel
B_c = half width of main channel at bankfull depth
D_r = relative depth = flood plain depth / total depth
g = exponent in equation (2) relating discharge ratio (Q_r) to relative depth (D_r)
G = coefficient in equation (2) relating discharge ratio (Q_r) to relative depth (D_r)
H = total depth
h = bankfull depth
k = exponent in equation (1) relating velocity ratio (V_r) to relative depth (D_r)
K = coefficient in equation (1) relating velocity ratio (V_r) to relative depth (D_r)
Q = compound channel discharge
Q_c = main channel discharge
Q_f = flood plain discharge
Q_r = ratio of main channel to flood plain discharge
s_1 = main channel side slope
s_2 = lateral inward slope of flood plain bed
s_3 = slope of flood plain bank
S_o = longitudinal bed slope
V = depth averaged velocity at a vertical section
Vav = average cross-sectional velocity
V_c = average main channel velocity
V_f = average flood plain velocity
V_r = ratio of main channel to flood plain velocity
y = lateral distance from main channel centre line

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