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Authors(s)	O'Sullivan, J. J., Myers, W. R. C., Lyness, J. F., Lambert, M. F.
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J. J. O'Sullivan
College Lecturer,
Department of Civil
Engineering, University
College Dublin, Ireland



W. R. C. Myers
Reader, School of the Built
Environment, University of
Ulster, Newtownabbey,
Northern Ireland



J. F. Lyness
Reader, School of the Built
Environment, University of
Ulster, Newtownabbey,
Northern Ireland



M. F. Lambert
Senior Lecturer, Department
of Civil and Environmental
Engineering, University of
Adelaide, Australia



Discharge assessment in mobile-bed compound meandering channels

J. J. O'Sullivan, W. R. C. Myers, J. F. Lyness and M. F. Lambert

Many discharge prediction methods have been developed for compound meandering channels. Most of these methods have been found to produce reasonable results for fixed-bed channels, but the effects of the presence of a mobile main channel bed on discharge assessment have yet to be assessed. Sediment movement increases the complexity of experiments by facilitating the creation of bedforms, which alter flow resistance. The shape characteristics of these bedforms and their associated roughness are known to depend on channel stage and geometry, and to vary with flow conditions. This paper seeks to assess the performance of six discharge assessment methods using the Phase C mobile-bed meandering UK Flood Channel Facility (FCF) overbank flow data. The results show that the accuracy of the different methods depends heavily on the boundary roughness, and the James and Wark (1992) method performed most consistently for the range of floodplain configurations tested. A modification to this method is also presented that is shown to improve the accuracy of the predicted discharges.

NOTATION

A	cross-sectional area
B	bankfull width
D_r	relative depth = $(H - h)/H$
E	measured error
F_1, F_2	factors in James and Wark discharge assessment method
f	Darcy–Weisbach friction factor
g	acceleration due to gravity
H	total channel depth
h	main channel depth (bankfull level)
K_e	coefficient in James and Wark discharge assessment method
L_m	path length of full meander
l	path length to point on meander
N	total number of observations
n	Manning's roughness coefficient
P	wetted perimeter
Q	discharge
Q_c	calculated discharge
Q_m	measured discharge
R	hydraulic radius
Re	Reynolds number
S	slope

s	sinuosity
V	mean velocity
ν	kinematic viscosity
θ	angle to main axis at any point on sine wave
θ_0	crossover angle

Subscripts

mc	main channel
fp	floodplain
mb	meander belt
1, 2, 3	zones of compound section

I. INTRODUCTION

Compound channels, or two-stage channels as they are sometimes known, have for some time played important roles in various flood alleviation schemes. These channels generally consist of a deep main channel flanked on either one or both sides by floodplains that become inundated in times of high flow, thereby increasing the discharge capacity of the channel. In drier periods, floodplains provide areas suitable for settlements, agricultural or recreational uses. On the basis that the conveyance capacity of undeviating channels was greater than those incorporating bends, early compound sections were designed to be straight. However, in recent times ecological factors have gained in importance, and the use of these straight channels, in which the faster-moving waters are unsuitable for the development of habitat conditions and aquatic life, is no longer acceptable. As such, compound channels with sinuous main channel planforms are becoming more popular, and in some situations meanders are being introduced into previously constructed straight compound channels.¹ The increasing use of compound meandering channels in flood relief schemes has led to the need for improved design guidelines to accurately predict the conveyance capacity of these channels.

An impetus to the study of two-stage meandering channels, initiated in 1989 by Phase B of the compound channel study, focused at the UK Flood Channel Facility (FCF), led to the development of a number of methods to estimate conveyance. These methods have been based and calibrated on rigid or fixed-bed channels, and their performance when applied to channels incorporating mobile beds has yet to be verified. In mobile-bed channels, the movement of bed material is accompanied by the formation of undulations on the bed that are appreciably altered with changes of flow condition.² The

resistance function of mobile-bed channels is linked to the growth or decay of these bed formations,³ and results in an additional complexity not reflected in commonly used discharge assessment methods. This paper seeks to assess the performance of the discharge assessment methods of James and Wark,⁴ Greenhill and Sellin,⁵ Shiono *et al.*,⁶ Lambert and Sellin⁷ and Rameshwaran and Willetts⁸ when applied to mobile-bed, compound meandering channels. The work described herein formed part of the Phase C FCF experimental programme into mobile-bed compound channels with both smooth and artificially roughened floodplains. An amendment to the James and Wark method that improved the accuracy of the results is also presented.

2. PREVIOUS WORK

Early methods of discharge prediction in compound meandering channels commonly used the standard resistance relationships of Chezy, Manning and Darcy–Weisbach applied to the total channel section, but since Toebes and Sooky in 1967 recommended that cross-sections were best divided by a horizontal division at bankfull,⁹ subdivision methods have become more popular. By treating channels in terms of non-interacting zones, total discharges are obtained by summing the individual discharges in each subsection. Although subdivision methods overcome the problems associated with the discontinuities in stage–discharge relationships at the bankfull level, they fail to account for other complexities associated with the main channel and floodplain interaction in meandering channel flows, and result in errors of up to 30% in the predicted discharge in these channels.⁵ Although Lipscomb¹⁰ reported that the effect of sinuosity on the conveyance capacity of channels either with small main channels or when the floodplain width is in excess of three times the meander belt width is insignificant, its effect on most channels, particularly at low depths, results in a substantial reduction in discharge capacity.¹¹ Flows in sinuous compound channels are fundamentally different from those in straight channels. Water no longer flows predominantly in the main channel or valley direction with mixing between the two regions restricted to the main channel–floodplain interface, but rather involves a three-dimensional interchange of water from the floodplain to the main channel and vice versa.¹² This bulk exchange of fluid, dependent on the main channel cross-sectional geometry and in particular the main channel and floodplain aspect ratio, is most pronounced in crossover regions where the floodplain flow is partially entrained by secondary flows in the main channel as it passes over, and results in a local plunging zone as indicated in Fig. 1.^{11,12} The plunging of the floodplain flow is most vigorous close to the main channel centre line, and produces strong secondary cir-

ulation cells that increase in magnitude from the convex side of bend apices. The secondary currents induced by this plunging rotate in opposite directions to those that would be observed during inbank flows, and diminish rapidly immediately downstream of bend apices where flow from this region is ejected onto the downstream floodplain.^{13–15} The interchange of floodplain and main channel flows and their subsequent expulsion back onto the floodplain is accompanied by the occurrence of maximum turbulence intensities on the downstream floodplains at the interface of crossover sections and at the inner bend of the main channel.^{14,16} Furthermore, the difference in direction between the main channel flow, which predominantly follows the direction of the main channel sidewalls, and the floodplain flow, which tends to follow the valley direction, facilitates the development of a horizontal shear layer at the bankfull level. The intensity of this layer is most pronounced at crossover sections where the directions of the inner channel and overbank flow deviate most. The difficulty in stage–discharge prediction for compound meandering channels lies in the difficulty in quantifying these sources of energy dissipation and assessing their effects on the behaviour of channels with different hydraulic and geometrical characteristics.

Ervine and Ellis in 1987 described a method of predicting stage and discharge for compound meandering channels by estimating the energy dissipation from five main sources:¹⁷ the frictional head loss around the wetted perimeter in the main channel; the flow resistance over the wetted area on the floodplain due to vegetation it may contain; the flow resistance due to secondary currents at river bends induced by outward centrifugal pressures; the flow resistance due to floodplain flow components passing normally over the main channel flow encountering sudden expansions and contractions; and the flow resistance due to co-flowing turbulent shear between the fast-flowing main channel and the slower-moving floodplain flow parallel to the main channel. In this method, Ervine and Ellis utilised a cross-section subdivision incorporating three areas that were considered separately in the allocation of energy

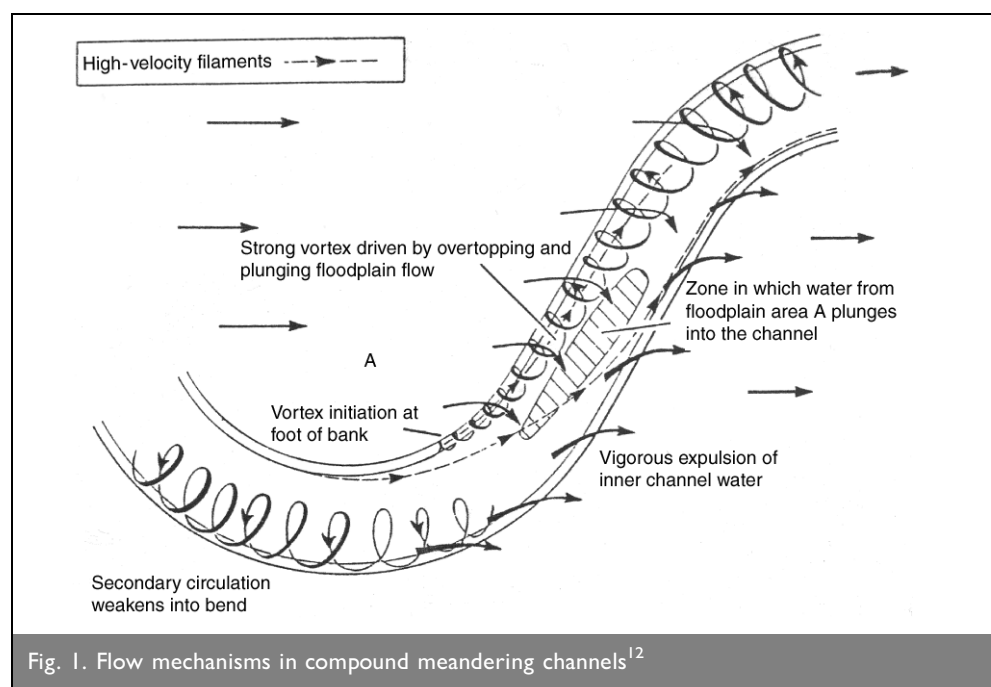


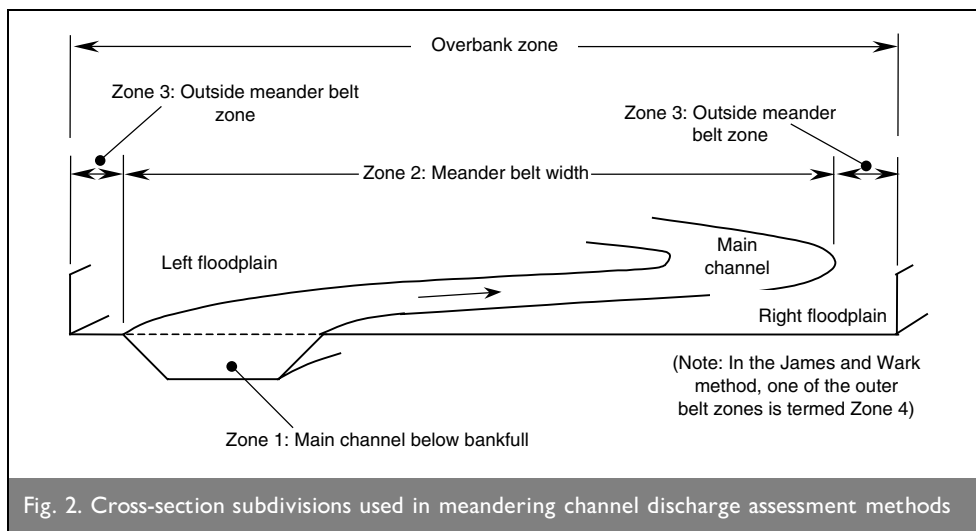
Fig. 1. Flow mechanisms in compound meandering channels¹²

losses. This division method isolates the main channel flow below the bankfull level (zone 1), the floodplain flow within the meander belt width (zone 2) and the floodplain flow outside the meander belt (zone 3), as shown in Fig. 2, and has been adopted by other researchers. James and Wark⁴ used a similar hydro-mechanics approach incorporating these channel subdivisions in a subsequent assessment method. However, these hydro-mechanics methods failed to account for the energy losses caused by turbulent shear stress on the 'horizontal' plane at the bankfull level, and these can be significant for some sinuosities and relative depths. Shiono *et al.*¹⁵ found that in the bankfull zone the energy loss due to this turbulence was of the same order of magnitude as that attributed to skin friction of the boundary, and in the meander belt zone the loss due to turbulent shear increased linearly with increasing sinuosity and contributed significantly to the total energy losses for a sinuosity of 1.57 and a relative depth of 0.15.

Based on the Manning–Strickler equation, Greenhill and Sellin⁵ attempted to minimise the number of channel subdivisions, but found that best results were obtained by analysing the three separate sub-areas. Initially the channel was divided into two distinct zones by incorporating a horizontal division across the main channel at the bankfull level. Large errors (up to 20%) were observed from measured values, and accordingly a further division between the meander belt and the outer floodplain zone beyond the meander belt refined the method. This division was initially vertical, but Greenhill and Sellin determined that the accuracy of predictions was improved by a 45° interface that accounted for the velocity gradient between the overbank zones. The total discharge, Q_{total} , was obtained by summing the zonal discharges as follows

$$Q_{total} = \frac{1}{n_1} S_{mc}^{1/2} R_1^{1/2} A_1 + \frac{1}{n_2} S_{mc}^{1/2} R_2^{2/3} A_2 + \frac{1}{n_3} S_{fp}^{1/2} R_3^{2/3} A_3$$

in which S_{mc} and S_{fp} are the main channel and floodplain slopes respectively, A is the flow area, R is the hydraulic radius, and n is Manning's roughness coefficient. The subscript 1 represents the main channel zone below bankfull, and subscripts 2 and 3 represent the meander belt and outer meander belt zones incorporating the 45° interfaces, so that



$$A_2 = A_{mb} + (H - h)^2$$

$$P_2 = P_{mb} + 2\sqrt{2}(H - h)$$

where A_{mb} and P_{mb} are the meander belt area and wetted perimeter with vertical interfaces, H is the total depth, and h is the bankfull depth.

Shiono *et al.*,⁶ based primarily on data from the FCF Phase B fixed-bed data, developed a 'whole' channel approach in which the Darcy–Weisbach resistance law is amended to incorporate the effects of channel sinuosity as follows

$$\frac{VR}{\nu} s = 10.012 \left(\frac{gR^3 S_{fp}}{\nu^2} \right)^{0.541851}$$

where V is the total section velocity, R is the total section hydraulic radius, S_{fp} is the floodplain gradient, s is the main channel sinuosity, g is the gravitational acceleration, and ν is the kinematic viscosity. The application of this equation is used to determine the section velocity, which is then multiplied by the total section area to yield the discharge

$$Q_{total} = VA$$

This method does not account for the additional flow resistance that arises from floodplain roughness, and is best suited to smooth or unobstructed floodplain cases. Rameshwaran and Willetts⁸ developed another 'whole' channel procedure for stage–discharge prediction in two-stage channels comprising a meandering main channel within straight floodplains. The method estimates the overall flow resistance in terms of Darcy–Weisbach resistance coefficients from nine system features using the Prandtl–von Karman resistance relationship: sinuosity, aspect ratio, bank side slope and cross-sectional geometry of the main channel, relative boundary roughness of the main channel and floodplain, floodplain longitudinal slope, meander belt width relative to floodplain width, relative overbank flow depth, and system scale. The method identifies two distinct domains of resistance behaviour. The first domain is representative of shallow flows where the flow resistance is dependent on Reynolds number and can be defined by an equivalent roughness size. The second domain is the roughness-dominated flow domain where flow resistance is not influenced by fluid viscosity.

Most recently, Lambert and Sellin⁷ developed an approach in which average cross-sectional properties and slopes are determined to model the meandering compound channel as an equivalent straight channel. This necessitates the determination of an average floodplain width and an average slope. The floodplain flow resistance results from fluid shear

stresses that act over its surface area, and consequently the average floodplain width is based on the total surface area of the floodplain under consideration. The total overbank area is therefore reduced by the plan area of the meandering main channel and divided by the length of the reach being investigated. This gives the *representative floodplain width*, which is then added to the main channel by distributing it equally on either side. Water flowing over the floodplain is, as previously recognised by Greenhill and Sellin⁵ among others, influenced by the local floodplain gradient, whereas that flowing in the main channel is influenced by the main channel gradient. Lambert and Sellin estimated an average slope for a reach by weighting the floodplain gradient by the volume of water flowing over the floodplain and weighting the main channel slope by the volume of water flowing in the main channel region. The sum of these weighted slope values is then divided by the total volume of water in the channel reach to give the *average slope value*, S_{AV}

$$6 \quad S_{AV} = \frac{A_{mc}S_{mc}s_{mc} + A_{fp}S_{fp}s_{fp}}{A_{mc}s_{mc} + A_{fp}s_{fp}}$$

where A_{mc} and A_{fp} are the cross-sectional areas in the main channel and floodplain respectively, s_{mc} and s_{fp} are the sinuosities in these zones, and S_{mc} and S_{fp} are the main channel and floodplain gradients respectively.

Using this method, the inner channel and meander belt discharges can be estimated by any of the straight channel methods of discharge prediction with the appropriate modifications to allow for the additional roughness attributable to the sinuosity and for the use of the average floodplain width and slope parameters. The total discharge is obtained by the addition of this equivalent straight channel discharge to that obtained for the outer meander belt zones. Although many straight channel methods of conveyance prediction can be applied to the Lambert and Sellin approach, O'Sullivan¹⁸ determined that single-channel methods (SCMs), particularly at higher flow depths, predict discharges closest to the observed results. The momentum transfer process in a compound meandering channel, characterised by flow 'plunging' and 'ejection', tends to produce a more uniform velocity distribution over the whole channel cross-section, and consequently the assumption that the main channel and floodplain velocity are identical, inherent in SCMs, is more likely to be correct in meandering channel flows. This is supported by observations reported by Lambert and Sellin.¹ Furthermore, divided channel methods (DCMs) fail to account for the complex interactions that occur at the vertical and horizontal interfaces between subregions and which result in the creation of secondary circulations of sufficient magnitude to affect the discharge in the subdivisions. Consequently, subdivision methods can be expected to perform more successfully for low-sinuosity channels where such interactions are less significant and where the flow behaviour tends towards that of a straight channel.

3. EXPERIMENTAL ARRANGEMENTS

The reported experiments were undertaken at the UK FCF, HR Wallingford, England. The conception of the FCF was presented by Knight and Sellin¹⁹ and described as a large shallow tank, 56 m in length by 10 m wide, within which compound channels of specified slope, planform geometry and cross-sectional shape

can be built. Its large size and maximum discharge capacity of 1.08 m³/s facilitate the modelling of prototype rivers by making it possible to reproduce three-dimensional flows with significant momentum transfer between the main channel and floodplain flows. The meandering planform of the channel tested in this investigation consisted of two sine-generated curves defined by

$$7 \quad \theta = \theta_0 \cos\left(2\pi \frac{l}{L_m}\right)$$

where θ_0 is the crossover angle, θ is the angle to the main axis at any point on the sine wave, L_m is the path length of a full meander, and l is the path length to any point on the meander. This expression is generally accepted to represent the planform of a regular ideal river, and it closely approximates the shape of real river meanders.²⁰

The following relationship developed by Hey²¹ relating meander, L_m , to the bankfull width, B , was also used to define the planform

$$8 \quad L_m = 4\pi B$$

The channel was designed to have a sinuosity of 1.34, resulting in a 60° angle between the main channel centre line and the centre line of the FCF at their crossing point. Sinuosity is defined as the ratio of the curved channel length, the thalweg, to the equivalent valley length. The adopted planform incorporated two repeated meander units centred between entry and exit transition sections of a random sinuosity as shown in Fig. 3. This array of uniform meanders, although different from conditions found in nature, improves the reliability of results, and simulates experimental set-ups used by others.^{12,22} The main channel, or slot geometry of the meandering section, incorporated a trapezoidal cross-section with 45° sloping side walls and a top width of 1.6 m (Fig. 4). A flat or screeded sand bed, 0.2 m below the bankfull level, was in place along the entire length of the channel prior to the commencement of each experiment. The sand was a closely graded, uniform sediment with d_{50} and d_{90} values of 0.835 mm and 1.110 mm. Although the overall floodplain width was 10 m, all tests were carried out with a reduced floodplain width of 8 m by installing temporary longitudinal walls on the floodplain. This enabled a greater floodplain depth to be obtained for a given discharge, and allowed side access onto the facility without upsetting flow patterns. These walls had a vertical slope of 45°, giving the upper channel a trapezoidal cross-section. The floodplains had no cross-fall normal to the axis of the flume. Post-construction surveys showed the floodplain or valley slope of the meandering channel to be 1.8593×10^{-3} .

The measured reach was located between chainages 27 m and 37 m from the upstream flume end. This corresponds to cross-sections I to O in Fig. 3. For all experiments, data were collected relating to water surface slopes, inner channel and overbank velocities, sediment transport and bed formations. Water temperatures to ascertain fluid viscosity were also recorded. Full details of the flume operation and data collection processes were documented in Reference 23. The overbank test programme consisted of seven experiments with typical durations of 70–80 h to allow flume conditions to reach dynamic

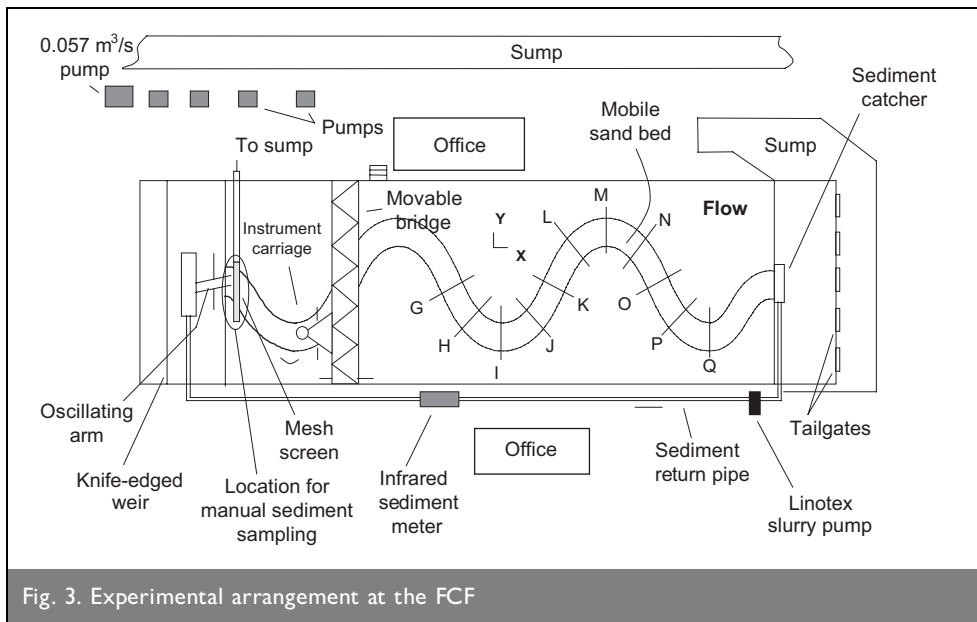


Fig. 3. Experimental arrangement at the FCF

combination of surface-penetrating and submerged elements that would be expected to become progressively flattened with rising overbank water depth. However, it allowed modelling of more severe growth conditions that result in greater water surface elevations along a river reach. Discharges of 0.175 m³/s, 0.250 m³/s, 0.350 m³/s and 0.600 m³/s, resulting in overbank depths ranging from 0.038 m to 0.178 m, were tested on roughened floodplains. Identical discharges, with the exception of 0.175 m³/s, were tested on smooth floodplains and resulted in overbank flow

depths that ranged from 0.042 m to 0.092 m. Flow data and boundary characteristics are summarised in Table 1.

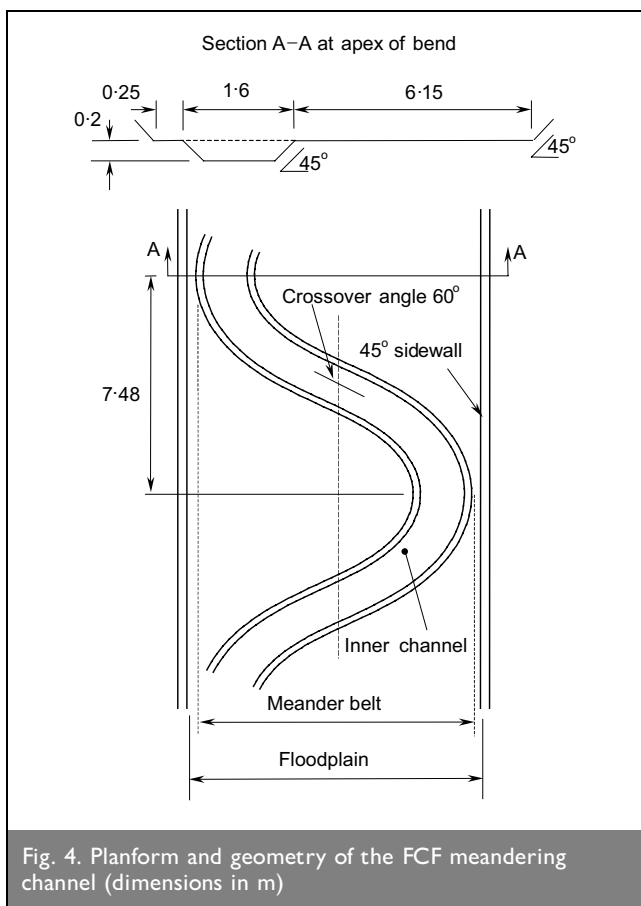


Fig. 4. Planform and geometry of the FCF meandering channel (dimensions in m)

4. BASIC RESISTANCE VALUES

The performance of any discharge prediction method is dependent largely on initial estimations of main channel and floodplain roughness. Much of the existing research has been carried out on relatively smooth, rigid boundary channels, and the smooth turbulent resistance law has provided accurate roughness estimations. With a mobile bed, however, flow characteristics and resistance values depend on flow conditions and sediment transport rates. These parameters are in turn strongly influenced by the bed configuration and its resulting roughness, and it is this dependence on such a large number of channel variables that contributes to the complicated nature of channel roughness, even under uniform flow conditions.

For the purposes of this paper the measured bankfull Manning's *n* value of 0.025 was used as the estimate of inner channel roughness. No distinction was made between the inner channel roughness values of the smooth and roughened floodplain channels, because the bedforms for each were assumed to contribute equally to the below-bankfull resistance. Although it is recognised that the bedform characteristics for these two

equilibrium. Four experiments were undertaken with roughened floodplains to simulate vegetation. This was achieved by means of a single configuration of vertical rods, 0.025 m in diameter, arranged in a regular rhomboidal pattern and held in place by frames that were above the water level (Fig. 5). Roughness elements were surface penetrating for all flow depths and covered the floodplain to a density of 12 rods/m². This system of roughening is not entirely representative of a natural floodplain, where vegetation would generally consist of a

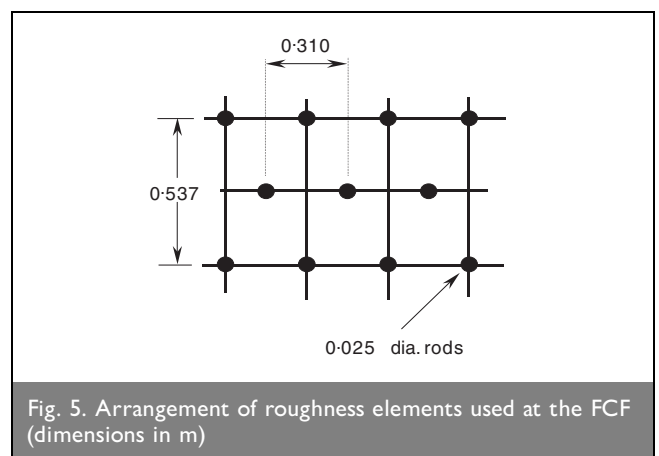


Fig. 5. Arrangement of roughness elements used at the FCF (dimensions in m)

Test No.	Q : m ³ /s	H : m	s	S_{fp}	Main channel boundary	Floodplain boundary
3	0.175	0.238	1.34	1.86×10^{-3}	0.835 mm sand	Rod roughness
4	0.250	0.265	1.34	1.86×10^{-3}	0.835 mm sand	Rod roughness
5	0.350	0.300	1.34	1.86×10^{-3}	0.835 mm sand	Rod roughness
6	0.600	0.378	1.34	1.86×10^{-3}	0.835 mm sand	Rod roughness
7	0.250	0.243	1.34	1.86×10^{-3}	0.835 mm sand	Smooth concrete
8	0.350	0.259	1.34	1.86×10^{-3}	0.835 mm sand	Smooth concrete
9	0.600	0.292	1.34	1.86×10^{-3}	0.835 mm sand	Smooth concrete

Table 1. Flow data and boundary characteristics for FCF Phase C meandering channel tests

floodplain channels differ, it is believed, in the absence of information to the contrary, that resistance values in this inner channel zone will be similar.

Floodplain resistance relationships are more straightforward, and in the case where the floodplains are unobstructed the smooth turbulent resistance law was used. This describes flow resistance in terms of the Darcy–Weisbach friction factor and Reynolds number as follows

$$10 \quad \frac{1}{\sqrt{f}} = C \log_{10}(Re\sqrt{f}) + D$$

where C and D are coefficients determined by Ackers²⁴ to have values of 2.02 and -1.38 respectively for the UK FCF. For the experimental work, where floodplain vegetation was simulated by surface-penetrating rods, the relationship by Ackers,²⁴ based on a developed set of formulae that allows for different numbers of rods in alternate rows, was used to calculate friction factors. Values of Manning's n predicted by the Ackers rod roughness method were found to be within $\pm 10\%$ of measured values for relative depths in the range $0 \leq D_r \leq 0.6$.¹⁸ In the case of the single-channel methods of the Lambert and Sellin approach, total channel friction factors were estimated using an equation in Ackers²⁴ similar to that developed by Horton²⁵ for channels of composite roughness. In this equation, the friction factors in the zones ($f_1, f_2, f_3, \dots, f_n$) comprising the single-channel section are weighted in terms of their wetted perimeters ($P_1, P_2, P_3, \dots, P_n$) such that, for the single-channel method, the total section friction factor, f_{total} , is defined as

$$11 \quad f_{total} = \frac{f_1 P_1 + f_2 P_2 + f_3 P_3 + \dots + f_n P_n}{P_1 + P_2 + P_3 + \dots + P_n}$$

where the geometry of the zones is governed by the nature of the division.

5. ANALYSIS OF RESULTS

Six discharge assessment methods developed for compound meandering channels formed the basis for comparison in this paper. These methods have been discussed in greater detail and are summarised as

- (a) the Greenhill and Sellin method⁵
- (b) the James and Wark method⁴
- (c) the Shiono *et al.* method⁶
- (d) the Rameshwaran and Willetts method⁸

- (e) the Lambert and Sellin method⁷: SCM with vertical divisions (SCM-V)
- (f) the Lambert and Sellin method: SCM with a horizontal division (SCM-H).

The results of these methods are compared with measured values obtained from orifice plate meters fitted in the pump delivery lines. Orifice plate meters were calibrated in accordance with BS 1042 part 3²⁶ and could measure discharges to an accuracy of $\pm 2\%$. The accuracy of the tested methods is determined in two ways. First, errors in predicted discharge for individual flows, Q_{error} , are calculated using the following equation

$$12 \quad Q_{error}(\%) = \left(\frac{Q_c - Q_m}{Q_m} \right) \times 100$$

where Q_c and Q_m are the calculated and measured discharges respectively. Second, in order to examine the efficiency of each method over the full depth range for which data are available, the root mean square error (E_{RMS}) was calculated for each data set from the following expression

$$13 \quad E_{RMS} = \sqrt{\frac{E_1^2 + E_2^2 + E_3^2 + E_4^2 + \dots + E_N^2}{N}}$$

where E_1, E_2, E_3 , etc. are the measured errors calculated from equation (12), and N is the total number of observations.

6. PREDICTIONS FOR SMOOTH FLOODPLAIN CHANNELS

The variations of predicted discharge with relative depth for the smooth floodplain tests are shown in Fig. 6, and the percentage errors for these data are displayed in Fig. 7. The solid lines in Fig. 6 represent measured values.

The predicted discharges for the smooth floodplain data in Fig. 6 show that all methods, with the exception of the Rameshwaran and Willetts method, overestimate the measured discharges by varying degrees. Although the extra resistance of the mobile sand bed is accounted for in the initial assumption of the bankfull or main channel friction parameter, the additional main channel and floodplain interaction and associated energy losses that arise with the presence of bedforms are not fully allowed for, and positive errors in predicted discharges are obtained. Although Fig. 6 shows the Greenhill and Sellin method to be most accurate for the examined data set, Fig. 7 shows that the errors in this method increase with depth, and above relative depths of 0.3, where the error is in the region of

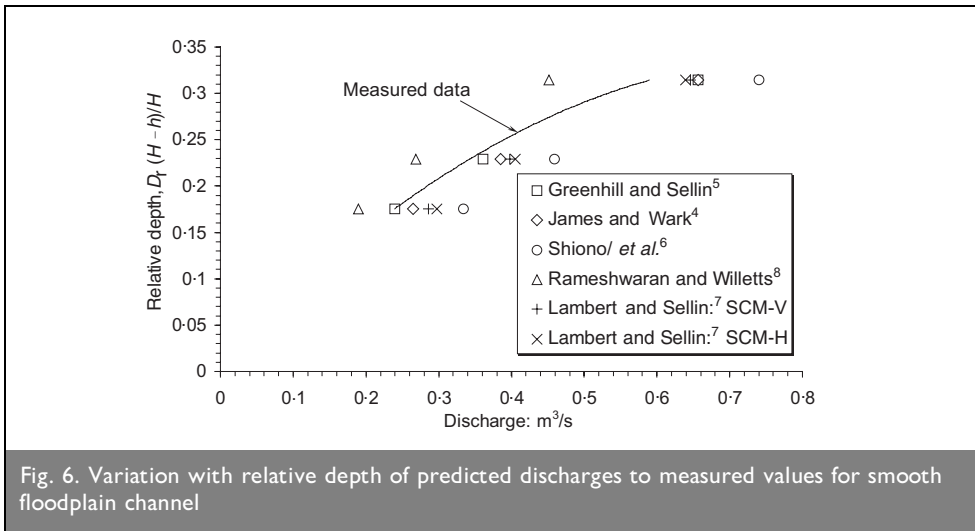


Fig. 6. Variation with relative depth of predicted discharges to measured values for smooth floodplain channel

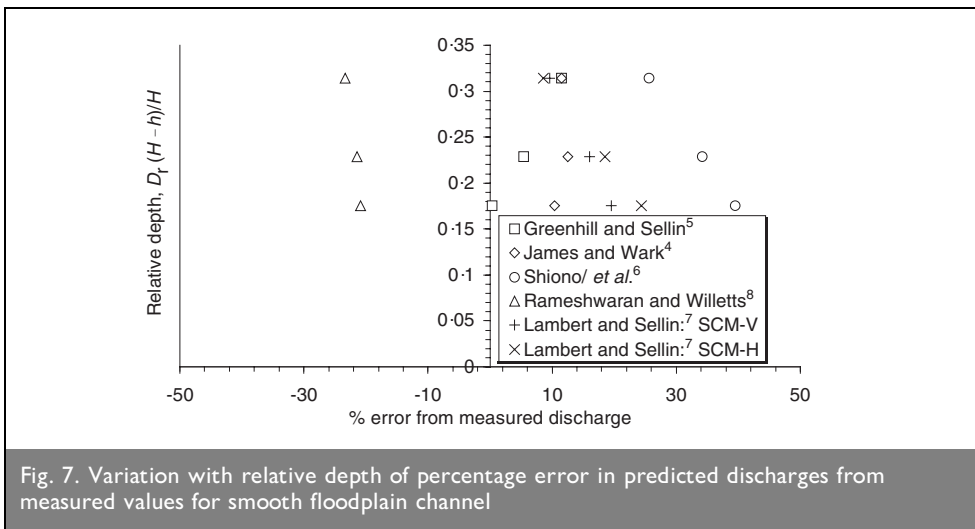


Fig. 7. Variation with relative depth of percentage error in predicted discharges from measured values for smooth floodplain channel

10%, different methods for this floodplain configuration could be more appropriate. The deteriorating accuracy of this method with depth results from the failure to account for the flow interactions, which become more vigorous with increasing discharge and velocity, at the interface of the main channel and the floodplain and between the meander belt and outer-meander belt zones. Calculated errors for the James and Wark method show little variation with depth, and overestimate the measured discharge by approximately 12%. Although the performance of this method is consistent for this channel, large variations in standard deviations for low- and high-sinuosity channels have been reported that suggest limitations to the use of this method.⁶

Differences between the predicted stage–discharge relationships and the experimental values for the single-channel approaches of the Lambert and Sellin method are most pronounced in the lower depth range, but as the velocity profiles become more uniform with increasing depth, calculated values tend towards measured values. The deficiencies of the Shiono *et al.* method, in which no facility is included to account for the increased resistance of the mobile bed, are highlighted in Fig. 7, where, although errors decrease from 40% to 26% over the relative depth range $0.175 \leq D_r \leq 0.314$, they are still excessively high for this method to be useful for this type of channel. Similarly,

errors in excess of 20% for the full range of flow depths to which the Rameshwaran and Willetts method was applied render it inappropriate for discharge prediction in compound meandering channels with geometrical and boundary roughness characteristics similar to those being reported.

The root mean square errors for the smooth floodplain data displayed in Table 2 confirm that, over the full range of depths tested, the Greenhill and Sellin and James and Wark methods, whose E_{RMS} values are 7.3 and 11.5 respectively, perform best.

7. PREDICTIONS FOR ROUGHENED FLOODPLAIN CHANNELS

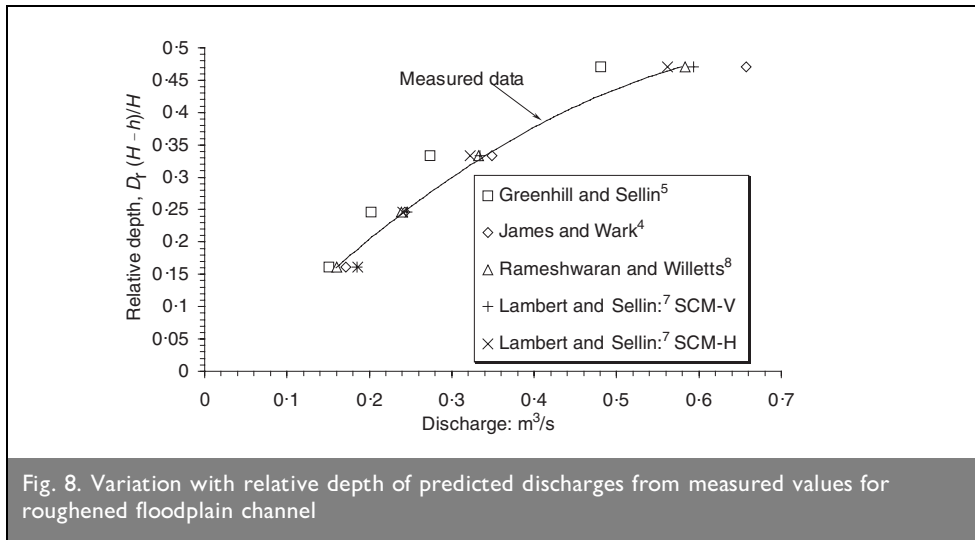
The predicted stage–discharge results and associated errors for the roughened floodplain test case are shown in Figs 8 and 9. Measured values are again represented by solid lines in Fig. 8.

Comparison between the measured and predicted dis-

charges shows that results for the roughened floodplain channel differ from those obtained for the smooth floodplain channel. The overall accuracy of the James and Wark, Rameshwaran and Willetts and Lambert and Sellin methods improves with the presence of roughened floodplains. Rather than being overestimated, predicted discharges through the depth range tend to be close to measured values, which suggests in some way that the presence together of a mobile bed and a roughened floodplain enhances the momentum transfer processes in compound meandering channels. The performance of the Greenhill and Sellin method is adversely affected by the presence of the floodplain roughness, but since

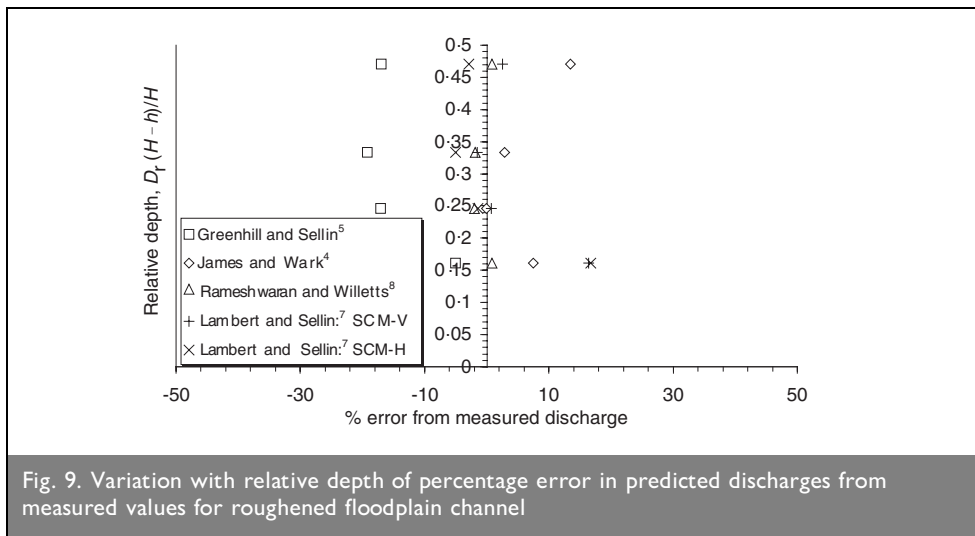
Assessment method	E_{RMS}
Greenhill and Sellin ⁵	7.329
James and Wark ⁴	11.498
Shiono <i>et al.</i> ⁶	33.601
Rameshwaran and Willetts ⁸	21.945
Lambert and Sellin: ⁷ SCM-V	15.627
Lambert and Sellin: ⁷ SCM-H	18.358

Table 2. E_{RMS} values of discharge prediction methods for smooth floodplain channel



channel is acted on by the local floodplain gradient, whereas that flowing in the main channel is under the influence of the main channel gradient. As there is considerable interaction between these bodies of water, it is likely that a significant proportion of floodplain water in the meander belt zone of a compound section is influenced to some degree by the main channel flow. Consequently, the velocity and hence discharge of the floodplain flow could be modelled more correctly by using an average slope (the value of which is between the main channel and valley slopes) for the discharge calculations in the floodplain meander belt zone.

Figures 10 and 11 show non-dimensionalised ratios of predicted inner channel and overbank discharges obtained from applying the James and Wark method to observed discharges. Observed discharges in these zones were obtained from integration of point velocities recorded from a two-dimensional Nortek ultrasonic velocity probe.



this method is based primarily on the smooth floodplain Phase B data set, its performance in this case is not surprising.

As was the case with the smooth floodplain data, the accuracy of the Lambert and Sellin methods improves with depth such that errors from measured discharges are within 30% at a relative depth of 0.47. Although the James and Wark method is reasonably accurate over the observed depth range, it deteriorates above relative depths of approximately 0.3, where over-estimated discharges and underestimated stages are determined. Discharge values obtained using the Rameshwaran and Willetts method are remarkably accurate when applied to the rod-roughened channel tested at the FCF.

Root mean square errors of 7.9, 8.4 and 8.9 in Table 3 show that, for the roughened floodplain channel, the James and Wark method and the two approaches of the Lambert and Sellin method perform consistently well for all depths. The Rameshwaran and Willetts method, however, with an E_{RMS} value of approximately 1.5, performs most accurately for the Phase C FCF channel with dowel-roughened floodplains.

8. MODIFIED JAMES AND WARK DISCHARGE ASSESSMENT METHOD

Water flowing over the floodplain of a compound meandering

Insufficient data were available to distinguish discharges in the meander and outer meander belt zones, and consequently only a total overbank flow value was obtained. Identical observed and predicted discharge values in these zones would be represented by ratio values of unity.

Note that although errors are inherent in the determination of zonal discharges from the integration of point velocities, particularly in mobile-bed channels where migrating bedforms in the vicinity of sampling locations can result in the measurement of erroneous velocities, the data in Figs 10 and 11 highlight where the deficiencies in the method exist and where improvement may be made. From these, it appears that the

Assessment method	E_{RMS}
Greenhill and Sellin ⁵	15.583
James and Wark ⁴	7.852
Rameshwaran and Willetts ⁸	1.466
Lambert and Sellin: ⁷ SCM-V	8.362
Lambert and Sellin: ⁷ SCM-H	8.883

Table 3. E_{RMS} values of discharge prediction methods for roughened floodplain channel

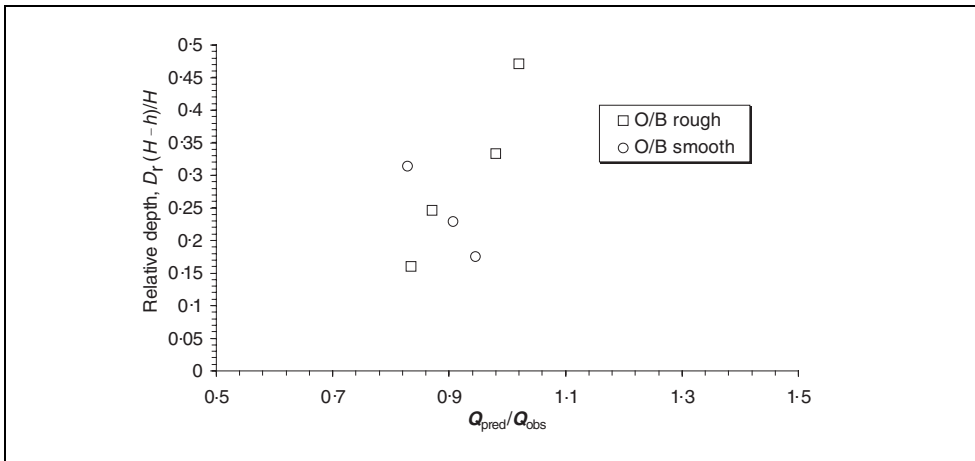


Fig. 10. Comparison of predicted inner channel discharges from the James and Wark method with observed values

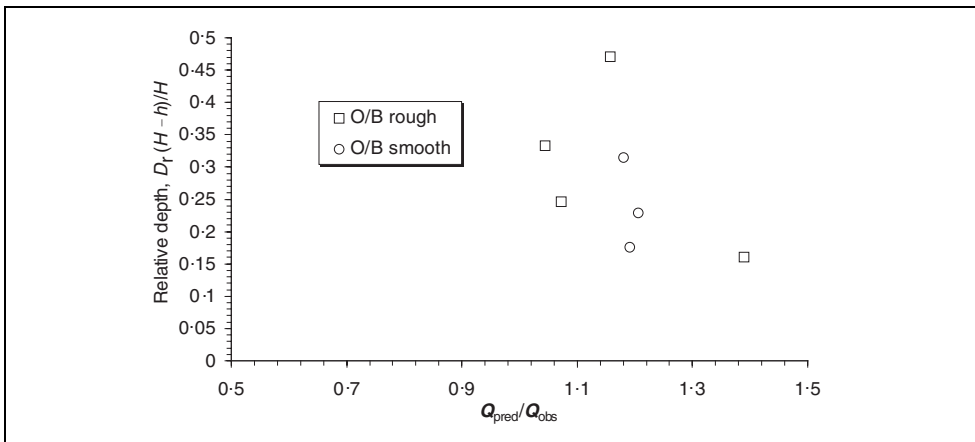


Fig. 11. Comparison of predicted overbank discharges from the James and Wark method with observed values

James and Wark method generally underestimates discharge in the inner channel (zone 1) and overestimates it in the overbank zone (meander and outer meander belt zones or zone 2 + zone 3 in Fig. 2).

The existing James and Wark method uses the following expression to define the flow velocity in the meander belt zone

$$V_2 = \left[\frac{2gS_{fp}L_m}{(F_2L/4R_2 + F_1F_2K_e)} \right]^{1/2} \quad (14)$$

where S_{fp} is the floodplain or valley slope, L_m is the meander wavelength, and F_1 , F_2 and K_e are factors in the method to allow for various sources of energy dissipation. By assuming that this velocity acts over the meander belt area, the discharge in this zone is calculated from the principle of flow continuity. It is clear from equation (14) that the introduction of a slope value of smaller magnitude would reduce the value of V_2 and hence the discharge in the meander belt. It is reasonable to assume that, as the depth of the floodplain flow increases, the proportion of the meander belt flow under the influence of the valley slope also increases, and therefore an arbitrary or standard average of the main channel and floodplain slopes that remains constant with increasing stage would be inap-

propriate. Consequently, the average or weighted slope of the type developed by Lambert and Sellin,⁷ defined previously in equation (6), is used.

By applying slope values obtained from equation (6) to equation (14), discharges were recalculated for the mobile-bed tests undertaken at the FCF as part of the Phase C meandering programme. Note that this modification has no effect on the discharge calculation in the inner channel or in the outer meander belt zones, and these are determined as per the original method.

The modified results for the smooth and rough floodplain test cases are plotted against relative depth in Fig. 12. Measured data are represented by solid lines.

Using this average slope, S_{AV} , for the overbank zone reduces the total discharge predicted by the method, and—as was shown in Figs 6 and 8 for the original method—a reduction in discharge for both the smooth and the roughened

floodplain configurations was required. Although Fig. 13 shows that errors in predicted discharges are not necessarily reduced for all flows, the improved accuracy of the modified method is reflected in the root mean square errors in Table 4, which show reductions of approximately 56% and 35% for the smooth and rough floodplain test cases respectively.

The improvement in predicted discharges made by this modification to the James and Wark method is not limited to mobile-bed channels. By applying the revised theory to a selection of fixed-bed data obtained from a channel of similar geometry tested as part of the Phase B FCF programme,⁴ O'Sullivan¹⁸ observed improvements in the overall accuracy of the method when the modification was included. The concept presented in this modification could be equally applied to other discharge assessment methods, but it was incorporated in the James and Wark method owing to the rigorous attempts of this method to quantify energy dissipation in compound meandering flows. Furthermore, its reasonable overall performance for the two floodplain configurations examined suggested that its application to this method would be most successful.

9. CONCLUSIONS

The performance of six discharge prediction methods developed for overbank flows in compound meandering channels with

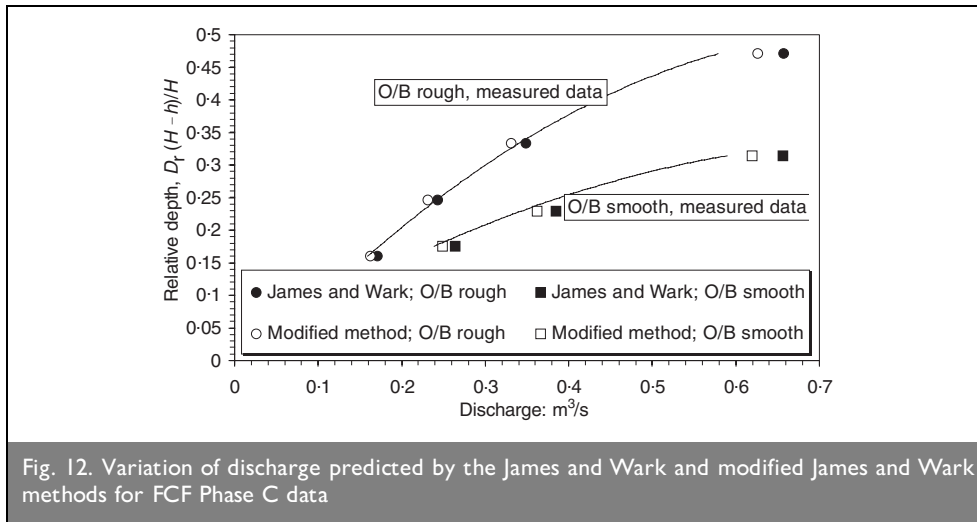


Fig. 12. Variation of discharge predicted by the James and Wark and modified James and Wark methods for FCF Phase C data

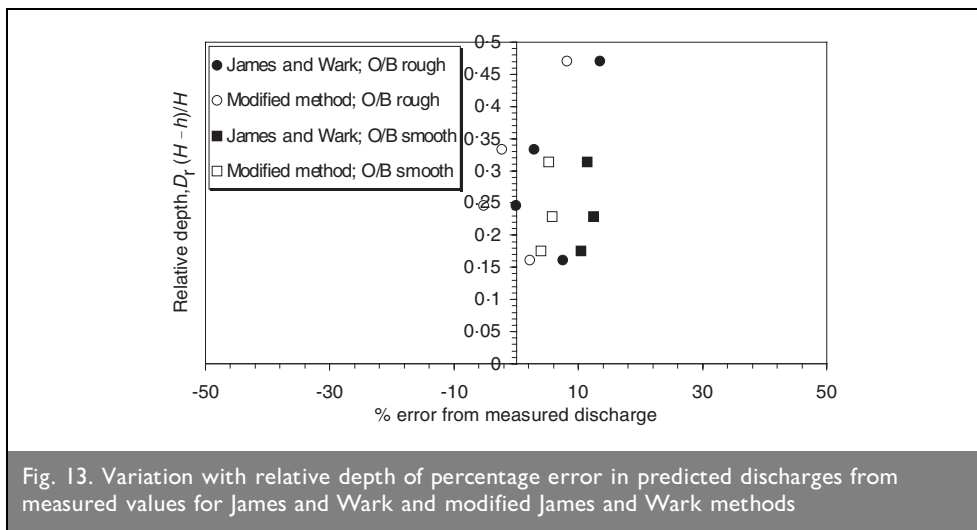


Fig. 13. Variation with relative depth of percentage error in predicted discharges from measured values for James and Wark and modified James and Wark methods

Method	E_{RMS} , O/B smooth	E_{RMS} , O/B rough
James and Wark method	11.498	7.852
Modified James and Wark method	5.073	5.119
Improvement in E_{RMS} values: %	55.9	34.8

Table 4. E_{RMS} values for the James and Wark and modified James and Wark discharge assessment methods

mobile beds of uniform sand has been reported. The principal conclusions are as follows.

- The presence of a very rough main channel, such as may occur with a mobile main channel bed, results in additional complexity, which has an adverse effect on discharge prediction methods.
- The accuracy of the methods is dependent on the boundary roughness, and none of the methods performs consistently well for both the rough and the smooth flow configurations. Furthermore, the deviation of predicted discharges from measured values varies with depth, and where a particular estimation method performed well over a depth

range, its performance at different flow depths was often inferior to that of other methods.

- For the geometries reported in this research, the Greenhill and Sellin and James and Wark methods estimated discharge most successfully for the smooth floodplain channel. When surface penetrating dowels were added to the floodplain, the Ramashwaran and Willetts and James and Wark methods proved most accurate.
- A modification to the James and Wark discharge assessment method, in which a weighted average water surface slope was used in the calculation of over-bank discharges, resulted in considerable improvements in the accuracy of the method over a wide range of flow depths.

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