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Overbank flow depth prediction in alluvial compound channels

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Algorithms based on simple one-dimensional stage–discharge models for compound channels have been developed and tested for overbank flow data from the UK Flood Channel Facility and the University of Ulster channel with straight and meandering planforms. The proposed divided resistance approach takes into account the grain resistance, the bed form resistance and the roughness characteristics of the floodplain but it was found to give unsatisfactory prediction of the flow depth for compound channels with rough floodplains. A simple algorithm for stage–discharge prediction based on a lumped resistance approach was then proposed. It requires calibration of the overbank Manning *n* for a relative depth zero and a coefficient of proportionality, and this is achievable if measurements of the flow depth and velocity are taken for at least three overbank flow discharges. The application of the lumped approach to various flume and field data showed good agreement between the measured and predicted flow depths.

NOTATION

A	cross-sectional area (m^2)
b	coefficient of proportionality
D_x	particle diameter such that x% is finer (m)
d	flow depth (m)
f	friction coefficient
g	gravitational acceleration (m/s^2)
h	bed form height (m)
k_s	equivalent roughness (m)
L	bed form length (m)
n	Manning n ($s/m^{1/3}$)
n^*	dimensionless Manning n parameter
P	wetted perimeter (m)
Q	water discharge (m^3/s)
q_t	sediment discharge
R^2	coefficient of regression
r	discrepancy ratio
S	channel slope
s	channel sinuosity
V	mean velocity (m/s)
Y	relative depth, $Y = (d - d_b)/d$
Y^*	relative depth parameter, $Y^* = YD_{50}^{1/6}/(g^{1/2}n_{tb}s)$
ν	kinematic viscosity (m^2/s)
σ	geometric standard deviation

Subscripts

b	bankfull
c	main channel
fp	floodplain
p	predicted
t	total cross-section

Superscripts

+	parameters determined experimentally

1. INTRODUCTION

The estimation of flow depth corresponding to a certain flow discharge is a common task for river engineers and the accurate prediction of the stage for overbank flows is very important as this issue is related directly to flood risk mitigation. While the procedure for estimation of the stage–discharge relationship for inbank flows is conventional, it becomes more difficult when flow goes overbank. The accuracy of estimations of overbank stage–discharge curves and the subsequent assessments of low, moderate and significant floodplain flood risk affect the drawing up of flood risk maps, property insurance premiums, floodplain property values, infrastructure location, planning requirements and floodplain land use.

The single channel method (SCM) and the divided channel method (DCM) are known to predict the flow depth in compound channels inaccurately.[1] A number of modifications to the DCM, which improve predictability of the stage–discharge, have been suggested.[1–6] Even though a particular approach may perform well in predicting the total channel discharge for a given stage, it may not necessarily imply that the method is soundly based.[7] The coherence method developed by Ackers[4,5] uses different adjustment factors for four different regions of overbank depth and it is established as one of the one-dimensional (1-D) approaches, which gives best results for overbank flow. All the methods mentioned above are applicable to straight compound channels only.

When the river planform is meandering, the complexity of the stage–discharge prediction increases because of the extensive three-dimensional (3-D) mixing of main channel and floodplain flows, resulting in significant lateral variation in main channel bed level and depth-averaged velocity.[8] Among the methods for overbank conveyance prediction of meandering compound

channels are those proposed by James and Wark,[9] Greenhill and Sellin,[10] Shiono *et al.*,[11] Rameshwaran and Willets,[12] and James and Myers.[13] Improvement of the stage–discharge predictability can be achieved by using two-dimensional (2-D) and 3-D models. One of the most crucial and problematic areas of 2-D and 3-D modelling is the calibration of the model and establishing appropriate values of model parameters.[14] While the 2-D models are expected to be used routinely for flood inundation problems in the near future, the 3-D modelling of river or channel flows is still predominantly a research tool and significant investigation and validation needs to be undertaken before its use becomes routine.[15]

Summarising the required future work on reducing uncertainty of river flood conveyance estimation in 1-D models, Knight[7] noted the necessity of development of simple stage–discharge methods for use on spreadsheets. The algorithm presented here uses simple 1-D stage–discharge models and can be incorporated easily into conventional data processing software.

2. EXPERIMENTAL PROCEDURES

Experimental work was undertaken in the UK Flood Channel Facility (FCF) at HR Wallingford and in the Ulster channel (UC). All tests were conducted in channels incorporating a mobile uniform sand bed with D_{50} of 0·835 mm for the FCF and 0·890 mm for the UC. Overbank flows with both smooth (OBS) and artificially roughened floodplains (OBR) were studied. Particular care was provided to ensure that steady, uniform flow was obtained and that bed load rates were in dynamic equilibrium for the duration of all tests.

The large-scale FCF channel was 8·0 m wide in total. The main channel was trapezoidal with top width of 2·0 m for the straight channel experiments and 1·6 m for the meandering channel experiments with sinuosity 1·34. The bankfull depth was 0·20 m. For the straight channel experiments a water surface slope of 0·00183 was used. For meandering channel experiments the average water surface slope was 0·00186. The facility recirculated both sediment and water. The sediment transport rate measurements were taken by a previously calibrated infrared meter placed in the sediment return pipe.

The overall width of the small-scale UC was 1·89 m and the central channel had a top width of 0·5 m. For the straight channel experiments a water surface slope of 0·00183 was used. For the meandering channel experiments sinuosities of 1·34 and 1·17 were tested. The tests for the 1·17 sinuosity UC were undertaken in two phases, with valley slopes of 0·00186 and 0·0025.
The channel was filled with sediment to a depth of 0·05 m below the floodplain. The UC only recirculated water and not sediment, so a sediment feeder was provided to keep the bed in dynamic equilibrium. The sediment feeder was calibrated to relate the variable speed dial to actual sediment discharge.

The FCF and the UC experiments with straight and meandering planforms have been previously described by Brown,[16] Cassells[17] and O'Sullivan.[18]

3. ALGORITHM FOR STAGE–DISCHARGE PREDICTION

Accurate prediction of flow depth requires an appropriate model for stage–discharge prediction and quality experimental data for river cross-sectional geometry, water discharge, slope, bed roughness and so on. One of the most important issues is to determine resistance coefficients. There is no theoretical relationship between flow depth and the resistance coefficients valid for overbank flow. Such a relationship can only be developed by using calibration methods. Some empirical stage–discharge relationships have been previously suggested.[1,2,19,20]

The algorithm presented here requires at least the discharge, $\boldsymbol{Q}$, the channel slope, S, the grain size, D, and the variation of the channel geometric characteristics with flow depth (cross-sectional area A, wetted perimeter, P) as input variables. The algorithm uses equations with wide application in hydraulic engineering practice and the method of calculation depends on the measured parameters available. The flow depth is found by an iteration procedure solving the continuity equation and the Manning or the Darcy–Weisbach uniform flow equations.

The average flow velocity is calculated using the continuity equation for an assumed depth and the predicted total flow velocity is calculated using the Manning or Darcy–Weisbach uniform flow equations. Thus, a resistance equation is necessary to determine the resistance coefficient (n or f) accurately. In the development of the algorithm two approaches have been applied: the divided resistance approach and the lumped resistance approach.

3.1. Divided resistance approach

The complexity of flow resistance in meandering compound alluvial channels arises from the large number of sources of energy loss and the difficulty of quantifying each source independently. The energy losses owing to interaction between the subsections are not considered separately in the algorithm presented herein. Flow resistance in the main alluvial channel is divided into grain resistance and resistance owing to bed forms, following the approaches developed by Einstein and Barbarossa[21] and White *et al.*,[22] among others.

The proposed algorithm uses the DCM to predict flow depth corresponding to a given discharge for overbank flows in straight and meandering channels. Most methods for discharge prediction in meandering channels assume a horizontal interface between the inner channel and the floodplains but are developed using data from channels with non-movable beds. Wormleaton *et al.*[23] found that vertical interfaces provide a sound basis from which to develop a discharge calculation method for meandering channels with mobile beds especially in the case of roughened floodplains.

For the alluvial main channel, the equivalent roughness is due to the grain roughness and the roughness is due to bed forms, and the equivalent roughness, k_s, was determined using the Van Rijn method.[24] Alternatively, the friction factor can be calculated as a sum of the grain friction factor and the friction factor due to bed form. The latter can be determined using the Engelund,[25] Vanoni–Hwang,[26] or other bed form resistance formulae found in the literature.

For the floodplain section, where bed forms do not usually occur, the roughness depends on the surface of the floodplains. For the studied flumes, values of the floodplain roughness depend on the material of the flume and the roughness elements used. For natural channels, the floodplain surface, the vegetation and

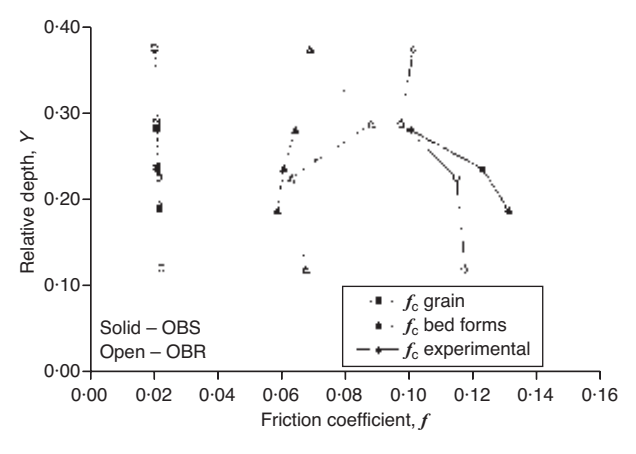

Fig. 1. Friction factor plotted against relative depth for the FCF

the man-made objects should be considered. The absolute roughness height is calculated from the total floodplain roughness using the Colebrook–White equation.

The friction coefficient, ***f***, is calculated separately for the main channel and the floodplain sections using the Colebrook–White equation, as suggested in the conveyance estimation system.[27] For meandering channels, the friction coefficient is corrected by applying the linearised soil conservation service method.[28]

The total discharge is calculated as the sum of the subsection discharges. If the error between the calculated and the measured flow discharge is more than 0·01%, a new value of the flow depth, d, is assumed.

In order to implement the calculation procedure the subsection discharges and the bed form dimensions are necessary. It is preferable to have the experimental main channel discharge but these data are not often available. When mean main channel velocity is not experimentally determined, a velocity prediction method is necessary. The algorithm suggests the use of a velocity prediction method proposed by Karamisheva *et al.*[29,30] for calculation of the mean main channel velocity. This method assumes that the variation of the main channel Manning n with relative depth, for the channel in consideration, has been determined.

The flow resistance due to bed forms represents a significant part of the total friction factor (Fig. 1). Thus, the accurate prediction of the geometric characteristics of the bed forms is an essential part of estimating the flow resistance and the consequent flow conditions. Bed form geometry in alluvial channels has been investigated intensively in recent decades. Comparisons between different bed form prediction methods applied to the FCF data have been reported previously by Karamisheva *et al.*[31] The Karim[32] and Julien and Klaasen[33] formulae gave best prediction for the bed form height in the FCF and UC. The results for the predictive capability for these methods are given in Table 1. The flowchart for the divided resistance approach for flow depth calculation is shown in Fig. 2.

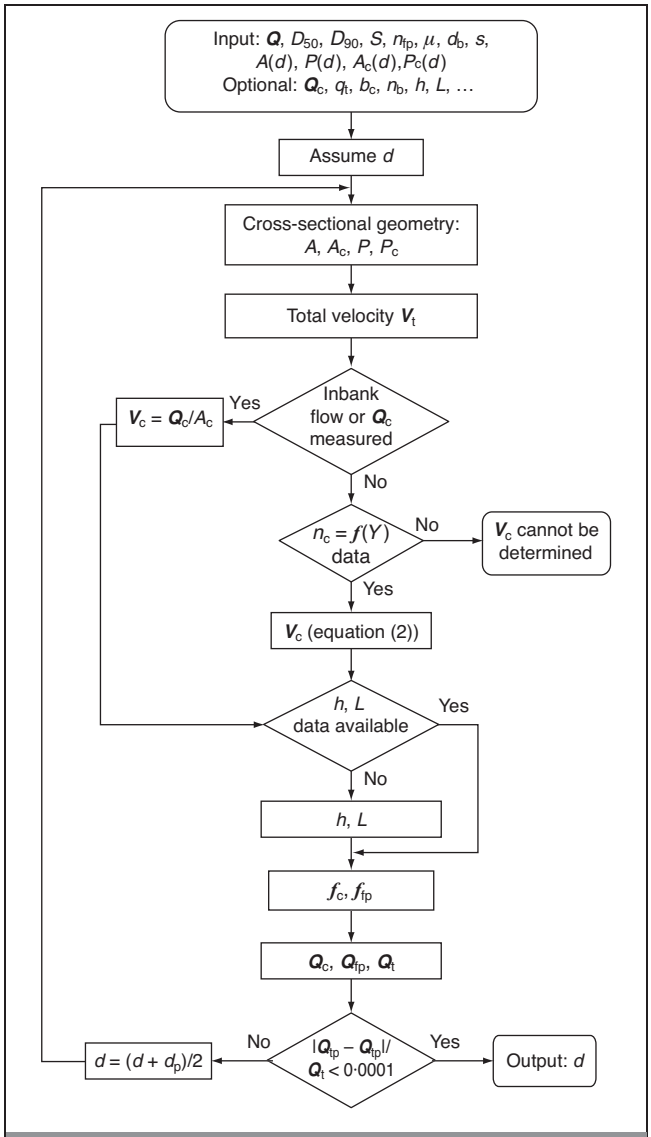

Fig. 2. Flowchart of the divided resistance approach for flow depth calculation

3.2. Lumped resistance approach

The Manning formula was applied to the whole cross-section to calculate the Manning n values for different overbank flow depths from the experimental mean cross-section velocities measured at the FCF and the UC. The total channel Manning n increased with the depth (Fig. 3). Such dependence has been observed previously.[19,34–36]

Statistical parameter	r	r	r	Percentage of r in range 0·8–1·25	Percentage of r in range 0·5–2·0
Bed form formula	FCF	UC	Overall	Overall	Overall
Karim[32]	1·29	0·96	1·23	56%	96%
Julien and Klaasen[33]	1·06	1·28	1·09	68%	100%

Table 1. Comparisons between predictive capability of the Karim and Julien and Klaasen bed form prediction methods

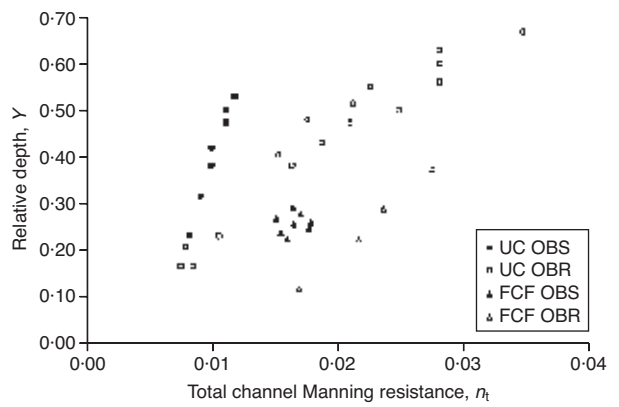

Fig. 3. Manning n plotted against flow depth for the UC with straight planform

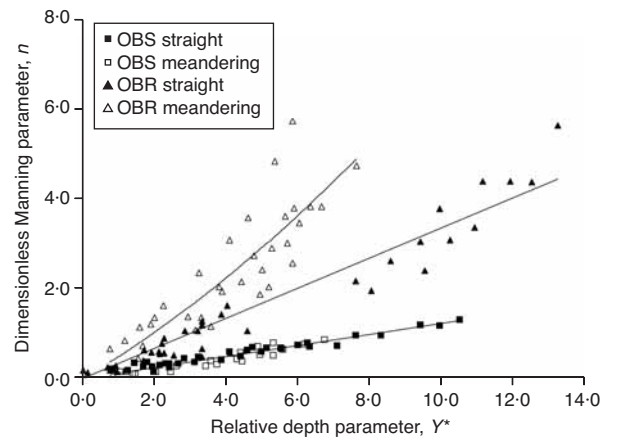

Fig. 4. Dimensionless Manning n plotted against relative depth parameter

In order to predict the flow depth for a given flow discharge, a prediction equation for the total channel Manning n is required. The relationship between the relative depth, Y, and Manning n, proposed earlier[29,30] for prediction of the main channel Manning n, was applied to the whole cross-section

$$n_{tp} = n_{tb} + bY\frac{D_{50}^{1/6}}{g^{1/2}s} \quad (1)$$

where n_{tp} is the predicted total channel overbank Manning n, Y is the relative depth defined as the ratio between the floodplain depth and the total flow depth $[Y = (d - d_b)/d]$, n_{tb} is the total channel overbank Manning n for relative depth $Y = 0$, D_{50} is the mean grain size on the main channel bed, s is the channel sinuosity and b is a coefficient of proportionality. The coefficient of proportionality, b, expresses how the Manning n value changes with the relative depth and it depends on the channel sinuosity and floodplain roughness. It can be determined by using regression analyses.

In dimensionless form the equation can be presented as

$$n^* = bY^* \quad (2)$$

where

$$n^* = \frac{n_{tp} - n_{tb}}{n_{tb}} \qquad Y^* = Y\frac{D_{50}^{1/6}}{g^{1/2}n_{tb}s} \quad (3)$$

The general tendency is for the dimensionless Manning's parameter, n^*, to increase with relative depth during lower (dune–ripple) flow regime. The total channel overbank Manning n for a relative depth $Y = 0$, n_{tb}, depends on the main channel grain size, floodplain roughness and the channel sinuosity.

A regression analysis was used to assess the relationship between the dimensionless Manning parameter, n^*, and relative depth dimensionless parameter, Y^*, using data obtained at the FCF, the UC, the laboratory flume at the University of Birmingham (BC)[37] (data also in www.flowdata.bham.ac.uk) and the River Main.[38,39] Statistical t-tests showed that there is a difference between the slopes of the regression lines for channels with different types of floodplains (smooth or rough) and for channels with different planforms (straight or meandering) for overbank flow with rough floodplains. The t-tests showed that there is not a significant difference between the slopes of the regression lines for straight and meandering channels when the floodplains are smooth. The data were separated into three groups: straight and meandering OBS (54 observations at the FCF, the UC and the BC), straight OBR (38 observations at the FCF, the UC and the River Main) and meandering OBR (34 observations at the FCF and the UC). The regression analyses showed that there is a regression between the dimensionless Manning n parameter, n^*, and relative depth–particle diameter parameter, Y^* (Fig. 4). The results obtained from the regression analyses are presented in Table 2. For meandering channels with rough floodplains the relationship between n^* and Y^* is a polynomial of second order rather than linear and the scatter of the data suggests that other parameters should be considered or that the regression coefficients should be determined separately for a particular data set.

The flowchart for the lumped resistance approach for flow depth calculation is shown in Fig. 5.

4. RESULTS AND DISCUSSION

4.1. Results

In order to compare the experimental measurements with the computed results, the discrepancy ratio, r, between predicted and measured flow depth and the standard deviation of the discrepancy ratio values, σ, were used. The overall results for the

Flow	Planform	R^2	F/t	Equations
OBS	Straight/meandering	0·919	<0·001	$n^* = 0{\cdot}128Y^*$
OBR	Straight	0·923	<0·001	$n^* = 0{\cdot}354Y^*$
OBR	Meandering	0·749	<0·001	$n^* = 0{\cdot}023Y^{*2} + 0{\cdot}500Y^*$

Table 2. Summary of the results of the regression between dimensionless Manning's n and relative depth parameter

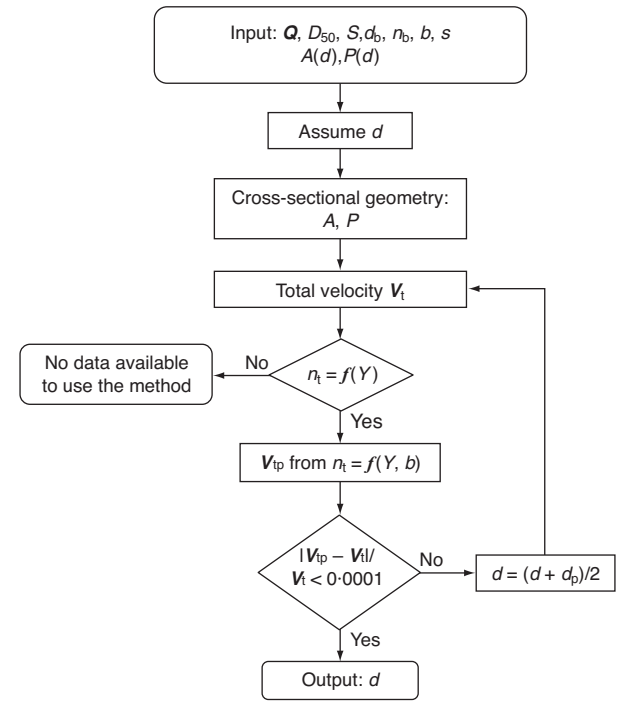

Fig. 5. Flowchart of the lumped resistance approach for flow depth calculation

Planform		Lumped approach $V_t = f(b, Y)$	Divided approach	
			V_c known	V_c predicted
Straight	r	1·00	1·01	1·07
	(σ)	(0·08)	(0·09)	(0·19)
Meandering	r	1·00	1·07	1·06
	(σ)	(0·08)	(0·17)	(0·15)
Overall	r	1·00	1·05	1·06
	(σ)	(0·08)	(0·15)	(0·17)

Table 3. Accuracy of the stage–discharge prediction methods

flow depth predicted by the divided and lumped resistance approaches are summarised in Table 3. The graphical presentation of the results for overbank flows in the FCF and the UC with straight and meandering planforms is given in Figs 6–9.

The divided resistance approach used with a known mean main channel velocity gave good prediction of the flow depths for some data sets. For other data sets, it underestimated the flow depth for high overbank flow and overestimated it for low overbank flow. The method gave an average discrepancy ratio of 1·01 and a standard deviation of 0·09 for straight channel experiments, but the overall discrepancy ratio was 1·05 and the standard deviation was high (0·15). The use of the main channel velocity predicted by the method proposed earlier[29,30] led to similar overall results. The divided channel approach used with the DCM and following the procedure described above did not give an accurate prediction of the flow depth.

The lumped resistance approach used with the proposed method for velocity prediction gave very good predictions for the flow depth. When the regression coefficients obtained separating the data into three groups were used, the average discrepancy ratio was 1·00 and the standard deviation was 0·08. The highest discrepancies were observed for high depths at the straight UC during inbank flow and overbank flows with rough floodplains, and for the FCF with meandering planform and rough floodplains.

4.2. Sensitivity analysis

A sensitivity analysis was performed to determine the relative significance of the input parameters. Flow depth was recalculated for 25% and 50% decrease and increase of the channel slope, S, and the grain size, D. For the lumped resistance approach overbank Manning n for relative depth $Y = 0$, n_{tb}, the parameters, b, and channel sinuosity, s, were also investigated. Influence of the floodplain Manning coefficient, n_{fp}, and bed form height, h, were considered for the model using the divided resistance approach. In Figs 10 and 11, the ratios between the calculated flow depths for altered parameters, d, and the calculated flow depths for the experimentally determined parameters, d^+, are shown. The grain size has very little influence upon the flow depth. Change of the slope, S, by 50% results in 17% average change of the calculated flow depth for the lumped resistance approach. The divided resistance approach is less sensitive to the slope and change of the slope by 50% results in 8% change of the flow depth. The divided resistance approach is most sensitive to changes in the Manning n value: an increase of n_{fp} by 50% results in 18% change in the flow depth. The sensitivity of the lumped resistance approach to changes in Manning n and the coefficient b is very pronounced: change of these parameters by 50% leads to an

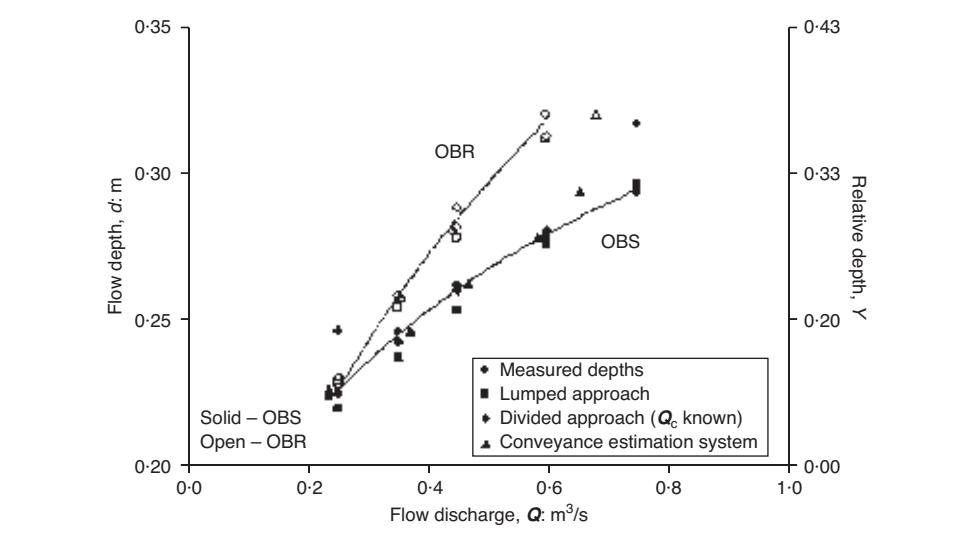

Fig. 6. Flow depth plotted against discharge for the FCF with straight planform

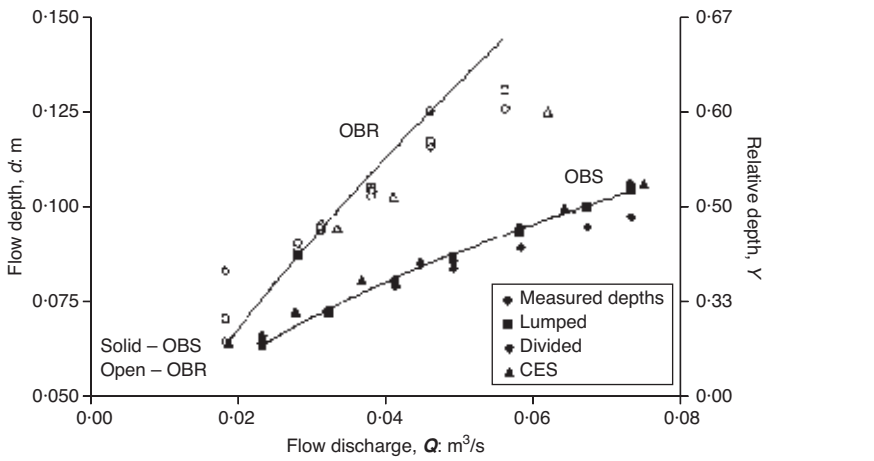

Fig. 7. Flow depth plotted against discharge for the UC with straight planform

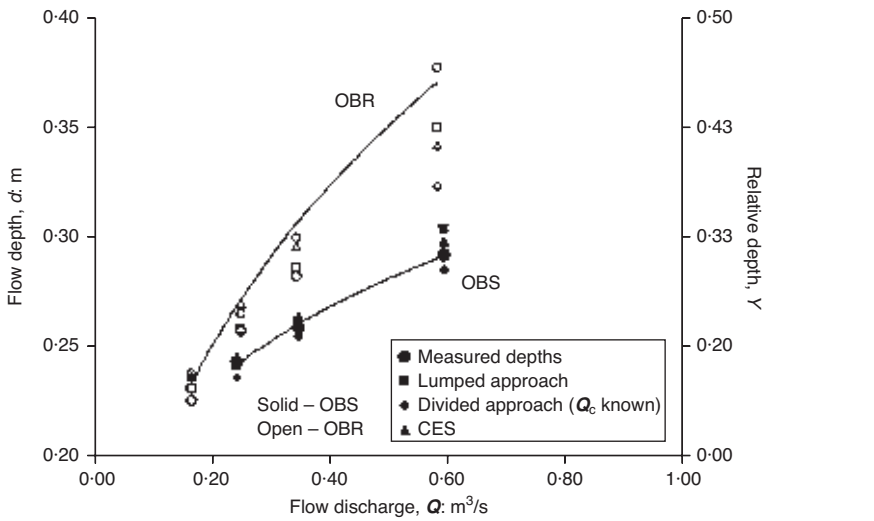

Fig. 8. Flow depth plotted against discharge for the FCF with meandering planform

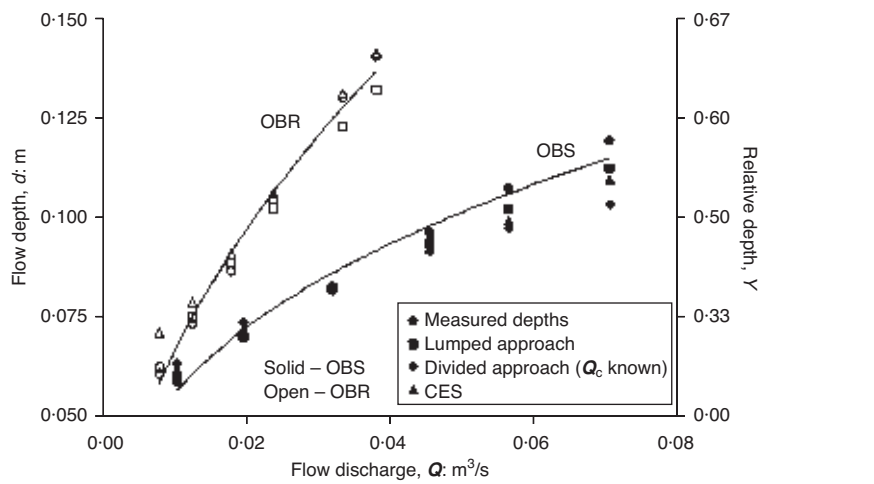

Fig. 9. Flow depth plotted against discharge for the UC with meandering planform

average change of the flow depth of 14%. The lumped resistance approach is most sensitive to channel sinuosity: a decrease of s by 50% results in 23% change in the flow depth. The values of increase and decrease of the studied parameters are assumed large and the channel slope, sinuosity, grain size and resistance to flow can be determined with better accuracy from experimental measurements. However, the calibration of the Manning n value is very important in both approaches.

4.3. Discussion of the method based on the divided resistance approach

Analysing the proposed calculation method based on the divided resistance approach and the data used in this study, some shortcomings were considered. One major shortcoming is that the method uses the DCM and it does not reflect the increasing resistance to flow in the case of very rough floodplains.

Although the bed form resistance is taken into account, the method still underestimates the flow depth for high overbank flows. Comparisons between the results obtained from the DCM and the conveyance estimation system 2-D method[27] were made (Figs 6–9). Different unit roughness values were assigned to the main channel bed, main channel walls and floodplains. Bed form roughness was taken into account when the friction factor of the main channel bed was calculated. The remaining energy losses are incorporated through the other parameters used in the method. The discrepancies between the measured and the predicted flow depth decreased but they still remain large for high overbank depths. The application of the coherence method developed by Ackers[4,5] improved the flow depth prediction for some data but

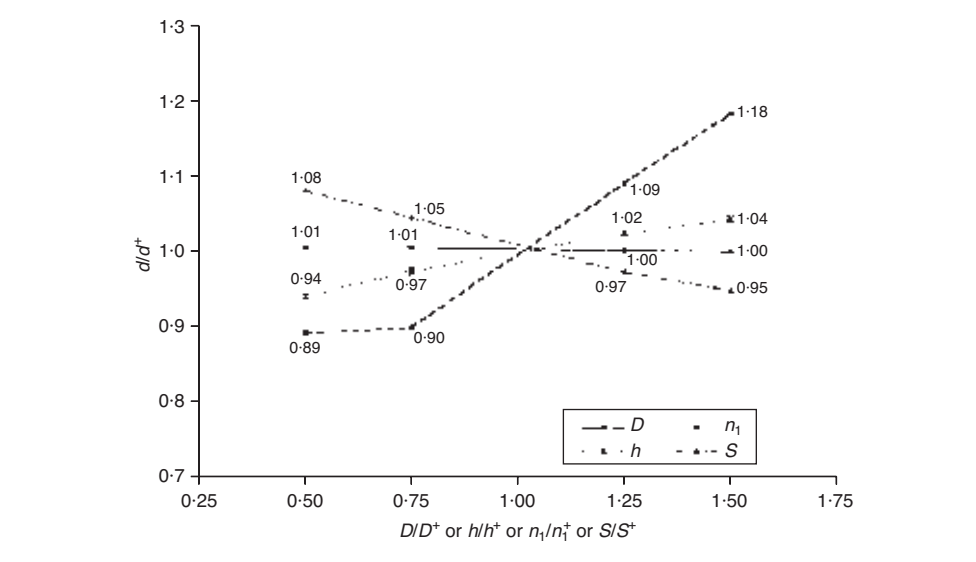

Fig. 10. Sensitivity analyses results for the divided resistance approach

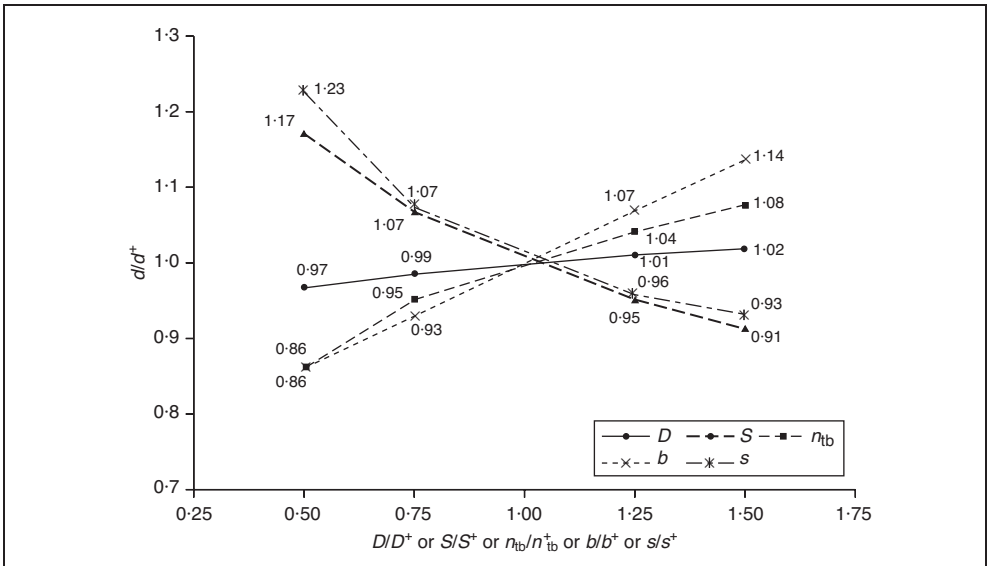

Fig. 11. Sensitivity analyses results for the lumped resistance approach

decreased the accuracy for others as it was developed for straight compound channels.

The bed form prediction methods discussed above gave good average discrepancy ratios for the experimental facilities studied. However, the average bed form height does not give information about the spatial variation of the bed forms. The study of statistical properties of bed forms, considering the bed form height and length as random variables of the probability distribution functions, did not give an explicit conclusion. The application of the chi-square and Anderson–Darling goodness-of-fit tests showed that for most data sets the variation of the bed form height can be described by the Weibull distribution, but for some experiments the normal distribution best fitted the data. These results are consistent with the divergence of opinion about the bed form distribution functions given in previous publications.[40] The calculated coefficients of variation were high for the studied flume data and varied between 0·5 and 0·9. For natural streams the variation of bed form height across the channel bed is expected to be higher.

Wilbers and ten Brinke[41] observed some difference in dune behaviour in the rivers Rhine and Waal in the Netherlands. They found that there was no relation between the changes in flow conditions and the dune height and wavelength in the Waal, while for the Rhine with discharge increases the dunes increase in size and become steeper. The authors compared their data with other published data on dune behaviour and concluded that both modes of dune behaviour can be found in other rivers around the world.

The divided resistance approach requires information about the discharge and resistance characteristics of both the main channel and the floodplain, and a measurement or prediction method for the bed forms' dimensions. Unfortunately, the above discussion and the results in this study do not confirm that this method is reliable for flow depth prediction.

4.4. Discussion of the method based on the lumped resistance approach

The proposed method based on the lumped resistance approach was applied to small- and large-scale flume data (the FCF and the UC) and field data obtained from the River Main. These experimental data include overbank flow measurements in compound channels with smooth and rough floodplains and straight and meandering planforms of the main channel. The accuracy of flow depth prediction achieved for the studied data sets is very good.

The application of the proposed algorithm to rivers requires field measurements of the water slope, flow depth and velocity to be taken for at least three overbank flow discharges. The availability of these data along with data for river cross-sectional geometry, channel slope, sinuosity and sediment size distribution will allow prediction of the flow depth for flow discharges outside of the known ranges.

Thus, the lumped resistance approach was also applied to the stage–discharge river data published at http://ncrfs.civil.gla.ac.uk. Data comprise both straight and meandering river reaches with

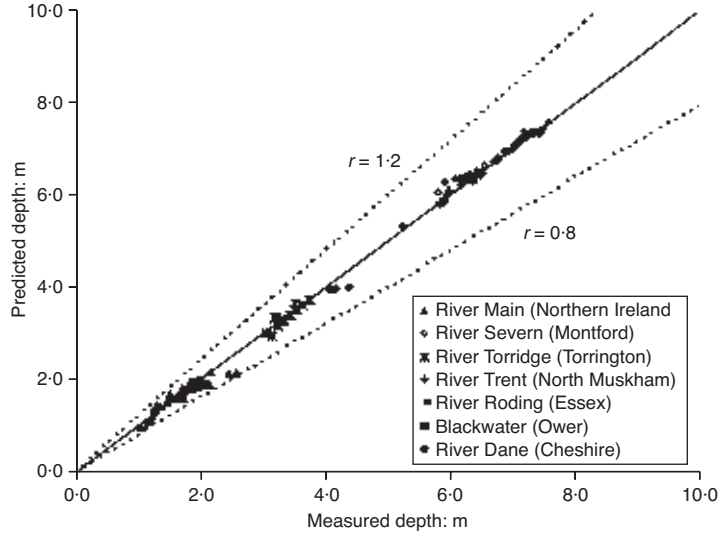

Fig. 12. Comparisons between measured river depths and depths predicted with the lumped resistance approach

slopes between 0·0002 and 0·0019, entrenchment ratios (total width to main channel width ratio) between 3·8 and 21·3 and bankfull depths up to 5·8 m. While no data about the sediment grain size are available, D_{50} was assumed to be 1 mm and the coefficient, b, was determined separately for each data set. An accurate agreement between the measured and the predicted flow depths was obtained (Fig. 12). The average discrepancy ratio for the river data was 1·01 and the standard deviation was 0·047. In order to apply the divided resistance approach to field data, more detailed measurements of the velocity distribution, grain size, floodplain resistance and bed form dimensions are necessary.

A summary of the river parameters and estimated relationships between n^* and Y^* is given in Table 4. For straight channels, the coefficient, b, varies between 0·303 and 0·578, even though the grain size was not taken into account for the calculation of Y^*. For a comparison, the coefficient, b, estimated for the FCF and UC with straight planforms and rough floodplains was 0·354. The coefficients given in Table 4 are determined by using all available measurements for the overbank flow discharges and depths. To assess the influence of the number of data used to determine the coefficient of proportionality, b, the data sets for the River Trent were divided into six groups with three data sets in each group and the coefficient, b, was determined separately for each group (Fig. 13). The calculated value for the coefficient, b, using all data sets for the River Trent was compared with the values calculated for each group and the results are shown in Table 5. The ratio between the coefficient b determined for a group of three data sets and the coefficient b determined for all data varied between 0·815 and 1·215.

The main advantage of the proposed lumped resistance approach is its simplicity. The algorithm requires water discharge, $\boldsymbol{Q}$, the mean particle diameter, D_{50}, water slope, S, channel sinuosity, s, and cross-section geometric characteristics to be measured experimentally and includes only two parameters to calibrate: the overbank Manning n value for relative depth $Y = 0$ and the coefficients of regression. However, good accuracy of stage–discharge prediction can only be achieved if the model parameters are well calibrated. The sensitivity analysis showed that this method is very sensitive to variations of the channel slope, the overbank Manning coefficient for a relative depth $Y = 0$ and the coefficient of regression between dimensionless parameters n^* and Y^*. The method is less sensitive to the sediment particle diameter and this suggests that it could be applied to channels with

River name	Date	Main channel width/bankfull depth: m	Floodplain roughness	Sinuosity	Slope ($\times 10^{-3}$)	n bankfull	$n^* = f(Y^*)$
River Maine, Northern Ireland	1991	14·0 width 1·0 depth	Rough $n_{fp}/n_b = 1–1·5$	1·0+	1·9	0·0235	$0·578Y^*$
River Torridge at Torrington, Devon	1993	30·0 width 2·78 depth	Rough $n_{fp}/n_b = 1–2·0$	1·0+	1·45	0·0160	$0·413Y^*$
River Trent, North Muskham	1993	72·0 width 5·7 depth	Rough $n_{fp}/n_b = 1·0$	1·0+	0·320	0·0152	$0·303Y^*$
River Blackwater at Ower, Hampshire	1993	6·0 width 1·7 depth	Rough $n_{fp}/n_{bf}1–2·0$	1·0+	1·60	0·0303	$0·502Y^*$
River Severn at Montford, Shropshire	1993	35·0 width 5·75 depth	Rough $n_{fp}/n_b = 1–1·5$	1·0+	0·195	0·0122	$0·427Y^*$
River Dane, Cheshire	1997	25·0 width 5·0 depth	Rough $n_{fp}/n_b = 1–1·5$	1·8	0·5	0·010	$4·13Y^{*2} - 1·108Y^*$
River Roding, Essex	1985–1989	6·10 width 0·9 depth	Rough $n_{fp}/n_b = 1–2·0$	1·37	1·4	0·0135	$0·0895Y^{*2} + 0·177Y^*$

Table 4. Summary of the river data

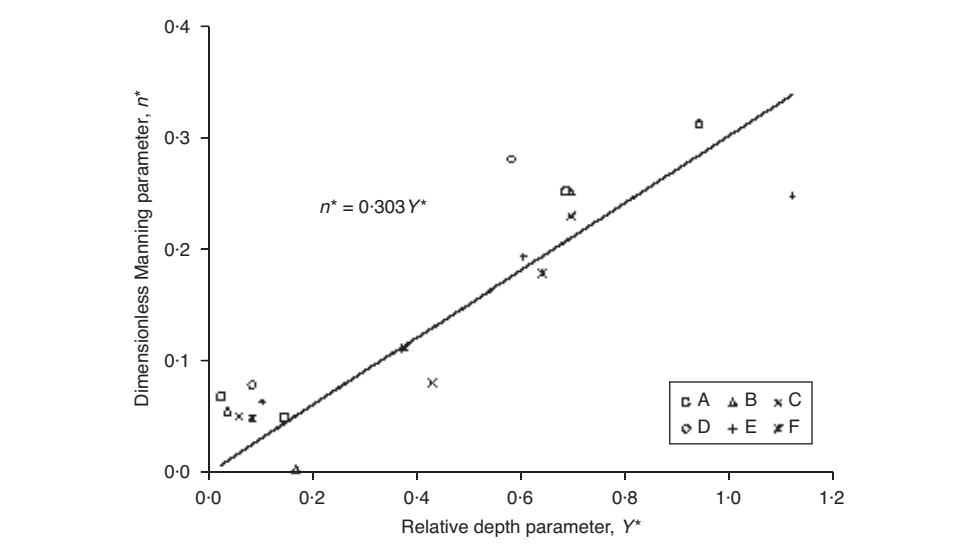

Fig. 13. Dimensionless Manning n plotted against relative depth parameter for the River Trent (data divided into groups)

	All data	A	B	C	D	E	F
b	0·303	0·368	0·347	0·295	0·345	0·247	0·288
b/b^+	1·000	1·215	1·145	0·974	1·139	0·815	0·950

Table 5. Results for the coefficient of proportionality, b, for River Trent, North Muskham

non-uniform sediments. The method gave very good prediction of the overbank flow depths in the River Main. The studied reach of the river comprises a main channel with non-uniform coarse gravel bed with $D_{50} = 20$ mm and up to 500 mm size of some materials, with floodplains formed of coarse sand, fine and medium gravels, and weed growing unhindered.[38]

A possible limitation of the proposed lumped resistance approach is its applicability to rivers with various planforms and floodplain roughness. Further study of the proposed method with river data will specify the limitation of its application for overbank flow prediction in rivers.

5. CONCLUSIONS

Algorithms based on simple 1-D stage–discharge models for compound channels, which can be incorporated into conventional data processing software, have been developed. Divided and lumped resistance approaches were proposed and studied for use with overbank flow data from the FCF and the UC with straight and meandering planforms.

The stage–discharge prediction algorithm based on the divided resistance approach uses the DCM to calculate the main channel and floodplain discharges and takes into account the grain resistance, the bed form resistance, and the roughness characteristics of the floodplain. The proposed divided resistance approach did not give satisfactory prediction of the flow depth for compound channels with rough floodplains. To improve the results for this case the interaction between the subsections needs to be taken into account.

A simple algorithm for stage–discharge prediction based on the lumped resistance approach has been proposed. It requires minimum input parameters and is simple to apply. The good predictability of the proposed method relies on the precise calibration of the Manning roughness coefficient and the coefficient of regression between dimensionless Manning's n parameter, n^*, and relative depth parameter, Y^*. The proposed algorithm is applicable to compound channels with different sinuosities and its application requires data for the channel cross-section geometry, channel sinuosity and measurements of water slope, flow depth and discharge taken for at least three overbank flood events. The method gave very good predictions of overbank flow depths in flumes and rivers and can be useful for approximate prediction of the stage–discharge relationship in cases where detailed data about flow and morphological characteristics of a river do not exist.

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REFERENCES

1. Wormleaton P. R. and Merrett D. J. An improved method of calculation for steady uniform flow in prismatic main channel/flood plain sections. *Journal of Hydraulic Research*, 1990, **28**, No. 2, 157–174.
2. Knight D. W. and Demetriou D. D. Flood plain and main channel flow interaction. *Journal of Hydraulic Engineering*, 1983, **109**, No. 8, 1073–1092.
3. Wormleaton P. R., Allen J. and Hadjipanos P. Discharge assessment in compound channel flow. *Journal of Hydraulic Division, ASCE*, 1982, **108**, No. HY9, 975–993.
4. Ackers P. Hydraulic design of two-stage channels. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy*, 1992, **96**, No. 4, 247–257.
5. Ackers P. Flow formulae for straight two-stage channels. *Journal of Hydraulic Research*, 1993, **31**, No. 4, 509–531.
6. Lambert M. F. and Myers W. R. C. Estimating the discharge capacity in straight compound channels. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy*, 1998, **130**, No. 2, 84–94.

7. Knight D. W. *Scoping Study on Reducing Uncertainty in River Flood Conveyance: Conveyance in 1-D River Models*. HR Wallingford, Oxfordshire, UK, 2001, Report for HR Wallingford and the Environment Agency.
8. Wormleaton P. R., Hey R. D., Sellin R. H. J., Bryant T., Loveless J. H. and Catmur S. E. Behaviour of meandering overbank channels with graded sand beds. *Journal of Hydraulic Engineering*, 2005, **131**, No. 8, 665–681.
9. James C. S. and Wark J. B. *Conveyance Estimation for Meandering Channels*. HR Wallingford, 1992, Report SR 329.
10. Greenhill R. K. and Sellin R. H. J. Development of a simple method to predict discharges in compound meandering channels. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy,* 1993, **101**, No. 4, 37–44.
11. Shiono K., Al-Romaih J. S. and Knight D. W. Stage–discharge assessment in compound meandering channels. *Journal of Hydraulic Engineering,* 1999, **125**, No. 1, 66–77.
12. Rameshwaran P. and Willetts B. B. Conveyance prediction for meandering two-stage channel flow. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy,* 1999, **136**, No. 3, 153–166.
13. James C. S. and Myers W. R. C. Conveyance of one- and two-stage meandering channels. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy,* 2002, **154**, No. 3, 265–274.
14. Wright N. G. *Scoping Study for Reducing Uncertainty in River Flood Conveyance: Conveyance Implications for 2-D and 3-D Modelling*. HR Wallingford, Oxfordshire, UK, March 2001, Report for HR Wallingford and the Environment Agency, p. 16.
15. Evans E. P., Pender G., Samuels P. G. and Escarameia M. *Scoping Study for Reducing Uncertainty in River Flood Conveyance*. HR Wallingford, Oxfordshire, UK, August 2001, Report to HR Wallingford and the Environment Agency, p. 119.
16. Brown F. A. *Sediment Transport in River Channels at High Stage*. PhD thesis, University of Birmingham, 1997.
17. Cassells J. B. C. *Hydraulic Characteristics of Straight Mobile Bed Compound Channels*. PhD thesis, University of Ulster, 1998.
18. O'Sullivan J. *The Hydraulic Performance of Meandering Mobile Bed Compound Channels with Uniform Sediment*. PhD thesis, University of Ulster, 1999.
19. Myers W. R. C. and Brennan E. K. Flow resistance in compound channels. *Journal of Hydraulic Research,* 1990, **28**, No. 2, 141–155.
20. Atabay S., Knight D. W. and Seckin G. Effect of overbank flow on fluvial sediment transport rates. *Proceedings of the Institution of Civil Engineers, Water Management,* 2005, **158**, No. 1, 25–34.
21. Einstein H. A. and Barbarossa N. L. River channel roughness. *Transactions of ASCE,* 1952, **117**, Paper No. 2528, 1121–1131.
22. White W. R., Bettess R. and Paris E. Analytical approach to river regime. *Journal of Hydraulic Division, ASCE,* 1982, **108**, No. HY10, 1179–1193.
23. Wormleaton P. R., Selin R. H. J. and Bryant T. Conveyance in two-stage meandering channels with mobile bed. *Journal of Hydraulic Research,* 2004, **42**, No. 5, 492–505.
24. Van Rijn L. C. Sediment transport, part III: Bed forms and alluvial roughness. *Journal of Hydraulic Engineering,* 1984, **110**, No. 12, 1733–1754.
25. Engelund F. Hydraulic resistance of alluvial streams. *Journal of Hydraulic Division, ASCE,* 1966, **92**, No. NY2, 315–326.
26. Vanoni V. A. and Hwang L. S. Relation between bedforms and friction in streams. *Journal of Hydraulic Division, ASCE,* 1967, **93**, No. HY3, 121–144.
27. Department for Environment, Food and Rural Affairs/Environment Agency. *Reducing Uncertainty in River Flood Conveyance, Interim Report 2: Conveyance Manual*. HR Wallingford Ltd, Oxfordshire, UK, 2004, Project W5A- 057/PR/1.
28. Fasken G. B. *Guide for Selecting Roughness Coefficient N Values for Channels*. Soil Conservation Services, US Department of Agriculture, Lincoln, Nebraska, 1963.
29. Karamisheva R., Lyness J. F., Myers W. R. C. and Cassells J. B. Improving sediment discharge prediction for overbank flows. *Proceedings of the Institution of Civil Engineers, Water Management,* 2005, **158**, No. 1, 17–24.
30. Karamisheva R., Lyness J. F., Myers W. R. C. and O'Sullivan J. Sediment discharge prediction in meandering compound channels. *Journal of Hydraulic Research,* 2006 (in press).
31. Karamisheva R., Lyness J. F., Myers W. R. C., O'Sullivan J. and Cassells J. Prediction of bed form height in straight and meandering compound channels. *Proceedings of the 3rd International Conference on Water Resources Management, Algarve, Portugal*, 11–13 April 2005, 311–320.
32. Karim F. Bed-form geometry in sand-bed flows. *Journal of Hydraulic Engineering,* 1999, **125**, No. 12, 1253–1261.
33. Julien P. Y. and Klaasen G. J. Sand-dune geometry of large rivers during floods. *Journal of Hydraulic Engineering,* 1995, **121**, No. 9, 657–663.
34. Knight D. W., Brown F. A., Valentine E. M., Nalluri C., Bathurst J. C., Benson I. A., Myers W. R. C., Lyness J. F. and Cassells J. B. The response of straight mobile bed channels to inbank and overbank flows. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy,* 1999, **136**, No. 4, 211–224.
35. Knight D. W. and Brown F. A. Resistance studies of overbank flow in rivers with sediment using the Flood Channel Facility. *Journal of Hydraulic Research*, 2001, **39**, No. 3, 283–301.
36. Lyness J. F., Myers W. R. C., Cassells J. B. C. and O'Sullivan J. J. The influence of planform on flow resistance in mobile bed compound channels. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy*, 2001, **148**, No. 1, 5–14.
37. Atabay S. *Stage–discharge, Resistance, and Sediment Transport Relationships for Flow in Straight Compound Channels*. PhD thesis, University of Birmingham, 2001.
38. Higginson N. N. J. *Evaluation of Hydraulic Resistance in Single and Two-stage Rivers*. PhD thesis, Queens University, 1992.
39. Myers W. R. C., Knight D. W., Lyness J. F., Cassells J. B. and Brown E. Resistance coefficient for inbank and overbank flows. *Proceedings of the Institution of Civil Engineers, Water, Maritime & Energy,* 1999, **136**, No. 2, 105–115.

40. Moll J. R., Schilperoort T. and De Leeuw A. J. Stochastic analysis of bedform dimensions. *Journal of Hydraulic Research,* 1987, **25**, No. 4, 465–479.

41. Wilbers A. W. E. and ten Brinke W. B. M. The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. *Proceedings of IAHR Symposium on River, Coastal and Estuarine Morphodynamics*, Genova, 6–10 September 1999, Vol. 1, pp. 303–311.