Proceedings of the Institution of Civil Engineers
Water Management 159
September 2006 Issue WM3
Pages 183–193

Paper 14461
Received 04/10/2005
Accepted 18/04/2006

Keywords:
floods & floodworks/hydraulics & hydrodynamics/river engineering





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Sediment transport formulae for compound channel flows

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Nine sediment transport formulae were reviewed and applied to both inbank and overbank flows in straight and meandering compound channels. The predictive capabilities of the formulae were evaluated using experimental data obtained from the large-scale UK Flood Channel Facility and the small-scale Ulster Channel. The Yang formula (1979) was found to give the best prediction for sediment discharge, performing well for both straight and meandering channels. The Schoklitch (1962) and Yang and Lim (2003) formulae also gave very good predictions for most of the data sets studied. The Ackers and White formula (1973) gave very good prediction for the large-scale facility but overpredicted the sediment discharge for the small-scale channel. The Karim and Kennedy (1981) formula could also be a good sediment discharge predictor, for the studied flow conditions, but the coefficient of proportionality used in the formula needs to be calibrated.

NOTATION

C_t	total sediment concentration (ppm)
C_v	coefficient of variation
D_{gr}	dimensionless particle diameter
D_x	sediment size such that x% is finer
d	flow depth
F_{gr}	dimensionless shear stress parameter
f	Darcy–Weisbach friction factor
G_{gr}	dimensionless sediment transport parameter
g	gravitational acceleration
I, J	parameters
k_i	coefficient
m_i	coefficient
n	Manning roughness coefficient
n'	Manning–Strickler grain roughness coefficient
Q	discharge
q	unit flow rate
q_b	bed sediment load
q_s	suspended sediment load
q_t	total sediment load
R^2	regression coefficient
r	discrepancy ratio
S	channel slope
s	specific gravity of sediment
T	transport stage parameter
U^*	shear velocity
$U^{*\prime}$	effective bed shear velocity
V	mean velocity
w	sediment particle fall velocity
Y	relative depth
α	coefficient
θ	Shield's dimensionless shear stress parameter
v	kinematic viscosity
Φ	dimensionless bed load discharge
Ψ	universal stream power

Subscripts

cr	critical value of a parameter

1. INTRODUCTION

The transport of non-cohesive sediments during steady uniform flow is a complex process, which becomes more complex to describe mathematically during overbank flow because of the interaction between the floodplain and main channel flows. For compound channels with meandering planforms a further degree of complexity is added. Sediment transport mechanisms have been studied for decades and a large number of sediment transport formulae for the calculation of the total, suspended or bed load sediment discharges have been developed. Sediment transport formulae are based on the physics of particle motion, similarity principles or dimensional analysis.

Sediment transport formulae are usually calibrated and verified using inbank flow data. In the present study they are applied to both inbank and overbank flows in compound channels with straight and meandering planforms. The data were obtained from the large-scale UK Flood Channel Facility (FCF) and the small-scale Ulster Channel (UC).[1,2] Overbank flows with both smooth floodplains (OBS) and artificially roughened floodplains (OBR) were studied. For all experiments a bed of uniform sand in the main channel was used.

Previous studies of sediment transport formulae performance do not give comprehensive answers about their range of applicability. The same formulae can be reported to have different ranges of accuracy by different authors for similar flow conditions. The goal of the current study is to demonstrate the performance of some specific sediment transport formulae for use with both inbank and overbank experimental data from channels with different sinuosities without the ambitious aim of providing a 'fully comprehensive' guide to performance of all possible sediment transport formulae.

2. SEDIMENT LOAD FORMULAE

The formulae proposed by Meyer-Peter and Muller,[3] Schoklitch,[4] Engelund and Hansen,[5] Ackers and White,[6,7] Yang,[8] Karim and Kennedy,[9] Van Rijn,[10,11] Molinas and Wu,[12] and Yang and Lim[13] were originally developed using inbank flume and field data from straight channels. In the current study, these formulae were demonstrated by their use with both inbank and overbank flow data from straight and meandering compound channels.

The sediment discharge, q_t, and the sediment concentration, C_t, are usually expressed as a function of some of the following parameters: the sediment size, D, water slope, S, flow depth, d, unit flow discharge, q, flow velocity, V, fall velocity, w, shear velocity, U^*, resistance coefficients, n or f, specific gravity of sediment, s. In some formulae these parameters are combined in dimensionless parameters such as the dimensionless shear stress parameter, θ, particle parameter, D_{gr}, sediment transport parameter, G_{gr}, and transport stage parameter, T, which are given below

$$\theta = \frac{dS}{D(s-1)} \tag{1}$$

$$D_{gr} = D\left[\frac{g(s-1)}{v^2}\right]^{1/3} \tag{2}$$

$$G_{gr} = \frac{C_t d}{sD}\left(\frac{U_*}{V}\right)^{m_1} \tag{3}$$

$$T = \frac{(U^*)^2 - (U^*_{cr})^2}{(U^*_{cr})^2} \tag{4}$$

A short review of the sediment transport formulae in their original form is given below.

Meyer-Peter and Muller[3] derived a bed-load transport formula using the results of an extensive experimental investigation

$$q_b = 8(s-1)^{0\cdot5}D_{50}^{1\cdot5}g^{0\cdot5}10^3\left[\left(\frac{n}{n'}\right)^{1\cdot5}\theta - \theta_{cr}\right]^{1\cdot5} \tag{5}$$

where q_b is the bed-load discharge per metre width in m^2/s; D_{50} is the mean sediment size, s is the specific gravity (ratio between the density of sediment and the fluid density), n is the Manning roughness coefficient; n' is the Manning–Strickler grain roughness coefficient, θ is the Shield's dimensionless shear stress parameter and θ_{cr} is Shield's critical dimensionless shear stress parameter.

Schoklitch[4] proposed a relationship between the bed-load sediment discharge, q_b, and the difference between the flow discharge per unit width, q, and the critical flow discharge, q_{cr}, given by the following expression

$$q_b = \frac{2\cdot5}{s}S^{3/2}(q - q_{cr}) \qquad q_{cr} = 0\cdot21S^{-1\cdot12}\sqrt{gD_{16}^3} \tag{6}$$

where q_b is the bed-load sediment discharge per metre width in m^2/s, S is the energy slope, and D_{16} is the size of sediment for which 16% of the sample is finer.

Engelund and Hansen[5] applied the stream power concept and the similarity principle to obtain a sediment transport equation. The dimensionless sediment load discharge, Φ is expressed as a function of the dimensionless shear stress parameter, θ, and the Darcy–Weisbach friction coefficient, f, and the total sediment discharge is expressed as follows

$$q_t = \frac{0\cdot1\theta^{5/2}}{f}\sqrt{[g(s-1)D_{50}^3]} \tag{7}$$

where q_t is the total sediment discharge per metre width in m^2/s.

Ackers and White[6,7] applied dimensional analysis techniques to develop a general sediment transport function in terms of the three dimensionless groups: particle parameter, D_{gr}, mobility parameter, F_{gr}, and sediment transport parameter, G_{gr}. They showed that the transport of fine materials is best related to the total shear velocity and the transport of coarse sediments is related to the mean velocity. The total sediment concentration, C_t, is expressed by the following equation

$$C_t = m_3\left(\frac{F_{gr} - F_{gr,cr}}{F_{gr}}\right)^{m_2}\left(\frac{V}{U^*}\right)^{m_1}\frac{D_{35}s}{d} \qquad F_{gr} = \frac{U^{*m_1}}{\sqrt{[gD_{35}(s-1)]}}\left[\frac{V}{\sqrt{32}\log\left(\frac{\alpha d}{D_{35}}\right)}\right]^{1-m_1} \tag{8}$$

where C_t is the total sediment concentration in ppm, d is the flow depth, D_{35} is the size of sediment for which 35% of the sample is finer, α is a coefficient, $F_{gr,cr}$ is the value of F_{gr} at initial motion, and m_1, m_2 and m_3 are parameters. The parameters $F_{gr,cr}$, m_1, m_2 and m_3 depend on the dimensionless particle parameter, D_{gr}.

Yang[8] hypothesised that the unit stream power, VS, defined as the time rate of potential energy dissipation per unit weight of water, is the dominant factor in determining the sediment concentration in alluvial channels. The relationship between the unit stream power and the total sediment concentration, C_t, is expressed by

$$\log C_t = I + J\log\left(\frac{VS}{w}\right) \qquad J = 1\cdot780 - 0\cdot360\log\frac{wD_{50}}{v} - 0\cdot480\log\frac{U^*}{w} \qquad I = 5\cdot165 - 0\cdot153\log\frac{wD_{50}}{v} - 0\cdot297\log\frac{U^*}{w} \tag{9}$$

where C_t is the total sediment concentration in ppm, V is the mean cross-section velocity, U^* is the shear velocity, w is the fall velocity, VS/w is the dimensionless unit stream power, v is the kinematic viscosity, and I, J are parameters determined from multiple regression analysis of a large range of experimental data.

Karim and Kennedy[9] used dimensional analysis to develop a power relationship between the total sediment discharge, q_t, and the flow velocity, V, shear velocity, U^*, the fall velocity, w, and

Sediment transport formula	Depth, d	Slope, S	Particle diameter, D	Viscosity, $\boldsymbol{\nu}$	Mean velocity, $\boldsymbol{V}$	Shear velocity, $\boldsymbol{U}^*$	Fall velocity, $\boldsymbol{w}$
Meyer-Peter and Muller[3]	Yes	Yes	Yes	–	Yes	–	–
Schoklitch[4]	–	Yes	Yes		Yes	–	–
Engelund and Hansen[5]	Yes	Yes	Yes	–	Yes	Yes	–
Ackers and White[6,7]	Yes	Yes	Yes	Yes	Yes	Yes	–
Yang[8]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Karim and Kennedy[9]	Yes	Yes	Yes	–	Yes	Yes	Yes
Van Rijn[10]	Yes	Yes	Yes	Yes	Yes	Yes	–
Molinas and Wu[12]	Yes	–	Yes	–	Yes	–	Yes
Yang and Lim[13]	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 1. Comparison of the input data needed for different calculation methods

the mean particle diameter, D_{50}

$$q_t = k_1 \left\{ \frac{V}{\sqrt{[g(s-1)D_{50}]}} \right\}^{2\cdot97} \left(\frac{U^*}{w} \right)^{1\cdot47} \sqrt{[g(s-1)D_{50}^3]} \tag{10}$$

where q_t is the total sediment discharge per metre width in m^2/s and $k_1 = 0{\cdot}00139$ is a coefficient of proportionality.

Van Rijn,[10,11] in a series of papers, presented theories for bed-load and suspended sediment transport. He proposed the following bed-load formula

$$q_b = 0{\cdot}053 \frac{T^{2\cdot1}}{D_{gr}^{0\cdot3}} [(s-1)g]^{0\cdot5} D_{50}^{1\cdot5} \tag{11}$$

where q_b is the bed-load sediment discharge per metre width in m^2/s, and T is the transport stage parameter, which expresses the mobility of the particles in terms of the stage of movement relative to the critical stage for initiation of motion.

The suspended load transport is calculated from

$$q_s = 0{\cdot}012 \left\{ \frac{V - V_{cr}}{[(s-1)gD_{50}]^{0\cdot5}} \right\}^{2\cdot4} D_{gr}^{-0\cdot6} D_{50} V \tag{12}$$

where q_s is the suspended-load sediment discharge per metre width in m^2/s, and V_{cr} is the critical mean flow velocity based on Shield's criterion. The total sediment transport is calculated as the sum of the bed-load and the suspended load.

Molinas and Wu[12] developed a sediment transport relationship based on the stream power concept. They replaced energy slope owing to grain resistance with a velocity term using the Darcy–Weisbach equation and a resistance equation for estimating the friction factor and established the following relationship between total sediment concentration, C_t, and the universal stream power, Ψ

$$C_t = \frac{1430(0{\cdot}86 + \sqrt{\Psi})\Psi^{1\cdot5}}{0{\cdot}016 + \Psi}$$
$$\Psi = \frac{V^3}{(s-1)gdw\left[\log\left(\frac{d}{D_{50}}\right)\right]^2} \tag{13}$$

Yang and Lim[13] used dimensional analysis to develop a sediment transport formula for flow in alluvial channels. They related the sediment discharge to a total load transport parameter, which involves the bed shear stress, $\boldsymbol{\tau}_0$, grain shear velocity, $U^{*\prime}$, critical grain shear velocity, $U^{*\prime}_{cr}$, and the fall velocity, w

$$q_t = k_2 \frac{s}{(s-1)} \boldsymbol{\tau}_0 \left(\frac{U^{*\prime 2} - U_{cr}^{*\prime 2}}{w} \right) \tag{14}$$

where q_t is the total discharge per metre width in kg/s/m, and $k_2 = 12{\cdot}5$ is a coefficient of proportionality.

A summary of the independent variables, which influence the results of the sediment discharge calculation for the various calculation methods, is presented in Table 1. All formulae include the sediment characteristics and mean flow velocity as input variables. The energy slope is also included as an input variable in all formulae except in the Molinas and Wu formula. The shear velocity, which relates to the fine particles sediment transport, is not included in the bed-load Meyer-Peter and Muller and Schoklitch transport formulae, but it is necessary to calculate the suspended part of the total sediment transport. The ranges of depth, slope, grain size and mean velocity applicable to all studied formulae are given in Table 2.

Sediment transport formula	Depth, d: m	Slope, S	Particle size, D: mm	Mean velocity, V: m/s
Meyer-Peter and Muller[3]	0·01–1·20	0·0004–0·02	0·4–29·0	0·36–2·9
Schoklitch[4]	0·01–0·22	0·00012–0·055	0·3–4·9	0·24–1·4
Engelund and Hansen[5]	0·06–0·31	0·000055–0·019	0·19–0·93	0·19–1·90
Ackers and White[6,7]	0·18–11·5	0·000022–0·0015	0·04–4·0	0·33–0·87
Yang[8]	0·01–15·0	0·000043–0·028	0·15–1·7	0·24–1·95
Karim and Kennedy[9]	0·03–5·20	0·00015–0·024	0·14–28·65	0·31–2·84
Van Rijn[10]	0·10–16·0	NA	0·19–3·6	0·34–1·55
Molinas and Wu[12]	1·50–62·2	0·000002–0·0025	0·02–2·6	0·20–2·42
Yang and Lim[13]	0·01–16·5	0·0003–0·013	0·02–57·0	NA

Table 2. Data ranges for different calculation methods

3. EXPERIMENTAL PROCEDURES AND RESULTS

Comparisons of the accuracy of the sediment transport calculation methods have been

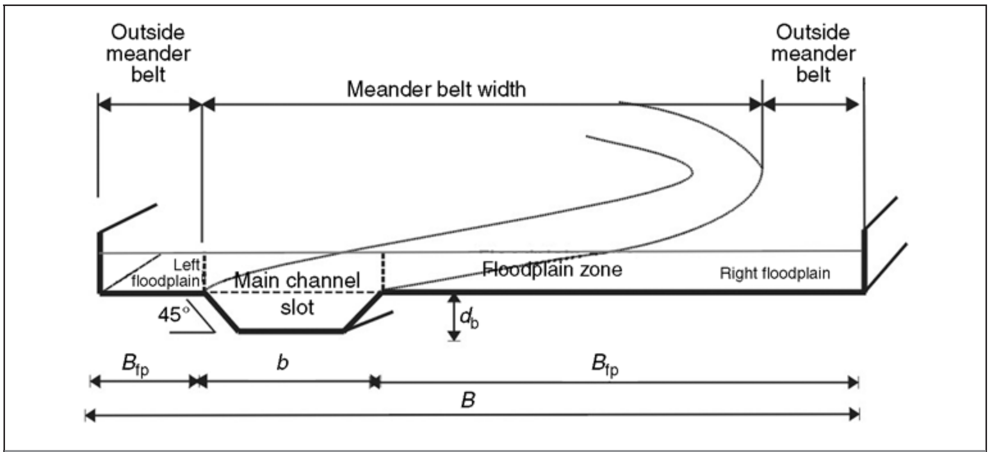

Fig. 1. Cross-section geometry of meandering compound channel

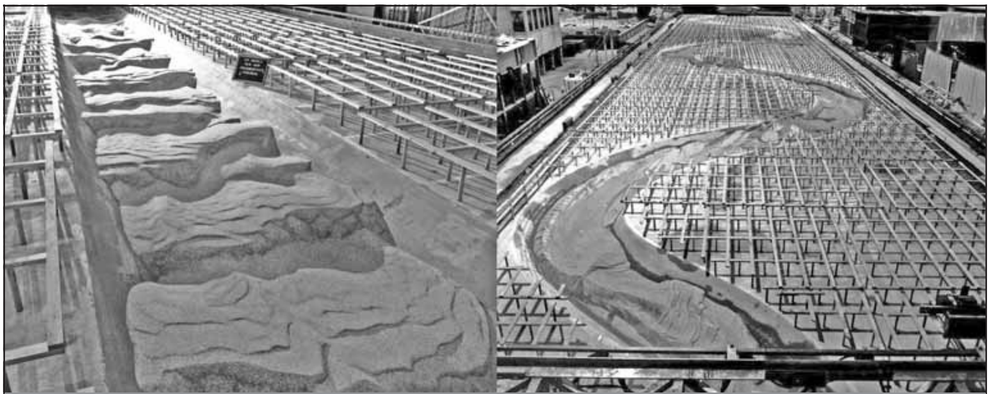
Fig. 2. The FCF with straight and meandering planforms

made using 69 data sets obtained at the large-scale FCF described previously by Myers *et al.*[14] and Lyness *et al.*[15] and in the small-scale UC described previously by Cassells[1] and O'Sullivan.[2] The cross-section of both channels is shown in Fig. 1.

The large-scale FCF channel is 45 m long by 8 m wide (Fig. 2). The main channel is trapezoidal in section with side slopes inclined at 45° and top width of 2·0 m for the straight channel experiments and 1·6 m for the meandering channel experiments. For the meandering channel experiments, the main channel was designed to have a channel sinuosity of 1·34. The experimental tests were carried out using a uniform sediment sand of $D_{50} = 0{\cdot}835$ mm. The sand was screeded to a mean bed level 0·2 m below the floodplains. The facility recirculated both sediment and water and the sediment transport rate was measured by an infrared meter.

The overall length of the small-scale UC is 18 m and its total width is 1·89 m (Fig. 3). The main channel has a top width of 0·5 m and side slopes of 45°. 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 0·001859 and 0·0025. The channel was filled with sediment sand to a depth of 0·05 m below the floodplain. The sediment particle diameter was $D_{50} = 0{\cdot}890$ mm. The UC only recirculated water and not sediment, so a sediment feeder was provided to keep the bed in equilibrium.

The discharges for these experiments are in the range 0·01–0·75 m^3/s and flow depths are in the range 0·044–0·360 m. For straight channel experiments, the trapezoidal main channel was extended with sidewalls during the inbank tests, allowing flow and sediment behaviour in channels with trapezoidal and compound channel sections to be compared. The maximum value of relative depth, Y, ($Y = (d - d_b)/d$, where d_b is the bankfull depth) for the overbank experiments was 0·67. Overbank flows with both smooth and artificially roughened floodplains were studied. All tests were conducted in channels incorporating a mobile sand bed using uniform sand with a density of 2·65 t/m^3. Particular care was provided to ensure that steady, uniform flow was


Fig. 3. The UC with meandering and straight planforms

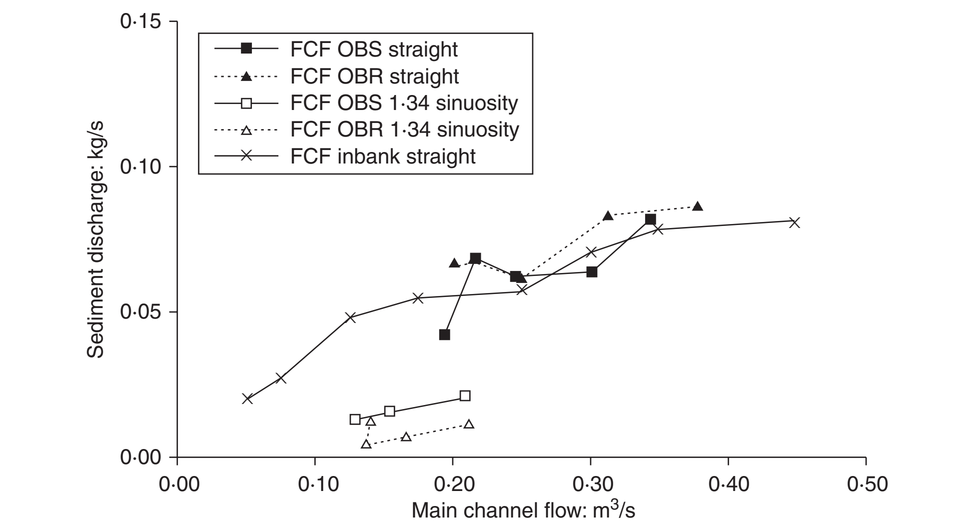

Fig. 4. Sediment discharges measured at the FCF

cross-sections were close to the sediment discharges measured during inbank tests and corresponding to the same flow discharge.

(*b*) For overbank flows the sediment discharge did not necessarily increase with the flow discharge; for UC with rough floodplains the sediment discharge started to decrease steadily after a certain flow discharge.

(*c*) For overbank flows in the FCF the sediment discharges were lower for channels with meandering planforms, but this was not observed for the UC.

(*d*) No clear relation between the main channel flow discharge (or mean main channel velocity) and the sediment discharge was observed.

obtained and that bed load rates were in dynamic equilibrium for the duration of all tests.

According to the Rosgen classification system,[16] the compound channels studied here can be classified as sand dune-ripple alluvial channels, slightly entrenched (total width–main channel width ratio varied between 3·8 and 5·0), low to average channel slope (0·00186–0·00250), low width–depth ratio (8·0–10·0), with low to moderate sinuosity (1·0–1·34).

The results for the measured sediment discharges in the FCF and the UC with different planforms and floodplain roughness are shown in Figs 4 and 5. For the UC with rough floodplains and meandering planform, sediment transport was not observed. Relations between the measured sediment discharge and the main channel flow were investigated and the following observations were made.

(*a*) For straight channel experiments, the sediment discharges during overbank flow in channels with compound

4. COMPARISONS OF ACCURACY FOR SEDIMENT TRANSPORT FORMULAE

The main objective of this paper is to select sediment transport formulae, which are reliable for both inbank and overbank flow and for compound channels with different sinuosities by comparing the measured sediment discharges and those calculated using different formulae. The following statistical parameters were used to assess the predictive capability of the sediment transport formulae: the discrepancy ratio between computed and measured results, *r*, the coefficient of variation, C_v, the sample percentages of the discrepancy ratio values within the ranges 0·75–1·33 and 0·50–2·00, and the regression coefficient between the computed and measured results, R^2. In order to compare the results, some assumptions about the 'acceptable ranges' of statistical parameters were made: mean discrepancy ratio, *r*, should be between 0·75 and 1·33; coefficient of variation, C_v, should be less than 0·50; percentage of discrepancy ratio values in the range 0·50–2·00 should be greater than 75%; and coefficients of regression, R^2, should be greater than 0·75. Results are compared separately for inbank and overbank flow, for straight and meandering planforms of the main channel, for the FCF and the UC and summarised in Table 3. Formulae with statistical parameters within the 'acceptable ranges' were considered to give very good predictions of the sediment discharge (these values are shaded in Table 3). The sediment transport formulae, which did not give good discrepancy ratios but did give good statistical results of the

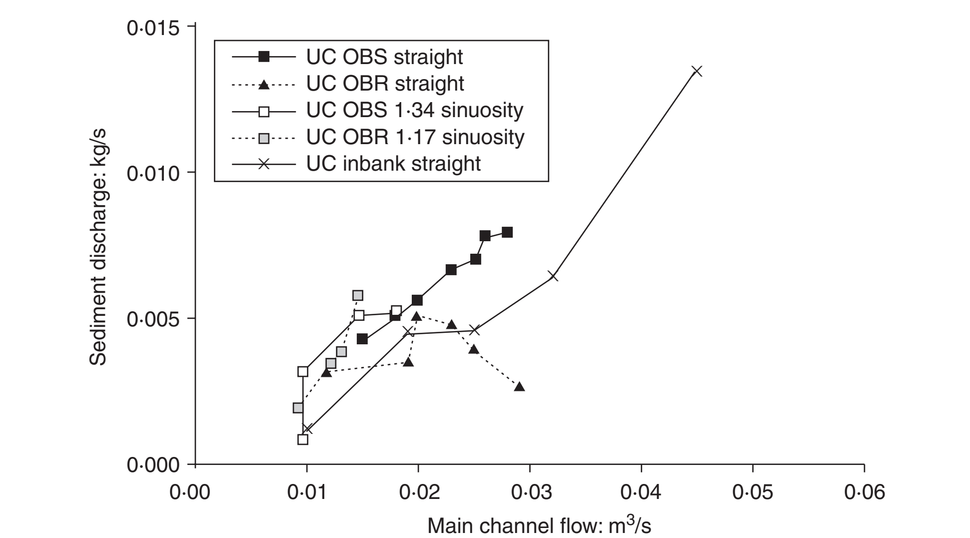

Fig. 5. Sediment discharges measured at the UC

Statistics	Formulae	Meyer-Peter and Muller[3]	Schoklitch[4]	Engelund and Hansen[5]	Ackers and White[6,7]	Yang[8]	Karim and Kennedy[9]	Van Rijn[10]	Molinas and Wu[12]	Yang and Lim[13]
FCF inbank	r	0·29	0·87	1·91	0·97	0·79	0·53	0·72	1·38	0·94
	C_v	0·59	0·35	0·58	0·54	0·49	0·41	0·58	0·31	0·40
UC inbank	r	5·70	1·35	0·66	1·89	0·99	0·78	2·39	5·58	1·68
	C_v	1·08	0·89	0·18	0·75	0·48	0·56	1·14	0·87	0·74
FCF straight	r	0·27	0·86	1·91	0·99	0·90	0·54	0·63	1·20	0·96
	C_v	0·53	0·22	0·20	0·40	0·32	0·29	0·47	0·27	0·37
UC straight	r	1·83	0·95	0·86	1·52	0·78	0·60	1·18	3·21	1·25
	C_v	0·72	0·33	0·79	0·42	0·27	0·24	0·56	0·29	0·28
FCF straight	r	0·11	2·98	11·78	0·88	1·75	1·03	0·45	1·65	0·99
	C_v	1·45	0·47	0·60	0·41	0·34	0·32	0·57	0·31	0·57
UC meander	r	1·63	1·21	1·34	1·33	1·03	0·71	0·94	3·34	1·16
	C_v	0·42	0·48	0·74	0·47	0·35	0·34	0·57	0·39	0·46
Overall	r	1·48	1·22	2·37	1·28	0·97	0·66	1·04	2·75	1·17
	C_v	1·68	0·73	1·65	0·57	0·47	0·42	1·08	0·80	0·52
	R^2	0·21	0·84	0·66	0·80	0·84	0·85	0·73	0·87	0·84
	0·75–1·33	9%	54%	26%	32%	57%	26%	28%	17%	39%
	0·50–2·0	19%	84%	57%	70%	84%	70%	61%	41%	80%

Table 3. Comparison of accuracy of the sediment transport formulae

regression coefficient and the coefficient of variation, were also considered and further studied.

The predicted sediment discharges were calculated using the sediment transport formulae described above and the measured data for flow velocity, flow depth, channel slope, cross-section geometry and so on. For the straight channel experiments, sediment transport occurred in the main channel only and the sediment discharges during overbank flows were calculated using the main channel data. For the meandering channel experiments, sediment transport takes place in the main channel (with vertical divisions) for relative depths up to 0·4.[17] For higher relative depths the sediment transport occurred on both the main channel and floodplains. Thus, for overbank flows in meandering channels, the mean velocity, $\boldsymbol{V}$, and the discharge, $\boldsymbol{Q}$, used in the sediment transport formulae are

$$\text{For } Y \leqslant 0{\cdot}4 \qquad V = V_c \qquad Q = Q_c$$
$$\text{For } Y > 0{\cdot}4 \qquad V = V_{ob} \qquad Q = V_{ob}A_{ob} \tag{15}$$

where V_c is the mean main channel velocity, calculated from the integrated discharge for the apex, Q_c; V_{ob} is the average velocity for total channel cross-section; and A_{ob} is the main channel plus part of the floodplain cross-section area where sediment transport was observed. For the experiments included in this study, it was observed that the fraction of the floodplain participating in the sediment transport was approximately 20%.

The Meyer-Peter and Muller formula was developed for bed-load transport prediction only. To calculate the total sediment discharge the suspended load calculated from the Van Rijn formula (equation (12)) was added. The Meyer-Peter and Muller formula overestimated the sediment discharges for the UC and underestimated them for the FCF. The coefficients of variation were high, the regression coefficient was low ($R^2 = 0{\cdot}21$) and only 19% of all discrepancy ratio values lay in the range 0·5–2·0.

The Schoklitch formula has been reported as the best predictor for bed-load transport in mountain streams.[18] Bravo-Espinosa *et al.*[19] compared seven bed-load equations and found that it gave the best prediction for the 22 alluvial streams studied. The Schoklitch formula gave very good prediction for the sediment discharges in the FCF and in the UC, as well. As this formula was developed for bed-load prediction, the suspended load calculated from equation (12) was added to calculate the total sediment discharge. The Schoklitch formula gave very good prediction of the sediment discharge for inbank flow and for overbank flow in straight channels, but overpredicted the sediment discharge for overbank flow in the FCF with meandering planform (Fig. 6). The Schoklitch formula gave overall mean discrepancy ratio of 1·22, 54% of the discrepancy ratio values between 0·75 and 1·33 and 84% of the discrepancy ratio values between 0·50 and 2·00. The formula is simple and the sediment discharge is expressed as a function of unit flow discharge, and not flow depth that is often difficult to predict accurately during overbank flows.

The Engelund and Hansen formula gave better prediction for the sediment discharges in the UC than for the FCF. The velocity, obtained during the calculation procedure from the effective depth and channel slope, increases with increasing depth and subsequently the sediment discharges increase. This velocity calculation method does not reflect the influence of the interaction between the subsection flows or the channel's sinuosity on the velocity. When the experimental mean channel velocity was used instead, the percentage of discrepancy ratio values in the range 0·50–2·00 increased from 57 to 74% but still the Engelund and Hansen formula overpredicted the sediment discharge for the large-scale FCF (Fig. 7).

The Ackers and White formula was calibrated by using a wide range of flume and field data with depths between 0·18 and 11·5 m. The authors stated that the formula is applicable for Froude number less than 0·8 and sediment with a mean particle size greater than 0·04 mm. The Ackers and White formula gave very good prediction of the sediment discharge for both inbank and overbank flow in the

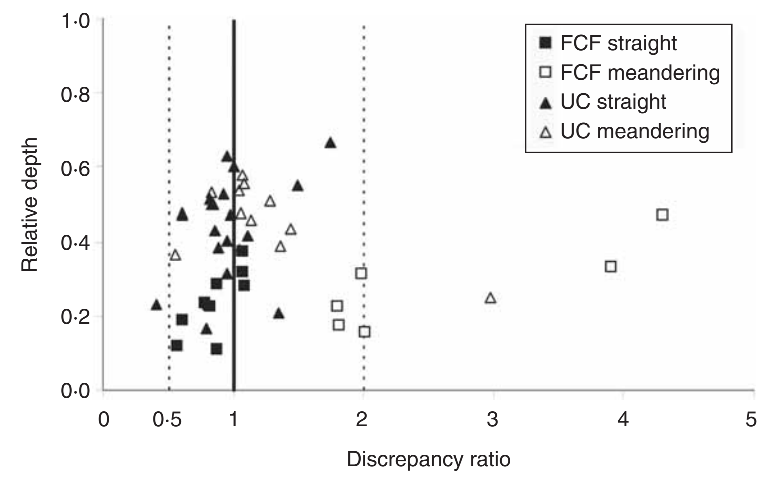

Fig. 6. Sediment discharges prediction with the Schoklitch formula

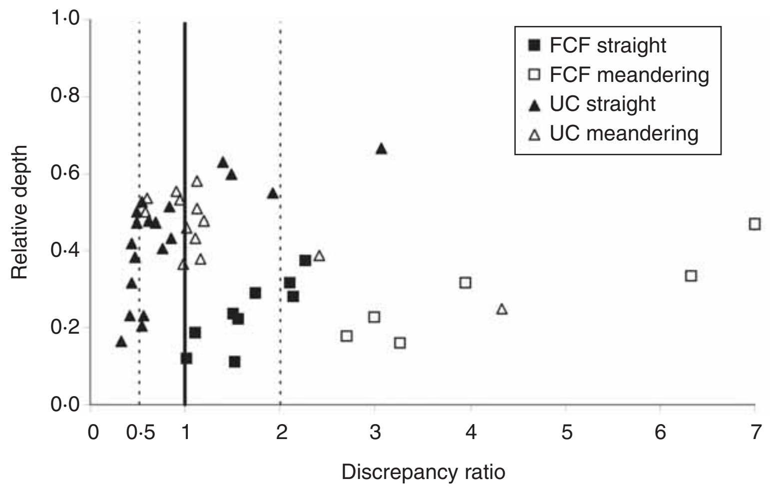

Fig. 7. Sediment discharges prediction with the Engelund and Hansen formula

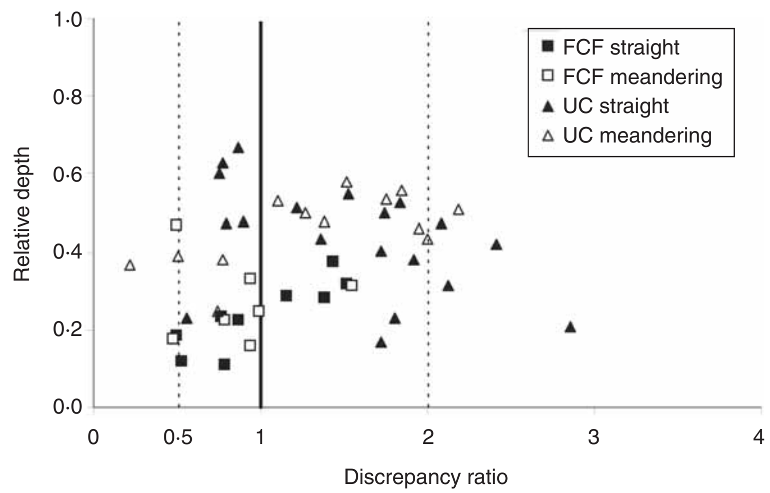

Fig. 8. Sediment discharges prediction with the Ackers and White formula

FCF with straight and meandering planform (Fig. 8). The formula did not show very good predictability for the small-sale UC, which investigated depths smaller than the depth range used to calibrate the Ackers and White formula. The mean discrepancy ratio for the UC was 1·52 and the coefficient of variation was 0·82. Overall, the Ackers and White formula gave a mean discrepancy ratio of 1·28 and 70% of the results in the range 0·50–2·00.

The Yang formula is a power relationship between the sediment concentration and the unit stream power. The coefficients, *I* and *J*, have been calibrated using a large range of data sets covering sediment particle diameters between 0·15 mm and 1·7 mm, flow depths between 0·01 and 15·0 m, channel slopes up to 0·028 and total sediment concentrations varying between 3 and 58 500 ppm. This suggests good predictability using the Yang formula for alluvial channels with sand bed. As only the grain shear stress is considered as effective for bed-load transport, the grain shear velocity calculated by using the Manning–Strickler equation was used. For the studied data, the Yang formula gave very good prediction of the sediment discharges in compound channels with straight and meandering planforms (Fig. 9). The mean discrepancy ratios and the coefficients of variation were within the 'acceptable' ranges for most data sets. The Yang formula gave a very good distribution of the discrepancy ratio values: 57% of the results were in the range 0·75–1·33 and 84% of the results were in the range 0·50–2·00. The good predictive capability for sediment transport of the Yang formula was also demonstrated by Alonso,[20] Yang and Molinas,[21] and Nakato[22] among others.

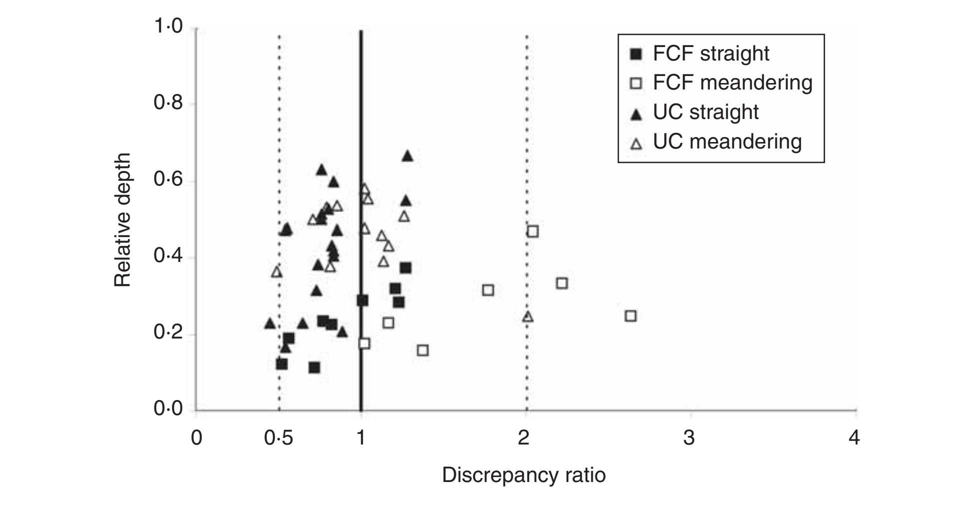

Fig. 9. Sediment discharges prediction with the Yang formula

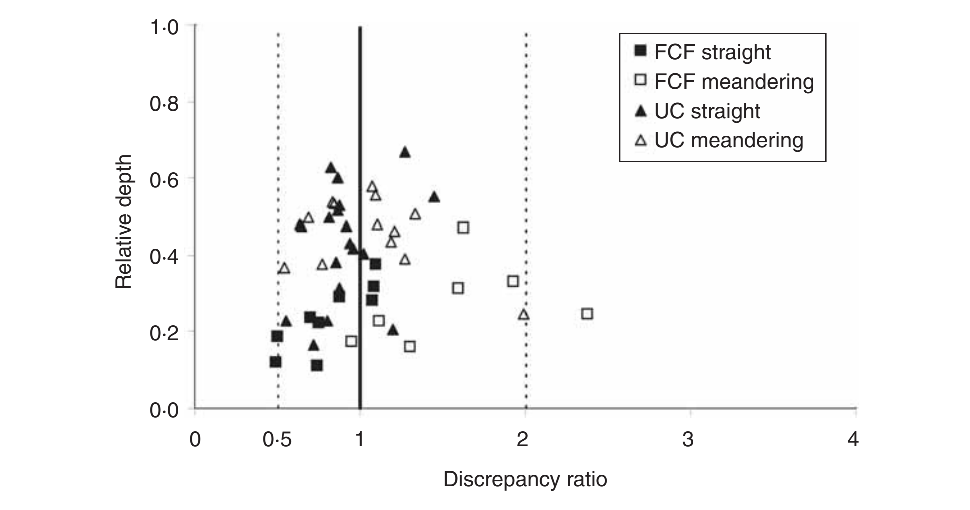

Fig. 10. Sediment discharges prediction with the Karim and Kennedy formula (with calibrated coefficient)

The Karim and Kennedy formula was developed using a wide range of data covering flow depths between 0·03 and 5·2 m, mean particle diameters of the sediment between 0·14 mm and 28·65 mm and mean sediment concentrations between 20 and 49 300 ppm. The formula underestimated the sediment discharges for most data sets but it gave the lowest coefficient of variation (0·43) and a very good regression coefficient (0·86). The results obtained with the original formula are shown in Table 3. Using the experimental data from the current study, a multiple regression analysis between the dimensionless parameters used in the Karim and Kennedy formula was carried out. The power coefficients were close to those estimated by Karim and Kennedy (2·91 against 2·97 and 1·30 against 1·47) but the coefficient of proportionality was larger (0·0022 against 0·00139). Subsequently the constant was re-estimated using the same power coefficients as in the Karim and Kennedy formula. The regression coefficient was 0·80 and the significance $P < 0.001$. The results for the discrepancy ratio values obtained using the Karim and Kennedy formula with the calibrated coefficient of proportionality are shown in Fig. 10. The calculated mean discrepancy value was 1·00 and 95% of the results were in the range 0·5–2·0. These results suggest that the Karim and Kennedy formula could be used for sediment discharge prediction in both inbank and overbank flows in channels with straight and meandering planforms but the coefficient of proportionality needs to be calibrated.

The Van Rijn formula is preferred by a number of researchers but some modifications to the original formula were introduced in some studies.[23,24] When the Van Rijn formula was applied to the studied data as originally proposed, it underestimated the sediment discharges for the FCF with straight planform, overestimated them for the UC with straight planform and underestimated the sediment discharges for both studied facilities with meandering planforms (Table 3). For some studied flows the value of the transport parameter was even negative. Julien and Klaassen[25] also mentioned that the grain shear stress calculated from the logarithmic relationship for the Chezy coefficient reaches the same order of magnitude as the critical shear stress and negative values of T are possible at low transport rates. Therefore, some modifications of the Van Rijn formula were made. Instead of using the Vannoni and Brooks method (cited in French[26]), the Manning–Strickler equation was used to calculate the bed-shear velocity, $\boldsymbol{U^{*\prime}}$. The grain roughness was assumed equal to D_{90}. The modifications of the Van Rijn formula led to improvement of the mean discrepancy ratio values for the studied data sets (Fig. 11). The overall mean discrepancy ratio was 1·03 but the coefficient of variation was still high (1·09) and only 61% of the discrepancy ratio values were between 0·5 and 2·0.

The Molinas and Wu formula overestimated the sediment discharge for the FCF and highly overestimated the sediment discharge for the smaller-scale UC. The overall coefficient of variation was high but the coefficients of variation for the individual data sets were low and the regression coefficient was high. Therefore, the relationship between the concentration and the stream power given by the Molinas and Wu formula was compared with the calculated values for the FCF and the UC. The FCF data followed the curve of the proposed relationship but for the UC the calculated values of stream power corresponding to the measured concentrations are much higher (Fig. 12). The Molinas and Wu formula is based on the stream power concept but the

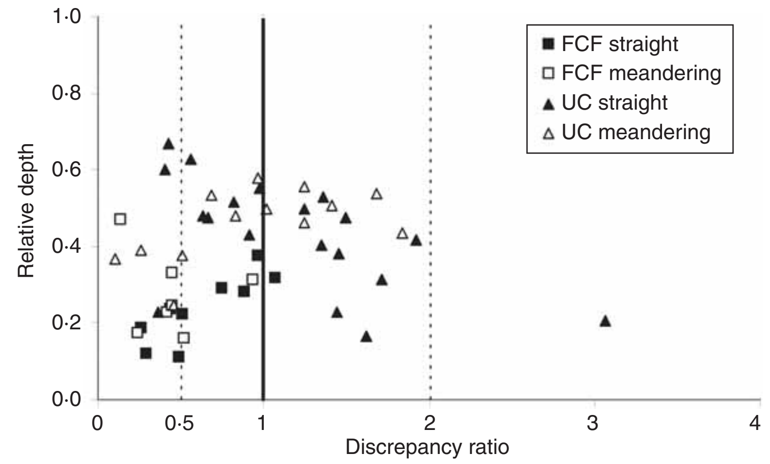

Fig. 11. Sediment discharges prediction with the Van Rijn formula (modified)

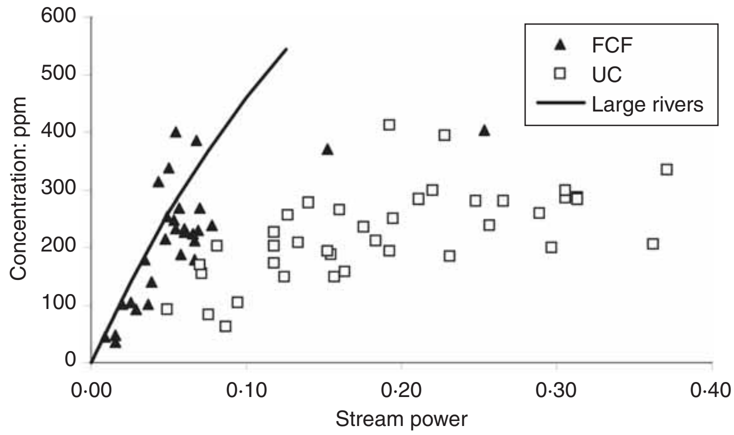

Fig. 12. Sediment discharges prediction with the Molinas and Wu formula

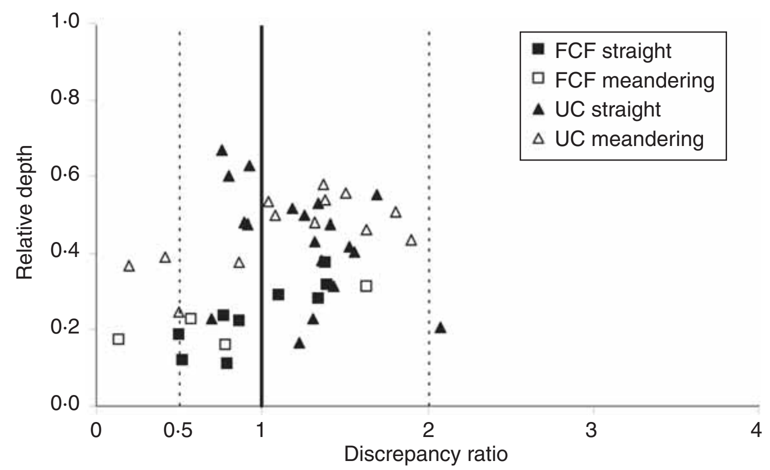

Fig. 13. Sediment discharges prediction with the Yang and Lim formula

parameters have been calibrated using data from medium and large rivers with depths between 1·5 and 62·2 m. In order to avoid the use of the energy slope, which is very sensitive to measurement errors when it is of the order of 10^{-5}, Molinas and Wu substituted the friction factor related to grain resistance with a logarithmic function of flow depth and grain size using a resistance equation valid for wide channels. The use of a resistance equation suitable for the overbank flows and the calibration of the coefficients for particular flow conditions might improve the accuracy of the Molinas and Wu formula for sediment discharge prediction in small streams.

The Yang and Lim formula gave very good prediction of the sediment discharges for most data sets studied (Fig. 13). For the FCF with meandering planform and rough floodplains the calculated shear velocities related to grains were lower than the critical shear velocity but most formulae failed to predict accurately the sediment discharge for this data set. Yang and Lim used dimensional analysis choosing the grain shear stress, the flow depth and the specific weight of sediment as the representative variables. They used a wide range of flume and field data covering sand and gravel sediments with D_{50} between 0·02 and 57·0 mm and flow depths in the range 0·029–16·5 m.[27] The Yang and Lim formula is user-friendly and showed very good agreement between measured and predicted sediment discharges for the studied data sets.

The Yang, Schoklitch and Yang and Lim formulae, which performed best for the studied data, were originally calibrated using data from experiments with a wide range of energy slopes. The Yang formula was previously tested for channels with a sand bed only, while Schoklitch and Yang and Lim formulae are suitable for both sand and gravel bed channels. In the current study, these formulae were tested with data obtained in laboratory channels with flow depths up to 0·36 m and a bed of uniform sand in the main channel. The accuracy of the sediment transport formulae when applied to overbank flow in rivers with uniform or non-uniform sand beds needs to be evaluated further.

The aim of the current study was to demonstrate which of the sediment transport formulae give least discrepancies between the predicted sediment discharges and the sediment discharges measured during both inbank and overbank flows in channels with different scales and sinuosities. Nevertheless, the determination of the sediment discharge with good reliability is important for river engineering practice and the accurate evaluation of the sediment transport formulae for each particular case is essential.

5. CONCLUSIONS

Nine sediment load transport formulae were investigated in this study. They were tested with experimental data obtained during inbank and overbank flows in compound channels with straight and meandering planforms. The comparisons between the measured and predicted sediment discharges showed the following.

(*a*) The formulae, which gave good predictions for sediment discharge for inbank flow, also predicted the sediment discharges for overbank flow with a good accuracy. Most formulae performed more poorly for overbank flow in meandering channels than for overbank flow in straight channels, but the mean discrepancy values were usually close.

(*b*) The Yang formula gave very good predictions of the sediment discharge and concentration for all studied data sets. The Yang and Lim and the Schoklitch formulae also gave very good agreement between the measured and predicted sediment discharges for most data sets. All three formulae failed to predict accurately the sediment discharges for the studied flows in the FCF with meandering planform and rough floodplains.

(*c*) The Karim and Kennedy formula could be a good predictor of the sediment discharge for inbank and overbank flows in channels with straight and meandering planforms but the constant of proportionality needs to be calibrated.

(*d*) The Ackers and White formula gave very good prediction for the FCF and a good overall mean discrepancy ratio but overpredicted the sediment discharge for the small-scale UC.

(*e*) The Molinas and Wu formula gave better prediction of the sediment discharges in the large-scale FCF while the Engelund and Hansen formula performed better for the small-scale UC.

(*f*) The Meyer-Peter and Muller formula and the Van Rijn formula did not give accurate predictions of the sediment discharges for the studied data sets.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided for these studies by the Engineering and Physical Sciences Research Council. The authors would also like to acknowledge the valuable assistance and cooperation received from HR Wallingford Limited and the Rivers Agency of the Department of Agriculture for Northern Ireland.

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