

A practical approach to estimating the flow capacity of rivers – application and analysis

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ABSTRACT: In 2001, the Environment Agency of England and Wales commissioned a Targeted Programme of Research (Evans *et al*, 2001) into reducing uncertainty in conveyance estimation, with the intention of bridging the gap between the advances in scientific knowledge over the past three decades and the calculation approaches adopted in United Kingdom industry practice. The key output was the Conveyance Estimation System (CES) software, which incorporates a methodology (Mc Gahey & Samuels, 2003) for estimating conveyance in a range of channel types and flow conditions, including straight, skewed and meandering plan form shape; simple, two-stage and multi-thread channels; and a variety of vegetation and substrate covers (Defra/EA, 2003; Mc Gahey & Samuels, 2004). In this paper, the CES methodology is applied to fourteen river sites from England, Northern Ireland, New Zealand, Ecuador and Argentina, illustrating reasonable model predictions over a broad application range. Discharge and lateral velocity predictions are compared to observed data, with emphasis on practical application, calibration technique and effects of scale. Consideration is given to the relative magnitude of the equation terms with depth, for example, the role of boundary friction, lateral shear and secondary flows, and how these relate to the observed flow structure and the local site characteristics.

1 INTRODUCTION

Rivers and their associated floodplains form the natural system for the transmission of flood flows. Knowledge of river water levels is essential to flood risk management tasks such as flood risk mapping, strategic planning, scheme design, flood warning and emergency evacuation and channel maintenance. In 2001, the Environment Agency of England and Wales commissioned a Targeted Programme of research into reducing uncertainty in conveyance estimation. The key output was the Conveyance Estimation System (CES) software, which provides a practical methodology for estimating flow capacity in rivers, based on the aggregation and extension of previous laboratory derived approaches for application to natural channels. An essential method requirement was the ease of application to rivers of any scale that may be characterised by irregular cross-section shapes, a variety of surface materials, plan form sinuosity and channel braiding.

Previous approaches to calculating flow capacity can broadly be divided into five categories:

1 *Hand calculation methods* commonly termed Single and Divided Channel Methods where the channel cross-sectional is treated as a single unit or divided into more than one flow zone respec-

tively. These include, for example, the methods of Manning (1889), Lotter (1933), Yen & Overton (1973), Ervine & Baird (1982), Lambert & Myers (1998) and Ackers (1991).

- 2 *Dimensional Analysis* approaches where the dimensionless channel properties such as relative roughness and Froude or Reynolds' Number are evaluated for scale models and assumed similar for the prototype (e.g. Rameshwaran & Willets, 1999).
- 3 *Additional energy losses due to bends*, for example, the Soil Conservation Service (SCS) and Linearised SCS methods and the work of Chang (1984).
- 4 *Energy 'loss' methods* which assume that the energy transfers within each flow zone (e.g. main channel or floodplain region) are proportional to the square of the local flow velocity and they are mutually independent and hence the principle of superposition can be applied. Well known methods include those of Ervine & Ellis (1987), James & Wark (1992) and Shiono *et al* (1999).
- 5 *Reynolds Averaged Navier-Stokes (RANS)* approaches, which are based on the depth-integration of the RANS equations for flow in the streamwise direction. Significant research contributions include Shiono & Knight (1988), Wark

(1993), Abril & Knight (2004), Spooner & Shiono (2003) and Bousmar & Zech (2004).

These previous conveyance approaches have largely focused on experimental channels, which are prismatic, symmetrical and comprise rectangular or trapezoidal cross-section shapes. Although they provide useful quantifiable parameters for estimating discharge such as width ratios, relative depth, relative roughness and main channel side slopes, they are less useful when applied to rivers with irregular, asymmetrical shapes that may be characterised by distributed roughness or channel braiding. The CES methodology utilizes the ‘as surveyed’ river cross-sections and the observed local roughness features, while incorporating the aforementioned parameter definitions as a guide to understanding and quantifying the energy transfer mechanisms, and hence deriving more universally applicable parameters. This paper demonstrates the broad application range of the CES methodology, through application to fourteen river sites from five countries. An analysis of the relative magnitude of the CES equation terms, i.e. energy transfers due to hydrostatic pressure, boundary friction, lateral shearing and secondary circulations, is undertaken for inbank, main channel overbank and floodplain flow conditions.

2 METHODOLOGY

The methodology is based on the depth-integration of the Reynolds-Averaged Navier-Stokes equations,

$$ghS_o - \frac{\varphi fq^2}{8h^2} + \frac{\partial}{\partial y} \left[\lambda h \left(\frac{f}{8} \right)^{\frac{1}{2}} q \frac{\partial}{\partial y} \left(\frac{q}{h} \right) \right] = \alpha\Gamma + (1-\alpha)C_{uv} \frac{\partial}{\partial y} [h] \quad (1)$$

where g = gravitational acceleration (ms^{-2}); q = streamwise unit flow rate (m^2s); h = local depth normal to the channel bed (m); S_o = reach-averaged longitudinal bed slope; y = lateral distance across the channel (m); φ = projection of the boundary shear stress onto the plane due to choice of Cartesian coordinate system; and α = function of the reach-averaged sinuosity. Equation 1 has four calibration coefficients: the local friction factor f , the dimensionless eddy viscosity λ , the secondary flow parameter Γ and the coefficient of meandering C_{uv} . The total flow rate, Q (m^3s^{-1}), is hence evaluated from,

$$Q \approx \int_0^b q dy \quad (2)$$

where b = the total channel width (m). The fourteen river sites are all located in straight reaches, and thus Equation 1 can be simplified to,

$$ghS_o - \frac{\varphi fq^2}{8h^2} + \frac{\partial}{\partial y} \left[\lambda h \left(\frac{f}{8} \right)^{\frac{1}{2}} q \frac{\partial}{\partial y} \left(\frac{q}{h} \right) \right] - \Gamma = 0 \quad (3)$$

(1) (2) (3) (4)

where Term 1 is the hydrostatic pressure, Term 2 is the boundary friction, Term 3 is the turbulence due to vertical interfacial shearing and Term 4 represents the secondary circulations due to turbulence in straight channels. The key difference between Equation 3 and the Shiono & Knight (1988) Method (SKM) is the evaluation of f and Γ in natural channels. Here, f is derived from a local unit roughness n_l , which is converted to an equivalent roughness size, k_s , and then the Colebrook-White Law is incorporated to evaluate the lateral distribution of f at each flow depth (Mc Gahey & Samuels, 2004). The dimensionless eddy viscosity is derived from (Abril & Knight, 2004),

$$\lambda = \lambda_{mc} \left(-0.2 + 1.2D_r^{-1.44} \right) \quad (4)$$

where λ_{mc} = main channel dimensionless eddy viscosity; and D_r = local relative depth given by h/h_{max} . Here, λ_{mc} is taken as 0.24 for rivers after Elder (1959). The secondary flow model Γ , which is based on the work of Abril & Knight (2004), is adapted to incorporate a transitional model Γ_{trans} for asymmetric channels and channels with floodplains at different bed elevations. The main channel inbank, overbank and floodplain formulae are given by (Abril & Knight, 2004),

$$\Gamma_{mci} = 0.05H\rho gS_o; \quad \Gamma_{mco} = 0.15H\rho gS_o; \quad \Gamma_{fp} = -0.25H\rho gS_o \quad (5a-c)$$

where ρ = fluid density (kg m^{-3}). For asymmetric channels or channels with floodplains situated at different bed elevations, the secondary flow model in the main channel transitional region is given by (Mc Gahey, in prep.),

$$\Gamma_{mc(trans)} = \frac{(\Gamma_{mco} - \Gamma_{mci})}{(Z_H - Z_L)} (h_l - Z_L) + \Gamma_{mci} \quad (6)$$

where Z_H and Z_L = bed elevation of the higher and lower floodplains respectively (mAD); and h_l = water surface level for the given depth of flow (mAD).

A further difference is that the CES solution technique is based on the continuity of the unit flow rate q rather than the depth-averaged velocity as previously used in the SKM approach. This is due to the strong continuity properties of q with variations in depth, for example, across a vertical face or ‘step’ in an engineered channel cross-section (Samuels, 1989; Knight *et al*, 2004). The approximation to the solution of Equation 3 is generated by the Finite Element Method (Defra/EA, 2003b).

3 DESCRIPTION OF DATA SETS

The methodology is applied to fourteen data sets from England, Northern Ireland, New Zealand, Ecuador and Argentina. These are summarized in Table 1, including information on bankfull flow rate Q_{bf} , bankfull depth h_{bf} , main channel width b_{mc} and the bed slope S_o . These data sets cover a range of channel types and scales, notably:

- 1 *Cross-section shape*: the river sections are all irregular in shape and they include simple (*), compound (**), and asymmetrical (***) shapes (Tab. 1) as well as a range of aspect ratios (b/h).

Table 1: Summary of data sets

Data Set	Q_{bf} m^3s^{-1}	h_{bf} m	b_{mc} m	S_o $\times 10^{-3}$
England				
1. ** River Severn, Montford Bridge (Knight, 1989)	184	5.75	35	0.195
2. *** River Trent, North Muskham (Knight, 1989)	392	6.2	55	0.17-0.74
3. *** River Trent, Yoxall (Knight, 1989)	~70	2.1	30	1
4. *** River Torridge, Torrington	187	2.78	28	1.45
5. ** River Blackwater, Ower	~12	2	6	1.6
6. ** River Dane, Rudheath (Ervine & MacLeod, 1999)	~90	5	26	0.5-1.1
Northern Ireland				
7. ** River Main, County Antrim (Myers & Lyness, 1990)	~17	0.95	14	2.97
New Zealand				
8. * River Heathcote, Sloan Terrace (Hicks & Mason, 1998)	~6.5	1.75	9	0.62-0.35
9. * River Ngunguru, Drugmores Rock (Hicks & Mason, 1998)	~30	~2.5	20	3.7-6.4
10. * River Waiwakaiho (Hicks & Mason, 1998)	~35 @2m	-	35	9.1-17.6
Ecuador				
11. * River Cuenca, Ucubamba (Abril & Knight, 2004)	~160	2.3	40	15
12. * River Tomebamba, Monay (Abril & Knight, 2004)	~28	1.53	25	17.6
Argentina				
13. * River Colorado, Patagonia (Tarrab, pers. comm.)	~420	3.6	60	1.3
14. * River La Suela, Cordoba (Tarrab, pers. comm.)	~65	2.14	25	0.9-1.8

* = Simple; ** = Compound; *** = Asymmetrical

- 2 *Channel cover*: the bed, bankside and floodplain ground material includes silt, gravel, cobbles and, small and large boulders well as different vegetation types such as grass, heavy weed growth and fallen trees (Tab. 2).

Table 2: Summary of roughness cover for each channel

River	Roughness description
1. Severn	Grass-covered floodplains
2. Trent, Mus.	Fine gravel & alluvial silts on bed, trees & bushes on floodplain
3. Trent, Yox.	Gravel bed, summer in-channel weed growth, grass & bushes on floodplains
4. Torridge	Trees on berm
5. Blackwater	Vertical sheet piling, fallen trees
6. Dane	Thick channel edge growth, less dense over floodplain
7. Main	Coarse gravel bed, quarry stone side slopes, heavy weed growth on berms
8. Heathcote	Angular cobbles, gravel, mud & silt on channel bed, long bankside grass
9. Ngunguru	Gravel & cobbles on bed, grazed grass & scattered brush on banks
10. Waiwakaiho	Large boulders ($d_{50} \sim 2$ m), sparse scrub
11. Cuenca	Small boulders ($d_{50} \sim 1$ m)
12. Tomebamba	Large boulders ($d_{50} \sim 1.3$ m)
13. Colorado	Clay bed, rock banks
14. La Suela	Alluvial with sparse bankside vegetation

- 3 *Longitudinal bed slope*: the data includes steep mountain rivers such as the Cuenca and Tomebamba as well as more gentle gradients such as the Severn and the Trent.
- 4 *Scale*: This includes a range of flow rates and channel sizes, where Q_{bf} ranges from $420 m^3s^{-1}$ in the Colorado to a mere $7 m^3s^{-1}$ in the Heathcote and similarly, h_{bf} varies from 1 through to 6 m. The main channel widths vary from 70 m in the Colorado to 6 m in the Blackwater and the floodplain widths vary from 500 m in the Dane to 30 m in the Main.
- 5 *Channel braiding*: The Torridge and the Blackwater are characterised by high banks or 'levees' with low adjacent floodplains, which provide an effective channel braiding.

4 VELOCITY AND DISCHARGE PREDICTION

Discharge and velocity predictions have been made for the fourteen river sites. The calibration philosophy is based on the bed friction only. The input local unit roughness n_i , from which the friction factor f is derived (Mc Gahey & Samuels, 2004), is varied in order to reduce the overall percentage difference Λ (%) between the predicted Q_{CES} and measured flow rates Q_{data} i.e.

$$\Lambda = \frac{\sum_{i=1}^n \left| \frac{Q_{data} - Q_{CES}}{Q_{data}} \right|_i}{n} * 100 \quad (7)$$

where n is the number of data points for comparison. The standard deviation ζ is given by,

$$\zeta = \sqrt{\frac{\sum_{i=1}^n \left[\left(\frac{Q_{data} - Q_{CES}}{Q_{data}} \right)_i - \left(\frac{Q_{data} - Q_{CES}}{Q_{data}} \right)_i \right]^2}{n}} \quad (8)$$

For a given channel cross-section, the unit roughness n_l is provided for a 1m depth of flow, and the depth-variation of roughness is introduced through the Colebrook-White Law. Once Λ has been minimised i.e. the overall flow predictions are reasonable for the full depth-range, the lateral distribution of n_l is refined in order to best predict the lateral depth-averaged velocity distributions at each depth of flow. This is based on visual inspection of the predicted and measured velocities. The velocity results are shown for three of the sites, selected to illustrate an example of a simple, compound and asymmetrical braided channel. Figures 1, 2 and 3 show the depth-averaged velocity predictions for the River Colorado, the River Severn and the River Trent at Yoxall and the calibrated n_l values are given in Table 3.

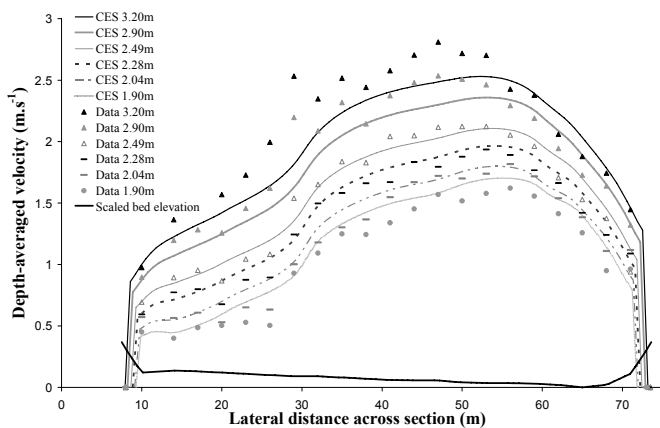


Figure 1: Depth-averaged velocity predictions for different flow depths in the River Colorado, Patagonia

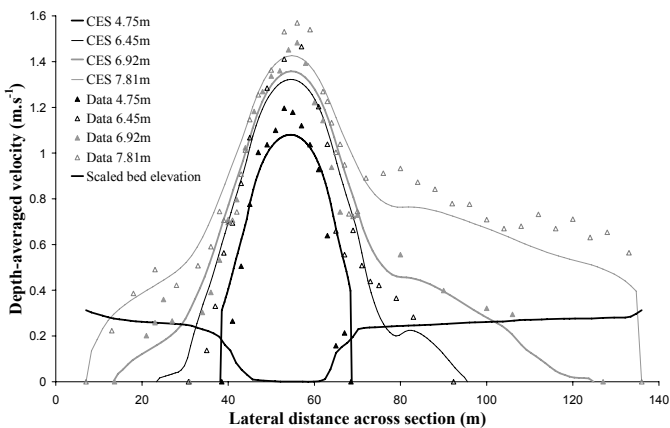


Figure 2: Depth-averaged velocity predictions for different flow depths in the River Severn at Montford Bridge

The River Colorado tends to under-predict the high velocities at large flow depths and slightly over-

predict the velocities at lower depths. This is most likely a short-coming in the use of the Colebrook-White formulation for establishing the variation of roughness with depth for this wide channel, where bed generated turbulence has a dominant role and the channel banks have less influence. The River Severn data is captured reasonably well, other than the very high velocities in the centre region of the channel. This may indicate that the CES model is over-representing lateral shearing through a large main channel dimensionless eddy viscosity λ_{mc} value of 0.24 in rivers, resulting in an increased retarding effect of the slower floodplain flow on the main channel flow. The River Trent data includes measurements for two depths of flow. The predictions here are considered reasonable given that the measurements indicate an overall velocity reduction in the main channel for a larger flow depth. For the braided flow depth, the predicted floodplain velocities are supported by the measurements.

In general, the measured velocities are reasonably well-predicted throughout the depth range for the three rivers.

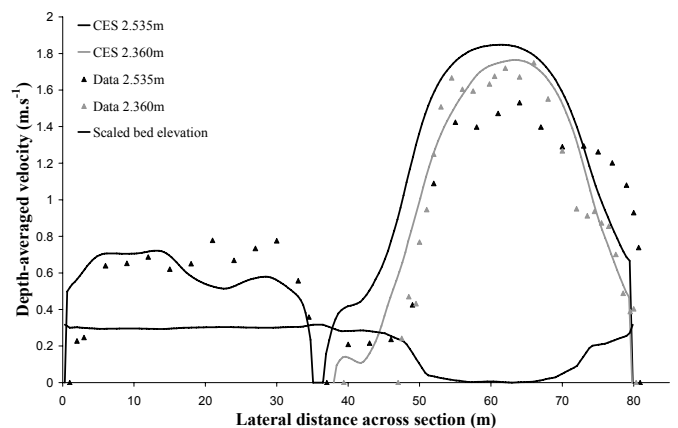


Figure 3: Depth-averaged velocity predictions for two flow depths in the River Trent, Yoxall

Table 3: Summary if unit roughness values, overall percentage flow difference and standard deviation

River	Calibrated n_l			Λ (%)	ζ
	left fp	Mc	right fp		
1. Severn	0.050	0.027	0.028	7.9	17.0
2. Trent, Mus.	-	0.030	0.030	6.6	10.8
3. Trent, Yox.	0.015	0.032	-	13.3	17.9
4. Torridge	0.035	0.029	-	4.8	5.5
5. Blackwater	0.100	0.061	0.100	4.2	5.8
6. Dane	0.082	0.033	0.082	14.7	23.1
7. Main	0.075	0.030	0.045	5.6	7.6
8. Heathcote	-	0.031	-	6.8	7.9
9. Ngunguru	-	0.068	-	3.5	48.9
10. Waiwakaiho	-	0.250	-	34.1	37.1
11. Cuenca	-	0.065	-	14.5	16.3
12. Tomebamba	-	0.165	-	8.3	7.9
13. Colorado	0.048*	0.028	0.048*	4.0	4.3
14. La Suela	0.048*	0.032	0.040*	10.9	13.3
<i>Average</i>				9.9	

*channel side banks

Figure 4 provides a comparison of the predicted flow rates Q_{CES} to the measured flow rates Q_{data} for all the river sites. A perfect match between the model prediction and the data would yield a gradient of 1.0 i.e. $Q_{CES} = Q_{data}$. A least squares regression line gives an R^2 value of 0.9889, indicating a ‘good’ fit, and a gradient, i.e. Q_{CES}/Q_{data} , of 0.9822. The latter is just less than 1.0, suggesting the CES tends to marginally under-predict the flow rate. Figures 4 and 5 demonstrate the range of scales for which the CES predictions are appropriate, from small rivers such as the Heathcote, with flow rates of $7 \text{ m}^3\text{s}^{-1}$, through to larger rivers such as the Severn, with flow rates in the range 200 to $300 \text{ m}^3\text{s}^{-1}$, and finally to much large rivers such as the Trent and the Colorado, with flow rates upwards of $400 \text{ m}^3\text{s}^{-1}$. The data shows an increasing degree of scatter with increasing flows. This is not surprising since there is more uncertainty associated with river measurements taken at high flows, for example, drowned gauge sites, and further to this, the empirically derived model coefficients and models such as Equations 4 and 5 for λ and Γ were largely based on laboratory measurements.

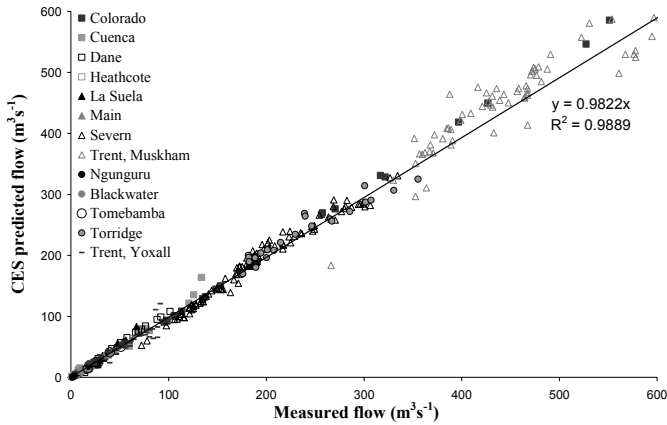


Figure 4: Predicted and measured flow rates for the thirteen river sites

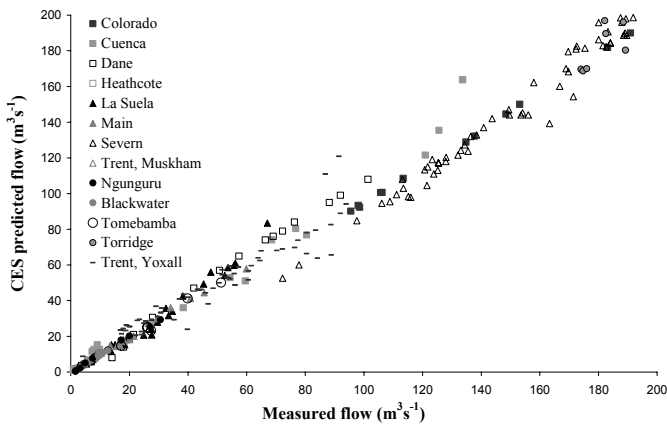


Figure 5: Predicted and measured flow rates for the thirteen river sites (flow rates $< 200 \text{ m}^3\text{s}^{-1}$)

Table 3 provides the overall percentage difference Λ for each data set, giving an average value for the fourteen data sets of 9.9%. This value is inflated by

the large contributions of the Trent at Yoxall, the Dane, the Waiwakaiho and the Cuenca. For the Trent, this is not surprising considering the aforementioned trend in the measured velocity data, where greater flow depths have lower velocities. In addition, there is more uncertainty associated with the floodplain measurements, which are beyond the range of the main channel cableway span, and are therefore based on four overbank gauge points. The Dane is characterised by dense seasonal vegetation, and as the high and low flows are typically measured in different seasons, the vegetation characteristics will be different. This seasonal variation is not incorporated in the roughness representation. The Waiwakaiho and the Cuenca are steep mountain rivers with large boulders, and the existing CES methodology does not incorporate a model for boulder roughness. Mc Gahey (in prep.) demonstrates the improvement in the CES predictions for mountain rivers through application of the Ramette (1992) approach to evaluate the lateral distribution of f with flow depth. Without these four river sites, the average percentage difference is reduced to 6.2%, suggesting a reasonable performance of the CES methodology to at least ten river sites.

Table 3 also includes the standard deviation ζ for each site. These values tend to be larger than the overall percentage difference Λ , as the expected or mean value is zero i.e. $Q_{CES} - Q_{data}$, and thus any variation on this mean has a large value relative to zero. The Ngunguru has the largest ζ despite the small value of Λ , indicating a high degree of scatter in the data. The Waiwakaiho has a large ζ , which is not unexpected considering Λ is a similar order of magnitude. Likewise, the large ζ values for the Dane and the Trent also reflect the large Λ values. For the remaining sites, the standard deviation ζ is small and corresponds to the average percentage difference, Λ . This indicates a reasonable model performance in predicting each measured value within each data set, as these measurements are reasonably well-distributed about the CES predicted values.

5 RELATIVE MAGNITUDE OF EQUATION TERMS

Quantifying the relative magnitude of the four principal equation terms in Equation 3 is useful in understanding which flow processes have a dominant role, how these mechanisms change with the depth of flow and what channel properties influence these changes. For example, in wide rectangular channels with no vegetation there may be less lateral mixing than in a heavily vegetated irregular-shaped channel. Essential to this is identifying where the relative contributions are the result of a prescribed model within the CES methodology, for example, a change in the role of the secondary flow term between in-

bank and overbank flow (Equation 5a-c), compared to external predetermined input parameters such as longitudinal bed slope, channel shape and roughness. The average contributions from the different terms are considered for inbank, main channel overbank and floodplain regions. The river cross-sections and flow depths which are considered are shown in Figures 6 to 16 (placed at the end to aid readability).

Figure 17 provides the relative magnitude of Terms 1 to 4 in Equation 3 for inbank flow conditions in seven rivers.

The averages values are 45% hydrostatic pressure, 43% boundary shear; 9%, vertical interfacial shear and 2% secondary circulations. The large contribution from Term 1 and 2 is not unexpected, as these these constitute the primary balance of forces in the absence of any lateral momentum transfers. Without Terms 3 and 4, Equation 3 would simplify to the well known Darcy-Weisbach equation. The Term 3 contribution is more variable, indicating different degrees of lateral shear. In wide shallow channels, the side-walls have less influence on the channel centre and the flow is therefore dominated by bed generated turbulence. The velocity gradient is therefore approximately zero in the channel centre, and the Term 3 contribution is small. In narrow deep channels, the side-walls play a larger role, and there is a greater degree of lateral shearing. Figure 18 provides a plot of the percentage lateral shearing versus aspect ratio where the data trend corroborates this reasoning.

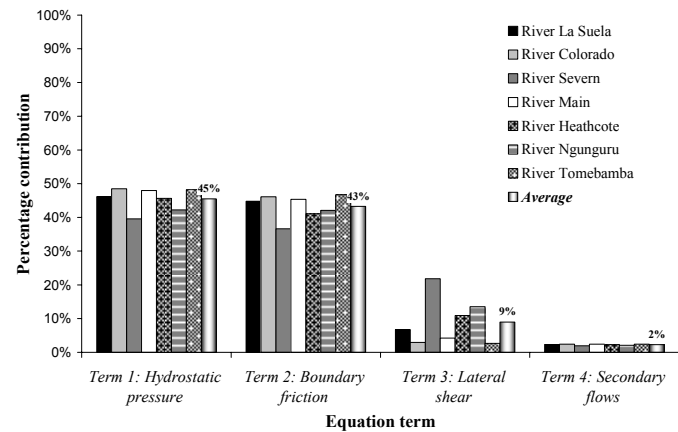


Figure 17: Relative magnitude of equation terms for inbank river flow

The Colorado, the Main, the Waiwakaiho and the Tomebamba all have modest lateral momentum transfers. This is partly due to the large aspect ratios, and partly that the channels have little vegetation and where there is vegetation or boulders there is limited information on the exact location, resulting in the use of average cross-section input unit roughness n_l values. The Heathcote and Ngunguru have a greater degree of lateral shearing which may be explained by the large roughness features which enhance the lateral velocity gradients. The Heathcote has vegetation on the banks and angular cobbles on

the channel bed and the Ngunguru is characterised by gravel and small cobbles.

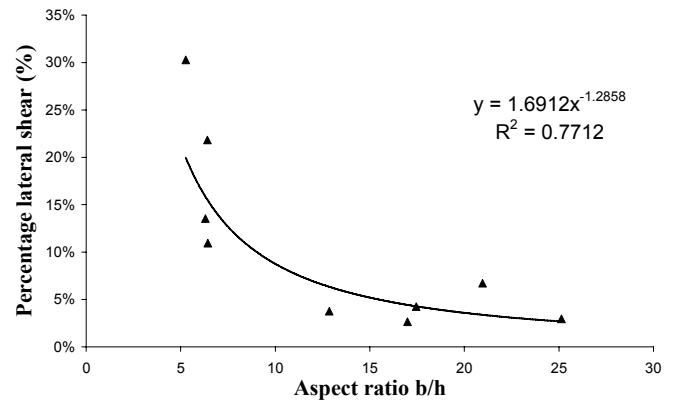


Figure 18: Variation of the percentage lateral shear (Term 3) with aspect ratio

Secondary circulations have a small role in inbank flow, which is reflected in the low empirically derived '0.05' value in Equation 5a, and hence through the small contribution of Term 4.

Some of the rivers differ from the more general trend, for example, the River Severn has a low hydrostatic pressure term and a high degree of lateral shear relative to the other sites. The former may result from incorporating a representative reach-averaged longitudinal slope based on measured water levels for at high flow depths, whereas in reality the surface water slope at Montford Bridge varies substantially with depth (Knight, 1989a). The latter may be attributed to the dense channel vegetation.

Figure 19 provides the relative magnitude of Terms 1 to 4 in Equation 3 for main channel overbank flow conditions in five rivers. The averages values are 44% hydrostatic pressure, 35% boundary shear; 14%, vertical interfacial shear and 7% secondary circulations.

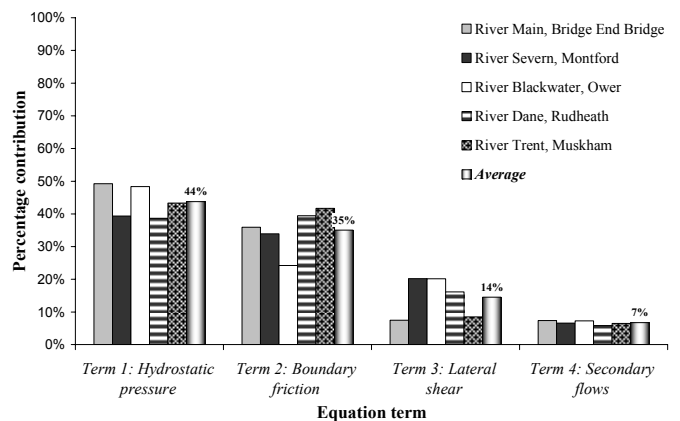


Figure 19: Relative magnitude of equation terms for main channel flow in two-stage rivers

The Severn and the Dane have small hydrostatic pressure contributions, which may be related to the high degree of lateral shearing present in the deep narrow main channel regions. As with the inbank case, the Main has substantially less lateral shearing, than for example, the Severn, as there is less vegeta-

tion present and the conveyance is therefore largely geometry driven.

The Blackwater has a noticeably small boundary friction contribution. This is most likely related to the cross-section geometry, in that the irregular geometry results in local steep velocity gradients and hence large lateral momentum transfers. This is reflected in the high lateral shear contribution, which off-sets the boundary friction term in balancing the hydrostatic pressure.

The secondary flow contribution for all sites is more than double that of the inbank flow sites, reflecting the larger '0.15' value in Equation 5b.

Figure 20 provides the relative magnitude of Terms 1 to 4 in Equation 3 for the floodplain flow conditions. The averages values are 36% hydrostatic pressure, 49% boundary shear; 5%, vertical interfacial shear and 9% secondary circulations.

The average hydrostatic pressure term is substantially smaller for floodplain flow, which may be attributed to the lower floodplain flow depths and the high boundary friction due to the presence of dense floodplain vegetation. The most variable contribution is the vertical interfacial shear. This is approximately zero for the Dane, which may be explained by the low floodplain depths. Conversely, the Trent has the highest lateral shear, which results from the steep velocity gradient at the floodplain main channel interface coupled with the relatively short floodplain width i.e. the inundated floodplain extent is not sufficiently wide to achieve a constant lateral velocity gradient.

The average secondary flow contribution is large, reflecting the large value of the prescribed CES model coefficient in Equation 5c.

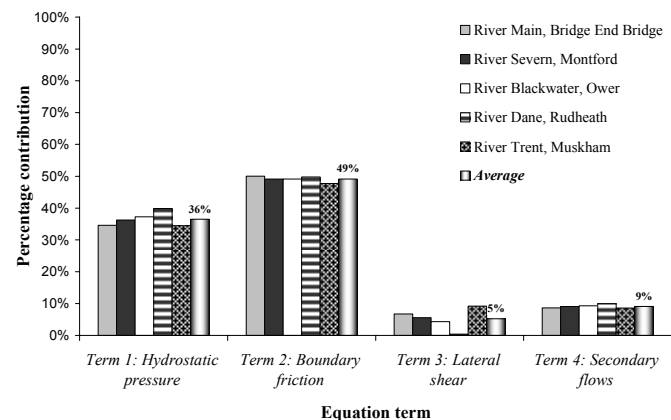


Figure 20: Relative magnitude of equation terms for floodplain flow in two-stage rivers

6 CONCLUSIONS

A practical approach to estimating the flow capacity of rivers has been demonstrated for fourteen rivers sites from five different countries, where the unit roughness n_l was the only calibration parameter. The depth-averaged velocity predictions compared rea-

sonably well to the measured data for a simple, compound and asymmetrical river example over a range of flow depths. The predicted Q_{CES} and measured Q_{data} flows for fourteen river sites showed a least squares regression fit of 0.9889, which is close to an ideal fit of 1.0. The ratio of Q_{CES} to Q_{data} was 0.9882, suggesting that the CES is more likely to slightly under-predict than over-predict the measured flow values. The average percentage difference Λ between the measured and predicted flows for all sites was 9.9%, demonstrating the effectiveness of the model over a range of scales and channel types. This value may be reduced to 6.2% if the mountainous rivers with large boulders are excluded. The CES methodology is therefore a useful approach for application in river engineering practice, as it incorporates models and parameters that can readily be applied to natural channels, over a range of scales, with irregular geometries, roughness features and channel braiding.

An analysis of the relative magnitude of the four equation terms in Equation 3 was undertaken for inbank, overbank and floodplain flow. As expected, the hydrostatic pressure and the boundary shear terms were large and they constituted the primary force balance. The boundary friction term was $\sim 10\%$ higher in the floodplain region due to low flow depths and greater vegetation roughness. The lateral shearing term was the most variable. For inbank flows, the variations were shown to be closely related to the aspect ratio. For overbank flow, this was dependent on the floodplain flow depths, where for low or very high floodplain depths, the floodplain flow has less retarding influence on the main channel flow. For main channel overbank flow, the degree of lateral shearing is linked to vegetation growth. The secondary flow contributions are generally small relative to the other equation terms, with a larger contribution in compound channels.

This analysis is useful in practice as it enables practitioners to focus their attention on particular river features. For example, river surveys should ideally include detailed descriptions of the exact cross-section location and nature of vegetation features. It further draws attention to the importance of the main channel dimensionless eddy viscosity λ_{mc} value as well as the rule applied in Equation 4, which may not always be appropriate in describing the lateral shearing in two-stage rivers.

7 RECOMMENDATIONS

The CES methodology has been demonstrated for fourteen river sites, all located in straight river reaches. For further testing, it is recommended that a targeted data acquisition programme is implemented, where the data collection focuses on straight and meandering two-stage natural channels, and

measurements include discharge, water level, depth-averaged velocities and, where possible, turbulence measurements.

The methodology incorporates the Colebrook-White Law to evaluate the lateral distribution of the friction factor for each depth of flow. For mountain streams with boulders, an alternative formulation, such as the method of Ramette (1992) is recommended.

The importance of the lateral shearing term in two-stage channels is highlighted. Thus, further investigation of the applicability of Equation 4 for the lateral distribution of the dimensionless eddy viscosity λ in two-stage rivers is advocated.

8 ACKNOWLEDGEMENTS

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CROSS-SECTION FIGURES 6 TO 16

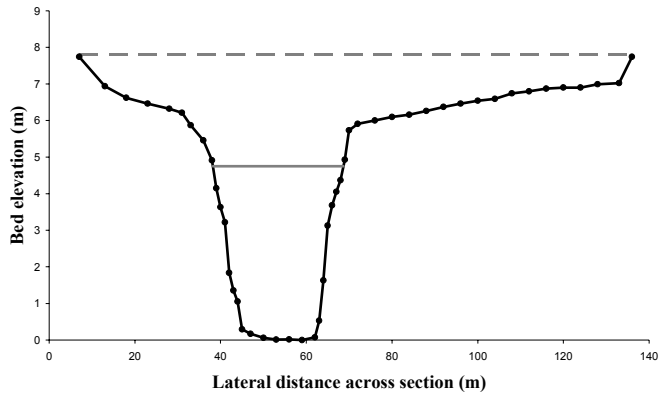


Figure 6: River Severn, Montford

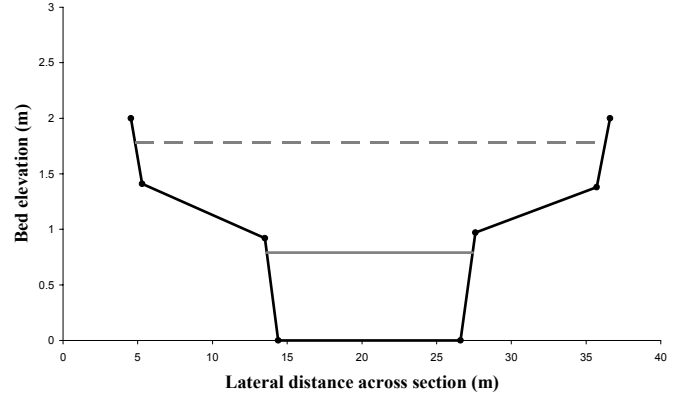


Figure 10: River Main, County Antrim

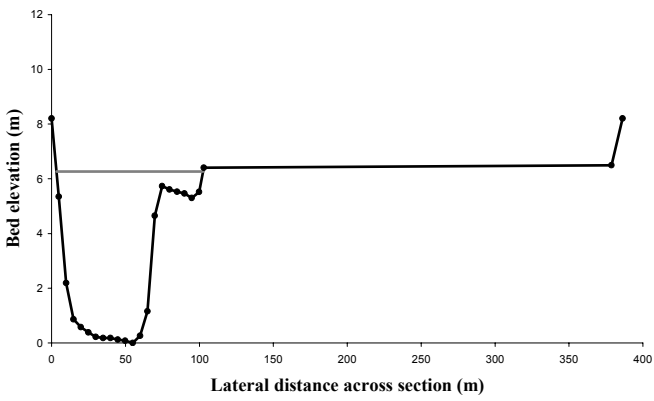


Figure 7: River Trent, North Muskham

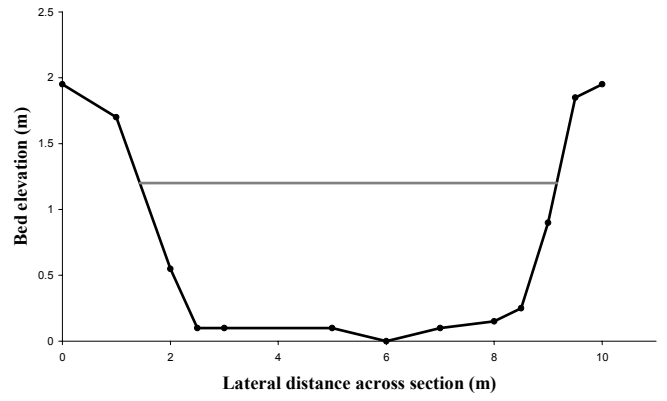


Figure 11: River Heathcote, Sloan Terrace

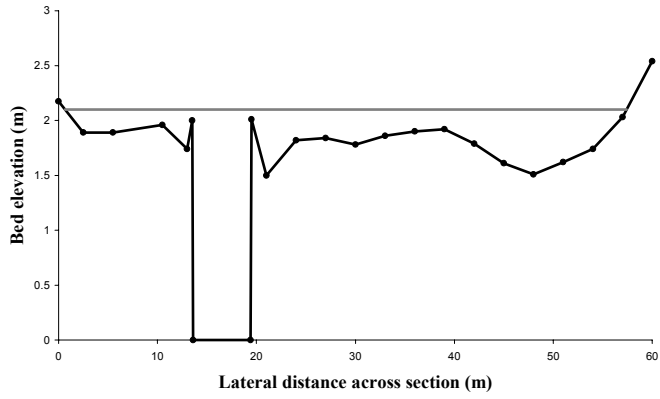


Figure 8: River Blackwater, Ower

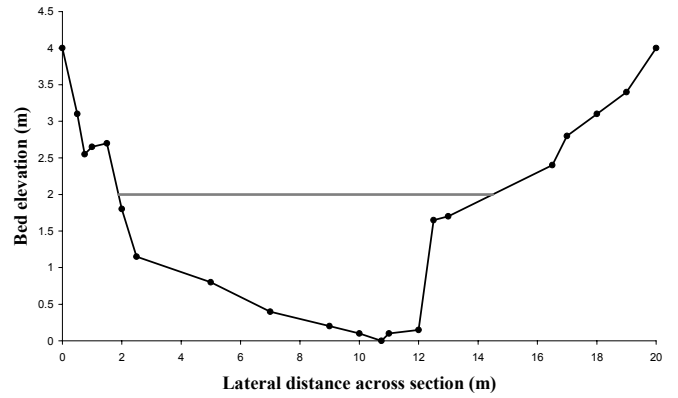


Figure 12: River Ngunguru, Drugmores Rock

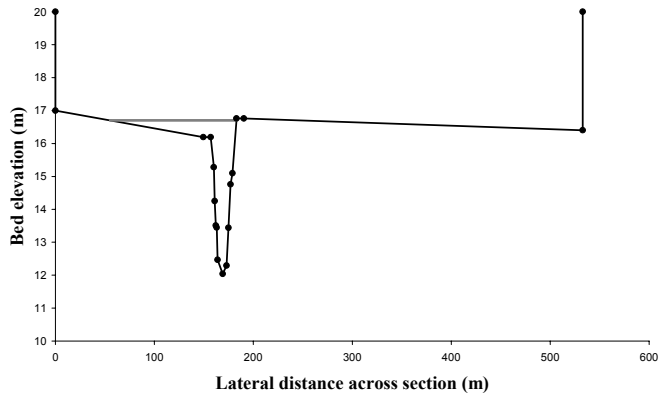


Figure 9: River Dane, Rudheath

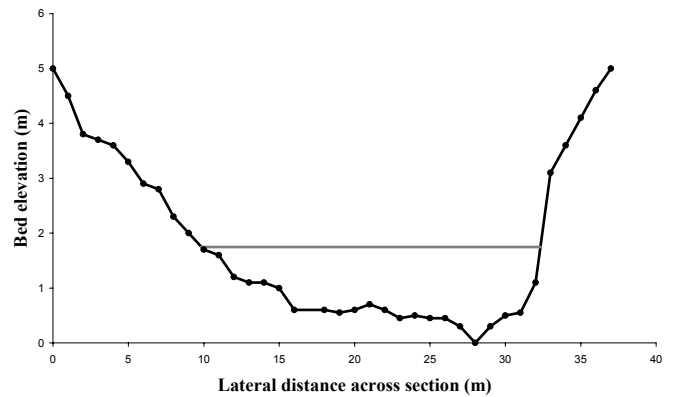


Figure 13: River Waiwakaiho, SH3

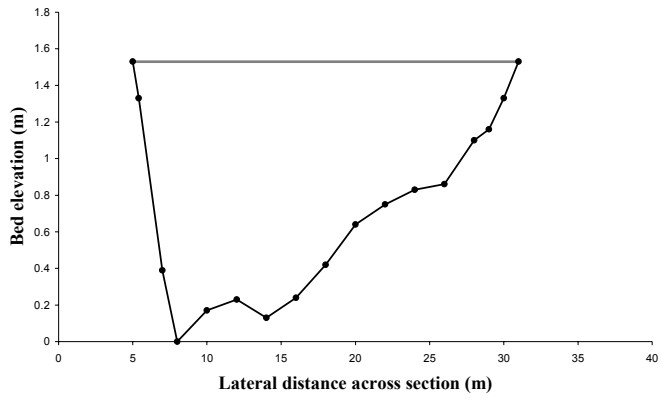


Figure 14: River Tomebamba, Monay

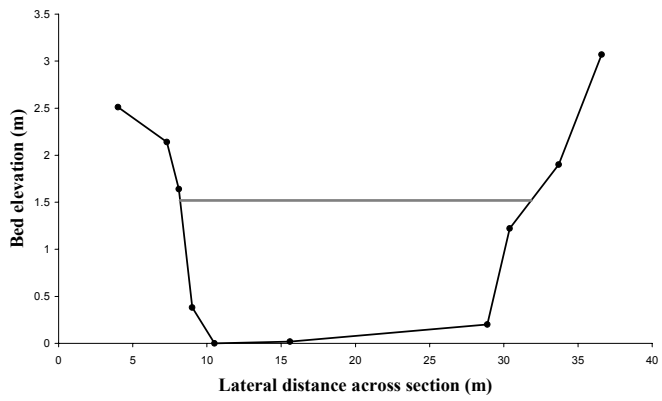


Figure 15: River La Suela, Cordoba

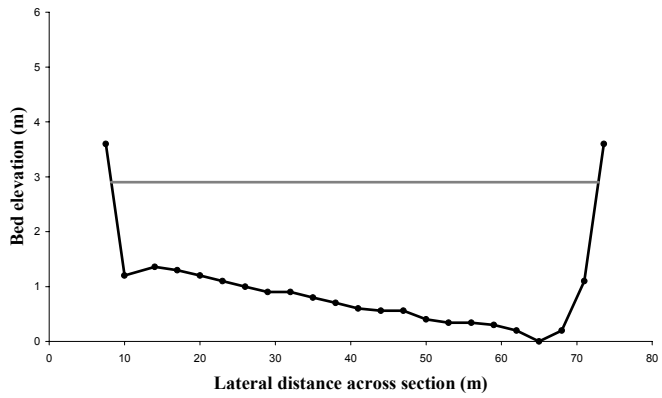


Figure 16: River Colorado, Patagonia