Revised paper submitted to the Journal of Hydraulic Research, following review P2916. Sent for publication 21/12/06.

THE CONCEPT OF ROUGHNESS IN FLUVIAL HYDRAULICS AND ITS FORMULATION IN 1-D, 2-D & 3-D NUMERICAL SIMULATION MODELS

By **Hervé Morvan** (School of Civil Engineering, The University of Nottingham, UK)**,** **Donald Knight** (Department of Civil Engineering, The University of Birmingham, UK), **Nigel Wright** (School of Civil Engineering, The University of Nottingham, UK), **Xiaonan Tang** (Department of Civil Engineering, The University of Birmingham, UK) and **Amanda Crossley** (School of Civil Engineering, The University of Nottingham, UK)

Abstract

This paper gives an overview of the meaning of the term 'roughness' in the field of fluvial hydraulics, and how it is often formulated as a 'resistance to flow' term in 1-D, 2-D & 3-D numerical models. It looks at how roughness is traditionally characterised in both experimental and numerical fields, and subsequently challenges the definitions that currently exist. In the end, the authors wonder: is roughness well understood and defined at all? Such a question raises a number of concerns in both research and practice; for example, how does one modeller use the roughness value from an experimental piece of work, or how does a practitioner identify the roughness value of a particular river channel? The authors indicate that roughness may not be uniquely defined, that there may be distinct 'experimental' and 'numerical' roughness values, and that in each field nuances exist associated with the context in which these values are used.

Keywords: Flow, modelling, resistance, rivers, roughness

1 Introduction: what is roughness?

Roughness appears in fluid mechanics as a consideration at wall boundaries, to account for momentum and energy dissipation that are not explicitly accounted for in the simplified or discrete formulae used in numerical engineering and science. In this way roughness is a model of the physical processes that are omitted. There is indeed no need for such an artefact in the continuum mechanics Navier-Stokes (NS) equations for laminar flow, or in the Reynolds Averaged Navier-Stokes (RANS) equations for turbulent flow, since all momentum and other energy losses – such as turbulence, shear, drag force, etc. - are implicitly contained in the equations. The issue only arises when the exact form of the equations needs to be simplified, as for example in discretisation purposes in three-dimensional (3-D) models, and for discretisation and conceptual reasons in 2-D and 1-D models. In the latter, the definition of the so-called 'roughness' or 'friction factor' becomes more uncertain, and therefore less rigorous in terms of definition and sizing, than it does for 3-D models, although it must be said that it does not account for the same thing as in 3-D models.

The number of reviews on roughness and flow resistance point to the importance of this topic for fluid mechanics in general (Jimenez 2004) and for the engineering community in particular, as this issue affects numerous calculation procedures in many different contexts. A large number of reviews regarding open channel flow resistance have been published over the last 80 years (Davies and White 1925; Ackers 1958; ASCE 1963; Rouse 1965; Yen 1991; Yen 2002; Dawson and Fisher 2004). There are also many specific reviews of different types of roughness (Sayre and Albertson 1963; ESDU 1979) as well as many useful textbooks on the subject (Reynolds 1974; Schlichting et al. 2004).

Historically, much of our early knowledge concerning roughness came from relatively simple experiments on the flow of liquids in circular pipes, driven by practical engineering considerations. For example, the 1-D Darcy-Weisbach equation relates the 'friction factor', f, for uniform flow in a circular pipe as a function of the channel geometry (in this case the diameter, d), flow (mean velocity, U, or more precisely turbulence) and pipe characteristics (i.e. surface roughness, often characterised by relative roughness, k_s/d, where k_s is a parameter known as the Nikuradse equivalent sand roughness size). However, although the Moody diagram for estimating f from Reynolds number and k_s/d is long established, its genesis and meaning (Colebrook and White 1937; Colebrook 1939) are often overlooked. The Darcy-Weisbach equation does not imply that f varies as U^2 or that the shape of the conduit is unimportant. For example, in the laminar flow region, in which f varies inversely with Re, (f = K/Re), it is easy to show that K varies very considerably with the shape of a closed duct by solving the Poisson equation. The solutions indicate that K varies from 53.3 for a triangular duct to 96.0 for flow between parallel plates, and is only 64.0 for the particular case of flow in a circular pipe (Schlichting et al. 2004). The variation of f with shape is also mirrored to a smaller extent in turbulent flow (Lai 1986). Moreover, the standard Moody diagram is wholly inappropriate when it comes to specifying head losses in compound channels or complex shaped ducts (Shiono and Knight 1991; Myers et al. 1999; Knight 2005), because the hydraulic radius, R (R= A/P) is not a very suitable 'characteristic' geometric parameter. In such channels or ducts, the wetted perimeter, P, will change abruptly at the bankfull stage, whereas the cross-sectional area, A, does not, giving rise to discontinuous relationships in the f v Re domain. This immediately raises questions in fluvial systems, where there are inevitably complex cross-sections and heterogeneous roughness distributions, as to how one should define the channel geometry and surface roughness. Many experimentalists and river engineers simply characterize their channel roughness by matching the channel slope with the free surface slope or the frictional head loss per unit length of the channel, adopting the hydraulic radius, R, as the single 'characteristic' dimension and lumping all 'roughness' considerations into a single value for k_s. This simple 1-D approach is clearly problematic.

From the above it is clear that the definition of a 'roughness' or 'friction factor' value needs to be more precise. It is also implicit that these are not only a function of the local geometrical conditions that exist at the channel bottom surface, but that other aspects such as channel geometry (R or P), flow regime (U^2) and therefore turbulence (intensities, vorticity and large scale flow structures) are also involved. Further implications are that the description level employed to characterise the flow theoretically leads to different levels of momentum and energy dissipation to be encompassed in these roughness parameters, so that a unique definition probably does not exist. This further implies that the methodology of matching 'roughness heights' and 'friction factors' via equivalence formulae is questionable. This particular issue is considered further in Section 3, after a brief consideration of the different types of roughness and boundary surface in Section 2. Section 4 then considers how roughness should be formulated in 3-D, 2-D and 1-D models.

Overall this paper aims to build on the second authors' work in experimental work over many years (www.flowdata.bham.ac.uk) and more recent work on modelling in 1-D, quasi-2-D, 2-D and 3-D (Morvan 2001; Morvan et al. 2002; Wright et al. 2004; Morvan et al. 2005; Morvan and Sanders 2005). The examination and comparison of the concept of roughness in each of these is informative and allows for the drawing of a number of conclusions of theoretical and practical interest. In discussing the issues reference is made to a substantial body of work that already exists in several areas and these are drawn together in a way that the authors believe has not been done before, with the combination of experiment and modelling in 1-D, 2-D and 3-D. In view of this the paper contains a large number of references that should be useful to those with an interest in this field.

2 Types of boundary and roughness

2.1 Types of boundary surface

The type of boundary surface affects the conceptual approach to defining what roughness parameter characterises the surface and also determines what flow mechanisms lead to energy loss and consequent resistance to flow. Surfaces may be classified as follows:

- rigid surface (e.g. composed of solid impermeable material, such as concrete or glass)
- mobile surface (e.g. composed of loose boundary material such as sand or gravel)
- flexible surface (e.g. composed of deformable material such as overbank vegetation, instream weeds or in areas such as haemodynamics, elastic blood vessels).

The nature of each surface also has to be specified, as different surfaces may have different boundary conditions, such as between porous and non-porous surfaces, with or without boundary layer suction, etc. For example, water intakes in rivers may take place through a bottom filter composed of fine to coarse sediments, giving rise to non-uniform flow over a boundary with suction leading to non-standard boundary layers and surface shear stresses (MacLean and Willetts 1986). Given that rigid surfaces are not entirely understood, this situation poses even greater challenges.

For a given boundary surface, the ‘energy losses’ leading to ‘flow resistance’ arise from the near boundary turbulence and the macro-flow structures within a given channel reach. Flow resistance is traditionally considered as being composed of 3 distinct, but related elements:

- Skin drag (e.g. roughness due to surface texture, grain roughness);
- Form drag (e.g. roughness due to surface geometry, bedforms, dunes, separation, etc.)
- Shape drag (e.g. roughness due to overall channel shape, meanders, bends, etc.)

Skin and form drag are essentially considered to occur on plane surfaces, whereas shape drag occurs as a result of the geometry of the surface being convoluted into a large scale 3-D pattern. Further, the representation of each is different depending on whether a 1-D, 2-D or 3-D approach is adopted. Finally, resistance to flow may be affected by the nature of the turbulence and fluid properties, e.g. damping of turbulence due to the presence of suspended material in the flow, sharp density differences at haloclines, or by long chain polymers inserted in the fluid. It is not surprising therefore that the definition of ‘roughness’ as distinct from ‘resistance’ is not a simple matter in fluvial systems. This is now illustrated through some practical examples.

2.2 Some exemplary fluvial resistance studies

In order to appreciate the issues involved and to show the complexity of the task, a very brief selection of some interesting fluvial roughness & resistance studies is now given.

For steady flow, one of the most comprehensive reviews of roughness in fluvial systems is that contained in Dawson & Fisher (Dawson and Fisher 2004). These data are now incorporated in the Roughness Advisor (RA), a dedicated piece of software recently produced by HR Wallingford for river modelling specialists (www.river-conveyance.net). It contains numerous examples of roughness values from a wide range of rivers, and how they vary with flow, season and type of vegetation. Because roughness is so important in all modelling procedures, there are many examples of regional studies, such as that carried out for New Zealand rivers by Hicks and Mason (1998). This covers gravel and vegetated rivers with discharges ranging from 0.1-353 m^3s^{-1} and bed slope from $1.0x10^{-5}$ to $4.2x10^{-2}$. A similar study for the Severn-Trent region in the UK is contained in an NRA roughness report by Pirt (1988). Much useful practical information is also contained in ‘Channel Flow Resistance:

Centennial of Manning's Formula', by Yen (1991) and in the reviews by the ASCE (1963) and by Yen (2002).

For unsteady flow, roughness studies are more difficult to undertake, but their results are important when dealing with resistance to flow in estuaries, in rivers during flood events and in coastal zones with oscillatory waves. One detailed estuarine study is described by Knight (Knight 1981), who measured the relative importance of the various terms in the 1-D St Venant equation through many tidal cycles on the Conwy estuary. Figure 1 shows some results, and Figure 2 shows how the resistance to flow is ebb-dominated as the sand dunes respond to the longer period of ebb flow. Figure 3 shows that for this particular tidal reach, the k_s values at low tide ($k_s \sim 8$ m when $h \sim 1$ m) are very much greater than at high tide ($k_s \sim 0.2$ m when $h \sim 6$ m), and indeed even greater than the depth of flow. Although surprising, this feature is not inconsistent with the meaning of k_s and the way in which it varies with the height of an individual roughness element, k, in this case the sand dunes on the estuary bed.

On a different, but related topic, Figure 4 shows that for a regular rib-type of roughness, the value of effective roughness height to actual height of the roughness varies considerably ($10 > k_s/k > 0.01$), and depends on at least two other parameters, h/k and λ/k, where λ is the longitudinal spacing of the roughness elements. The friction factors for many other types of rib-roughness are documented in an Engineering Sciences Data Unit report (ESDU 1979), on account of their use in heat transfer calculations. In general it is known that resistance will peak when the λ/k value is between 8 and 12, as shown by the data for square rib elements in Figure 5. For these types of roughness it is more appropriate to use a factor, χ, which then produces a logarithmic variation with U/U_*, (Sayre & Albertson, 1963) governed by

$$\frac{U}{U_*} = 6.06 \ln\left(\frac{h}{\chi}\right) \qquad (1)$$

as shown in Figure 6, provided it is specified as shown in Figure 7. The use of χ should be seen as a surrogate or alternative for k_s. Further details are available elsewhere (Knight and Macdonald 1979). The unusually large k_s value may lead to conceptual difficulties in 1-D models, in the same way that in 3-D CFD models if k_s is larger than the computational cell size adjacent to a boundary, there will be conceptual, and consequently numerical, difficulties if one links k_s and k directly. These studies also show the importance of recognising that there are other key 'characteristic' dimensions for roughness other than the single value of a roughness 'height', k_s, usually considered as being normal to the mean position of the boundary surface. The actual mean position of the surface (i.e. datum plane) is particularly important when considering sediment beds with dunes (1984), rivers with variable topography (Nicholas, 2001) or rib-type roughness (Macdonald, 1976).

Unsteadiness in the flow is known to alter the turbulence structure (Song and Graf 1996) and consequently bed shear and resistance. An important study of the impact of unsteadiness in flood analysis is shown by Sellin & van Beesten (Sellin and van Beesten 2004) who monitored the floodplain resistance on the River Blackwater. Figure 8 shows the typical looped nature of floodplain resistance. Flattening of vegetation may produce a clockwise sense of rotation in the loop rather than the customary anticlockwise one associated with the 1D convective and local acceleration terms. Laboratory studies in unsteady flow by Graf & Qu (Graf and Qu 2004) and Lai et al. (Lai et al. 2000) not only confirm the looped nature of resistance but also some problems of defining a bed friction factor. For periodic flows, a review of how boundary shear is affected by oscillatory boundary layer effects is given by Knight (Knight 1978). This has implications not only for near bed dynamics in coastal zones, but also in small scale physical models of estuaries where oscillatory boundary effects are enhanced (Knight and Ridgway 1976, 1977; Sleath 1984).

Vegetation within or alongside a river channel also greatly affects the resistance to flow. Seasonal growth and decay, as well as managed weed cutting programmes, mean that instream and bankside vegetation typically vary spatially and temporally within most managed river systems. General guidance about the effects of vegetation on resistance is given elsewhere (Kouwen and Unny 1973; Klaassen and van der Zwaard 1974; Kouwen and Li 1980; Kouwen et al. 1980; Hasegawa et al. 1999; Yen 2002; Dawson and Fisher 2004; Jarvela et al. 2006). The vegetation on floodplains may be of a more varied and dense nature and may require special treatment (Ikeda et al. 1992; Centre 1994; Ikeda et al. 1999). The effect of vegetation on flow structure in compound channels has been described by Okada & Fukuoka (Okada and Fukuoka 2002, 2003).

Sediment likewise has a profound effect on flow resistance in alluvial channels. Traditionally the hydraulic resistance is considered to be composed of grain and form resistance, arising from resistance due to the textural roughness of the plane surface, and that due to form roughness arising from separation and vortex shedding on the downstream side of bed forms. The total resistance is then considered to be the sum of the two components. Since the geometry of bed forms change with velocity and depth of flow, alluvial resistance relationships are much more complex than those of rigid boundary channels (e.g. f v Re for different $k_s/4R$ values, as in the Moody diagram or Colebrook-White equation (Myers et al. 1999; Knight and Brown 2001).

Assuming that the resistance of an alluvial channel may be conceptualised in this way, then either the energy gradient, S_f, or the hydraulic radius, R, may be considered to be divisible into two elements. Thus, the energy slope may be written as

$$S = S' + S'' \tag{2}$$

where S' is the slope of the energy line due to grain resistance on a plane bed, and S'' is the additional slope due to the bed forms. Using the Darcy-Weisbach law for S gives

$$\frac{fU^2}{8gR} = \frac{f'U^2}{8gR} + \frac{f''U^2}{8gR} \tag{3}$$

$$\therefore \qquad f = f' + f'' \tag{4}$$

where f' and f'' are the friction factor counterparts to S' and S''. Alternatively by considering the hydraulic radius, R, to be divisible into two components, then

$$R = R' + R'' \tag{5}$$

where R' is the component associated with grain resistance and R'' is that associated with form resistance. Multiplying Equation (5) by $\rho g S_f$ gives

$$\rho g R S_f = \rho g R' S_f + \rho g R'' S_f \tag{6}$$

$$\therefore \qquad \tau_o = \tau_o' + \tau_o'' \qquad (7)$$

where τ_o' is the boundary shear stress associated with grain resistance and τ_o'' is the boundary shear stress associated with form resistance. It should be remembered here that τ_o is a 'global' 1D value, and that the distribution of 'local' boundary shear stress around the wetted perimeter of an open channel is governed by the shape of the cross section, the number and pattern of secondary flow cells and other considerations (Knight et al. 1994).

The values of R' and S' may be determined from traditional plane bed rigid boundary resistance laws, such as the Colebrook-White equation or its corresponding graphical form, the Moody diagram. Eqs (4) & (7) indicate that f' and τ_o' are counterparts to S' whereas f'' and τ_o'' are counterparts to S''. The main difficulty encountered in sediment resistance studies is in determining suitable relationships for f'' (of its corresponding Manning value, n'') for different flow and sediment conditions. The general form of the resistance relationship for an alluvial channel is shown in Figure 9. Below threshold the resistance typically decreases as the Reynolds number (or velocity) increases. Once threshold has been passed, the resistance increases rapidly by a factor of 3 or 4 as ripples and dunes are formed, reaching a maximum before decreasing again as the dunes are washed out as transitional flow is reached. The resistance thus peaks in the lower flow regime, reaches a minimum in transitional flow and then increases again in the upper flow regime. The details of this relationship are described in many specialist texts (Raudkivi 1967; Garde and Ranga-Raju 1977; van Rijn 1984; Chang 1988; Yen 1991; Simons and Senturk 1992; Yalin and Ferreira da Silva 2001). An example of how the bed forms affect resistance is shown for the River Padma, Pakistan, by Shen (Shen 1971). The latter also highlights the subtle effect of water temperature on flow resistance, a feature often ignored, using data from the Mississippi River.

A final consideration in roughness studies involving 1-D modelling, and to a certain extent in 2-D modelling, is the issue of how the longitudinal energy gradient, S_f, should be averaged over a channel reach. This is discussed by Laurenson (1986), and is of significant practical interest. Guidance on how heterogeneous roughness may be obtained from disparate inputs is also of significance, and further details are available in the Roughness Advisor (RA), produced by HR Wallingford.

3 Roughness characterised by a roughness height

3.1 General approaches

Despite the difficulties outlined above and in the absence of any alternative, many engineers still feel the need to characterise fluvial roughness by a specific roughness or resistance 'height'. This is especially true when they deal with rigid planar surfaces. Indeed, many researchers have erroneously attempted to investigate the physical meaning of this parameter, simply because it makes some sense from an experimental or practical standpoint. Because of the vast types of roughness in rivers, this paper will concentrate on planar surfaces and not consider resistance from either sedimentary bedforms or vegetation. Quantification of these different effects remains difficult as evidenced by the widespread range of formulations available in the literature (Yen 1991). As a result, with the current available knowledge, roughness height mostly remains a calibration parameter, used to tune numerical model outputs to measured data. Its meaning is however unsure. Because of its continued use, it will be explored briefly now, prior to considering in detail how roughness should be formulated in 1-D, 2-D & 3-D models.

3.2 Roughness Height and Roughness Value

Historically, the relationship between roughness and particle diameters was investigated in relatively smooth experimental channels to quantify the roughness height, k_s, on the grounds that the most obvious form of roughness was that created by grain irregularities at the wall. Clearly this approach limits the use of k_s and its widespread application in numerical models. Nevertheless, this type of relationship has remained and has been implemented in much practical research, relating roughness height to particle size in channels.

Several formulations such as $k_s = 3.5 \times D_{84}$ or $k_s = 6.8 \times D_{50}$, where D_{xx} stands for the grain diameter for which xx% of the particles are finer, have been given as reported in Clifford et al. (1992). Unfortunately, the nature of the momentum loss mechanism included in such formulae is not really well known; the level of theoretical detail considered in the formulation of the problem, in order to link both roughness height and grain diameter, and the flow characteristics are often not tied to the equation when it is subsequently used which is equivalent to using the result of a theorem without satisfying its hypothesis. The investigation by Clifford et al. (1992) attempted to distinguish grain from bedform roughness using large particles (D_{50} = 40 mm), which resulted in the calculation of different coefficients, e.g. quite logically for grain roughness, $k_g = 0.3 - 0.5 \times D_{50}$ (skin friction). The use of Clifford's results shows that the grain-roughness relationship is inadequate for determining the overall roughness height, as grain-related roughness seems to cause low momentum losses. Formulae such as $k_s = 6.8 \times D_{50}$ therefore include several momentum loss mechanisms that are not well understood, nor quantified, resulting in inappropriate roughness height values when different grains or different flow conditions are modelled.

There is still uncertainty regarding the relevance of the above formulae outside the range of conditions for which they have been derived. Most of the work that has led to the above formulations has been done for limited ranges of particle diameters. For example, Whiting & Dittrich (1990) reported a range of values between 0.68 and 7.7 mm and seem to include all roughness effects shown previously, while Clifford et al. (Clifford et al. 1992) used a mean diameter in the region of 40 mm. Formulae such as $k_s = 6.8 \times D_{50}$ or $k_s = 3.5 \times D_{84}$ seem to have been derived for relatively small grains, yet are now applied beyond these ranges by some Computational Fluid Dynamics users without being questioned. In some cases this has lead to values of k_s being as large as 0.250 m (Nicholas and Walling 1997; Hodskinson and Ferguson 1998). This is quite problematic on both numerical and physical grounds: in such cases the cell next to the wall should be larger than the value of k_s which requires large cells that reduce accuracy. Therefore the roughness value cannot be chosen independently of numerical and physical considerations relevant. The fundamental problem is using a roughness model based on theory from sand-grain roughness for roughness elements that are considerably larger.

Finally, although not considered here, it should again be emphasised that use of a single parameter such as 'roughness height' will be inadequate wherever other spatial scales exist, such as in periodically spaced roughness, where the wavelength, λ, is important (e.g. rib roughness or earlier discussions on sediment and bed forms). Similarly when vegetation is present and becomes submerged, a horizontal shear layer form will form in the surface flow region above the canopy and penetrate to some depth within the plants, giving rise to unusual turbulence and problems of reducing depth-averaged flow fields to equivalent k_s values (Lane, 2005; Lane et al. 2005; Dittrich et al., 2006).

4 Roughness in the 1D, 2-D and 3-D transport equations

As mentioned in the introduction, roughness does not appear explicitly in the 3-D Navier-Stokes equations. Roughness is introduced at the walls to account for small momentum and energy losses that are not embedded in the discrete formulation of the continuous problem. Roughness also appears in the St Venant form of the Navier-Stokes equations in 2-D and 1-D, usually accompanied by a decreasing level of accuracy in terms of the physics embedded in the model, e.g. turbulence and the effect of geometry. The following sections discuss the meaning of roughness for these various models.

4.1 Roughness in 1-D models

From the previous comments, it is clearly difficult for a modeller to attribute a roughness height to a given channel. Hydraulicians often prefer to use a Manning's n roughness coefficient when it comes to open channel friction losses as it is often (mistakenly) regarded as less flow dependent. All such "lumped" parameters, including the Colebrook-White friction factor, f, and Chézy's C, are subjective to determine and are dependent on the channel geometry and flow characteristics (levels). Additionally the level of detail encompassed in the model also affects the meaning of these parameters. A typical example is whether the description encompasses turbulence effects or not. In a 1-D representation the roughness model does encompass turbulence, but in some 2-D models it does not: therefore, a 2-D model should not necessarily use the friction factor from a 1-D model

General formulae have been proposed to relate particle diameters to Manning's n values and the latter to equivalent roughness height. One is derived from the HR Wallingford tables (Ackers 1958) and yields:

$$k_s\,(\text{mm}) = \left(n/0.038\right)^6 \qquad (8)$$

This only applies for a limited range of k_s where the condition $10 \le R/k_s \le 100$ (R = hydraulic radius) is satisfied, which confirms application to rough engineered canals and natural channels.

A more general approach is therefore needed. Massey (Massey 1995) gives a theoretically derived equivalence in his textbook

$$k_s(SI) = 14.86 \cdot R / \exp_{10}\left(\frac{0.0564 \cdot R^{1/6}}{n}\right). \qquad (9)$$

(9) is quite close to the derivation in Chow (1959)

$$k_s(SI) = 12.20 \cdot R / \exp_{10}\left(\frac{0.0457 \cdot R^{1/6}}{n}\right) \qquad (10)$$

From (10) Strickler (1923) arrived at an average:

$$k_s(\text{ ft}) = (n / 0.0342)^6 \qquad (11)$$

assuming a median grain-size. As reported in Chow (1959), Equation (10) was successfully applied in the United States, and in particular on the Mississippi. Krishnappan and Lau (1986) also used (11) for their three-dimensional model of floodplain flow.

For the FCF experiment (Knight and Sellin 1987) however an equation such as (8) yields an improbably small value of the order of a fraction of a micrometer. When R/k_s is calculated for this experiment, it appears that it is 3 to 4 orders of magnitude larger than the upper limit. Consequently equations (9) to (10) are used and yield values in the range 2.0×10^{-4} to 8.0×10^{-4} m, which seems to fit reasonably well with the table given in French (French 1985) for simple, smooth materials or surfaces. However, as underlined in Chow (Chow 1959), the above formulae were usually used to evaluate Manning's n values from values of k_s, for which the resulting n is relatively insensitive, see Figure 10, based on Equation (12), in the range $10 < R/k_s < 100$ and Yen (1992). The converse is not true and leads to large ranges of roughness height values for small variations of Manning's n, especially when n is large, see Figure 11.

$$n = k_s^{1/6}\left[\frac{(R/k_s)^{1/6}}{18\log(11R/k_s)}\right] \qquad (12)$$

For the purposes of channel resistance, the mean boundary shear stress is also traditionally linked to the section-mean velocity, U_A, by the 'global' or overall friction factor, f, by the empirical, yet dimensionally valid, relationship given by the first part of equation (19).

The resistance relationship for flow in smooth and rough pipes of circular cross-section is usually given by the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left[\frac{k_s}{14.8R} + \frac{2.51}{(4UR/\nu)\sqrt{f}}\right] \tag{13}$$

where U = Q/A, R = d/4, d = pipe diameter, and k_s = Nikuradse equivalent roughness size. Such a relationship assumes a logarithmic velocity distribution within the boundary layer that applies over the bulk of the cross-section. In a river, it is often assumed that the vertical distribution of the streamwise velocity distribution may be approximated by that in a boundary layer on a flat plate in rough turbulent flow. Near the bed the steep velocity gradient is indicative of large shear stresses, considered as turbulent Reynolds stresses applied internally on the fluid by the action of the flowing liquid. Assuming a rough turbulent flow, then the local velocity, u, distance z above the bed is given by

$$\frac{U}{U_*} = 5.75\log\left(\frac{30z}{k_s}\right) \tag{14}$$

where the customary 'rough turbulent' coefficient of 8.5 in the standard 'rough' law for f has been subsumed into the log term. Since the depth mean velocity occurs at $0.37 \times \text{depth}$, Equation (14) becomes

$$\frac{U_d}{U_*} = 5.75\log\left(\frac{11h}{k_s}\right) \tag{15}$$

where h is the depth of flow. The value of k_s may be related to the mean grain size, D_{50}, as previously reported.

If the Manning equation is adopted instead of the Darcy-Weisbach equation, then the link between Manning's n and k_s may be given by Equation 12. It should however be remembered that the use of simple logarithmic velocity relationships should be carried out advisedly, given alternative analyses and the definitions of boundary shear stress (Prokrajac et al. , 2006; Nikora et al. 2004; Olsen & Stokseth 1995).

4.1.1 Roughness in quasi-2-D models

For straight prismatic channels, the streamwise depth-averaged RANS equation is given by Knight and Shiono (Knight and Shiono 1996) as

$$\rho g H S_o - \tfrac{1}{8}\rho f U_d^2\left(1+\frac{1}{s^2}\right)^{1/2} + \frac{\partial}{\partial y}\left\{\rho\lambda H^2\left(\frac{f}{8}\right)^{1/2} U_d \frac{\partial U_d}{\partial y}\right\} = \frac{\partial}{\partial y}\left[H\left(\rho UV\right)_d\right] \quad (16)$$

where s = transverse side slope of channel (1:s, vertical: horizontal) and λ = dimensionless eddy viscosity ($\bar{\tau} = \rho\bar{\varepsilon}_{yx}\partial U_d/\partial y$ and $\bar{\varepsilon}_{yx} = \lambda U_* H$). Equation (16) may be written as

$$\tau_b\left(1+\frac{1}{s^2}\right)^{1/2} = \rho g H S_o + \frac{\partial}{\partial y}\left\{H\,\bar{\tau}_{yx}\right\} - \Gamma \quad (17)$$

where it is assumed that the boundary shear stress, τ_b, is related to the depth-mean velocity, U_d, by a local friction factor, f, the turbulence is simulated by an eddy viscosity approach, and Γ is the right hand side of Equation (17).

When using resistance coefficients in these models, care then needs to be taken to distinguish between 'global', 'zonal' and 'local' friction factors, based on using the section-mean velocity, U_A, the zonal velocity U_z, or the depth-mean velocity, U_d, respectively. In the latter case, U_d is used technically to replace the law of the wall approach in 3-D models, in that it relates boundary shear with a 'local' velocity. Thus by analogy with the 1-D Darcy-Weisbach equation, it follows that:

$$\tau_o = \left(\frac{f}{8}\right)\rho U_A^2 \qquad \tau_z = \left(\frac{f_z}{8}\right)\rho U_z^2 \qquad \tau_b = \left(\frac{f_b}{8}\right)\rho U_d^2 \quad (18)$$

(global) (zonal/sub-area) (local/depth-averaged)

Equation (18) indicates that the boundary shear stress, τ_b, is influenced by the lateral shear and secondary flow and may differ significantly from the value based on local depth ($\tau_b \approx \rho gHS_f$), as mentioned previously. Unlike 1-D methods, which have just one lumped parameter, such as f or n, in the Shiono & Knight Method (SKM) there are now three calibration coefficients, f, λ and Γ, concerned with bed friction, lateral shear (via depth-averaged eddy viscosity) and secondary flow (via lateral gradient of $H(\rho UV)_d$) respectively. There is now therefore the possibility of simulating the lateral variations of U_d, τ_b, $\bar{\tau}_{yx}$ and Γ within the river channel. A numerical or analytical solution to Equation (16) may be obtained by discretising the cross-section boundary into a number of linear elements, and specifying the three coefficients, f, λ, and Γ, for each sub-area. Further details can be found elsewhere (Knight and Abril 1996; Abril and Knight 2004).

Analysis shows that the relative contributions of the depth-averaged Reynolds stress term, $\bar{\tau}_{yx}$, and the secondary flow term, $(\rho UV)_d$, to the apparent shear stress (ASS) are known to be roughly comparable in magnitude (Knight and Shiono 1990; Shiono and Knight 1991), highlighting the importance of vortex structures in resistance studies. Numerical work by Thomas & Williams (1995), using data from test series 22 from the FCF and a large eddy simulation (LES), confirms this finding.

The stage-discharge relationships in most 1-D commercial software packages for river engineering are typically based on one of the 1-D ‘divided channel’ methods (DCM), described elsewhere (Knight 2005). These methods all assume quasi-straight river reaches, and since they do not include any lateral momentum transfer effects, they are inevitably not particularly suitable for predicting accurately either the water level in compound river channels or the proportion of flow that occurs on the floodplains. More recent 1-D river engineering software (www.river-conveyance.net) will include the effect of flow structure, through the adoption of improved methods (Knight, 2005). These may be grouped under the headings: the ‘divided channel method’ (DCM), the coherence method (COHM), the Shiono & Knight method (SKM), and the ‘lateral division method’ (LDM). Several authors have presented examples of these methods applied to fluvial problems (Knight et al. 1989; Knight 2005).

4.2 Roughness in 2-D models

4.2.1 Friction representation in 2-D Shallow Water models

The 2-D Shallow Water equations can be derived by physcial arguments similar to those used in 1-D or by vertical integration of the Navier-Stokes equations. Friction is parameterised in a similar way to 1-D through, for example, Manning's n or Chezy's C. The appropriate equations are (Nezu and Nakagawa 1993):

2-D mass conservation:

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=Q_l \qquad (19)$$

2-D momentum conservation:

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial huv}{\partial y}+gh\frac{\partial h}{\partial x}=gh(S_{ox}-S_{fx}) \qquad (20)$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hv^2}{\partial y}+gh\frac{\partial h}{\partial y}=gh(S_{oy}-S_{fy}) \qquad (21)$$

where

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{7/3}} \text{ or } S_{fx}=\frac{u\sqrt{u^2+v^2}}{C^2h} \text{ and } S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{7/3}} \text{ or } S_{fy}=\frac{v\sqrt{u^2+v^2}}{C^2h}$$

Other terms can be included to represent the effects of turbulence, although this is often left to the friction term. The determination of n is not straightforward and this raises a number of issues that are similar to those discussed earlier in the context of 1D modelling (www.river-conveyance.net). Therefore they are not addressed here.

As mentioned briefly before, even though 1-D and 2-D representations use Manning's or Chezy's coefficient, the roughness model is different. The 1-D representation is using the friction factor to represent the shear stress exerted by the entire bed and banks bounding the flow whilst a 2-D model is using the factor to represent the shear stress exerted at the base of a vertical column of water: these are not the same situation. Additionally, the 1-D representation does not take explicit account of the effects of turbulence in removing energy from the flow so this effect is also included in the friction factor through calibration: in 2-D, turbulence models are sometimes explicitly included through terms in addition to the friction term and in these cases the friction factor will differ.

4.3 Roughness in 3-D models

The term 3-D model is taken here to mean models that solve the Navier-Stokes equations in all three dimensions. In such models a no-slip condition usually applies at the walls, which means that the velocities tangential and normal to the walls are zero. Close to the walls, the Navier-Stokes equations would require a very fine grid to properly resolve the linear sub-layer and the turbulent boundary layer. This requirement is removed by replacing the grid by a model of the boundary layer in 3-D models, i.e. the wall function. This function allows for the computation of the wall effect at the first node inside the domain.

In the vicinity of the wall it is assumed that the fluid shear stress is equal to the wall shear stress, $\nu_t\left(\partial u_\tau/\partial n\right) = u_*|u_*|$, for which the local shear velocity u_* is required. In the laminar sub-layer of the boundary layer, the velocity distribution is given by:

$$\frac{u_\tau}{u_*} = y^+ \qquad (22)$$

where u_τ is the tangential velocity, parallel to the wall, u_* is the shear velocity, and $y^+ = yu_*/\nu$ is the non-dimensional distance normal to the wall. The transition between laminar and turbulent flow regions has been determined experimentally to be between $y^+ = 5$ to 30 (buffer layer), with various transition velocity laws proposed (Reynolds 1974). In order to simplify boundary layer analysis, it is sometimes assumed that the transition occurs at the position where the laminar and turbulent laws distribution laws meet, i.e. at $y^+ = 11.63$ (Chang 1988).

In the turbulent shear flow region a general form for the law of the wall can be given as:

$$\frac{u_\tau}{u_*} = \frac{1}{\kappa}\ln(E(k_s^+)\cdot y^+) \qquad (23)$$

where, $E(k_s^+)$ is a function of the non-dimensional roughness height, $k_s^+ = k_s u_*/\nu$, in which k_s is the roughness height, κ is von Karman's constant usually taken equal to 0.41 and ν is the kinematic viscosity. The nature of the function $E(k_s^+)$ depends on the boundary condition itself. Chang (1988) gives a function for $E(k_s^+)$ as follows:

i) Hydraulically smooth:

$$\frac{u_\tau}{u_*} = \frac{1}{\kappa}\ln(y^+) + 5.5 \Leftrightarrow E(k_s^+) = E \approx 9.0$$

ii) Transition:

$$\frac{u_\tau}{u_*} = \frac{1}{\kappa}\ln(\frac{y^+}{k_s^+}) + f(k_s^+) = \frac{1}{\kappa}\ln(y^+) + \frac{1}{\kappa}\ln\left(g(k_s^+)\right) \Leftrightarrow E(k_s^+) = g(k_s^+)$$

iii) Hydraulically rough:

$$\frac{u_\tau}{u_*} = \frac{1}{\kappa}\ln(\frac{y^+}{k_s^+}) + 8.5 \Leftrightarrow E(k_s^+) = \frac{30}{k_s^+}$$

where y^+ is the non-dimensional distance from the wall. However, a function needs to be formulated for $E(k_s^+)$ in the transition condition.

In most CFD codes, the hard-coded formula for the law of the wall is valid for smooth surfaces. A function that will extend the validity of the law of the wall beyond smooth surface boundary conditions and/or low turbulence models is consequently required. This is not difficult for a hydraulically rough surface as the function is clearly defined by the theory (see (iii) above), and it has been successfully implemented in Launder and Spalding (1974) for example. However, a general function for $E(k_s^+)$, which covers the whole range of boundary conditions while remaining sufficiently robust needs to be formulated so that it can cover the entire range of k_s^+ values independently and more flexibly.

The difficulty lies in formulating a function $g(k_s^+)$ that is continuous and tends asymptotically towards 9.0 for small k_s^+ values and towards $30/k_s^+$ when k_s^+ becomes larger than 70. Mathematically a simple first assumption could consequently be looking at a function of the type $g(k_s^+) = \frac{a}{b + c \cdot k_s^+}$, with $\frac{a}{b} = 9.0$ and $\frac{a}{c} = 30.0$. The simplest function of this kind is:

$$g(k_s^+) = \frac{9.0}{1 + 0.3 \cdot k_s^+} = \frac{E}{1 + 0.3 \cdot k_s^+} \tag{24}$$

Because of the function properties, one can generalise the above proposal to give:

$$\forall k_s^+,\ E(k_s^+) = \frac{E}{1 + 0.3 \cdot k_s^+} \tag{25}$$

The above function is very close to a proposal made by Naot (Naot 1984), who gave:

$$E(k_s^+) = \frac{E}{\left\{ \dfrac{1 + 0.3k_s^+}{\left(1 + \dfrac{20}{k_s^+}\right)} \right\}} \tag{26}$$

A similar approach is adopted in the commercial codes (i.e. FLUENT and CFX) under the general form $E(k_s^+) = \frac{E}{1 + c \cdot k_s^+}$ (c = constant).

Other approaches consider the experimental work of Nikuradse (Nikuradse 1933) on roughness, and use the experimental results to fit a function to his data points. Three other approaches are by Cebeci and Bradshaw (1977), Yalin (1992) and Sajjadi and Aldridge (1993). These are relatively complex which may not make them suitable as a robust all-purpose model.

Whichever formula is applied, attention should also be paid to the position of the first node on the grid, close to the wall. A near wall flow is taken to be laminar if $y^+ < 11.63$. It is therefore important to ensure that the finite element grid does not encroach into this region, otherwise a transport equation validated for turbulent region will be applied in a region of laminar flow and a significant error will occur. Modern solvers have this facility built in and are able to move the node “algebraically” in order to allow for a suitable implementation of the law. In flows with recirculation at the wall, the velocity component parallel to the wall at the re-attachment point is zero, which means that the simulation reverts to the laminar case (Versteeg and Malalasekera 1995), which further demonstrates the difficulty of this approach.

One should also try to ensure that the first node is well inside the log layer where the law of the wall is valid to obtain an accurate transition between the boundary layer and the turbulent flow velocity profiles. Despite increasing computer power this is not always achievable when modelling large-scale geometries and this should be taken into account during the discussion of the results. With the ever increasing computer power available to modellers, this is becoming less of an issue.

The law of the wall is then incorporated into the model equations via an extra shear term that mimics the effect of the wall on the fluid at the first node off the wall. The law of the wall therefore allows the physical effect of the wall boundary to be reflected into the discrete domain, where the discretised Navier-Stokes equations are solved.

As an alternative to the law of the wall approach to modelling roughness the effects of vegetation and large boulders at a boundary are sometimes modelled using a 'porosity' approach. These porosity terms enable the computation of an 'equivalent' momentum loss added to the Navier-Stokes equation where a large obstruction is present and Lane (Lane et al. 2005) has recently suggested this approach as a suitable alternative.

5 Discussion

Whichever resistance coefficient (f, n or k_s) is used, its origin and basis should be understood, and its numerical value properly assigned in order to obtain the correct boundary shear stress from calculated or measured velocities. It should also be noted that the sub-area and depth-averaged friction factors defined in Equation (18) implicitly include the effects of secondary flow, vorticity and lateral shear. This also implies that appropriate f, λ and Γ values must be specified in SKM if lateral distributions of both U_d and τ_o are to be determined accurately. Likewise, k_s values need to be specified carefully in 2-D and 3-D numerical models. Whatever resistance coefficient is used, it should always be remembered that resistance values are usually strongly depth, and hence flow, dependent (ASCE 1963; Knight 1981; Wallis and Knight 1984; Knight et al. 1989; Hicks and Mason 1998; Dawson and Fisher 2004).

It is sometimes convenient to use a 'composite' roughness coefficient for the whole channel, based on aggregating values from individual sub-areas, rather than many individual values. Although the difficulties in using this approach for channels with complex variations in geometry have been highlighted, there are occasionally problems where it is convenient to adopt this approach. See Yen (Yen 1991; Yen 2002) for further details.

5.1 Should calibration use the roughness coefficient or friction factor?

The practice in experimental work and St Venant based modelling is to characterise the wall surface in order to select an appropriate friction coefficient and to adjust the model outputs via this parameter. This is understandable since the roughness coefficients appear explicitly in the equations and can have a significant effect on solutions. For example, using Chezy's model for roughness in the 1D momentum equation:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial h}{\partial x} = g\left(S_0 - S_f\right)$$
$$\begin{cases} S_o = \sin\phi \\ S_f = \dfrac{U^2}{C^2 \, A/R} \end{cases} \tag{27}$$

It is clear that the impact of the roughness factor (viz. roughness term or energy loss term S_f) on these equations is significant, especially as the "channel" gets "rougher", as can be seen in Figure 12, where S_f varies exponentially with increased roughness. For a given surface slope the level of uncertainty in the choice of the roughness value and the relationship between roughness and discharge are very clear. The energy loss term is just one amongst the local acceleration term, convection term and head and gravity forces. The magnitude of the term on the right hand side has significant consequences for the numerical convergence and therefore as part of the iterative solution process it is usually preferable to have small forcing terms such as $g(S_o - S_f)$ in the previous equation.

On the other hand roughness is a much smaller term when solving the full 3-D Navier Stokes equations. Roughness appears in the boundary condition rather than as a term in the equations (as in 1-D and 2-D). The impact roughness has on the solution is therefore much more localised and limited. Thus, it is clear that in different dimensional representations in open channel flow, the role and impact of the roughness value upon the solution are very different and this value does not represent the same physical effect. This is illustrated in Figure 13 which shows numerical results based on Kenneth Yuen's Experiment 16 (Yuen 1989). The figure compares results from a 3-D CFD simulation (Wright et al. 2004) and results based on Manning's equation in 1-D with the experimental measurements. It can be seen that the 1-D results are significantly more sensitive to changes in the roughness parameter than the 3-D simulation. It is clear that the role of roughness in terms of calibration is more limited in higher dimensions. Other effects have to be considered in addition to roughness. As a consequence, it must be said that roughness cannot compensate for errors in the numerical technique or the physical model. Therefore calibration based on roughness values should be limited in its scope and it should be ensured that roughness values remain within physically appropriate limits.

It is difficult to define the roughness of one region generically without consideration of the flow characteristics, physical models and level of numerical discretisation used in the simulation. This makes the process of model calibration very uncertain and the "establishment" of one roughness value impossible. The authors' experience combining experimental with numerical work shows that if the "physical" roughness value is adjusted to ensure the correct value for the free surface position, discharge and slope, then an equivalent numerical roughness value can be calculated. The exact values of this depends on the turbulence model and numerical characteristics of the simulation, and is usually different from the experimental value. In recent work for simple channels (Wright et al. 2004; Morvan et al. 2005) the mass flow and bed shear stress values, known from the experiments and the theory, were used as objective functions to adjust the roughness values. In most cases the roughness values necessary were different between k-ε and Reynolds Stress Models, typically by about 10% but, on occasions, by as much as 50%. This is shown in Table 1 based on a number of simulations (Wright et al. 2004) of experiments carried out by Yuen at the University of Birmingham (Yuen 1989; www.flowdata.bham.ac.uk). Clearly these values do not match with experimental data which are given in the tables based on Manning's equation and Equation (12), although their variation is consistent with the CFD values. This is not inconsistent as the different values are representing different models: the physical one typically represents a bulk value based on bulk shear stress and the numerical one in 2-D and 3-D represents a local shear stress on the bed.

Turbulence model	Roughness height (mm)	Maximum velocity	Mass flow rate
EXPERIMENT 8			
k-ε	Smooth	0.6044	4.14
SSG	Smooth	0.5918	4.19
k-ε	0.50	0.5243	3.51
SSG	0.55	0.5099	3.53
Experiment	0.22	—	3.50
EXPERIMENT 4			
k-ε	Smooth	0.4806	1.93
SSG	Smooth	0.4659	1.96
k-ε	0.30	0.4233	1.76
SSG	0.28	0.4366	1.73
Experiment	0.18	—	1.75
EXPERIMENT 1			
k-ε	Smooth	0.3600	0.78
SSG	Smooth	0.3563	0.80
k-ε	0.65	0.3053	0.65
SSG	1.0	0.2935	0.65
Experiment	0.41	—	0.65

Table 1. Summary of results for trapezoidal Experiment 8, 4 and 1 (Yuen, 1989). Experiment roughness values are back calculated from the mass flow rate value, using Manning's equation and equation (12). SSG is the Reynolds stress turbulence model by Sarkar, Speziale and Gatski (1991).

The above leads to the conclusion that, in 3-D, roughness is a calibration parameter in a somewhat similar, but less significant, way to simpler 1-D models. The main difference for roughness and roughness values is in the amount of physics that each level of flow model encompasses (lateral and vertical velocity, density, turbulence) and this leads to roughness having a quite different meaning at each dimensional resolution. The points raised in this paper show that whilst we may have an understanding of the nature of roughness at each level of representation or model, each approach eventually leads to its own definition and values of roughness. On the subject of scales, the paper has raised another issue of interest: roughness does not have the same measure in all models or model substantiation. A 1D modeller or an experimentalist will talk about the reach or flume roughness, whilst a 3-D modeller will talk about skin roughness with the other components being embedded in the geometry, turbulence and particle models for example. This argument can be illustrated by the approach that a river modeller would take compared to a CFD modeller: the former would usually adjust roughness to improve model results whilst the latter would not think to do this until they had examined the mesh quality, discretisation and turbulence modelling.

What we cannot systematically represent mathematically or physically we cannot really "measure" and therefore one thing we know is that proposals for constitutive laws linking roughness to particle diameter, for example, are misguided – especially without the bounds of the assumptions for which the equation was established. Furthermore roughness is implicit: it is a function of the flow it governs, as the reach roughness depends on the water depth and low speed in the river for example. It is not a function of the grain size only, as many may have forgotten in the wake of Nikuradse's particular experiments. This is just the same as with eddy viscosity: whilst viscosity is a fluid property, eddy viscosity is a property of the flow. One has to accept that roughness is still a calibration parameter in computational models, especially when we model natural geometries where the insights that we have gained in an idealised laboratory channel do not always apply. This does not make things easy for practitioners. However, trying to correlate field data with a unique k_s value is potentially dangerous without a warning message attached to the formula.

Consequently it is quite legitimate to find that there exist several roughness values for the same model: one experimental, that can be used as an initial guess in the CFD model, and some numerical ones, functions of the other models and the updates that the educated user makes.

5.2 Use of roughness to represent large features

Traditionally and following Nikuradse's pioneering work researchers have attempted to relate particle size to roughness height. This has been proved to work for small size particles such as sand particles. Further work carried out by environmental scientists has followed the same route, and either they or other users have attempted to use these relationships in the context of numerical modelling, without questioning their validity and the size of the sink term they represented and comparing it to the sink term necessary to truly balance the equations. In the context of numerical models, additional numerical considerations are indeed necessary to make sure this approach satisfies the equation balance but also, and equally importantly, to ensure that the roughness parameter is consistent with its physical interpretation in terms of size relative to the grid size and therefore in relation to the obstruction to fluid movement within the cell. Increasing the size of the roughness parameters has serious impact on the algebraic equations as illustrated in Figures 12 and 13. These considerations are sometimes ignored by modellers.

The authors believe that this approach is flawed for any particle that is large relative to the problem size. A lot of the approaches attempting to relate particle size and roughness rely on a simple logarithmic profile to build the equivalence and are often found to be river or reach dependent, which indicates that the approach probably does not consider all the necessary parameters but, more importantly it is likely not to be the correct approach. This is, again, made worse when trying to apply the same approach to models 1-D, 2-D and 3-D for which roughness has a different meaning. In the context of numerical modelling the authors would favour solely numerical considerations in setting up a model with subsequent comparison with measurable physical values such as shear stress, etc.. A roughness model should be a sink term, the suitability of which could be measured in terms of equation balance considerations and water level slope in hydraulics. It is also clear that more work is required to understand fluid behaviour at the walls. The authors are actively investigating quadratic porosity models based on Darcy’s equation. The factors for these are derived using models of flow around the kind of dowels used in experiments.

5.3 Roughness and modelling in engineering practice

This issue is crucial in 1-D river modelling where practitioners seek a conveyance coefficient $K = Q / S_f^{1/2}$ which often relies on a “roughness” value associated to a list of physical characteristics such as particle size(s) and vegetation type. Unfortunately such a definition, already difficult conceptually, is made even more complex as the model dimension decreases because the roughness factor accounts for more physical phenomena such as turbulence, particularly in 1-D. Of course it must be recognised that in 1-D the real issue is to determine a value of conveyance and a friction factor is only a means to that end. It is this that brings some hope to a practitioners dilemma through the development of approaches such as the Conveyance Estimation System (www.river-conveyance.net) by HR Wallingford for the Environment Agency which is helpful in moving the focus from the uncertainties of estimating friction factors to conveyance estimation and also implementing state-of-the-art methods for estimating conveyance such as the SKM mentioned above.

When moving from 1-D to 2-D matters are not much easier despite the possible introduction of turbulence modelling. In 3-D the identification of what roughness stands for is made easier because more physics is included; yet, the definition of the "roughness height" is also very limited by the lack of fundamental understanding of what roughness is and the lack of a generic law describing its effects.

6 Conclusions

It is clear that modelling open-channel flows is not straightforward and needs the combined expertise of experimentalists and numerical modellers. On the basis of experience in both these fields, the authors have drawn a number of conclusions:

- Roughness varies between models which represent different dimensions. Consequent on this, it must be recognised that reach-scale roughness is a different concept from local roughness.
- Using roughness to represent features other than sand-grain roughness lessens the validity of the underlying theory and is questionable.
- Models of roughness in 1-D hydraulic models are valid and will continue to be useful when based on CES and calibrated appropriately. Conveyance estimation can ensure that the latest results from experimental work and complex numerical modelling are transferred into practice.
- 1-D modellers should focus more on estimating conveyance than establishing one sole value of Manning's n or Chezy C for a channel.

These arguments indicate that even the modelling of idealised laboratory channels is not straightforward and therefore the modelling of real rivers is an even more complex task.

All the above may make hydraulic modelling seem fraught with difficulty and may lead practitioners to ask whether hydraulic modelling is of any benefit. The authors believe that there is significant benefit of using hydraulic models compared with say, hydrological models, but it is hoped that this paper has demonstrated that care must be taken in their application.

This paper is clearly part of an ongoing discussion on these issues. The authors hope that others will contribute to this in the future.

List of Symbols

a = constant

A = cross-sectional area

b = constant

c = constant

C = Chézy C

d = diameter

D_{xx} = grain diameter for which xx% of the particles are finer

f = friction factor $\left(\frac{fU^2}{8gR} = \frac{f'U^2}{8gR} + \frac{f''U^2}{8gR}\right)$

f ‘= friction factor (associated with grain resistance)

f ‘’= friction factor (associated with bed forms)

g = acceleration of gravity

h = flow depth

k_s = Nikuradse equivalent sand roughness

k_s^+ = non dimensional equivalent sand roughness $\left(k_s^+ = \frac{k_s u_*}{\upsilon}\right)$

k = roughness height

K = conveyance coefficient $\left(K = \frac{Q}{S_f^{1/2}}\right)$

n = Manning’s n

P = wetted perimeter

Q = mass flow

R = hydraulic radius $\left(R = \frac{A}{P}\right)$

Re = Reynolds number $\left(Re = \frac{Ud}{\upsilon}\right)$

s = transverse side slope

S = energy slope $(S = S' + S'')$

S’ = slope of the energy line due to grain resistance on a plane bed

S’’ = additional slope due to the bed forms

u = velocity along the x-axis

U = mean velocity

U_A = area mean velocity

U_d = depth mean velocity

U_z = local/zonal velocity

V = transverse velocity

u_τ = tangential velocity

u_* = shear velocity

v = velocity along the y-axis

y^+ = non dimensional distance from the wall

z = a distance (e.g. from the wall)

λ = longitudinal spacing of roughness elements; dimensionless eddy viscosity

υ = kinematic viscosity

τ_b = boundary shear stress (depth averaged, function of U_d)

τ_o = boundary shear stress (global value, function of U_A)

τ_o' = boundary shear stress associated with grain resistance

τ_o'' = boundary shear stress associated with form resistance

χ = roughness parameter used in Eq (1)

References

Abril, J. B. and D. W. Knight (2004). "Stage-discharge prediction for rivers in flood applying a depth-averaged model." Journal of Hydraulic Research **42**(6): 616-629.

Ackers, P. (1958). Hydraulics Research Paper: Resistance of fluids flowing in channels and ducts, HMSO. **1:** 1-39.

ASCE (1963). "Friction factors in open channels [Task Force on Friction Factors in Open Channels], Journal of the Hydraulics Division, Proc. ASCE, Vol 89, HY2, March, 97-143 (Discussion in Journal of the Hydraulics Division, Vol 89, July, Sept. & Nov., 1963 and closure in Vol. 90, HY4 July 1964)." Journal of the Hydraulics Division Proc. ASCE, Vol 89, HY2: 97-143.

Cebeci, T., Bradshaw, P. (1977). Momentum Transfer in Boundary Layers, McGraw-Hill.

Centre, T. R. (1994). Proposed guidelines on the clearing and planting of trees in rivers, Technology Research Centre for Riverfront Development, Ministry of Construction, Japan**:** 1-144.

Chang, H. H. (1988). Fluvial processes, J Wiley.

Chow, V. T. (1959). Open channel flow, McGraw-Hill.

Clifford, N. J., A. Robert and K. S. Richards (1992). "Estimation of Flow Resistance in Gravel-Bedded Rivers: A Physical Explanation of the Multiplier of Roughness Length." Earth Surface Processes and Landforms **17**: 111-126.

Colebrook, C. F. (1939). "Turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws." Journal of the Institution of Civil Engineers **11**: 133-156.

Colebrook, C. F. and C. M. White (1937). "Experiments with fluid friction in roughened pipes." Proceedings Royal Society A **161**: 367-381.

Davies, S. J. and C. M. White (1925). "A review of flow in pipes and channels" - Reprinted by the Offices of Engineering, London, 1-16."

Dawson, H. and K. R. Fisher (2004). Roughness Review & Roughness Advisor, UK Defra/Environment Agency Flood and Coastal Defence R&D Programme, Report on Project W5A-057, July 2003. (available online at http://www.river-conveyance.net/documents/Conveyance Manual.pdf).

Dittrich, A. and Jarvela, J. (2006). "Flow-vegetation-sediment interaction", Water Engineering Research, **6**(3), 123-130.

ESDU (1979). Losses caused by friction in straight pipes with systematic roughness elements, Engineering Sciences Data Unit (ESDU) Engineering Sciences Data Unit (ESDU), September, Engineering Sciences Data Unit, London, 1-40. London, Engineering Sciences Data Unit (ESDU)**:** 1-40.

French, R. H. (1985). Open-channel hydraulics, McGraw-Hill.

Garde, R. J. and K. G. Ranga-Raju (1977). Mechanics of sediment transportation and alluvial stream problems, Wiley Eastern Ltd.

Graf, W. H. and Z. Qu (2004). "Flood hydrographs in open channels." ICE Journal of Water Management **157**(1): 45-52.

Hasegawa, K., S. Asai, S. Kanetaka and H. Baba (1999). "Flow properties of a deep open experimental channel with dense vegetation bank." Journal of Hydroscience and Hydraulic Engineering, JSCE **17**(2): 59-70.

Hicks, D. M. and P. D. Mason (1998). Roughness characteristics of New Zealand Rivers. New Zealand, National Institute of Water and Atmospheric Research, NIWA.

Hodskinson, A. and R. Ferguson (1998). "Numerical modelling of separated flow in river bends: model testing and experimental investigation of geometric controls on the extent of flow separation at the concave bank." Hydrological Processes **12**: 1323-1338.

Jarvela, J., Aberle, J., Dittrich, A., Rauch, H.P. & Schnauder, I. (2006). "Flow-vegetation-sediment interaction: research challenges", RiverFlow2006 [Eds, Ferreira, Alves, Leal & Cardoso], Vol. 2, Taylor & Francis, 2017-2026.

Ikeda, S., N. Murayama and T. Kuga (1999). "Stability of horizontal vortices in compound open channel flow and their 3-D structure, Periodic vortices at the boundary of vegetated area along river bank (in Japanese)." J. Hydraulic, Coastal and Environ. Eng. JSCE, **509/II-30**: 131-142.

Ikeda, S., K. Ohta and H. Hasegawa (1992). "Periodic vortices at the boundary of vegetated area along river bank (in Japanese)." J. Hydraulic, Coastal and Environ. Eng., JSCE, **443/II-18**: 47-54.

Jimenez, J. (2004). "Turbulent flows over rough walls." Annual Review of Fluid Mechanics **36**: 173-196.

Klaassen, G. J. and J. J. van der Zwaard (1974). "Roughness coefficients of vegetated flood plains." Journal of Hydraulic Research **12**(1): 43-63.

Knight, D. W. (1978). "Review of oscillatory boundary layer flow." Journal of the Hydraulics Division, ASCE **104**(6): 839-855.

Knight, D. W. (1981). "Some field measurements concerned with the behaviour of resistance coefficients in a tidal channel." Estuarine, Coastal and Shelf Science **12**: 303-322.

Knight, D. W. (2005). River flood hydraulics: theoretical issues and stage-discharge relationships. River Basin Modelling for Flood Risk Mitigation. D. W. Knight and A. Y. Shamseldin, Balkema. **Chapter 17**.

Knight, D. W. and B. Abril (1996). "Refined calibration of a depth averaged model for turbulent flow in a compound channel." Instn of Civil Engineers, Water, Maritime and Energy **118**: 151-159.

Knight, D. W. and F. A. Brown (2001). "Resistance studies of overbank flow in rivers with sediment using the Flood Channel Facility." Journal of Hydraulic Research **39**(3): 283-301.

Knight, D. W. and J. A. Macdonald (1979). "Hydraulic resistance of artificial strip roughness." Journal of the Hydraulics Division, ASCE **105**(6): 675-690.

Knight, D. W. and M. A. Ridgway (1976). "An experimental investigation of tidal phenomena in a rectangular estuary". Proc. Int. Symp. on Unsteady Flow in Open Channels, British Hydromechanics Research Association.

Knight, D. W. and M. A. Ridgway (1977). "Velocity distributions in unsteady open channel flow with different boundary roughnesses". Proc. 17th Congress, IAHR, Baden-Baden, Germany.

Knight, D. W. and R. H. J. Sellin (1987). "The SERC Flood Channel Facility." Journal of the Institution of Water and Environmental Management **1**(2): 198-204.

Knight, D. W. and K. Shiono (1990). "Turbulence measurements in a shear layer region of a compound channel." Journal of Hydraulic Research **28**(2): 175-196.

Knight, D. W. and K. Shiono (1996). River channel and floodplain hydraulics. Floodplain Processes. M. Anderson, D. E. Walling and P. Bates, J. Wiley**:** 139-181.

Knight, D. W., K. Shiono and J. Pirt (1989). Prediction of depth mean velocity and discharge in natural rivers with overbank flow. Int. Conf. on Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters, University of Bradford, Gower Technical Press.

Knight, D. W., K. W. H. Yuen and A. A. I. Alhamid (1994). Boundary shear stress distributions in open channel flow. Physical Mechanisms of Mixing and Transport in the Environment. K. Beven, P. Chatwin and J. Millbank. London, Wiley**:** 51-87.

Kouwen, N. and R. M. Li (1980). "Biomechanics of vegetative channel linings." Journal of Hydraulics Division, ASCE **106**(HY6): 1085-1103.

Kouwen, N., R. M. Li and D. B. Simons (1980). Velocity measurements in a channel lined with flexible plastic roughness elements. Fort Collins, Colorado, Department of Civil Engineering, Colorado State University.
Kouwen, N. and T. E. Unny (1973). "Flexible roughness in open channels." Journal of Hydraulics Division, ASCE **99**(HY5): 713-728.
Krishnappan, B. G. and Y. L. Lau (1986). "Turbulence Modeling of Flood Plain Flows." Journal of Hydraulic Engineering **4**: 251-256.
Lai, C. J. (1986). Flow resistance, discharge capacity and momentum transfer in smooth compound closed ducts. Department of Civil Engineering. Birmingham, University of Birmingham.
Lai, C. J., C. L. Liu and Y. Z. Lin (2000). "Experiments on flood-wave propagation in compound channels." Journal of Hydraulic Engineering, ASCE **126**(7): 492-501.
Lane, S., (2005) "Roughness - time for a re-evaluation?", Earth Surface Processes and Landforms , **30**(2): 251-253
Lane, S. N., R. J. Hardy, R. I. Ferguson and D. R. Parson (2005). A framework for model verification and validation of CFD schemes in natural open channel flows. Computational Fluid Dynamics: Applications in environmental hydraulics. P. D. Bates, S. N. Lane and R. I. Ferguson. Chichester, Wiley.
Launder, B. E. and D. B. Spalding (1974). "The numerical computation of turbulent flows." Computer methods in applied mechanics and engineering **3**: 269-289.
Laurenson, E. M. (1986). "Friction slope averaging in backwater calculations." Journal of Hydraulic Engineering, ASCE **112** (12): 1151-1163.
Lopez, F. (1997) Open channel flow with roughness elements of different spanwise aspect ratios: turbulent structure and numerical modelling, PhD thesis, Department of Civil and Environmental Engineering, University of Illinois at Urbana_Champaign, USA.
Macdonald, J. A. (1976). On the resistance to flow of water in open channels, PhD thesis, Department of Civil Engineering, The University of Birmingham (www.flowdata.bham.ac.uk).
MacLean, A. G. and B. B. Willetts (1986). "Measurement of boundary shear stress in non-uniform flow." Journal of Hydraulic Research **24**(1): 39-51.
Massey, B. S. (1995). Mechanics of Fluids, Chapman and Hall.
Morvan, H. P. (2001). Modelling river floods using Computational Fluid Dynamics. Department of Civil Engineering, University of Glasgow.
Morvan, H. P., A. J. Crossley and N. G. Wright (2005). "Flood Flow Mechanics in 3D". Joint ASME ASCE McMAT Conference, Baton Rouge, USA.
Morvan, H. P., G. Pender, N. G. Wright and D. A. Ervine (2002). "Three-dimensional hydrodynamics of meandering compound channels." Journal Of Hydraulic Engineering-Asce **128**(7): 674-682.
Morvan, H. P. and B. Sanders (2005). "Modelling open channel flow with horizontal recirculation zones: comparison of 2D and 3D models and turbulent closure schemes". Joint ASME ASCE McMAT Conference, Baton Rouge, USA.
Myers, W. R. C., D. W. Knight, J. F. Lyness, J. Cassells and F. A. Brown (1999). "Resistance coefficients for inbank and overbank flows." Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy Division **138**(2): 105-115.
Naot, D. (1984). "Response of channel flow to roughness heterogeneity." Journal of Hydraulic Engineering **110**(11), 1558-1587.
Nezu, I. and H. Nakagawa (1993). "Turbulence in Open-Channel Flows." IAHR Monograph Series: 1-281.
Nicholas, A. P. and D. E. Walling (1997). "Modelling Flood Hydraulics and Overbank Deposition on River Floodplains." Earth Surface Processes and Landforms **22**: 59-77.

Nicholas, A. P. (2001). “Computational fluid dynamics modeling of boundary roughness in gravel-bed rivers: An investigation of the effects of random variability in bed elevation.” Earth Surf. Process and Landforms **26**: 345–362.
Nikora, V., Koll, K., McEwan, I., McLean, S., and Dittrich, A. (2004). “Velocity distribution in the roughness layer of rough-bed flows.” Journal Hydraulic Engineering, **130** (10): 1036-1042.
Nikuradse J. (1933). “Strömungsgesetze in rauhen Rohren.” Forsch. Geb. Ingenieurwes., Ausg. Beill. 4, 361 (English translation: NACA Technical Memorandum, 1291).
Okada, S. and S. Fukuoka (2002). Land-form features in compound meandering channels and classification diagram of flood flows based on sinuosity and relative depth. River Flow 2002, Louvain-la-Neuve, Balkema.
Okada, S. and S. Fukuoka (2003). "Plan shape features in compound meandering channels and classification diagram of flood flows based on sinuosity and relative depth." Journal of Hydroscience and Hydraulic Engineering, JSCE **231**(1): 41-52.
Olsen, N.R.B. and Stokseth, S. (1995). "Three-dimensional numerical modelling of water flow in a river with large bed roughness", Journal Hydraulic Research, **33**(4): 571-581.
Pirt, J. (1988). Roughness data for rivers in the Severn-Trent region, National Rivers Authority.
Pokrajac, D., Finnigan, J.J., Manes, C., McEwan, I. and V. Nikora, On the Definition of the shear velocity in rough bed open channel flows, RiverFlow2006 [Eds, Ferreira, Alves, Leal & Cardoso], Vol. 1, Taylor & Francis, 89-98.
Raudkivi, A. J. (1967). Loose boundary hydraulics, Pergamon.
Reynolds, A. J. (1974). Turbulent flows in engineering. London, UK, J. Wiley and Sons.
Rouse, H. (1965), "Critical analysis of open channel flow resistance", Journal Hydraulics Division, **91**(HY4): 1-25.
Sayre, W. W. and M. L. Albertson (1963). "Roughness spacing in rigid open channels." Transactions of American Society of Civil Engineers, ASCE **128**(1): 343-427.
Schlichting, H., K. Gersten, E. Krause and H. J. Oertel (2004). Boundary-Layer Theory, Springer.
Sellin, R. H. J. and D. P. van Beesten (2004). "Conveyance of a managed vegetated two-stage river channel." ICE Journal of Water Management **157**(1): 21-33.
Shen, H. W. (1971). River Mechanics, Vols I & II, Colorado State University, USA.
Shiono, K. and D. W. Knight (1991). "Turbulent Open-Channel Flows with Variable Depth across the Channel." Journal of Fluid Mechanics **222**: 617-646.
Simons, D. B. and F. Senturk (1992). Sediment transport technology; water and sediment dynamics. Colorado, Water Resources Publications.
Sleath, J. F. A. (1984). Sea bed mechanics, Wiley.
Song, T. and W. H. Graf (1996). "Velocity and turbulence distribution in unsteady open-channel flow." Journal of Hydraulic Engineering, ASCE **122**(3): 141-154.
Strickler, A. (1923). Beiträge zur Frage der Geschwindigkeits formel und der Rauhigkeitszahlen für Ströme, Kanale und geschlossene Leitungen. Mitteilungen des Eidgenössischen Amtes für Wasserwirtschaft No. 16, Bern, Switzerland. Translated into English by: Roesgan, T. and Brownie, W.R. (1981). Contributions to the Question of a Velocity Formula and Roughness data for Streams, Channels and Closed Pipelines. Translation No. T-10. Pasadena, CA: California Institute of Technology, W.M. Keck Laboratory of Hydraulics and Water Resources.
Thomas, T. G. and J. J. R. Williams (1995). "Large Eddy Simulation of a symmetric trapezoidal channel at a Reynolds number of 430,000." Journal of Hydraulic Research **33**(6): 825-842.

van Rijn, L. C. (1984). "Sediment transport, Part III: Bed forms and alluvial roughness." Journal of Hydraulic Engineering, **110** (12): 1733-1754.
Versteeg, H. K. and W. Malalasekera (1995). An introduction to computational fluid dynamics-The finite volume method. London, Longman Group Ltd.
Wallis, S. G. and D. W. Knight (1984). "Calibration studies concerning a one-dimensional numerical tidal model with particular reference to resistance coefficients." Estuarine, Coastal and Shelf Science **19**: 541-562.
Wright, N. G., A. J. Crossley, H. P. Morvan and T. Stösser (2004). Detailed Validation of CFD for Flows in Straight Channels. River Flow 2004. Naples, Italy.
Yalin, M. and A. M. Ferreira da Silva (2001). Fluvial processes, IAHR Monograph.
Yalin, M. S. (1992) River mechanics, Pergamon, Oxford.
Yen, B. C. (1991). Channel flow resistance: centennial of Manning's formula. Colorado, USA, Water Resources Publications.
Yen, B. C. (2002). "Open channel flow resistance." Journal of Hydraulic Engineering **128**(1): 20-39.
Yuen, K. W. H. (1989). A study of boundary shear stress flow resistance and momentum transfer in open channels with simple and compound trapezoidal cross section. Department of Civil Engineering. Birmingham, University of Birmingham.

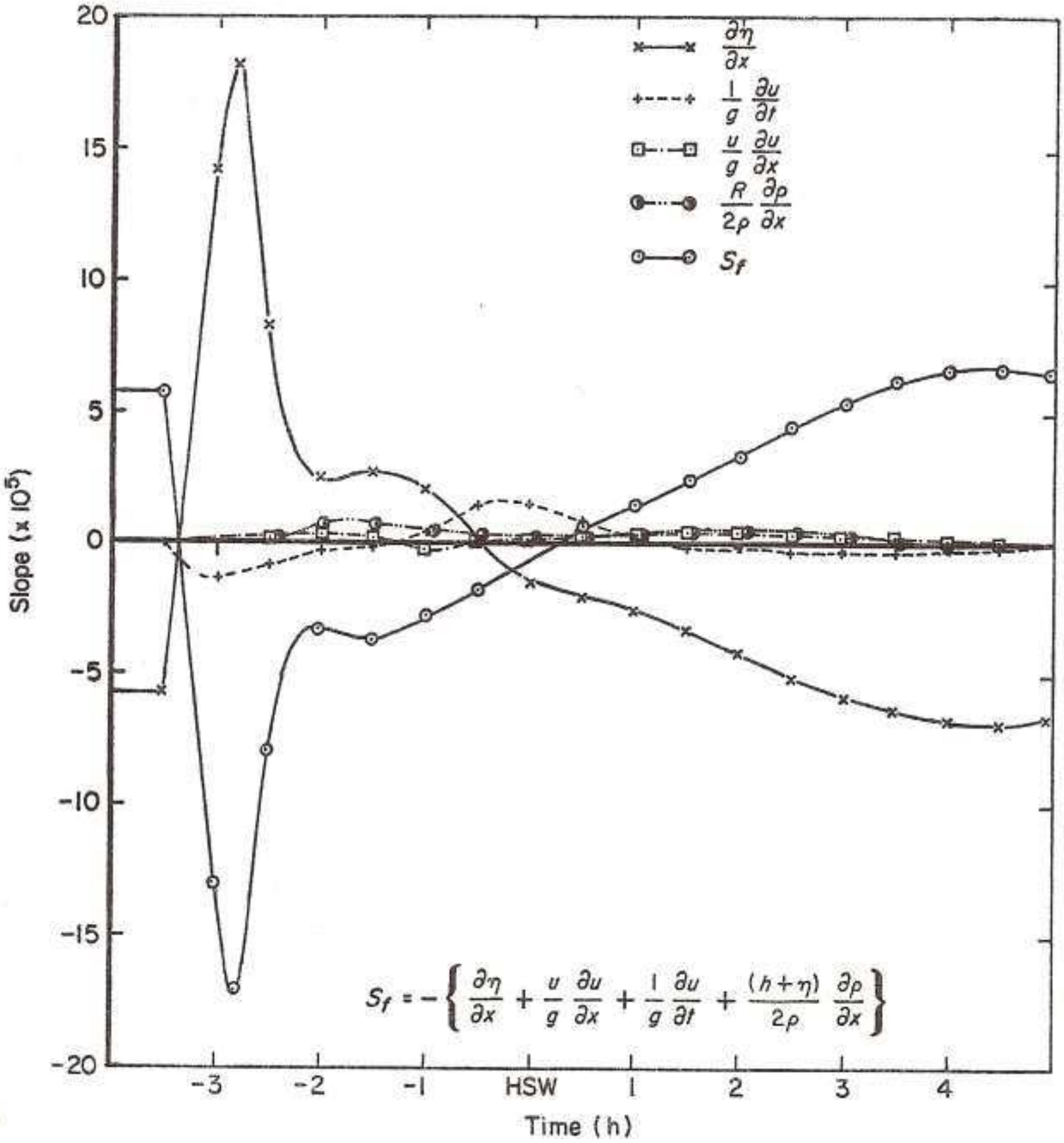


Fig. 1 Resistance data for Conwy estuary

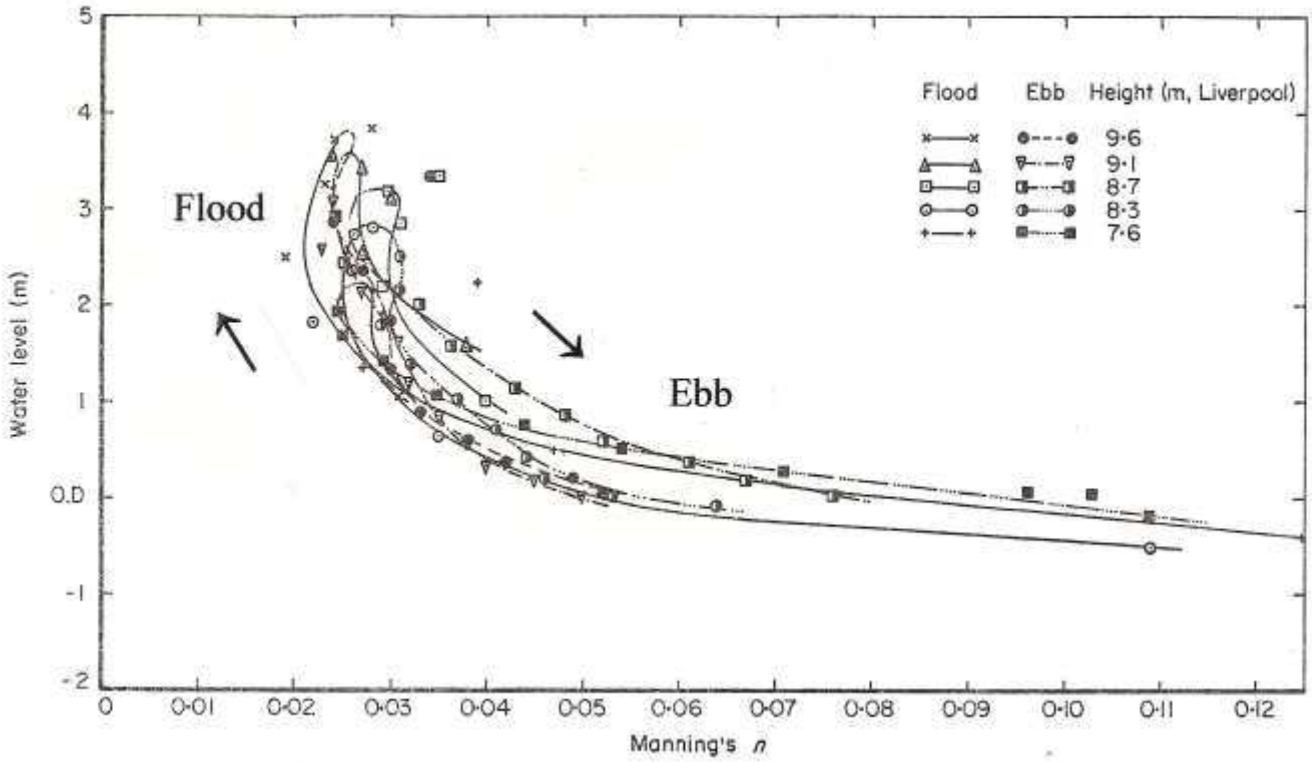


Fig. 2 Variation of resistance in test reach

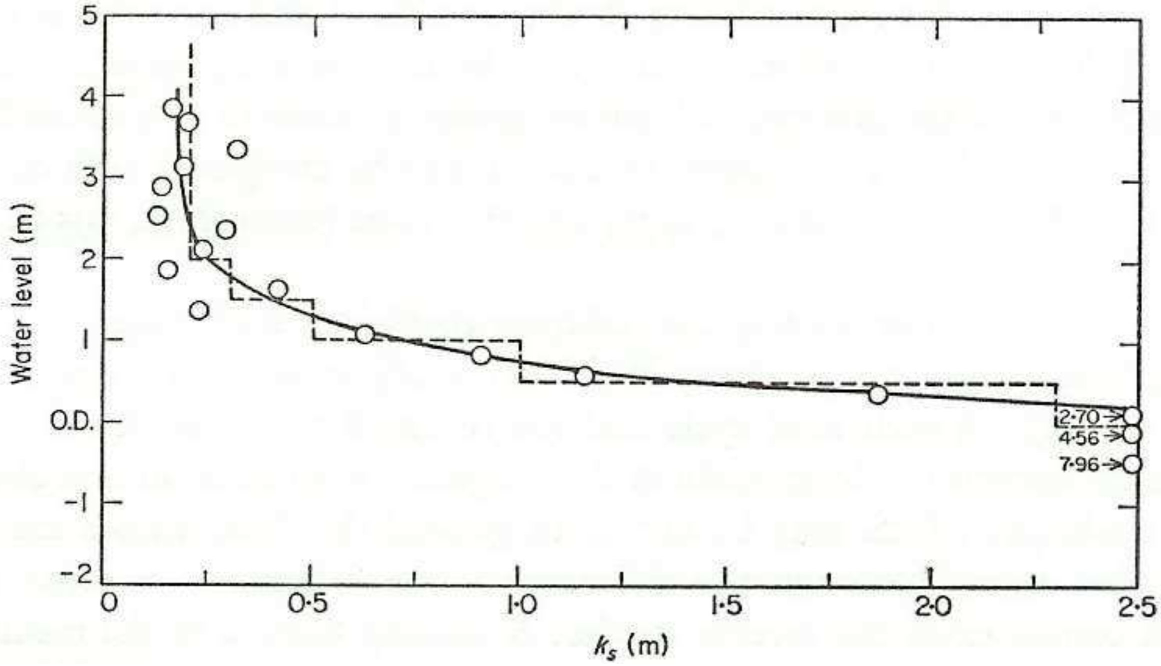


Fig. 3 Variation of k_s with depth

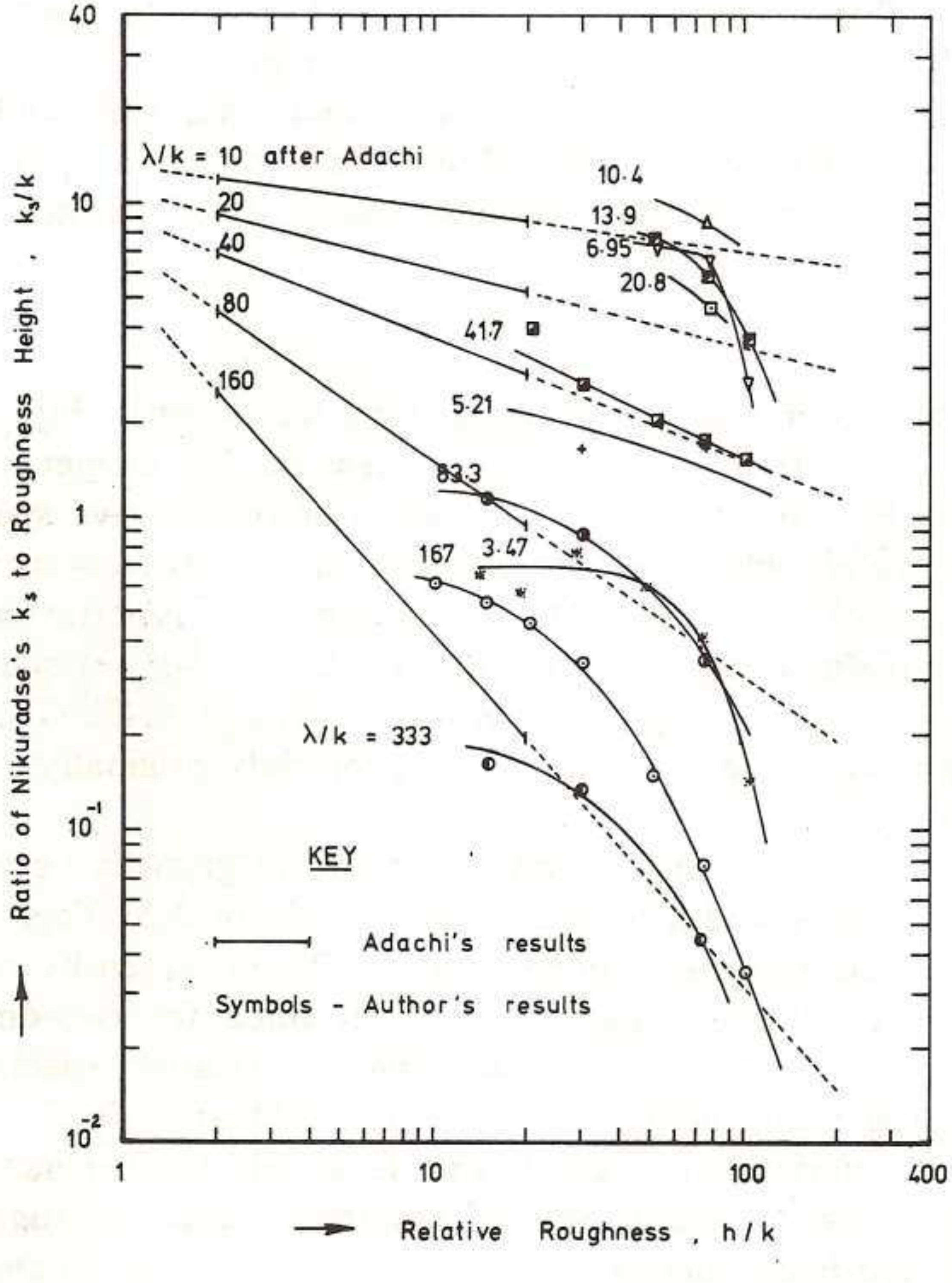


Fig. 4 Rib roughness resistance

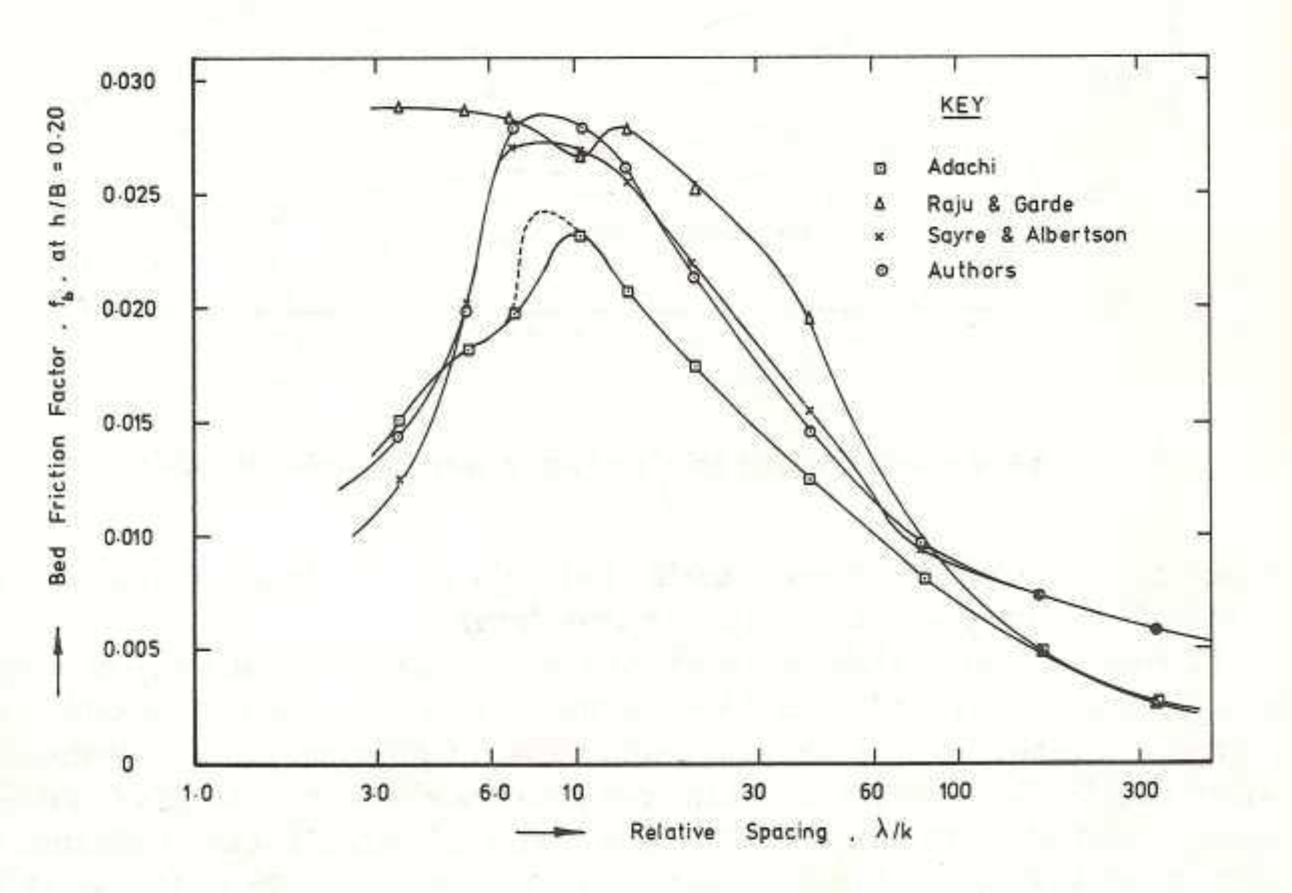


Fig. 5 Variation of f for rib roughness

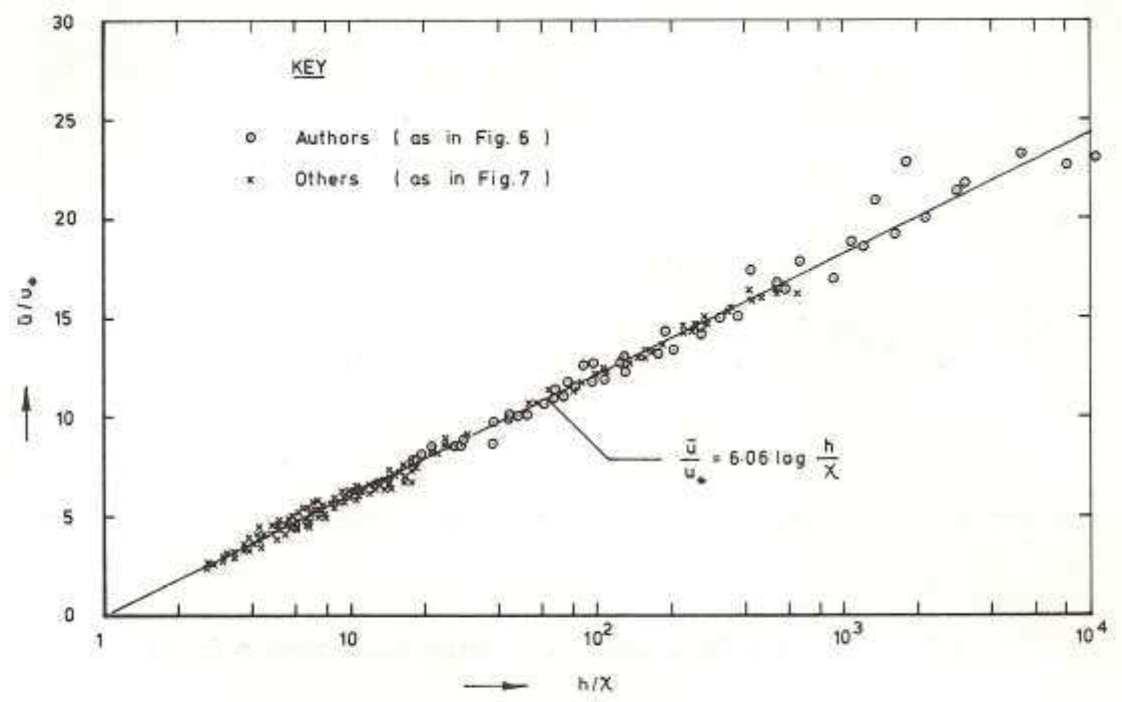


Fig. 6 Logarithmic function

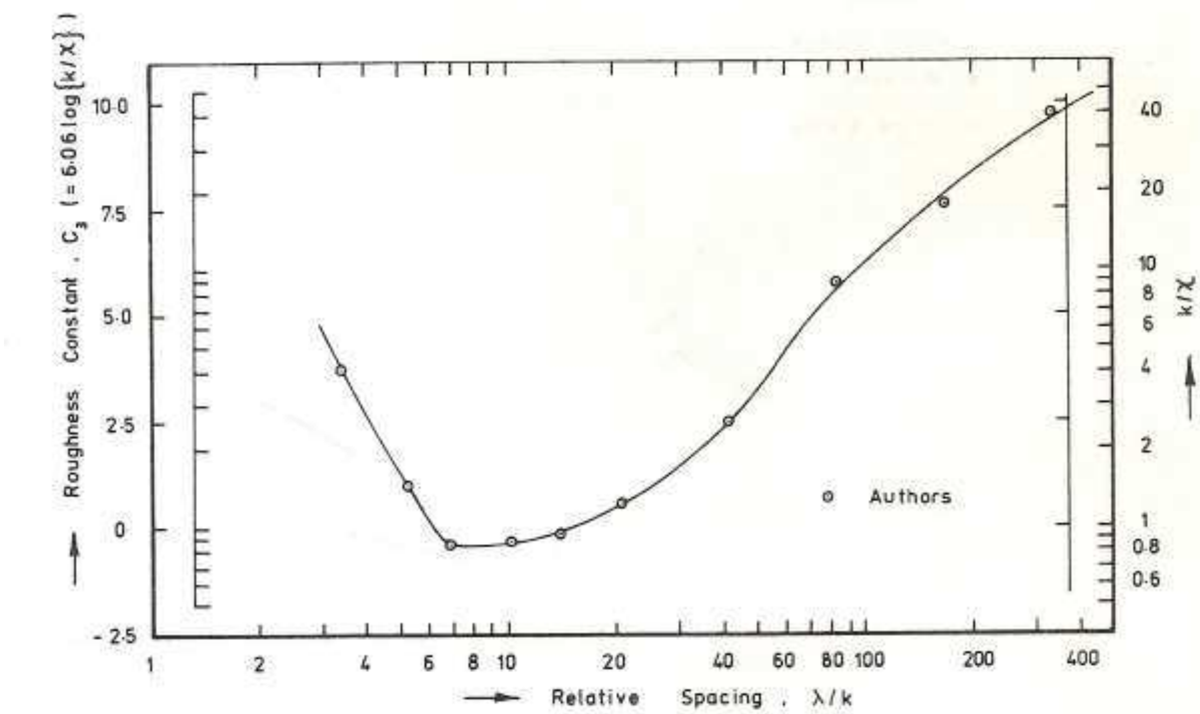
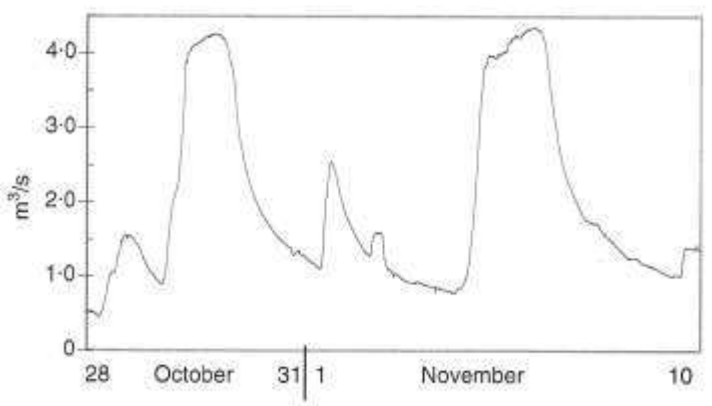
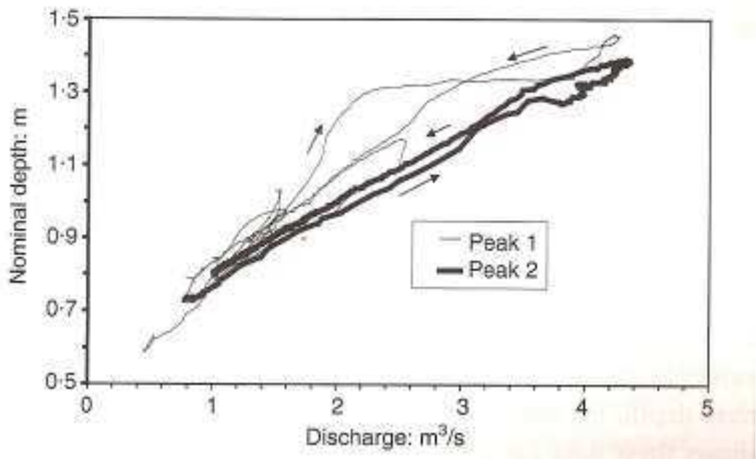


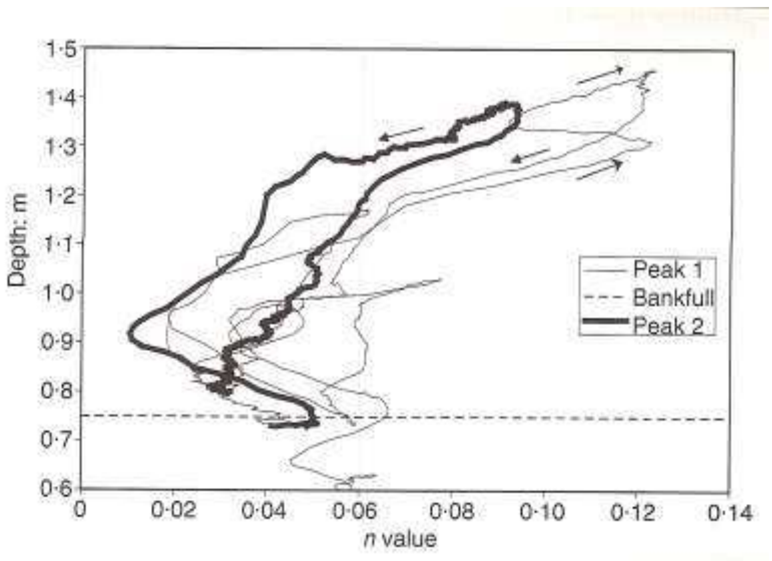
Fig. 7 Resistance parameter, χ, for rib roughness



(a) Discharge hydrograph: 28 October – 10 November 2000



(b) Variation of depth and discharge: 28 October – 10 November 2000



(c) Variation of Manning's n with depth: 28 October – 10 November 2000

Fig. 8 Looped stage-discharge and looped resistance relationships for a compound two-stage channel with vegetated floodplains (after Sellin & van Beesten, 2004)

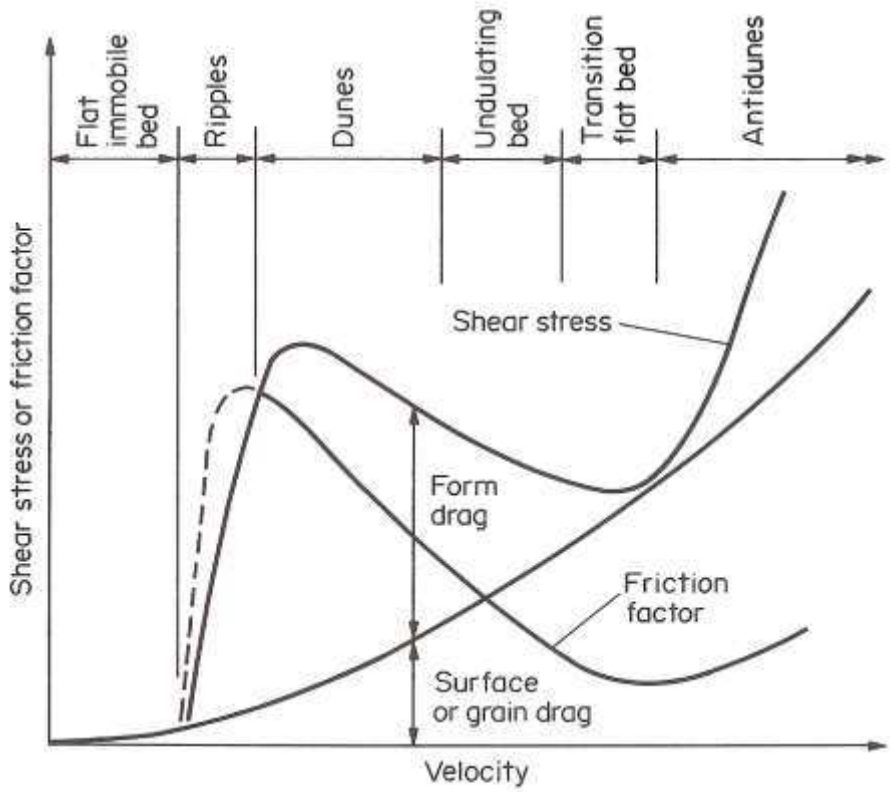


Fig. 9 Variation of surface and form drag, with bedforms (after Raudkivi, 1967)

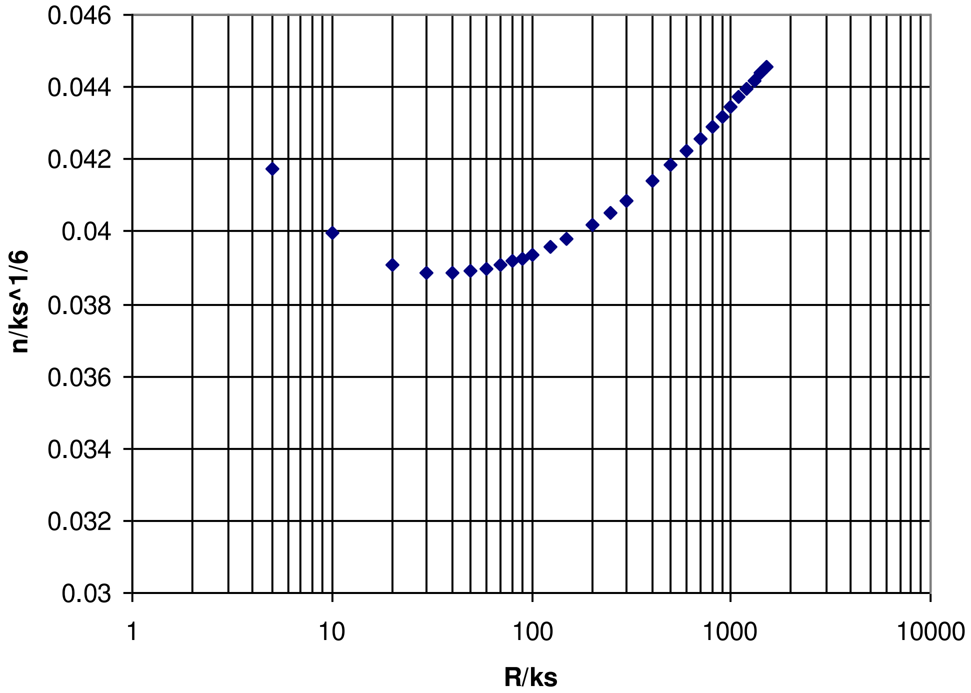


Fig. 10 – Roughness Behaviour according to Equation 12.

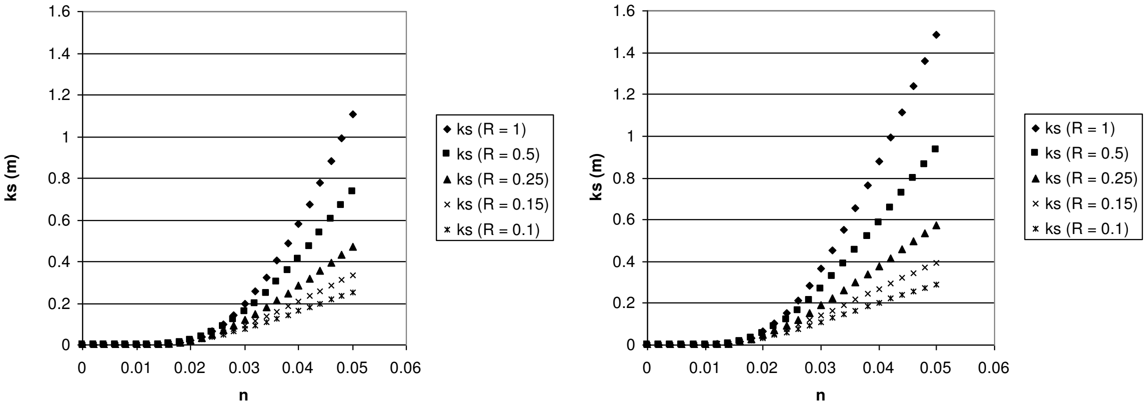


Fig. 11 – k_s as a Function of Manning's n (Equations 9 and 10, where R is the hydraulic radius).

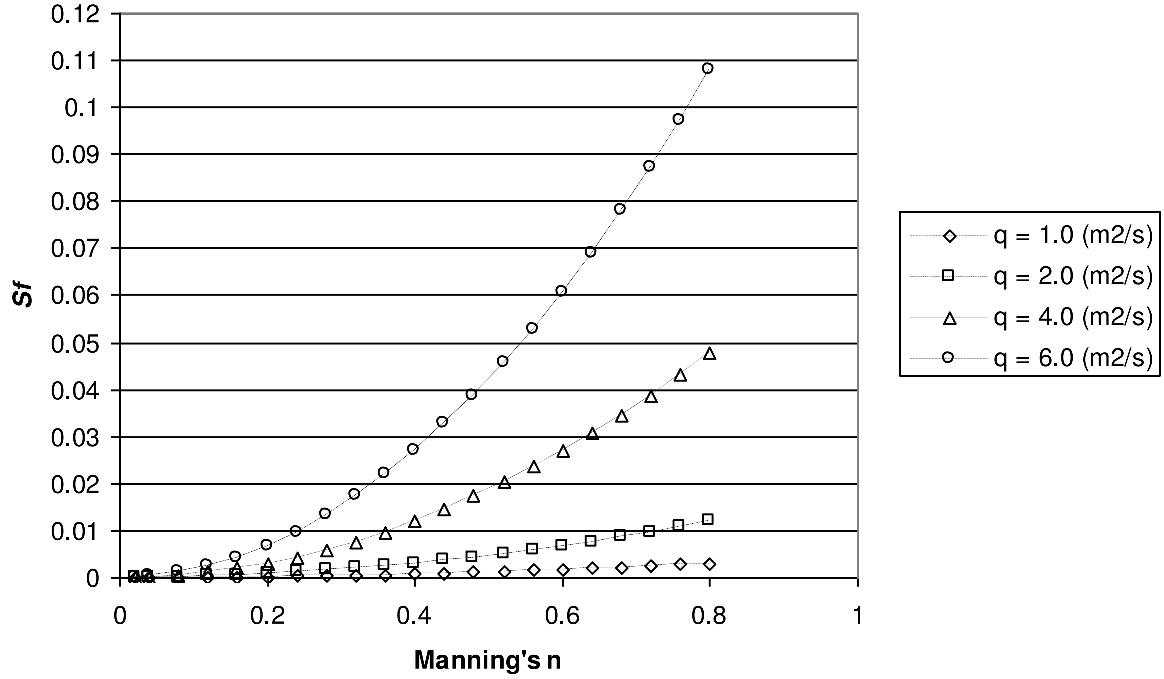


Fig. 12 – S_f as a function of Manning's n (Example).

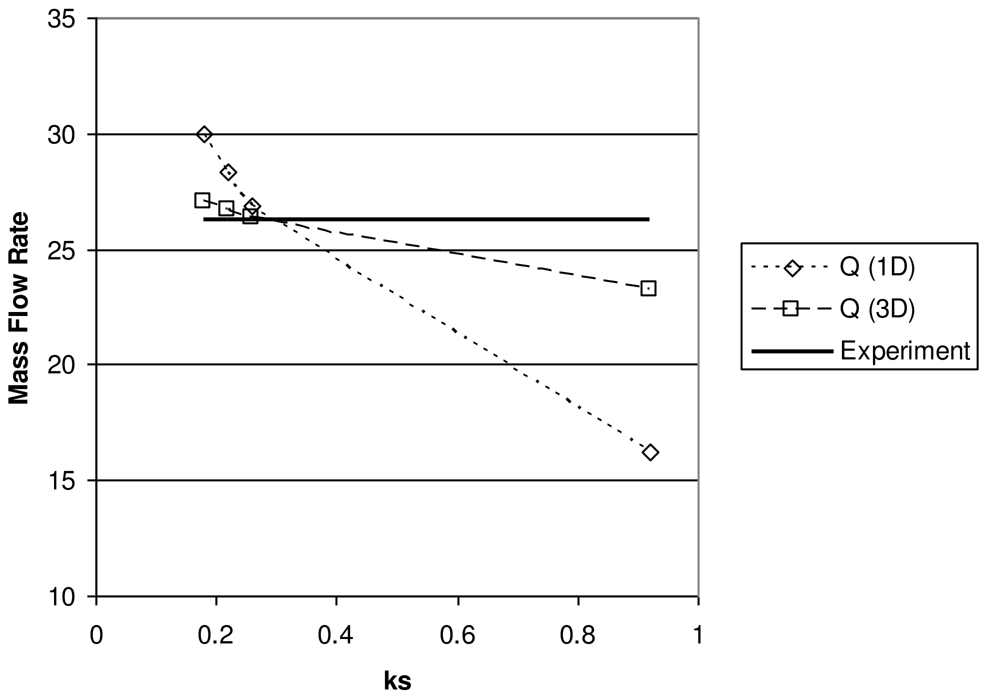


Fig. 13 – Variation of the mass flow rate in 1D and 3D for Kenneth Yuen's experiment 16 (Yuen, 1989) compared against the measured value. The 1D case is computed from Manning's equation using equation (16) for conversion purposes.