Conference Paper, Published Version

Knight, Donald William

A Review of Some Laboratory and Field Data for Checking Models of Rivers with Inbank and Overbank Flows

A REVIEW OF SOME LABORATORY AND FIELD DATA FOR CHECKING MODELS OF RIVERS WITH INBANK AND OVERBANK FLOWS

Donald Knight[1]

[1] Emeritus Professor, Department of Civil Engineering, The University of Birmingham
Edgbaston, Birmingham, B15 2TT, UK, e-mail: d.w.knight@bham.ac.uk

ABSTRACT

This paper describes some of the issues with regard to data frequently encountered when attempting to model river flows. Since sufficient spatial and temporal data are not usually available, it is therefore particularly important to appreciate how the underlying physical processes at work at reach scales should be interpreted at cross-section or basin scales. A selection of references is given on some published or readily available data for steady and unsteady flows in prismatic and non-prismatic channels. Although limited in scope, by virtue of the general dearth of data available, as well as by length restrictions of a conference paper, it is hoped that analysts may find this short summary useful.

Keywords: benchmarking, data, overbank flows, rivers

1. INTRODUCTION

This paper offers a broad overview on some of the issues involved when one attempts to model flows in rivers, taking particular regard to data. Since data are generally not available at both spatial and temporal scales in sufficient detail, it is important to appreciate the limits that this places on model calibration at a reach or basin scale. Models are often developed in terms of cross-sections, albeit made up of numerous cells, or panels in a depth-averaged model, and formed into 3D elements in plan form. Rivers in 1D or 2D models are also often treated as a series of reaches up to basin scales.

At conferences on hydrodynamic modelling there is usually a tendency to concentrate more on the mathematical and numerical aspects of modelling rather than on data, and so this paper attempts to redress the balance. This bias towards numerical aspects is understandable, given the complexity of natural river systems, the cost of field work and the difficulty in finding sufficiently detailed studies that are comprehensive enough for the purposes of checking numerical river models. However, as the application of advanced turbulence models to practical engineering problems develops apace, so does the need for high quality data to increase with it. Since this is so, this paper lists some references and sources to some laboratory and field studies that those involved in modelling rivers might find useful. Because of length restrictions, this paper cannot be truly comprehensive, but is offered as an initial review, in order to encourage others to do the same.

In a recent review of data, concepts and calibration issues in river modelling by Knight (2008), some general aspects of overbank flow were described, concentrating on steady flow in prismatic channels. Although this is mentioned briefly herein, data on overbank flows in non-prismatic channels are also referred to, as well as data on certain aspects of unsteady flow. Figures and diagrams have been deliberately excluded from this text, and use should therefore be made of the many references and the accompanying PowerPoint presentation (available at www.flowdata@bham.ac.uk).

2. SOME ISSUES IN MODELLING RIVER FLOWS

General issues in modelling river flows

Before considering any of the details of flow structure, mathematical representation or numerical algorithms, it is sometimes salutary to pause and consider why it is that the modelling of river flows is so difficult (Knight *et al*., 2006). For example, the river engineer needs to bear in mind at least some of the following issues:

- Our knowledge of some of the major issues in hydraulics is incomplete (Knight, 1996). See end-of-the-century snapshot of these given by Nakato & Ettema (1996).
- Our knowledge of turbulence in open channel flow is incomplete. See for example Nezu & Nakagawa (1993), Jakirlic & Hanjalic (2002) and Roussinova *et al*. (2008).
- Our knowledge of the reliability and accuracy of modelling systems is incomplete. See Garcia-Navarro & Playan (2008), Wang (2005) and Wang *et al*. (2008).
- Our knowledge of sediment mechanics and fluvial systems is limited. See Chang (1988), Toro-Escobar *et al*. (2000), Hu & Tan (2004), Ikeda & Parker (1989).
- Our knowledge of river regime principles at a basin-scale is limited. See Yang (1987), Barker *et al*. (2008), Bettess & White (1987) and Mengoni *et al*. (2004).
- Our knowledge of the effects of vegetation and how to model it are limited. See Jarvela *et al*. (2006).
- Our knowledge of how to handle data via evolutionary algorithms is limited. See Babovic, (2008) and Sharifi *et al*. (2008).

Notwithstanding these limitations, much progress has been made, and it is important to remind oneself that modelling still forms the preferred option when dealing with many practical problems in river engineering. Moreover, the role and extent of numerical modelling are only likely to increase further in the future. A short list of specific issues and difficulties that may be encountered when modelling river flows is now given.

Specific issues and difficulties encountered in modelling river flows

Although there are some generic similarities between river basins and types of river, each is unique and may therefore pose particular issues for the modeller. A brief list of some of these is as follows:

- there is usually limited data on flow parameters (discharge, velocity, turbulence, energy gradient, water surface behaviour, etc.).
- there is often very limited data on channel roughness (typically depth, flow and season dependent. Sediments and vegetation create particular problems).
- there is usually limited data on any hydraulic structures present in a river (typically these are often of a non-standard type).
- there is sometimes limited data on channel bathymetry (especially when there are morphological changes in plan form).
- the schematisation of the river may not be straightforward (due to shifts in control points, historic changes in floodplain use, etc.).
- the river flow itself may not comprise a stationary series (due to anthropological, morphological and climate changes).

There are of course many other issues that could be listed, but even with this limited selection, the modeller has to know about a wide range of related topics. To illustrate this, and to indicate the additional hydraulic knowledge that needs to be considered, consider just three topics: the stage–discharge relationship, channel roughness and climate change.

The stage-discharge relationship at given site is usually of particular importance when calibrating a numerical model. The modeller must however recognise that the functional relationship between *H&Q* is usually based on observed data over a range of flows, as assembled by a hydrometric team over a period of years. The stationarity of the series is thus crucial and usually reliant on negligible changes in morphology and river management.

However, since numerical models are frequently used in flood forecasting of extreme flows, the *HvQ* relationship may need to be extrapolated to flows much higher than actually observed. This requires considerable knowledge of overbank flow hydraulics, as well as the effects of changes in both geometry and roughness, as one switches from inbank to overbank flow conditions, as illustrated for the River Severn by Knight *et al*. (1989). It may also involve the reduction of unsteady flow data to quasi-steady flow conditions, in order to account for the traditional anti-clockwise looped rating curve arising from dynamic effects, or indeed the reverse clockwise looping effect, due to the flattening of floodplain vegetation by the rising floodwaters and the consequent reduction in resistance on the recession limb of the flood hydrograph. For further details on theoretical aspects, see Knight (2006 & 2008).

For ungauged catchments, where reliance is placed on some rainfall-runoff hydrological model to predict the extreme flow, and hence level, since peak flood discharges used in any pooling group are usually estimates, taken themselves typically from an extrapolated *HvQ* relationship, then these high flows should be treated with caution, as there may be some inherent systematic errors involved, due to the hydraulic reasons mentioned previously. This is often overlooked by modellers, who may not be so familiar with the circularity in this procedure when hydrological models, such as used in the Flood Estimation Handbook (FEH), are combined with hydraulics models. Although this *HvQ* topic has concentrated mainly on high discharges and overbank flow, there are also some issues to consider even for inbank flows. The first is the definition of bankfull discharge, again a concept widely used in non-dimensionalising parameters or in geomorphology. As shown by Navratil *et al*. (2004), the actual average 'bankfull' discharge may vary along a relatively short reach of river and the average have to be determined by one of a number of rational procedures. Backwater effects also need to be considered, for both inbank and overbank flows, as they may not only affect the *HvQ* relationship systematically, but also the streamwise water surface slope. Typically the water surface slope will vary with *Q* as different parts of a river exercise downstream control on the flow at different discharges (assuming subcritical flow conditions). The longitudinal water surface slope also has a direct bearing on how roughness is calculated and how rivers should be schematised. The schematisation of a river into a numerical model also needs some thought, bearing in mind flow structures and the nature of the problem to be analysed, as indicated by Samuels (1989).

Channel roughness is a complex topic, and therefore the prescription of hydraulic resistance to a reach at a particular flow in a numerical river model is not a trivial task. The correct choice of resistance coefficient is also important as the inertial and resistance terms are often the two dominant terms in the St Venant equations, even in tidal flows, as shown by Knight (1981). Accordingly, much effort has been expended on this roughness issue by hydraulicians, and useful summaries are provided by Dawson & Fisher (2004), Hicks & Mason (1998), Morvan *et al*. (2008) and Yen (1991). Recent work by HR Wallingford in producing the 'Roughness Advisor' (RA) software (at www.river-conveyance.net) should help modellers considerably. It not only provides standard values of roughness for different types of substrate and vegetation, but also gives guidance about the seasonal growth and decay of key aquatic plants, with re-growth characteristics following any weed cutting program. It thus may be used as a standard calibration tool as well as a tool for deciding on river maintenance regimes, where often the balance has to be struck between enhancing conveyance and maintaining ecological biodiversity. It has been tested against a number of rivers world-wide, each with different roughness conditions. See McGahey (2006) and McGahey *et al*. (2006). It should be remembered that hydraulic 'resistance' is different from the concept of hydraulic 'roughness' and, furthermore, that water levels may also be affected by other forms of resistance than that arising solely from the channel boundary. Certain hydraulic structures, such as bridges and culverts, as well as surface trash, may also impede the flow of water in times of flood. Particular attention may therefore need to be paid to bridge afflux, which differs from energy loss, in flood flows. To assist with this, HR Wallingford has recently produced the 'Afflux Estimator' (AE) that sits with the Conveyance Estimator, Roughness Advisor and Uncertainty Estimator, all within the Conveyance Estimation System (CES). See website (www.river-conveyance.net) for further details.

Climate change and its effects on river discharges are of particular significance today. Many studies on the potential changes in rainfall and consequent effects on river management have been published. See for example, Bronstert (2006), Knight & Samuels (2007) and Oshikawa *et al*. (2008). The recent UK Foresight project, the current European Commission (EC) Floodsite and Peseta project on climate issues all indicate the strength of activity in flood research (see Table 1 for websites). The (EC) has in fact funded over 100 research projects on flooding since the early 1980s, and these are itemised in a report by the University of Birmingham (see actif-ec.net website in Table 1).

Table 1 Links to some useful flood related studies

Project	**Link**
RIBAMOD	http://www.hrwallingford.co.uk/projects/RIBAMOD/index.html
RIPARIUS	http://www.nwl.ac.uk/ih/www/research/briparius.html
MITCH	http://www.hrwallingford.co.uk/Mitch/default.htm
IMPACT	http://www.samui.co.uk/impact-project
University of Birmingham	http://www.actif-ec.net/library/review_EU_flood_projects.pdf http://www.flowdata.bham.ac.uk
CES	http://www.river-conveyance.net
FLOODSITE	http://www.floodsite.net
FORESIGHT	http://www.foresight.gov.uk
PESETA	http://peseta.jrc.es
EU directive	http://europa.eu.int/ /comm/environment/water/flood_risk/index.htm

Data issues when checking models of river flows

Having considered some of the general and specific issues relevant to river modelling, it is now appropriate to consider what kind of data are required, before describing the sites where they may be found. The checking of numerical models may be undertaken at various levels, a quick back-of-the-envelope type of calculation, in order to check the order-of-magnitude of key values, specific checking of particular algorithms within the code, for example a bridge afflux routine, the detailed checking of the validity of the whole code, and finally some means of evaluating the accuracy and competence of the whole system through comparison with exemplary data sets. Quality assurance audit trails are now commonplace in software development, and are becoming increasingly important in areas such as flood risk management where loss of life and significant infrastructure damage cost are possibilities. The IAHR produced its own guidelines some years ago (IAHR, 1994) and these perhaps now need updating, along with the provision of benchmarked data sets. The role of high quality data is thus assuming more significance than it used to. Items to be considered are:

- Degree of spatial and temporal data required to check model?
- Parameters to be measured? e.g. Q & H; U (streamwise only); U_d (depth-averaged velocity); UVW (all components and hence obtain vorticity and secondary flows); uvw (intensities); Reynolds stresses; turbulence correlations; spectra; etc.
- Scale of available data – small experimental scale, large scale or based on fieldwork?
- Shape of cross-section, prismatic or non-prismatic?

- Uniform, non-uniform flow, sub-critical or super-critical, range of Reynolds number?
- Steady or unsteady flow? Flood routing, estuarial dynamics, transient pollutants, seasonal timescales?
- Sediment transfers? Sediment transport, erosion, deposition, dispersion, etc.

It is clear that the more complex the model the more demanding are the constraints on the data required to calibrate or validate the model. CFD models, like rainfall-runoff models, contain so many parameters, that one has to discriminate down to the key ones requiring particular emphasis. Equifinality is then an issue (Beven & Freer, 2001). It is therefore likely that 3D models based on CFD may only be validated for simple shapes via detailed PIV and turbulence measurements in the laboratory. Although CFD models are applied to rivers, their use is somewhat in advance of the data to satisfactorily verify them.

3. SOURCES OF DATA FOR CHECKING MODELS

A very brief list in now given of some of the sources where data sets may be found, categorized by the type of flow conditions and with a brief description concerning the nature of the facilities involved. Although there are many books, journal publications and research literature available, there is a general dearth of specific data freely available, often on the grounds of cost to acquire them and commercial or institutional secrecy. Perhaps we need in hydraulic engineering something akin to the Stanford conference in 1968, which was wholly devoted to collecting key data and information, in that case the two constants in the logarithmic velocity formula. See Coles & Hirst (1969) and Coles (1968). There is now an urgent need for equivalent data, relevant to river flow modelling, on websites, available to all.

Laboratory studies - inbank flows

There have been many studies over the last two centuries that have been undertaken in straight prismatic channels with fairly simple cross-section shapes, such as rectangular and trapezoidal geometries, arising from the numerous experimental studies in flumes at research institutions. Examples of these are given by Knight et al. (1992, 1994 & 2007), Knight & Shiono (1996), Shiono & Knight (1991), Nezu & Nakagawa (1993), Tominaga *et al*. (1989) and Yen (1991). See Table 2 and the website (www.flowdata.bham.ac.uk) for a summary of recent studies which contains some of these data. For inbank flows in bends and meandering channels, see Booij (2004), Fukuoka (2002), Ikeda & Parker (1989) and Muto (1997).

Laboratory studies - overbank flows

There have been a considerable number of studies in recent decades on overbank flow, arising from its importance in flood investigations. Examples of recent work are given by Ikeda & McEwan (2008), the FCF studies (1986-1996), Atabay & Knight (2006), Knight & Abril (1996), Abril & Knight (2004), Shiono & Muto (1998), Willetts & Rameshwaran (1996), Ervine *et al*. (1993 & 2000) and Fukuoka *et al*. (1996).

Laboratory studies – hydraulic structures

There are numerous books that contain information and selected data on hydraulic structures of all types. See for example Ackers *et al*. (1978), Bos *et al*. (1984), Miller (1994), Hamill(1999), international and national codes. For afflux at bridges see recent data and reports on conveyance website (www.river-conveyance.net).

Table 2. University of Birmingham database (data available at www.flowdata.bham.ac.uk)

Name	Date of PhD	No. of exps	Facility	Type of channel/duct
Alhamid	1991	38	Bham, 22m flume	Trapezoidal channel with heterogeneous roughness
Atabay	2001	50	Bham, 18m flume	rect compound, rigid & mobile
Ayyoubzadeh	1997	25	Bham, 18m flume	small scale, rigid & mobile
Brown	1997	26	FCF, HR Wallingford	FCF, large scale, mobile
Chlebek	2008	many	Bham 22m flume	Overbank flow with skewed floodplains
Lai	1986	61	Bham 11m wind tunnel	compound duct, variable geometry
Mohammadi	1998	10	Bham 15m & 9m flumes	V-shaped channels + others
Patel	1984	66	Bham 11m wind tunnel	rect & compound duct, smooth & rough
Rezai	2006	many	Bham 22m flume	Overbank flow with non-prismatic floodplains
Rhodes	1991	48	Bham 25m wind tunnel	rect and compound very wide cases, immense detail
Shiono	-	many	FCF, HR Wallingford	FCF, large scale, rigid (straight & meandering)
Sterling	1998	24	Bham 22m flume (with circular pipe)	circular part full and with flat beds (~ deposited sediment)
Yuen	1989	75	Bham 22m flume	trapezoidal & compound (sub & super-critical flow)
Knight	1970-85	150	numerous flumes	rect simple & compound
Knight	1987-89	74	FCF, HR Wallingford	compound (15 Volumes)
Knight	1990-96	many	FCF, HR Wallingford	meandering simple/compound
Knight	1980-04	many	various	collected sets from elsewhere

Field studies

For resistance data in 40 New Zealand rivers, see Hicks & Mason (1998), and for UK rivers see Dawson & Fisher (2004). Notable field studies on overbank flow are those by Babaeyen-Koopaei *et al.* (2002), Sellin & van Beesten (2002 & 2006) and McGahey *et al.* (2006).

Prismatic & non-prismatic floodplains

Since most of the preliminary work on overbank flow has been conducted in straight prismatic channels, experimental studies with non-prismatic sections and floodplains are few, with the exception of Bousmar & Zech (2002), Rezaei (2006), Chlebek (2008), Chlebek & Knight (2008) and the linked work of Prooijen (2004).

Rigid, loose and flexible boundary resistance, some with unsteady flow

See Brown (1997), Huthoff (2007), Gunawan *et al*. (2008), Knight & Brown (2001), Sellin & van Beesten, (2002 & 2004), Tang & Knight (2006) and Wormleaton *et al*. (2005). For unsteady flow effects, see Lai *et al*. (2000), Knight (1981) and Wallis & Knight (1984).

REFERENCES

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

Ackers, P., White, W.R., Perkins, J.A. & Harrison, A.J.M. (1978), *Weirs and flumes for flow measurement*, J Wiley, pp.1-327.

Atabay, S. and Knight, D.W. (2006), 1-D modelling of conveyance, boundary shear and sediment transport in overbank flow, *Journal of Hydraulic Research,* IAHR, 44(6), pp.739-754.

Babaeyan-Koopaei, K., Ervine, D.A., Carling, P.A. & Cao, Z. (2002), Velocity and turbulence measurements for two overbank flow events in River Severn, *Journal of Hydraulic Engineering,* ASCE, Vol. 128 (10), Oct., pp.891-900.

Babovic, V. (2008), Data-driven knowledge discovery: Four roads to vegetation-induced roughness formulae, in *Numerical modelling of hydrodynamics for water resources*, [Eds Garcia Navarro & Playan], Taylor & Francis, pp.77-94.

Barker, D.M., Lawler, D.M., Knight, D.W., Morris, D.G., Davies, H. & Stewart, E.J. (2008), Longitudinal distributions of river flood power: the novel CAFES – Combined Automated Flood, Elevation and Stream power - methodology, *Water Resources Research* (in press).

Bettess, R. and White, W.R. (1987), Extremal hypotheses applied to river regime, In *Sediment transport in gravel bed rivers* [Eds Thorne, Bathurst & Hey], J Wiley, pp. 767-789.

Beven, K. and Freer, J. (2001), Equifinality, data assimilation, and uncertainty estimation in deterministic modeling of complex environmental systems using the GLUE methodology, *Journal of Hydrology*, Vol. 249, Issues 1-4, August, pp.11-29.

Booij, R. (2004), Negative eddy viscosity in bends, *River Flow 2004*, [Eds Greco, Carravetta & Della Morte], Taylor & Fancis, Vol. 1, pp.307-315.

Bousmar, D. and Zech, Y. (2002), Periodical turbulent structures in compound channels, *River Flow 2002*, [Eds Bousmar & Zech], Balkema, Vol. 1, pp.177-185.

Bos, M.G., Reploge, J.A. & Clemmens, A.J. (1984), *Flow measuring flumes for open channel systems*, J Wiley, pp.1-321.

Bronstert, A. (2006), Overview of current perspectives on climate change *and* Effects of climate change on flooding, In *River Basin Modelling for Flood Risk Mitigation* [Eds Knight & Shamseldin], Taylor & Francis, Chapters 3&4, pp.59-91.

Brown, F.A. (1997), Sediment transport in river channels at high stage, *PhD Thesis,* The University of Birmingham, UK.

Chang, H.H. (1988), *Fluvial processes in river engineering*, Wiley, pp.1-432.

Chlebek, J. (2008), Modelling of simple prismatic channels with varying roughness using the SKM and a study of flow in smooth non-prismatic channels with skewed floodplains, *PhD Thesis, The University of Birmingham* (in preparation).

Chlebek, J. and Knight, D.W. (2008), Observations on flow in channels with skewed floodplains, *River Flow 2008* (in press).

Coles, D.E. (1968), The young person's guide to the data, Computation of turbulent boundary layers, AFOSR-IFP_Stanford Conference, August 1968 – Vol. I, pp.1- .

Coles, D.E. and Hirst, E. (1969), Computation of turbulent boundary layers, AFOSR-IFP-Stanford Conference, August 1968 – Vol. II, Compiled data, pp.1-
Dawson, H. and Fisher, K.R. (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 www.river-conveyance.net).
Ervine, D.A., Willetts, B.B., Sellin, R.H.J. & Lorena, M. (1993), Factors affecting conveyance in meandering compound flows, *Journal of Hydraulic Engineering,* ASCE, Vol. 119 (12), Dec., pp.1383-1399.
Ervine, D.A., Babaeyan-Koopaei, K. & Sellin, R.H.J. (2000), Two-dimensional solution for straight and meandering overbank flows, *Journal of Hydraulic Engineering*, Vol. 126 (9), Sept., pp.653-669.
Fukuoka, S., Miyazaki, H, Ohgushi, H., & Kamura, D. (1996), Flow and bed topography in a meandering compound channel with phase difference between the alignment of the main channel and the levee, *Annual Journal of Hydraulic Engineering*, JSCE, 40, pp.941-946.
Fukuoka, S. (2002), River management for hydraulic harmony between flood control and environmental considerations, *RiverFlow2002*, [Eds Bousmar & Zech],Balkema,pp.45-56.
Garcia-Navarro, P. and Playan, E. (2008), *Numerical modelling of hydrodynamics for water resources*, Taylor & Francis, pp.1-389.
Gunawan, B., Sun, X., Sterling, M., Knight, D.W., Shiono, K., Chandler, J., Rameshwaran, P., Wright, N.G., Sellin, R.H.J., Tang, X. & Fujita, I. (2008), An integrated and novel approach to estimating the conveyance capacity of the River Blackwater, *Proc. 8th ICHE, Nagoya*, Japan (in press)
Hamill, L. (1999), *Bridge hydraulics*, Taylor & Francis, pp.1-367.
Hicks, D.M. and Mason, P.D. (1998), Roughness Characteristics of New Zealand Rivers, *National Institute of Water and Atmospheric Research Ltd, NIWA,* Christchurch, New Zealand, Water Resources Publications, pp.1-329.
Hu, C. and Tan, Y. (2004), River Sedimentation, *Proc. of the 9th Int. Symp. on River Sedimentatiom*, Yichang, China, 4 Vols , Tsinghua University Press.
Huthoff, F. (2007), Modelling hydraulic resistance of floodplain vegetation, *PhD Thesis, Twente university*, Belgium.
IAHR (1994), *Guidelines for documenting the validity of computational software*, Int. Association for Hydraulic Research, IAHR, pp.1-24.
Ikeda, S. and Parker, G. (1989), River meandering, *Water Resources Monograph 12*, American Geophysical Union, Washington, pp.1-485.
Ikeda, S. and McEwan, I.K. (2008), Flow and sediment transport in compound channels: the experiences of Japanese and UK research, *IAHR Monograph*, (in press).
Jarvela, J. Aberle, J., Dittrich, A., Rauch, H.P. & Schauder, I. (2006), Flow-vegetation-sediment interaction: Research challenges, *River Flow 2006*, [Eds, Ferreira, Alves, Leal & Cardoso], Taylor & Francis, Vol. 2, pp.2017-2026.
Jakirlic, S. and Hanjalic, K. (2002), A new approach to modelling near-wall turbulence energy and stress dissipation, *J Fluid Mechanics,* 249, pp.139-166.
Knight, D.W. (1981), Some field measurements concerned with the behaviour of resistance coefficients in a tidal channel, *Estuarine, Coastal and Shelf Science*, Academic Press, London, No. 12, pp.303-322.
Knight, D.W. (1996), Issues and directions in river mechanics - closure of sessions 2, 3 and 5. In *'Issues and directions in hydraulics',* [Eds Nakato & Ettema], An Iowa Hydraulics Colloquium in honour of Professor John F Kennedy, Iowa Institute of Hydraulic Research, Iowa, USA, Balkema, pp.435-462.
Knight D.W. (2006), River flood hydraulics: theoretical issues and stage-discharge relationships. In *River Basin Modelling for Flood Risk Mitigation* [Eds Knight &

Shamseldin], Taylor & Francis, Chapter 17, pp.301-334.
Knight, D.W. (2008), Modelling overbank flows in rivers – data, concepts, models and calibration, Chapter 1 in *Numerical Modelling of Hydrodynamics for Water Resources* [Eds Garcia-Navarro & Playan], Taylor & Francis, pp.3-23.
Knight, D.W. & Abril, B. (1996), Refined calibration of a depth-averaged model for turbulent flow in a compound channel, *Proc. Instn. of Civil Engineers, Water , Maritime and Energy Division*, London, 118(3), Sept., pp.151-159.
Knight, D.W. and Brown, F.A. (2001), Resistance studies of overbank flow in rivers with sediment using the Flood Channel Facility, *Journal of Hydraulic Research*, IAHR, Vol. 39 (3), pp.283-301.
Knight, D.W. and Samuels, P.G. (2007), Examples of recent floods in Europe, *Journal of Disaster Research*, Fuji Technology Press, Tokyo, Japan, Vol. 2 (3), pp.190-199.
Knight, D.W. and Shiono, K. (1996), River channel and floodplain hydraulics. In *Floodplain Processes*, (Eds Anderson, Walling & Bates), Chapter 5, J Wiley, pp. 139-181.
Knight, D.W., Al-Hamid, A.A.I. & Yuen, K.W.H. (1992), Boundary shear in differentially roughened trapezoidal channels. In *Hydraulic and Environmental Modelling:Estuarine and River Waters* [Eds Falconer, Shiono & Matthew], Ashgate Press, pp. 3-14.
Knight, D.W., Omran, M. & Tang, X. (2007), Modelling depth-averaged velocity and boundary shear in trapezoidal channels with secondary flows, *Journal of Hydraulic Engineering*, February, ASCE, 133(1), pp.39-47.
Knight, D.W., Shiono, K. and Pirt, J. (1989), Prediction of depth mean velocity and discharge in natural rivers with overbank flow, *Proc. Int. Conf. on Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters*, [Eds. Falconer, Goodwin & Matthew], Gower Technical, University of Bradford, September, Paper 38, pp.419-428.
Knight, D.W., Yuen, K.W.H. & Alhamid, A.A.I. (1994), Boundary shear stress distributions in open channel flow. In *Physical Mechanisms of Mixing and Transport in the Environment,* [Eds Beven, Chatwin & Millbank], Chapter 4, J. Wiley, pp.51-87.
Knight, D.W., Cao, S., Liao, H., Samuels, P.G., Wright, N.G., Liu, X. & Tominaga, A. (2006), Floods – are we prepared?, *Journal of Disaster Research*, Fuji Technology Press, Tokyo, Japan, Vol. 1 (2), pp.325-333.
Lai, C.J., Liu, C.L. & Lin, Y.Z. (2000), Experiments on flood-wave propagation in compound channels, *Journal of Hydraulic Engineering*, ASCE, Vol. 126 (7), July, pp.492-501.
McGahey, C. (2006), A practical approach to estimating the flow capacity of rivers. *PhD Thesis*, Open University, Milton Keynes, UK.
McGahey, C., Samuels, P.G. & Knight, D.W. (2006), A practical approach to estimating the flow capacity of rivers – application and analysis, *River Flow 2006*, [Eds, Ferreira, Alves, Leal & Cardoso], Taylor & Francis, Vol.1, pp.303-312.
Mengoni, B., Paris, E. & Bettess, R. (2004), On the validity of analytical regime theory, *River Flow 2004*, [Eds Greco, Carravetta & Della Morte], Taylor & Fancis, pp.119-126.
Miller, D.S. (1994), *Discharge characteristics: IAHR Hydraulic Structures Design Manual No 8*, Balkema, pp.1-249.
Morvan, H., Knight, D.W., Wright, N.G., Tang, X. & Crossley, M. (2008), The concept of roughness in fluvial hydraulics and its formulation in 1-D, 2-D & 3-D numerical simulation models, *Journal of Hydraulic Research, IAHR*, Vol. 46 (2), pp.191-208.
Muto, Y. (1997), Turbulent flow in two-stage meandering channels, *PhD Thesis*, University of Bradford.
Nakato, T. and Ettema, R. (1996), *Issues and directions in hydraulics*, Balkema, pp.1-495.
Navratil, O., Albert, M.B. & Gresillon, J.M. (2004), Using a 1D steady flow model to compare field determination methods of bank-full stage, *River Flow 2004*, [Eds Greco, Carravetta & Della Morte], Taylor & Fancis, Vol. 1, pp.155-161.

Nezu, I. and Nakagawa, H. (1993), Turbulence in Open-Channel Flows, *IAHR Monograph*, Balkema, Rotterdam, pp.1-281.

Oshikawa H., Hashimoto, A., Tsukahara, K. & Komatsu, K. (2008), Impacts of recent climate change on flood disaster and preventive measures, *Journal of Disaster Management*, Fuji Technology Press, Tokyo, Japan, Vol. 3(2), pp.131-141.

Prooijen, B.M. (2004), Shallow mixing layers, *PhD Thesis*, Delft University of Technology Report 04-1, ISSN 0169-6548.

Rezaei, B. (2006), Overbank flow in compound channels with prismatic and non- prismatic floodplains, *PhD Thesis,* The University of Birmingham, UK.

Roussinova, V., Biswas, N. & Balachandar, R. (2008), Revisiting turbulence in smooth uniform open channel flow, *Journal of Hydraulic Research*, Vol. 46 (Extra), pp.36-48.

Samuels, P.G. (1990), Cross-section location in 1-D models, *Proc. Int. Conf. on River Flood Hydraulics,* (Ed. W.R.White), J. Wiley, Wallingford, September, Paper K1, 339-348.

Sellin, R.H.J. and van Beesten, D.P. (2002), Berm vegetation and its effect on flow resistance in a two-stage river channel: an analysis of field data, *River Flow 2002*, [Eds. Bousmar and Zech], Balkema, pp.319-327.

Sellin, R.H.J. and van Beesten, D.P. (2004), Conveyance of a managed vegetated two-stage river channel, *Water Management,* Proceedings of the Instn. of Civil Engineers, London, Vol. 157, Issue WM1, March, pp.21-33.

Sharifi, S. Knight, D.W. & Sterling, M. (2008), Modelling Flow Using SKM and a Multi-Objective Evolutionary Algorithm, *River Flow 2008* (in press)

Shiono, K. and Knight, D.W. (1991), Turbulent open channel flows with variable depth across the channel, *Journal of Fluid Mechanics*, 222, pp.617-646 (and Vol. 231, pp.693).

Shiono, K. and Muto, Y. (1998), Complex flow mechanisms in compound meandering channels with overbank flow, *Journal of Fluid Mechanics*, Vol. 376, pp.221-261.

Tang, X. and Knight, D.W. (2006), Sediment transport in river models with overbank flows, *Journal of Hydraulic Engineering,* ASCE, Vol. 132 (1), January, pp.77-86.

Tominaga, A., Nezu, I., Ezaki, K. & Nakagawa, H. (1989), Turbulent structure in straight open channel flows. *Journal of Hydraulic Research*, IAHR, 27(1), pp.149-173.

Toro-Escobar, C.M., Paola, C., Parker, G., Wilcock, P.R. & Southward, J.B. (2000), Experiments on downstream fining of gravel. II: wide and sandy runs, *Journal of Hydraulic Engineering*, ASCE, 126(3), pp.198-208.

Wallis, S.G. and Knight, D.W. (1984), Calibration studies concerning a one-dimensional numerical tidal model with particular reference to resistance coefficients, *Estuarine, Coastal and Shelf Science*, Academic Press, London, No. 19, pp.541-562.

Wang, S. (2005), On the reliability and accuracy of computational models for Hydroscience and Engineering investigations, *US-China Workshop on Advanced Computational Modelling in Hydroscience and Engineering*, Oxford, Mississippi, USA, 19, September.

Wang, S. *et al*. (2008), *Verification and validation of three-dimensional free surface flow models*, American Society of Civil Engineers, ASCE Monograph, (in press).

Willetts, B.B. & Rameshwaran, P. (1996), Meandering overbank flow structures, In *Coherent Flow Structures in Open Channels,* (Eds Ashworth, Bennett, Best & McLelland), Chapter 29, J Wiley, pp.609-629.

Wormleaton, P.R., Hey, R.D., Sellin, R.H.J., Bryant, T., Loveless, J. & Catmur, S.E. (2005), behaviour of meandering overbank channels with graded sediments, *Journal of Hydraulic Engineering, ASCE*, Vol. 131(8), August, pp.665-681.

Yang, C.T. (1987), Energy dissipation rate approach in river mechanics, In *Sediment transport in gravel bed rivers* [Eds Thorne, Bathurst & Hey], J Wiley, pp. 735-766.

Yen, B.C. (1991), Channel flow resistance: centennial of Manning's formula, Water Resources Publications, Colorado, USA, Water Resources Publications, pp.1-453.