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FOUR

MANNING'S *N* – PUTTING ROUGHNESS TO WORK

SARAH J. WHATMORE AND CATHARINA LANDSTRÖM

1. Introduction

In a research project on the science and politics of flood risk,[1] we found ourselves fascinated by the ubiquity of a small, italicised symbol – '*n*' – in the working practices of hydraulic modellers. On closer examination, it became clear just how densely packed this symbol is as a factual statement about the world claiming that hydraulic roughness is a property of rivers that can be approximated and represented by a single numerical value.

n is a parameter that does crucial work in a commonly used equation for calculating discharge for uniform water flow in open channels:

$$Q = \frac{AR^{2/3} S_f^{1/2}}{n}$$

where Q = discharge, A = channel cross-sectional area, R = hydraulic radius, S_f = energy slope and n = Manning's roughness coefficient (Fisher and Dawson 2003). Despite recent academic challenges to the validity of *n*, it remains undisturbed as a cornerstone of the working practices of engineering consultants that inform the policy and management of flood risk in the UK.[2]

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[1] This chapter, and the presentation on which it is based, was written under the auspices of a research project funded under the Rural Economy and Land Use Programme (www.relu.ac.uk) on 'Environmental knowledge controversies: the case of flood risk management' (www.knowledge-controversies.ox.ac.uk). We are grateful to our collaborators, particularly Stuart Lane and Nick Odoni, for enlightening discussions on Manning's *n*.

[2] Flood risk policy and management in the UK is divided between Defra (the Department of Environment, Food and Rural Affairs), which is responsible for policy development, and the EA (Environment Agency), which is responsible for implementation (with organisational variations) in England and Wales.

Our fascination deepened when our pursuit of *n* drew us into the work of its originator, Robert Manning, an Irish drainage engineer practising in the second half of the nineteenth century who presented it first, in a still-cited paper, to the Institution of Civil Engineers of Ireland in 1889 as a proxy for roughness, or the effects of friction on the movement of water, that can be derived from a visual assessment of the shape and character of a river channel. How and why has this parameterisation proved so durable in the changing practices of hydraulic science and engineering?

We do not address these questions through a chronological account of the travels of Manning's *n* but rather through one that reflects our process of investigation, which began with the demands of flood risk science and politics today. This genealogical device works against the deceptive production of a singular 'trajectory' and the historical determinism that this would imply, insisting instead on an enfolding of past and present, not least through the framing interests of those embarking on any historical investigation. By focussing on the work Manning's *n* does at different moments in time, we aim to capture the combination of stability and elasticity that enable this conceptualisation of hydraulic roughness to travel through time and between communities of practice. Our account draws on historical archives and documentary records, interviews with flood modellers in academic and consultancy practice and our own first-hand experience of one-dimensional (1D) modelling software through participation in professional training courses.

Our interrogation works through three specific moments in the career of Manning's *n*. We begin in the early twenty-first century, a moment witnessing a surge in scientific critiques of the *n*-value and Manning's equation (invented to calculate flow velocity) as a formula that over-simplifies the complex dynamics of energy loss in water flow. These critiques reach beyond the pages of scientific journals, and we analyse a concerted attempt to develop and institutionalise an alternative calculus – the Conveyance Estimation System (CES), sponsored by the policy agencies responsible for flood risk management in the UK. Its limited success in breaking the hold of Manning's *n* as an industry standard provides an important lens through which to examine the extraordinary durability of Manning's formula. In the second of our analytical moments, nineteenth-century Ireland, we examine Manning's work in the land drainage regime that underpinned the programme of public works of the British colonial administration. Our analysis focuses on the interwoven influences of Manning's day job as a water engineer and the mathematical calculations that occupied his spare time in the development of a 'general equation' for calculating discharge that was simple and effective enough to appeal to his contemporary practitioners over established and competing methods. The last of the three moments examined here moves us forward in time again to the re-packaging of *n* in the twentieth century that underpins hydraulic modelling to this day. In this intervening period, we focus on the ways in which Manning's formula becomes incorporated as a standard element in hydraulic modelling software and the visual estimation of *n*-values for rivers becomes regularised through photographic reference handbooks compiled for engineers.[3]

2. Moment 1: Manning's *N* under Fire

2.1 Too Simple for the Twenty-First Century

We begin this first moment of investigation with journals in the geosciences in which the ubiquitous use of Manning's equation and the *n*-value in hydraulic engineering practice has recently become a target of critique. The critics question the idea that hydraulic roughness is a phenomenon that can be represented as a single numerical value. In other words, it is a critique of what we might call the 'fact' packaged as Manning's *n*. Its indictment as a formulation that over-simplifies roughness, both conceptually and empirically, is illustrated here by reference to two papers.

In a paper in *Earth Surface Processes and Landforms*, Lane (2005) exhorted his fellow water scientists to re-evaluate the hydraulic variable of roughness because of its lack of conceptual clarity. His primary concern is the habitual treatment of roughness as a singular independent variable, arguing that it is a more complex feature of an already complex physical system and ought to be treated as such. His critique is directed at those who routinely elevate Manning's formula – today mainly used to estimate the impact of roughness on water levels – to the status of a law, thereby effectively taking its assumptions for granted, rendering it immune to interrogation (examples cited include Govindaraju and Erickson 1995 and Zhang and Savenije 2005).

Lane goes on to argue that because roughness, formulated as Manning's *n*, has become an automated calibration parameter in flood modelling on which production of 'the correct relationship between flow and water level' (2005, p. 251) is reliant, the concept of roughness has become even further

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[3] For parallel cases in which man-made facts (as opposed to these 'facts of nature') travel in artefacts, and for pictorial representations of them, see Valeriani and Schneider, both in this volume.

distanced from the dynamics of friction in any actual physical system. For example, he points out that roughness is physically both laminar- and scale-dependent. It is laminar in that 'provided the surface topographic variability extends beyond a thin layer of fluid (the laminar sub-layer) close to the bed, the bed is hydraulically rough, and friction between the bed and the flow will depend upon surface topographic characteristics (e.g., grain size)' (op cit). It is scale-dependent in that 'as the spatial scale of consideration is changed, we change the amount of topography that must be dealt with implicitly, that is, parameterised as frictional resistance' (2005, p. 252). Lane's paper challenges his fellow scientists to find better ways of articulating current scientific knowledge about this complex physical phenomenon and, thereby, of improving the calculability of roughness.

Just such an alternative way of articulating roughness is suggested in a paper two years later by Smith, Cox and Bracken (2007). Appreciating the entrenchment of Manning's *n* in the flood science community, Smith and his colleagues begin their paper by identifying and challenging the assumptions that underpin the study of overland flow hydraulics. They develop a detailed argument for an alternative formulation, the most interesting aspect of which, for our purposes here, is their discussion of the enhanced technical capacity for measuring roughness (as resistance to overland flow) since Manning developed his original formula. Reviewing a large number of research publications, Smith and his colleagues profile a range of experimental methods that have been used in attempts to measure resistance more accurately but which they consider deficient because such laboratory-based studies ignore 'real-world' processes such as 'changing soil surface configurations with distance downslope' (2007, p. 382). They go on to argue that such deficiencies can be overcome 'by embracing new technologies available to assist the acquirement of accurate measurements of flow depth and velocity' (op cit) over different surfaces. They champion terrestrial laser scanning as a technique likely to enable much better measurement of resistance to flow than methods used to date. On this account, new techniques for measuring hydraulic roughness are rendering its parameterisation as *n* redundant; when the phenomenon can be empirically described and measured, there is no need for estimating it for use in an equation.

These critics of Manning's *n* do not, it appears, take issue with its ability to capture relationships between water levels and energy loss due to friction in pipes or artificial channels. It is the routine application of Manning's *n* to flow in natural rivers and over floodplains that is in dispute. For these academic scientists, Manning's formula used for estimating the energy loss due to hydraulic roughness is too simple, even simplistic, an approach to a complex phenomenon that is now amenable to much more effective conceptualisation and empirical analysis. It may be too soon to judge whether the critique will effect the changes in practice for which these authors call. However, it seems doubtful that lack of attention to conceptualisation or methodological innovation suffices to explain the persistent use of Manning's *n*, given that just these issues have been the dedicated focus of a practitioner-led research programme on 'Reducing uncertainty in river flood conveyance,' which concluded in 2004, before either of the critical papers cited previously had been published.

2.2 The Conveyance Estimation System

'Reducing uncertainty' was a research programme initiated by the major governmental sponsors and users of flood risk science in the UK – the Department of Food, Environment and Rural Affairs (Defra) and the Environment Agency (EA). The programme enrolled a number of flood scientists and engineers in the quest for new ways of working with roughness in computer modelling. Led by the water engineering consultancy HR Wallingford (Ltd.), the programme brought together scientific experts from the academic, public and commercial sectors in a review of current practice. This included a concerted effort to replace Manning's *n* as the standard parameter for roughness in the estimation of conveyance in the flood models on which Defra and the EA base their policy and management activities. Documents archived on-line provide some insights into this programme, including why it was considered important enough to fund at the time. [4]

> The Environment Agency for England and Wales identified the need to reduce the uncertainty associated with flood level prediction through incorporating the recent research advances in estimating river and floodplain conveyance. Existing methods for conveyance estimation that are available within 1D Hydrodynamic modelling software, e.g., ISIS, MIKE11, HECRAS, HYDRO-1D, are based on some form of the Manning Equation, first published in 1890. With the substantial improvement in knowledge and understanding of channel conveyance that has taken place over the past twenty years, there is a need to make these more advanced techniques available for general use in river modelling. (Defra/EA, 2004, p. 1)

The premise of this initiative was that Manning's equation was dated in its approach to roughness and surpassed by improved scientific understandings of the physical process of conveyance. As one of the senior scientists

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[4] See: www.river-conveyance.net/index.html

working on this programme told us in an interview, their efforts centred on treating roughness as a more complex phenomenon.[5] This involved subdividing roughness into three friction types or zones: skin friction (energy loss from movement over a surface or bed, a factor similar to Manning's *n*), secondary occurrence (energy loss from the movement of water around a river bend) and turbulent shearing (energy loss from turbulence within the water itself). This threefold re-conceptualisation of roughness was tested using a combination of experimental flume studies, field data and computer models. The initiative both addressed the physical complexity that was later emphasised by Lane and allowed for empirical testing not unlike that subsequently proposed by Smith and his colleagues. The rationale for replacing Manning's *n* at work here is epistemic, to improve the representation of a phenomenon occurring in nature. The ambition of the programme, according to another scientist who took part, was to take *n* apart, to approach the different aspects of energy loss with an empirically derived equation and then re-conceptualise *n* as a value relating solely to the friction of the surface over which water moves.[6]

The 'Reducing uncertainty' programme produced a new 'Conveyance Estimation System' that treats roughness as one component of a complex physical phenomenon and accounts for uncertainties in the relationship between energy loss, velocity and water levels more comprehensively. Programme records claim that considering 'the substantial improvement in knowledge and understanding of channel conveyance that has taken place over the past twenty years, there is a need to make these more advanced techniques available for general use in river modelling' (Defra/EA, 2004, p. 1).

Interrogating the programme records made us aware that Manning's *n* is rarely encountered by those engaged in the modelling of flood events as an element in an equation to be solved by assigning a numerical value to a variable. Rather, in the everyday working practices of modellers working on flooding, it is more usually encountered as an embedded feature of routinely used software packages. This helps to explain the programme's investment in creating a new software product – the CES – which, as the programme literature describes it, is

> a software tool that enables the user to estimate the conveyance or carrying capacity of a channel. /.../ The CES includes a component termed the 'Roughness Advisor', which provides advice on this surface friction or 'roughness', and a component termed the 'Conveyance Generator', which determines the channel capacity based on both this roughness and the channel morphology. In addition, the CES includes a third component, the 'Uncertainty Estimator', which provides some indication of the uncertainty associated with the conveyance calculation. (Defra/EA 2004, p. 1)

In this, the consortium of academic scientists and engineering researchers involved in the 'Reducing uncertainty' initiative can be seen to be attempting to package their understanding of roughness in a way that would make it travel as readily as Manning's *n*. In so doing, they draw attention to the ways in which the effectiveness of *n*, which they hoped CES could emulate, rested less in the mobilisation of roughness as an accepted fact than as a working tool in the production of knowledge about flood risk. As a tool rather than as a fact, the success of this re-packaging would be reliant on flood modellers and river engineers changing the ways in which they worked. The three components of the CES software require the modeller to undertake three different activities to estimate the energy loss previously parameterised as Manning's *n*. The 'Roughness Advisor' requires input of measurement data in order to provide output values for surface friction in units that are then used to compute values for 'roughness zones', which provide numbers that are then input in the cross-sections as 'n_1' values.[7] Next, the modeller needs to use the 'Conveyance Generator' to compute energy losses due to other factors – for example, sinuosity. The third step is to use the 'Uncertainty Estimator' to generate upper and lower bands of values within which modelled water levels from a given flow may vary.

This new way of modelling roughness as a discrete three-step activity that feeds into the normal model-building process is presented as a change for the better.

> This task is now modularised and mimics the model building activities. /.../ Modellers are provided with a flexible interactive tool with a great deal of freedom. /.../ As a result of this new freedom, defensibility of the results becomes a more important issue than before. /.../ The key difference to previous modelling is that an insight is gained into the role of conveyance in the overall hydraulic performance of the system, in an uncertain background. (Defra/EA 2004, p. 4)

The CES has been included in the ISIS modelling software package as a separate application that a user may choose to use or not to use. On the evidence of the ongoing scientific critique, as well as our interviews and ethnographic work with flood-modelling practitioners, few users appear to

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[5] Interview by S. W. 2007.
[6] Interview by S. W. 2008.
[7] Mansnerus, this volume, also discusses how facts are used as inputs to create other, 'model-produced' facts.

choose to employ the CES. To begin to understand why these efforts to replace Manning's *n* have made so little headway, we must go back in time, first to look more closely at Robert Manning's achievement in the nineteenth century, and then to examine some of the devices through which it has taken hold in twentieth-century engineering practice.

3. Moment 2: Making Roughness Estimation Practicable

3.1 Drainage Engineering and Public Works in Nineteenth-Century Ireland

Robert Manning was elected to membership of the British Institute of Civil Engineers in London in 1858 and rose to become president of the Institution of Civil Engineers of Ireland in the year in which it received its royal charter – 1877. This was the audience to which he presented his still-famous paper: 'On the flow of water in open channels and pipes,' first in December 1889 (Manning 1891) and later, in a refined and copiously annotated version, in June 1895 (Manning 1895). His career as an engineer had been rather more precarious than these impressive credentials of professional standing suggest. Born in British-occupied France and schooled in Ireland, Manning's eminence as an engineer was an achievement born of practical learning rather than university education – an approach to knowledge that he came to advocate at the height of his career. In his presidential address to the institution in 1877, he observed that

> [w]hen I entered the profession more than thirty years ago I found that it was considered a greater disgrace not to know the workmen's name for a tool or a particular kind of work than to be ignorant of the very elements of mathematical and mechanical science. /.../ But things have changed since then. The knowledge that was then looked upon as ridiculous and impractical theory is now viewed as the merest elementary smattering. /.../ I trust that while our younger members will not fail to acquire a competent knowledge of mathematics there are none of them who are so immersed in the integration of circular functions, or other applications of the calculus, as not to learn how a dozen men are to be set profitably to work with a pick, shovel and barrow .... (Manning 1878, p. 80)

His working life began in estate management for his uncle in County Wexford. In the late 1840s, his skills found their place in the Public Works regime at the office of the Drainage Engineer in Louth, initially in a clerical post, and two years later as district engineer in the drainage districts of Meath and Louth and subsequently Ardee and Glyde. After an interlude working as estate engineer to Lord Downshire (1855–67), Manning returned to the ranks of the Board of Works (now Office of Public Works) in 1868, first as Second Engineer and then as Principal Engineer, a post to which he was promoted in 1874 (Dooge 1989). Manning's career in public administration coincided with a sustained investment in arterial drainage as the lynchpin of a colonial project to raise the productivity of land and the profitability of agriculture in Ireland. Public administration in Ireland was directed by the British Parliament via a system of grand juries, the jurisdiction of which extended from the administration of law to fiscal and then civil government at national and local levels via a system of boards and agencies operating in the 34 counties. In 1817, the Board of Works took responsibility for coordinating the activities of county surveyors whose appointment became subject to a system of public examination introduced in the Grand Jury (Ireland) Act of 1833. Pay was poor, and most county surveyors were Irish nationals whose activities were regulated by the allocation of grants and loans for major infrastructural investments (from bridges to drainage) by the Board of Works. As a district engineer employed by the Board, Robert Manning would have been directly responsible for overseeing the work of county surveyors, whose job description was more accurately that of county engineers (McCabe 2006).Throughout his varied career, Manning made and recorded extensive observations of aspects of rainfall, river volume and water runoff, publishing papers on his methods and findings – for example, 'on the flow of water off the ground,' describing rainfall-runoff measurements in connection with a new water supply system in Belfast (Manning 1866),[8] and on 'triangulation for survey of the Downshire estates' (Manning 1882).

One of the most challenging drainage schemes on which Manning worked was that concerning the River Glyde in County Louth, which flows into the sea in confluence with the River Dee at Annagassen in the north-east of Ireland. He was personally responsible for much of the surveying carried out in the mid-1840s in his capacity as assistant to the District Engineer Samuel Roberts. In Manning's annual report to the commissioners in 1851, he records the employment of some 76,122 men in drainage work in the county, with a maximum number in any one day of 656, commenting that he had work (but not funds) for at least double that number (Commissioners of Public Works 1851). Along with the clearance of some fifteen miles of waterway, his report provides details of the excavation of the River Glyde, deepening its seventy-foot-wide channel by some five

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[8] This paper was awarded the Telford Gold medal by the Institute of Civil Engineers in London.

feet above its confluence with the River Dee. The purpose of these labours, he notes, is to relieve the 'lands between these points' from floods and, in the process, to increase the land values (and rents) by an estimated 7sh 6d per acre. He pays particular attention to the construction of two mill-races at the junction with the Dee, diverting water to the mill industries at Annagassen. Manning's extensive experience here and elsewhere in practical river hydraulics, from surveying to engineering, generated one of the two main sources of data that informed his efforts to render roughness a calculable dimension of the 'mean forward velocity' of water (discharge) and its management. The other was his extensive private reading of the theoretical works and empirical observations of his civil engineering contemporaries, particularly those in France and the United States, who were at the forefront of their profession in his day. In an early paper on 'the flow of water off the ground' (1866) reporting on the results of a series of observations in Woodburn District for a twelve-month period between 1864 and 1865, he traces the dependence of 'all formulae for the discharge of water… upon the principle that the velocity is proportional to the square root of the head' to the work of Torricelli, a student of Galileo, published in 1643, which derives this 'settled principle accepted by all hydraulicians [from] the laws of the fall of heavy bodies' (1866, appendix, p. 467). Notwithstanding sustained endeavours in the science of hydraulics, Manning defines the outstanding problem thus:

> Although the science of hydraulics is now nearly 250 years old, it is less than half that time since anyone could calculate even approximately the velocity or surface inclination of water flowing in an open channel of given dimensions. /…/ Anyone who has carefully studied the subject must have come to the conclusion that it is almost hopeless to obtain a strictly mathematical solution of the problem, and that even to observe and record correctly the physical data required is a matter of extreme difficulty, not to say impossibility. (1891, p. 161–2)

3.2 *N* Makes Discharge Calculation More Reliable

Given the precariousness of employment and heavy workload that the under-resourced regime of public works afforded him, it should come as no surprise that Manning valued his practical experience as a working engineer as highly as the published work of leading 'hydraulicians' over three centuries in Europe and North America. The work he most admires is that of those who, like himself, base their scientific formulations of the laws governing the motion of water in channels on first-hand observations and experiments. Characterising this approach as one concerned with 'empirical formulae' (i.e., formulae deduced from experimental observations), Manning is insistently circumspect about their 'generalisability' and about the balance to be struck between the ambition to formulate a 'rationale theory' with ever-greater demands in terms of mathematical complexity and the exigencies of practical engineering, which 'force the profession [into] the habit of rough generalisation and what is called "rapid approximation"' (1866, p. 466). Thus, for example, he later refers approvingly to Cunningham's observation in a paper to the Institution of Civil Engineers in 1882[9] that for all the impressive increase in mathematical sophistication over more than a century between the hydraulic formula of de Chezy (1775) and that of Kutter (1876), 'practical hydraulicians /…/ should determine to abide by the [de Chezy's] simple formula that has stood the test of so many years, which most of them had verified for themselves, and which they know was practically accurate within the limits they had occasion to use it' (1891, p. 169). This also goes some way to explaining the modesty with which he presents his own formulation as a furtherance, or supplement, to those of some of his predecessors rather than as a superior replacement.

Manning's working method in both the 1891 and 1895 versions of his seminal work on the 'flow of water in open channels and pipes' is to survey the empirical formulae produced by a selection of earlier 'hydraulicians' and compound the experimental observations (and varying measurements) on which they are based through a series of tabular composites, thereby magnifying, so to speak, their deductive power (see Figure 4.1).

He is careful to stress that while the 'close agreement between the observed and calculated velocities [across such an] extended range of data /…/ must to a certain extent give confidence in its [the equation's] use as a general formula' (1891, p. 164), such an agreement 'is not an absolute proof of the correctness of such formulae' (ibid). Rather, it is the 'great difficulty (if not impossibility) of establishing a strictly mathematical theory of the motion of water in canals [that] excuses, if it does not justify, their adoption' (ibid). The formulae of de Chezy (1775) and Du Buat (1786, 2nd edition) in the eighteenth century and of Bazin (1865) and Ganguillet and Kutter (1889) in the nineteenth are particularly influential in framing the contribution he sets out to make to the 'science of hydraulics.' This he defines as finding a 'general equation [for the uniform motion of water in open channels] which will hold good for all measures without the necessity of changing coefficients' (1891, p. 162) and be 'sufficiently accurate for practical purposes and calculations by which are easy' (1891, p. 167). Where

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[9] Cunningham (1883) was presented orally to ICE in 1882.

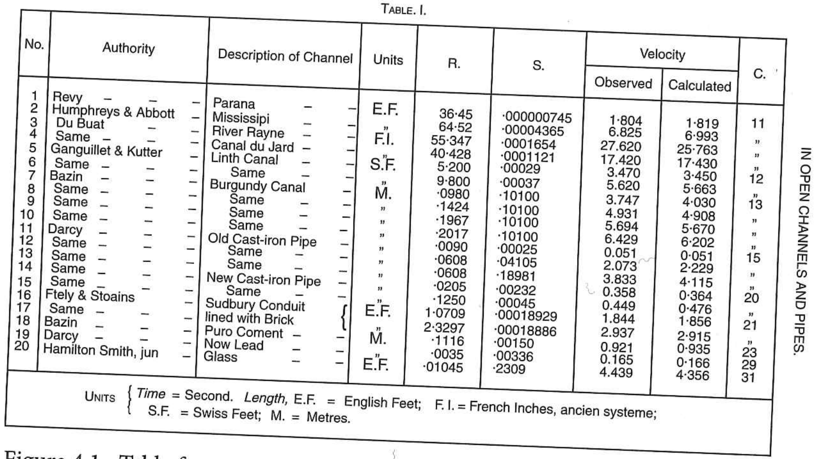

TABLE. I.

No.	Authority	Description of Channel	Units	R.	S.	Velocity		C.
						Observed	Calculated	
1	Revy – – –	Parana – –	E.F.	36·45	·000000745	1·804	1·819	11
2	Humphreys & Abbott –	Mississipi –	"	64·52	·00004365	6.825	6·993	"
3	Du Buat – –	River Rayne – –	F.I.	55·347	·0001654	27.620	25·763	"
4	Same – – –	Canal du Jard – –	"	40·428	·0001121	17.420	17·430	"
5	Ganguillet & Kutter –	Linth Canal – –	S.F.	5·200	·00029	3.470	3·450	12
6	Same – – –	Same – –	"	9·800	·00037	5.620	5·663	"
7	Bazin – – –	Burgundy Canal –	M.	·0980	·10100	3.747	4·030	13
8	Same – – –	Same – –	"	·1424	·10100	4.931	4·908	"
9	Same – – –	Same – –	"	·1967	·10100	5.694	5·670	"
10	Same – – –	Same – –	"	·2017	·10100	6.429	6·202	"
11	Darcy – – –	Old Cast-iron Pipe –	"	·0090	·00025	0.051	0·051	15
12	Same – – –	Same – –	"	·0608	·04105	2.073	2·229	"
13	Same – – –	Same – –	"	·0608	·18981	3.833	4·115	"
14	Same – – –	New Cast-iron Pipe –	"	·0205	·00232	0.358	0·364	20
15	Same – – –	Same – –	"	·1250	·00045	0.449	0·476	"
16	Ftely & Stoains –	Sudbury Conduit	E.F.	1·0709	·00018929	1.844	1·856	21
17	Same – – –	lined with Brick	"	2·3297	·00018886	2.937	2·915	"
18	Bazin – – –	Puro Coment – –	M.	·1116	·00150	0.921	0·935	23
19	Darcy – – –	Now Lead – –	"	·0035	·00336	0.165	0·166	29
20	Hamilton Smith, jun –	Glass – –	E.F.	·01045	·2309	4.439	4·356	31

UNITS { *Time* = Second. *Length,* E.F. = English Feet; F. I. = French Inches, ancien systeme;
S.F. = Swiss Feet; M. = Metres.

IN OPEN CHANNELS AND PIPES.

Figure 4.1. Table from Manning's 1891 paper explained in the original article as a list of the experiments he recalculated to show the reliability of his formula which numbers agree with the flow velocities attained by other scientists. The first column names the scientists whose data he used, the second identifies the river channel studied and the third provides the units in which the original calculations were made. Columns 'R' and 'S' note the hydraulic radius and the slope for each channel studied; these are followed by the observed velocities and those calculated by his own formula in inches per second and, finally, 'C' the 'coefficient which varies with the nature of the bed,' later to be known as *n*.

these earlier formulations had made important advances in calculating the 'four functions of velocity – "gravity," "surface inclination," "mean hydraulic depth" and "viscosity" [friction between water molecules]' – they had failed to provide satisfactory or reliable answers to key questions, like whether or not the nature of the bed surface affected the velocity of flow, or whether the surface velocity of the water was different to that at the bed.

Taking his lead from the parallel but separate efforts of Du Buat and de Chezy,[10] Manning directs his efforts to the 'key of hydraulics' – the taxing issue of 'the equation between the accelerating and retarding forces in uniform motion' (1891, p. 184) and the unresolved question of the effects of the 'rugosity' or roughness of the bed. As contemporary hydraulicians like Bazin had already recognised, this was highly consequential because it meant that 'it was certainly not accurate to represent all [channel] radii by the symbol R whether the bed is rough or smooth' (1891, p. 182). Where others had conducted experiments that permitted the qualification of R by coefficients for 'rugosity' derived for a variety of different bed conditions in specific contexts, the problem, as Cunningham (1883) had already noted, was that 'the truth of any such equations must altogether depend on that of the observations themselves, and it cannot in strictness be applied to a single case outside them' (Manning 1891, p. 191). This is the problem to which Manning directed his efforts, to produce a formula that accounted for roughness but which avoided these objections and provided an 'equation [that] is homogeneous /…/, consistent with such natural laws as we are acquainted with and [corresponds] very closely [with] experimental velocities' (op cit).

For all the regard in which his work as a drainage engineer was held by his fellow engineers and colonial administrators in Ireland[11] and his own modesty about his scientific abilities, Manning's enduring reputation is freighted by a single algebraic letter, '*n*', the coefficient for roughness in the equation he devised for calculating the 'forward velocity of water flowing in an open channel.' He first presented this formulation in a paper read to the Institution of Civil Engineers of Ireland in December 1889 (published 1891). In it, he compares the velocities calculated by seven of the leading hydraulics authorities in circulation among his contemporaries (including calculations from the United States, France and Germany, as well as his own), which, in turn, derive from some 160 experiments and 210 observed cases (see Figure 4.1). Having standardised their diverse units of measurement into metres (length) and seconds (time), he takes the mean results of all seven to arrive at 'an approximation to the truth' (1891, p. 172). His formulation was founded on five principles 'upon which there is little, if any, disagreement among hydraulicians' (1891, p. 191). These are the 'laws of gravity' (the accelerating force); the 'retarding forces which balance the acceleration' (principally friction between the bed and water molecules and, to a lesser degree, between water molecules themselves and between the surface of the water and the air); the 'resistance of the bed,' which 'increases directly as the length of the perimeter in contact with the fluid, and inversely as the area of the transverse section'; and 'the resistances increase in a less ratio than the square of the velocities' (1891, p. 191).

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[10] Du Buat and de Chezy's accounts are more or less contemporaneous and very similar, but differ critically on the question of the influence of rugosity or roughness, such that du Buat's equation states the resistances to be in a less ratio than the square of the velocity or, in other words, that the velocity increases in a greater ratio than that given in de Chezy's formula (Manning 1891, p. 183).

[11] For example, Manning's accounts of designing channel dimensions for mill-power and navigation, such as a catchment involving 250 falls per mile increasing in depth by a tenth of a foot, with 8,200 different sections and 11 different side slope conditions, were published by the Board of Works and became the norm for engineering irregular channels under the Drainage Acts textbook cases for standard practice.

After having undergone some further work (including a review of 643 experiments and observed cases), his formula was represented to the Institution of Civil Engineers of Ireland in a paper read in June 1895 (published that same year). What became known as Manning's equation took the form that remains a staple element in any calculation of discharge (forward velocity) underpinning the science and management of flood risk to this day:

$$V = \frac{k_n}{n} R^{2/3} S^{1/2}$$

where V is the cross-sectional average velocity, R is the hydraulic radius, S is the energy slope, $k_n = 1.486$ (English units) and n is the Manning resistance coefficient. The 'n-value' is an estimation of roughness, or the effects of friction on the movement of water generated by the shape and character of the channel through which it is flowing. Where abstract theory and empirical measurement failed, this pragmatic proxy rendered friction amenable to calculation in a reliable way. We may be no nearer to formulating the 'exact theory,' which his interlocutors at the Institution of Civil Engineers of Ireland in 1889 held dear, but his pragmatic approach to producing a 'simple formula as easily remembered as Chezy's' has proved sound in that engineers for more than a century since have been

> … satisfied to consider the velocity sought as that which, multiplied by the area of the transverse section, will give the discharge (which has been well called 'the mean forward' velocity), [such that] a general equation may be found which will hold good for all measures without the necessity of change to the coefficients. (Manning 1891, p. 162)

4. Moment 3: Automating Manning's N

4.1 Twentieth-Century Software Embedding

Present-day hydraulic engineers do not need to worry about working out equations in the field; they can use computers to perform extremely complicated calculations. However, this growth in computational power and complexity seem to have intensified the importance of the n-value that Manning invented to create a 'simple formula' rather than supersede it. What has made it such a durable and ubiquitous component of flood-modelling practice? In the first instance, we would point to the incorporation of Manning's equation and n-values into the software packages that established 1D computer models as the standard technology of hydraulic modelling. Over the course of the twentieth century, the assessment of flood risk and appraisal of management options on which public policy agencies in the UK rely came to fall increasingly to commercial engineering consultancies. The hydraulic modelling practices of these consultants have become more standardised, coming to rely on three widely used software packages: HEC-RAS, a free download developed by the U.S. Army Corps of Engineers; ISIS, proprietary software jointly developed by Wallingford Software and Halcrow in the UK; and MIKE 11, another commercial product developed by the Danish Hydrological Institute (DHI).[12]

Participating in courses introducing new users to these packages, we quickly realised that a university degree in engineering or hydrology was not necessary to work with them, since, like most software products today, they are designed to be user-friendly. Training to use HEC-RAS to simulate flow in a river, we followed instructions to begin by constructing a 'geometry' of the river to be modelled, using survey data from an actual river. These first steps are undertaken in a graphic interface that enables us to draw a line representing the river by 'clicking' on the symbol of a pencil. The next step in creating the virtual river geometry is to construct a series of cross-sections, river stations at which the profile of the river bed and sides are defined on two axes. In the training session we were shown how to bring up an on-screen table in which to enter the measurements for the first cross-section with a roughness value (see Figure 4.2). Our instructor told us to enter a Manning's n-value of 0.03. A brief lecture on what this action amounted to led us to understand that for workaday flood modellers, Manning's n is a number that influences how fast the model lets the virtual water move down the virtual river. If the virtual channel is rougher (i.e., has a higher n-value), the loss of energy in the flow of water will be greater and, hence, the forward movement of the water will be slowed, whereupon the level of water in the river will rise and eventually spill over the banks.

We learned that the way to find the appropriate value for Manning's n was to use a photographic reference guide showing values for different types of river channels. Several such guides are available, both in print and on-line. One on-line version simply presents reference tables with different values for different types of channels – for example, a minimum value of 0.025 (normal 0.030 and maximum 0.033) for a clean, straight, main channel at bank full stage with no rifts or deep pools in which the water

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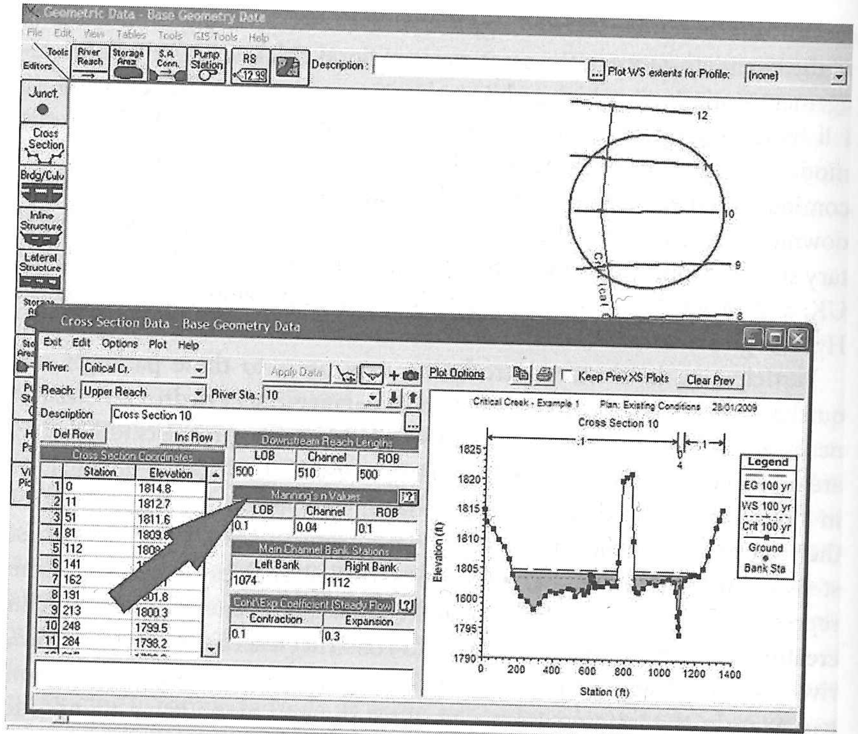
[12] These three packages were subject to a comparative assessment in a bench-marking study commissioned by Defra in the 2000s and have since functioned as standards for 1D hydraulic modelling in the UK.



River: Critical Cr.
Reach: Upper Reach
River Sta.: 10
Description: Cross Section 10

Cross Section Coordinates

	Station	Elevation
1	0	1814.8
2	11	1812.7
3	51	1811.6
4	81	1809.8
5	112	1808
6	141	[illegible]
7	162	[illegible]
8	191	1801.8
9	213	1800.3
10	248	1799.5
11	284	1798.2

Downstream Reach Lengths

LOB	Channel	ROB
500	510	500

Manning's n Values

LOB	Channel	ROB
0.1	0.04	0.1

Main Channel Bank Stations

Left Bank	Right Bank
1074	1112

Cont\Exp Coefficient (Steady Flow)

Contraction	Expansion
0.1	0.3

Figure 4.2. Screenshot from HEC-RAS. The inserted arrow indicates the table in which to enter *n*-values for each cross-section LOB (Left Over Bank), Channel and ROB (Right Over Bank) when defining the 'geometry' of the modelled channel. Behind the arrow is a table for cross-section coordinates and to the right a graph representing a cross-section. The window in the background is a representation of the river reach as a line with numbered cross-sections.

flows very fast.[13] At the opposite end of the scale, it gives a minimum value of 0.110 (medium 0.150 and maximum 0.200) for a level floodplain with dense willows in summer, over which water moves very slowly.

We also learned that manipulating the *n*-value is a convenient means of making the simulated flow of the virtual river 'fit' with recorded observations, a procedure known as model calibration. If a run of the model produces water levels in a channel that are much lower than those observed, increasing the *n*-value will slow the movement of water down and raise the level so that the simulated water levels agree with those observed. One of the modellers we interviewed described model calibration in this way:

> … assuming all my rainfall data is right, and I am confident in the hydrology (and that is a big assumption) what that means is that the model is underestimating the levels and it is too late, so what it probably needs is that I need to raise the channel resistance in that reach. You raise the channel resistance which would tend to put the level up a bit, but it might not give you the right timing. Then you reassess the assumption of the hydrology and you say – well, maybe I got the timed peak wrong on the catchment, so I go and reassess the timed peak on the catchment, so what you end up with is something that looks like that. So you think – well, maybe I am overestimating too much so perhaps I will bring my Manning's *n* down a bit. Got the timing right now. So lo and behold you have got your really good match /…/ it is that sort of iterative process. (Interview by C. L., 30th October 2007)

The 'User's manual' accompanying HEC-RAS explains this use of *n*-values as one of the eight essential steps to follow in the calibration of an unsteady flow model (Brunner 2006). The calibration process entails the production of multiple hydrographs at different stages, from which one chooses the ones that correspond best with observed water levels. The manual explains that 'when Manning's *n* is increased the following will occur: (1) stage will increase locally in the area where the Manning's *n*-values were increased; (2) peak discharge will decrease (attenuate) as the flood wave moves downstream; (3) the travel time will increase; (4) the loop effect will be wider (i.e., the difference in stage for the same flow on the rising side of the flood wave as the falling side will be greater)' (Brunner 2006, pp. 8–53). Roughness values work in the same ways in the other two Defra/EA-approved software packages, ISIS and MIKE 11. This means that for a modeller using any of the standard modelling software packages, Manning's *n* works as a tuning device, increasing or decreasing the roughness coefficient such that the water levels in the model can be adjusted to correspond with measurements taken in the physical system. Manning's *n* is here a feature of the computer programme, not a 'real-world' measurement.

It is easy to manipulate model output by changing the *n*-value, but modellers are aware of the problems associated with 'forcing empirical adequacy' this way. For example, the HEC-RAS manual warns users not to

> force a calibration to fit with unrealistic Manning's *n*-values or storage. You may be able to get a single event to calibrate well with parameters that are outside of the range that would be considered normal for that stream, but the model may not work well on a range of events. Stay within a realistic range for model parameters. (Brunner 2006, p. 8–54)

Determining what a 'realistic' *n*-value is requires knowledge not incorporated in the software, but it is an aspect of engineering skill that the hydraulic modeller has to learn. As our HEC-RAS instructor had made us

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[13] Values from www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm

aware, this practical skill has become regularised since the 1960s through the publication of photographic reference works.

4.2 Embodied Skill

The stabilisation of *n*-values to the degree that on-line tables of numbers to employ in modelling software have become useful has been achieved with the development of specialist handbooks for water engineers, which explicate roughness through compilations of photographs of rivers with established *n*-values.[14] We have found works of this type from the early 1960s through the 1990s.[15] The oldest guide that we have come across is a booklet from the United States compiled using previously produced photographs in order 'to illustrate the wide range of the roughness coefficient "*n*" of Manning's formula for channel velocities related to actual channel conditions' (Fasken 1963, p. 3). The author suggests that the '[s]tudy of the pictures and information shown should assist in selecting realistic values of "*n*" for both present and future constructed channels' (ibid) and identifies six key considerations:

> 1. The material through which the channel will be constructed, such as earth, rock, gravel, and so on.
> 2. Surface irregularity of the sides and bottom of the channel.
> 3. Variations of successive cross-sections in size and shape.
> 4. Obstructions which may remain in the channel and affect the channel flow.
> 5. Vegetation effects should be carefully assessed.
> 6. Channel meandering must also be considered.
>
> (Fasken 1963, pp. 3–4)

This guide ties thirty-nine engineered and two natural channels in the United States to specific *n*-values. Each channel is presented in one or more photographs, accompanied by captions that provide information about the location and the photograph, for example – 'Pigeon Creek, Dredged Channel near Cresent, Iowa. Approximate bottom width 15 feet. Picture taken in 1917' (ibid, p. 5). Each black-and-white photograph is followed by a table that lists dates of observation and measurements of average maximum depth, average surface width, discharge, average cross-section, mean velocity, mean hydraulic radius, slope of water surface, the roughness coefficient *n* calculated by the author using 'the measured values of slope, hydraulic radius and discharge in the Kutter formula for velocity' (1963, p. 3), plus a detailed description of the hydraulic characteristics of the watercourse. We note that Fasken does not use Manning's formula to calculate the *n*-values he suggests that his readers accept as accurate representations of the characteristics of riverbeds. However, his rationale for producing a guide referring to Manning's *n* and no other parameterisations of roughness is that it is the most widely used because 'it is simpler to apply than other widely recognised formulas and has been shown to be reliable' (1963, p. B.1). His style of presentation suggests that Manning's *n* is a phenomenon that can be observed, which is consistent with his claim that 'Manning's formula is empirical,' an estimation of 'the net effect of all factors causing retardation of flow in a reach of channel under consideration' (op cit). Fasken tries to defend the independence of the *n*-value from the person doing the estimation while recognising that the 'estimation of *n* requires the exercise of critical judgement in the evaluation of the primary factors affecting *n*' (op cit).

The question of exactly what the *n*-value refers to and how to regularise its estimation is handled differently in the second of our 1960s photographic handbooks compiled by Barnes in 1967. Here, the estimation of *n*-values is defined as a skill that has to be honed by practice, in which the 'ability to evaluate roughness coefficients must be developed through experience' (Barnes 1967, abstract). He identifies three ways in which an engineer might improve his estimation of the *n*-value for a particular river reach:

> (1) to understand the factors that affect the value of the roughness coefficient, and thus acquire a basic knowledge of the problem, (2) to consult a table of typical roughness coefficients for channels of various types, and (3) to examine and become acquainted with the appearance of some typical channels whose roughness coefficients are known. (1967, p. 2)

Barnes is more circumspect than Fasken about the applicability of Manning's *n* to natural river systems characterised by non-uniform flow conditions. Nonetheless, his guide presents *n*-values exclusively for natural channels without any particular elaboration. His *n*-values are based on the reverse version of Manning's equation:

$$n = \frac{R^{2/3} S_f^{1/2}}{V}$$

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[14] For another case of the importance of visual images in communicating facts about nature, see Merz; and for a contrasting case of how technological facts are packaged for practical use in the field, see Howlett and Velkar (both this volume).

[15] Chow 1959 is referenced by the on-line table and mentioned by many authors discussing Manning's *n*; unfortunately, we have not been able to find it.

(n = Manning's roughness coefficient, R = hydraulic radius, S_f = energy slope, V = mean flow velocity).

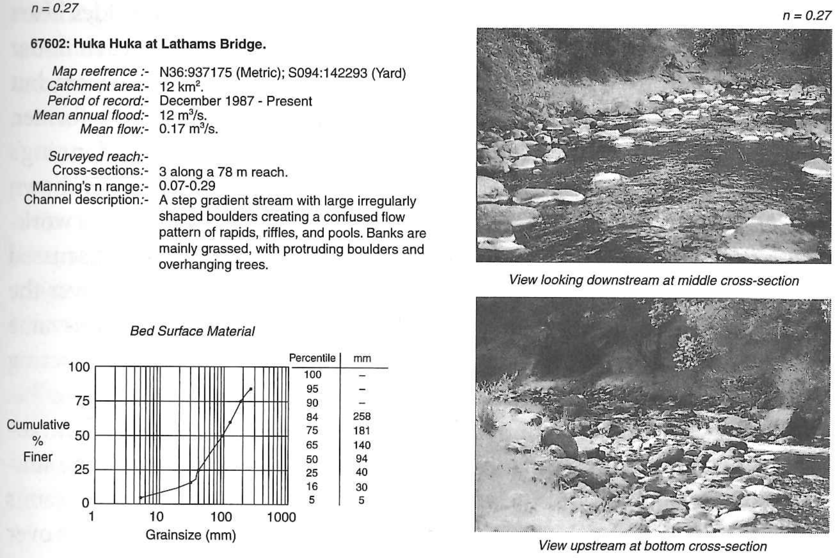
Barnes's examples are also from the United States, and he locates them in relation to permanent gauging stations used by the U.S. Geological Survey to generate stream-flow records. The selected rivers are presented in ascending order by their *n*-values, starting at 0.024 (Columbia River at Vernita, Washington) and finishing with 0.075 (Rock Creek near Darby, Montana). Each *n*-value is exemplified by one or more rivers. On the first page of each entry, the author provides information about gauge location, drainage area, date of flood, gauge height, peak discharge and what he calls the 'computed roughness coefficient' (*n*), together with a description of the channel and a table listing the reach properties. The following page includes sketch plans of the reaches, marking the position of the photographer and cross-sections for each reach. This information is complemented by colour photographs with captions that indicate the direction of flow.

Fasken and Barnes produced their guides for a market of U.S. water engineers in the 1960s, contemporary with the invention of the first computer models in the genealogy of HEC-RAS, but the third reference guide we look at here is much more recent. Produced in New Zealand and published in 1991, this work is presented as a product of sustained research.

> The information presented here is the culmination of a three-year field programme in which roughness and other hydraulic parameters were measured at 78 reaches representing a broad range of New Zealand rivers. The aim of the programme was to provide a reference dataset for use in visually estimating roughness coefficients. This responded to a need for a reference set of reaches representative of New Zealand conditions – our own combination of channel size, gradient, bed material, and vegetation – that would also cater for variations in roughness with discharge. (Hicks and Mason 1991, p. 1)

However, the authors echo the U.S. guides from the 1960s in envisaging that their 'handbook will be used mainly to aid the assignment of roughness coefficients, for example during the application of the slope-area method for estimating flood peak discharge' (1991, p. 11). The format is similar to that of Barnes, with the bulk of the text dedicated to photographs accompanied by descriptions, tables and graphs, but it covers a more extensive range of *n*-values – from 0.016 to 0.27 (Figures 4.3a and 4.3b).

Despite their similarities, these handbooks imply three different approaches to roughness. For Fasken, it is an empirical fact; for Barnes, a way of seeing a physical phenomenon; for Hicks and Mason, a parameter value that can be generated through research. All three works invoke engineering as an embodied skill, requiring a trained eye to be able to 'see' the



n = 0.27

n = 0.27

67602: Huka Huka at Lathams Bridge.

Map reefrence :- N36:937175 (Metric); S094:142293 (Yard)
Catchment area:- 12 km^2.
Period of record:- December 1987 - Present
Mean annual flood:- 12 m^3/s.
Mean flow:- 0.17 m^3/s.

Surveyed reach:-
Cross-sections:- 3 along a 78 m reach.
Manning's n range:- 0.07-0.29
Channel description:- A step gradient stream with large irregularly shaped boulders creating a confused flow pattern of rapids, riffles, and pools. Banks are mainly grassed, with protruding boulders and overhanging trees.

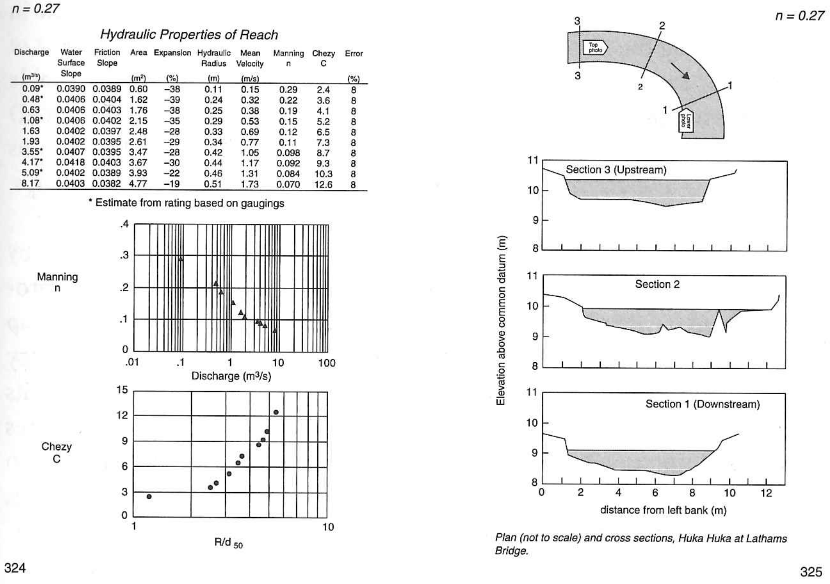
View looking downstream at middle cross-section

Bed Surface Material

Percentile	mm
100	–
95	–
90	–
84	258
75	181
65	140
50	94
25	40
16	30
5	5

View upstream at bottom cross-section

Figure 4.3a. Presentation of *n*-value 0.27 by example of the river Huka Huka. *From*: Hicks and Mason 1991.



n = 0.27

n = 0.27

Hydraulic Properties of Reach

Discharge (m$^{3/s}$)	Water Surface Slope	Friction Slope	Area (m^2)	Expansion (%)	Hydraulic Radius (m)	Mean Velocity (m/s)	Manning n	Chezy C	Error (%)
0.09*	0.0390	0.0389	0.60	–38	0.11	0.15	0.29	2.4	8
0.48*	0.0406	0.0404	1.62	–39	0.24	0.32	0.22	3.6	8
0.63	0.0406	0.0403	1.76	–38	0.25	0.38	0.19	4.1	8
1.08*	0.0406	0.0402	2.15	–35	0.29	0.53	0.15	5.2	8
1.63	0.0402	0.0397	2.48	–28	0.33	0.69	0.12	6.5	8
1.93	0.0402	0.0395	2.61	–29	0.34	0.77	0.11	7.3	8
3.55*	0.0407	0.0395	3.47	–28	0.42	1.05	0.098	8.7	8
4.17*	0.0418	0.0403	3.67	–30	0.44	1.17	0.092	9.3	8
5.09*	0.0402	0.0389	3.93	–22	0.46	1.31	0.084	10.3	8
8.17	0.0403	0.0382	4.77	–19	0.51	1.73	0.070	12.6	8

* Estimate from rating based on gaugings

Plan (not to scale) and cross sections, Huka Huka at Lathams Bridge.

Figure 4.3b. Presentation of *n*-value 0.27 by example of the river Huka Huka. *From*: Hicks and Mason 1991.

n-value of a channel. The existence of these and many similar guides bears witness to the difficulty of estimating the value of *n* for a river reach under varying conditions. *n*-values are supposed to express facts about rivers, but the latter do not seem to behave in a way that allows stability in the former, even though their relationship can be effectively captured in Manning's equation when it is reversed and used for calculating roughness (as shown earlier). Today's on-line reference table, easily accessed by modellers working on their computers, mobilises reference guides like the three discussed earlier in the everyday practices of river engineers in locations all over the world. The small keyboard gesture of the modeller who selects an *n*-value and inserts it into a scroll-down table on the computer screen is enacting decades of engineering knowledge.

The incorporation of Manning's equation and *n*-value in the first hydraulic computer programmes of the 1960s probably owes something to the simplicity of this method of putting roughness to work. Technical constraints on computer power at that time would have favoured simple solutions over more complicated calculations. It might also have resulted from the ways in which *n*-value estimation had already entered into engineering culture as an embodied skill. Whatever the reasons, the hardwiring of *n* into modern technologies of calculation continues to have a hold on hydraulic engineering practice today. 1D modelling software is used everyday in consultant engineering firms undertaking work for a range of UK bodies responsible in law for assessing the impact of their activities on flood risk and the impact of flooding on people and property. Their major challenge is to produce reliable predictions of possible and likely events. In this context, developments in 2D hydrodynamic modelling are enabling better representations of floodplains by calculating the movement of water laterally across topographic maps, with elevations and built structures, derived from digital terrain data.

One software package that is already widely used, and is approved by the Environment Agency, is the Australian TUFLOW. This modelling programme starts with digital terrain data to construct a topographic map across which the flow of water can then be simulated, calculating the energy loss due to friction using Chezy's equation. Despite the sophistication of its treatment of surface topography, the calculation of energy loss still requires the user to input a value called *n*. Unable, as yet, to turn automatically to reference photographs in the estimation of *n*-values for different surfaces, TUFLOW users have begun working out some 'rules of thumb' for common surface coverage, such as grass or multi-level car parks. The desire to develop a set of standard *n*-values for use in TUFLOW floodplain modelling reflects the distance between critical scientists and practising engineers with regard to the utility of Manning's *n*. Where critical scientists regard *n*-values as a dated simplification that obscures important physical processes, practising engineers using TUFLOW continue to find it useful.

5. Conclusions

This chapter has been propelled by a fascination with the apparent hold of a nineteenth-century mathematical formula for estimating hydraulic roughness on the machinery of flood risk science and management today. Our analysis has focused on three related concerns. The first has been to understand hydraulic roughness as a feature of river dynamics constituted differently through changing practices of calculation. The second has been to illuminate the ways in which roughness has been harnessed as a reliable factor in the modelling of river hydraulics in varying contexts. Third and finally, we have sought to highlight the tensile role of *n* in putting roughness to work, at once black-boxing it as an operational standard and representing its effects as a mirror image of 'real' river dynamics.

Robert Manning's work in the nineteenth century was constitutive of 'roughness' as a working estimate of the effects of friction on the velocity of water travelling in a non-uniform channel, a parameter that earlier hydraulic formulations had proved unable to grasp adequately, either mathematically or empirically. Manning's equation and the *n*-value have proved a highly effective packaging of this precarious knowledge claim or, more accurately, method of approximation in terms of its durability and reach in hydraulic science and engineering. What persists above all is a tension in the continued use of Manning's *n* between its practical relevance to the engineer engaged in the urgent business of calculating flood risk and its simplification of a complex physical process to which scientific objections can be raised – a tension that Manning epitomised in his own professional life.

To gain some insight into the durability of this 'fact' of roughness – Manning's *n* – we have examined some of the ways in which it has been more or less successfully packaged and repackaged for use in different techno-scientific regimes of hydraulic engineering. It has travelled from a handy and reliable means of estimating roughness and, thereby, enabling the calculation of velocity for the late-nineteenth-century hydraulic engineer, to a component in automated computer models linked to physical river features via annotated photographs in engineering handbooks. We have argued that in present-day flood-modelling software, *n* is not mainly important as a 'fact,' that is, as an empirical statement about a phenomenon in nature, but as a necessary and reliable means of enabling flood models to work. In contemporary flood-modelling software, *n* is the most amenable lever with which to tune the virtual movement of water through the river channel with that previously observed and, thereby, to validate a model's predictive claims.

Whilst the technologies of calculation and computational power have changed beyond recognition, the purchase of Manning's *n* in the practice of hydraulic science and engineering remains as he originally 'packaged' it – a labour-saving means of estimating roughness. A challenge by twenty-first–century hydraulic scientists claiming that this parameterisation of roughness is an oversimplification both conceptually and empirically has made little dent on its hold on engineering practice. As the apparent lack of success of the Defra/EA programme to replace Manning's *n* suggests, it is not the conceptual or empirical adequacy of this formulation that underlies its durability. Rather, the more sophisticated method of calculating the effects of friction on conveyance that this programme proposed failed to match its practical appeal, making modelling more time-consuming and complicated by removing the possibility of 'tuning' a model by changing one variable. For the critical scientist, the knowledge claim packaged into *n* may no longer be compelling as a parameter of hydraulic modelling, but for the consultant engineer, it remains the handiest way of putting roughness to work.

Acknowledgements

We are grateful to the librarians and archivists at the Institution of Civil Engineers of Ireland (John Callanan) and the Office of Public Works (Valerie Ingram) in Dublin and at the Institute of Civil Engineers in London for their generous and knowledgeable assistance in locating papers and records related to the work of Robert Manning.

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