Contract Report HL-93-1
March 1993

US Army Corps of Engineers
Waterways Experiment Station

Flood Control Structures Research Program

Velocity and Scour Prediction in River Bends

by *Colin R. Thorne*
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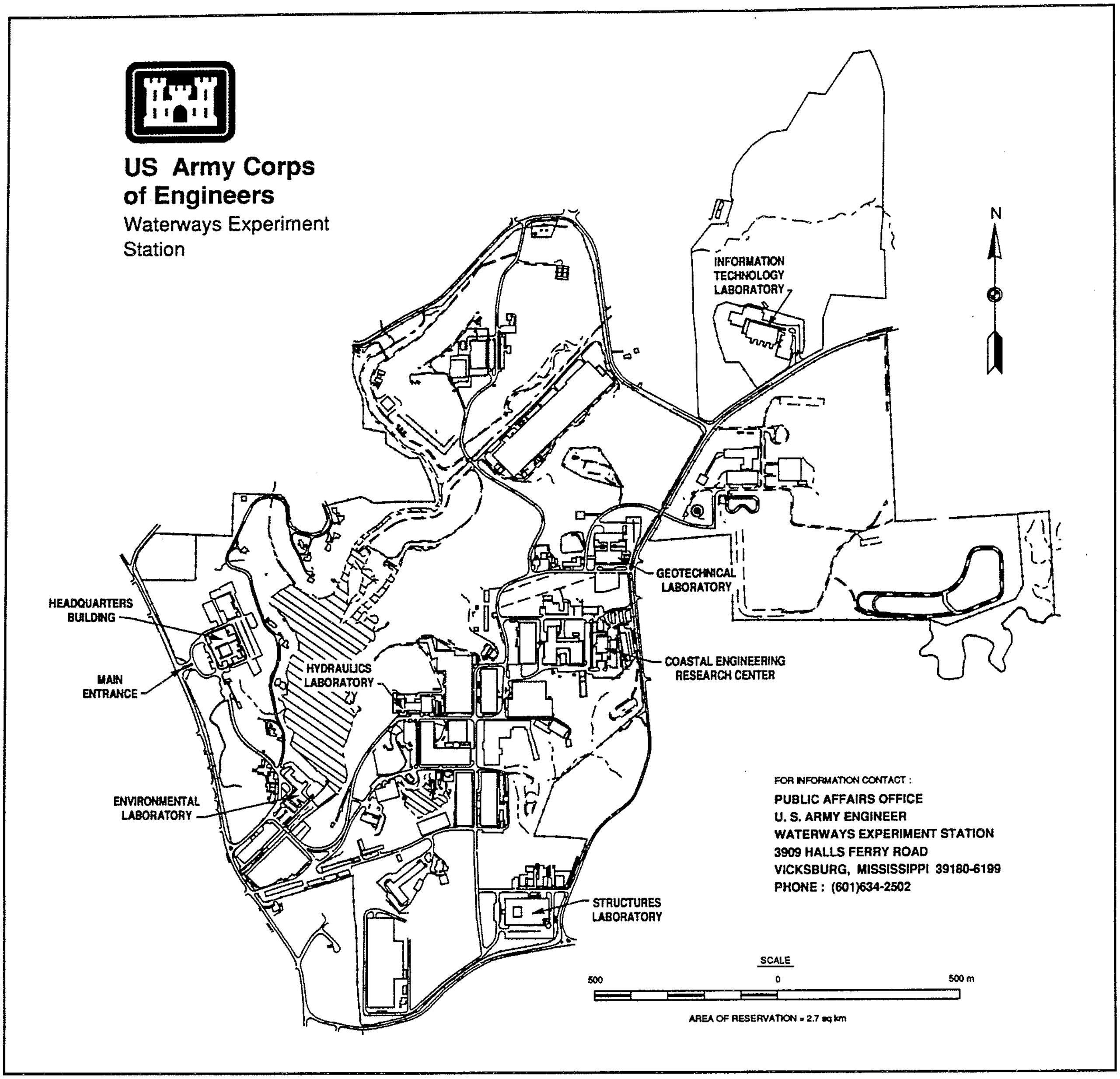

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PREFACE

The two studies reported herein were performed at Colorado State University, Fort Collins, CO, and the University of Nottingham, Nottingham, England, under contract to the US Army Engineer Waterways Experiment Station (WES) during the period October 1989 to June 1992. This investigation was sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), under the Flood Control Structures Research Program as part of Civil Works Investigation Work Unit No. 32544, "Riprap Toe and End Section Design," under HQUSACE Program Monitor, Mr. Tom Munsey.

This investigation was accomplished under the direction of Messrs. F. A. Herrmann, Jr., Director of the Hydraulics Laboratory (HL), WES; R. A. Sager, Assistant Director of HL; and G. A. Pickering, Chief of the Hydraulic Structures Division, HL. The Contracting Officer's Representative was Dr. S. T. Maynord, who was under the direct supervision of Mr. N. R. Oswalt, Chief of the Spillways and Channels Branch, Hydraulic Structures Division, HL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

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ESTIMATION OF VELOCITY AND SHEAR STRESS AT THE OUTER BANK IN RIVER BENDS

prepared for

US Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

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SUMMARY

Bank erosion is a serious problem to river engineers concerned with channel stabilization and navigation. Severe erosion often occurs at the outer bank in channel bends, where flow velocities adjacent to the bank are elevated due to the effects of curvature on channel flow. Eroding banks may be stabilized and protected from erosion using riprap. When selecting the appropriate size of stone to be used to protect a bank in a given bend, it is necessary to be able to predict the intensity of flow attack on the bank. This may be represented by either the near bank velocity or the boundary shear stress on the bank. This report deals with the development of improved methods to predict outer bank velocities and shear stresses. Two approaches are examined. The first uses a statistical treatment of observed data from natural and artificial channels to formulate predictive equations for the ratio of depth avaraged longstream velocity over the toe of the outer bank and for the shear stress in that location. The second tests two analytical models of bend flow to gauge their accuracy and set limits to their applicability in predicting outer bank velocity.

The results show that several factors appear to influence outer bank velocity at a natural bend. Multivariate equations involving radius of curvature to width ratio, relative bend length, width to depth ratio, relative depth and bank angle are proposed to predict the ratio of outer bank toe velocity to average velocity. Simplified equations using only the radius of curvature to width ratio are also proposed. The configuration of the channel upstream of the bend is shown to be important, and separate appproaches are formulated for bends downstream of straight and meandering reaches. For artificial channels Rc/w dominates the analysis, but it is also shown that the mobility of the bed strongly influences the outer bank velocity and shear stress.

Model tests reveal that the model developed by Bridge (1982) consistently predicts the observed outer bank toe velocity to within +/- 15%. Errors grow alarmingly for bends with Rc/w values less than 2 and the model crashes for bends with Rc/w < 1. Odgaard's (1989) model tended to under predict outer bank velocity by between 5 and 40%. This was the case because the model did not predict outer bank scouring in bends with bed material coarser than medium sand. However, its application was limited because it predicted negative depths at the inner bank and crashed for long bends. In contrast to Bridge's model, Odgaard's model remained stable at very low Rc/w bends, errors remaining in the 5 to 40% range.

It is recommended that the results of this study be further tested and verified. However, on the basis of the results to date, the model developed by Bridge is recommended for use in bends with Rc/w valus greater than 2. For very tight bends, Odgaard's model shows strong potential, but it must be modified to allow greater mobility and scour of coarse bed materials.

PREFACE

This project was sponsored by the Hydraulics Laboratory at the US Army Engineer Waterways Experiment Station (WES). The project was monitored by Dr. Steve Maynord. Dr. Maynord also made available field and laboratory data which were very useful in carrying out the work. Helpful advice was given by Mr. Randy Oswalt at WES on a number of occasions. Data assimilation and reduction were undertaken by a research assistant, Sue Reed, with great diligence and skill. The menu-driven programming of the Bridge and Odgaard bend flow models was performed by Andy Markham in the course of his graduate studies. The Principal Investigators wish to record their thanks to each of these individuals for their valuable contributions to the project.

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MAIN TEXT

Introduction

Serious bank erosion often occurs at the outer bank in meander bends. This erosion is driven by the natural tendency of river meanders to increase in amplitude and migrate downstream through time. The severity of flow attack on the bank is known to be controlled by the hydraulics of flow adjacent to the bank and especially the propensity for scour in the area of the bank toe. Conversely, the mechanics of failure and the sequence of events involved in the erosion, collapse and basal clean-out phases of bank retreat are closely related to the engineering properties of the bank materials and the bank stratigraphy. But the overall rate of retreat of the bank is known to be determined by the capacity of the near-bank flow to entrain and remove slumped bank materials, while continuing to erode the bank and trigger further failures (Thorne, 1982; Lapointe and Carson, 1986).

The importance of bank attack and toe scour by the flow have long been recognised, and their intensity has been found to be a function of the boundary shear stress acting on the bed and bank at the outer bank in a meander. But in practical terms the boundary shear stress is a particularly difficult parameter to predict accurately. Indeed, none specialists even find it difficult to visualize boundary shear stress. Consequently, it is desirable to relate the severity of bank attack and toe scour to less obscure flow descriptor, such as near-bank velocity. Some modelers even prefer to relate bank attack and retreat rates to near bank velocities instead of bank shear stress (Odgaard, 1990). Theory shows that near-bank velocity and boundary shear stress are in any case closely related, although the relation between them is neither simple, or easily quantified for real world situations.

The preferred treatment to stabilize and protect the outer bank in a meander bend uses a blanket of loose stone called riprap. When using riprap it is necessary to select the appropriate size for the stone on the basis of the intensity of flow attack as represented by either the boundary shear stress on the outer bank or the flow velocity over the toe of the outer bank. Presently, this achieved using semi-empirical diagrams (Figs. 1 and 2).

The first (Fig. 1) predicts the ratio of velocity over the outer bank toe to average velocity in the approach channel (Vtoe/Vavg) as a function of the radius of curvature to width ratio for the bend (Rc/w). The second (Fig. 2) predicts the ratio of outer bank shear stress to average boundary shear stress in the approach channel (t_b/t_o) as a function of the radius of curvature to width ratio for the bend.

Fig. 1 WES design diagram for prediction of outer bank velocity at a bend

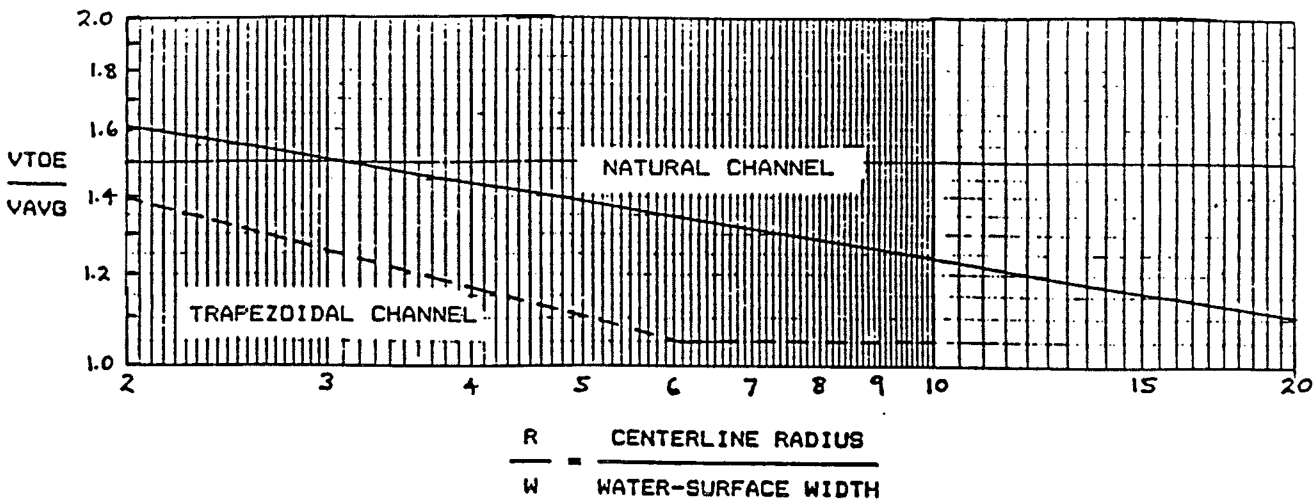
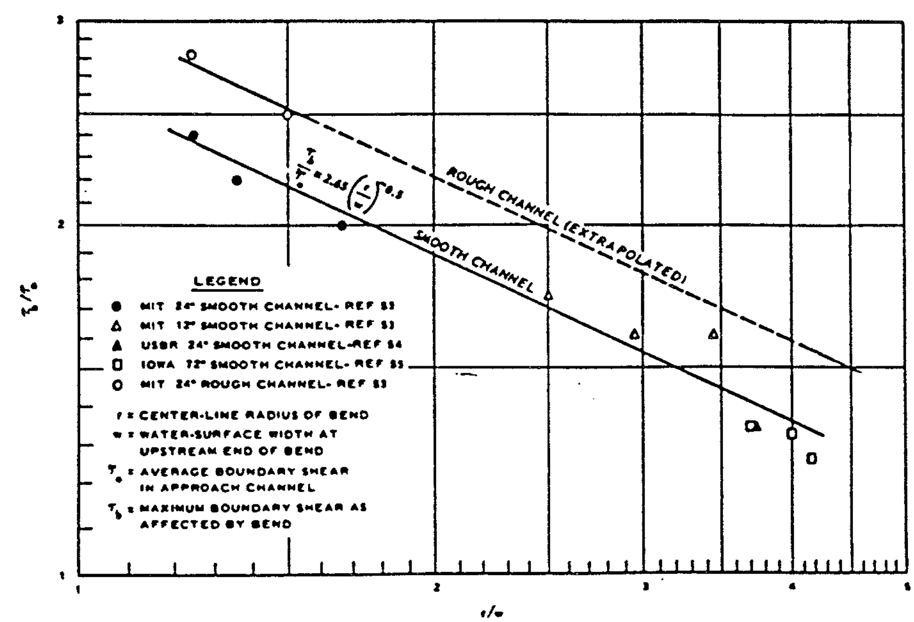


Fig. 2 WES design diagram for prediction of outer bank shear at a bend



MAXIMUM SHEAR AT CHANNEL BENDS

The velocity diagram uses a logarithmic scale for the independent variable (Rc/w) and a linear scale for the dependent variable (Vtoe/Vavg). Two lines are plotted, corresponding to natural channels (with asymmetrical cross-sections) and trapezoidal channels (with symmetrical cross-sections), respectively. The ratio of outer bank to mean velocity is markedly higher in natural than trapezoidal channels. Plotted as straight lines on a semi-log graph, these lines indicate logarithmic relations between (Rc/w) and (Vtoe/Vavg) for the two types of channel. The equations of the lines are not given, but analysis of the graph suggests that they approximate to:

<u>Natural Channels</u>

$$\frac{V_{TOE}}{V_{AVG}} = 1.75 - 0.5 \log \left(\frac{R}{w}\right) \qquad (1)$$

<u>Trapezoidal Channels</u>

$$\frac{V_{TOE}}{V_{AVG}} = 1.6 - 0.71 \log \left(\frac{R}{w}\right) \qquad (2)$$

The shear stress diagram uses logarithmic axes for both independent (Rc/w) and dependent (t_b/t_o) variables. Again, two lines are plotted, this time corresponding to smooth and rough channels. All data appear to come from laboratory flumes, no data from natural rivers are included. Rough channels are found to have significantly higher stress ratios than smooth channels, for the same value of (Rc/w), although the line for rough channels is fitted to only two points and is heavily extrapolated. Plotted as straight lines on log-log graph, these lines indicate power function relations between (Rc/w) and (t_b/t_o). The equation for the smooth channel line is given on the diagram as:-

$$\frac{t_b}{t_o} = 2.65 \left(\frac{R}{w}\right)^{-0.5} \qquad (3)$$

No equation for the rough channel line is given, but examination of the graph suggests that the line may be described by:-

$$\frac{t_b}{t_o} = 3.11 \left(\frac{R}{w}\right)^{-0.5} \qquad (4)$$

While either diagram can give reasonable results when used with sound engineering judgement and with careful consideration of the limits to its applicability, it is nonetheless desirable to develop improved procedures that better account for the parameters of flow hydraulics, boundary roughness and channel geometry that are believed to influence flow intensity at the outer bank in a meander bend. Several other aspects of bend geometry, channel shape and boundary roughness have been shown to influence bend flow patterns significantly on both theoretical and practical grounds (Thorne, 1978; Hooke and Harvey, 1983; Rais, 1984; Lapointe and Carson, 1986; Pizzuto, 1987; Thorne and Osman, 1988; Odgaard, 1989), and a methood which uses only a single parameter to characterize the bend, ignoring all others, cannot account for these effects.

Objectives

The objectives of this study are to develop improved analytical techniques to estimate the velocity and shear stress distributions at the outer bank in a river bend. The approach adopted is to examine these distributions as functions of the planform and cross-sectional geometry of the bend, the nature of the bed and bank materials, and the planform and average flow parameters in the approach channel.

The primary objective is to concentrate on defining maximum values of depth averaged velocity that occur in the bend along the outer bank (that is over the toe of revetted banks). The second aim is to produce the equivalent relationships for boundary shear stress at the outer bank in a meander bend.

Emphasis is placed on basing the relationships on parameters readily available to design engineers, rather than variables such as "centerline mean velocity" which although theoretically significant, are usually unkown and which would themselves be difficult to predict or estimate.

Approaches Adopted

Broadly, two approaches have been used. The first is based on statistical analysis of a data base on bend flow assembled from published and unpublished reports of studies made on rivers and in laboratory flumes all over the world. The second attempts a more theoretical approach, being based on application of three recently developed mathematical models of bend flow hydraulics. There are advantages and disadvantages to both approaches and these are discussed in the sections concerned with the Final Discussion and Conclusions.

Data-Based Approach

Sources of Data

Data were obtained from a number of diverse sources. The sources actually used are listed in Appendix A. The initial data came from studies undertaken by the Principal Investigators and their colleagues at Colorado State University, London University, UK and the University of East Anglia, UK. These data were readily to hand and included all of the parameters necessary for this analysis. They required only a little time and effort to assemble.

The second source of data was from researchers known to be working on bend flow problems and with whom the Principal Investigators have good working relationships. In response to requests from the PI's or their research associates, copies of research reports and published articles containing full data sets were supplied by these individuals, mostly in a timely fashion. This allowed easy extraction of the relevant parameters. In cases where a particular measurement was not reported, telephone calls to the original researchers usually elicited the missing information.

The third source of data was from papers published in professional and learned journals. This proved to be the least satisfactory source. Journal papers almost never contain full data sets, and published summary diagrams of the distribution of parameters such as depth-averaged velocity are too small to be used for data extraction with any degree of accuracy or precision. The addresses given in articles are often incomplete or out of date and telephone and FAX numbers are omitted. Most authors were extremely slow to respond to written enquiries sent by ordinary mail and some seemed reluctant to part with data at all. These problems led to several promising leads being reluctantly abandoned and data sets excluded from the analysis.

The data set which has resulted is then not universal in its scope. It does, however, contain only data which the Principal Investigators opinions is sound and complete. The range of sizes and types of channel encompassed is large and there is a sufficient number of entirely independent data sets to support the statistical analysis. Consequently, it is probable that the addition of a few further data is unlikely to materially alter the overall distribution of data or the outcome of the analyses.

Data base

The basic data assembled in this study are listed in Tables 1, 2 and 3, for Natural Rivers, Trapezoidal Channels and Rectangular Channels respectively. The published and unpublished sources of data are listed separately in the reference section of this report.

TABLE 1 - BASIC DATA FOR NATURAL RIVERS

RESEARCHER	RIVER	SITE	BEND NUMBER	RADIUS OF CURVATURE (m)	BEND LENGTH (m)	WIDTH (m)	MEAN DEPTH (m)	X-SECT SHAPE ...N/T/R...	OUTER BANK ANGLE (Degrees)	OUTERBANK ROUGHNESS ...S/I/R...	D50 (m)	BEDFORMS ...R;D;P...	APPROACH CHANNEL ...S/M/B...	AVERAGE VELOCITY (m/s)	DEPTH-AVE TOE VELOCITY (m/s)
Markham/Thorne	Fall	Reach B	1	23.50	41.00	8.20	0.65	N	60	R	0.0140	P	S	0.53	0.80
Thorne et al.	Fall	Reach A	1	10.30	19.00	12.50	0.76	N	75	R	0.0097	P	M	0.57	0.80
Thorne et al.	Fall	Reach A	2	8.30	16.00	11.00	0.92	N	85	R	0.0038	P	M	0.46	0.60
Thorne et al.	Fall	Reach A	3	8.71	21.00	9.90	0.96	N	70	R	0.0130	P	S	0.71	1.10
Markham/Thorne	Roding	Loughton	1	21.00	66.00	12.00	1.30	N	60	R	0.0130	P	S	1.13	1.35
C.R. Thorne	Fall	Reach 1	1	11.00	50.80	8.80	0.89	N	65	I	0.0010	R,D	S	0.51	0.80
C.R. Thorne	Fall	Reach 1	2	13.50	48.00	10.60	0.66	N	64	I	0.0010	R,D	M	0.58	0.74
D. Anthony	Fall	Reach 4	1	13.75	60.40	10.81	0.79	N	63	R	0.0042	D	S	0.48	0.70
J.S. Bridge	South Esk	Glen Cova	1	67.10	115.00	23.00	1.22	N	58	I	0.0018	R,D	S	0.48	0.69
N.G. Bhowmik	Kaskaski	Reach 1	1	301.80	332.23	38.10	3.77	N	34	R	0.0022	D	S	0.84	1.05
N.G. Bhowmik	Kaskaski	Reach 1	2	298.70	286.60	45.40	3.59	N	45	R	0.0005	R,D	M	0.86	0.95
N.G. Bhowmik	Kaskaski	Reach 1	3	136.60	204.20	36.30	4.01	N	30	R	0.0009	D	M	0.84	1.03
N.G. Bhowmik	Kaskaski	Reach 1	4	40.80	103.73	36.30	3.84	N	46	R	0.0034	D	M	0.62	0.80
N.G. Bhowmik	Kaskaski	Reach 1	5	32.00	85.45	39.90	3.48	N	58	R	0.0057	D	S	0.69	0.93
N.G. Bhowmik	Kaskaski	Reach 2	2	380.40	505.99	48.60	3.41	N	61	R	0.0052	D	S	0.61	0.83
N.G. Bhowmik	Kaskaski	Reach 2	3	91.40	298.55	47.10	3.68	N	53	R	0.0025	D	M	0.61	0.74
N.G. Bhowmik	Kaskaski	Reach 2	4	213.40	371.98	45.40	3.69	N	51	R	0.0048	D	S	0.61	0.70
Bathurst/Thorne	Severn	Maes Mawr	1	95.00	41.00	25.00	0.65	N	80	R	0.0317	P	S	0.94	0.98
Bathurst/Thorne	Severn	Rickety Bridge	1	44.00	32.50	9.10	0.87	N	90	R	0.0630	P	S	1.35	1.60
S. Maynord	Missouri	Browers Bend	1	3625.50	4023.00	202.50	5.55	N	27	I	0.0003	R,D	M	1.32	1.46
S. Maynord	Missouri	Snyder Bend	2	3238.50	4345.00	199.50	5.50	N	22	I	0.0003	R,D	S	1.36	1.53
S. Maynord	Missouri	Glovers Point Bend	3	2000.25	4023.25	200.00	5.65	N	23	I	0.0003	R,D	S	1.27	1.62
S. Maynord	Missouri	Winnebago Bend	4	1952.63	4827.90	209.00	5.30	N	28	I	0.0003	R,D	M	1.35	1.55
S. Maynord	Missouri	Upper Omaha Mission	5	1857.38	1609.30	225.75	5.00	N	25	I	0.0003	R,D	M	1.42	1.69
S. Maynord	Missouri	Middle Omaha Mission	6	2714.63	4023.50	196.00	5.45	N	22	I	0.0003	R,D	M	1.44	1.81
S. Maynord	Missouri	Lower Omaha Mission	7	2047.88	2413.95	212.50	5.45	N	28	I	0.0003	R,D	M	1.40	1.55
S. Maynord	Missouri	Upper Monona Bend	8	2143.13	1609.30	231.50	5.03	N	36	I	0.0003	R,D	M	1.37	1.55
S. Maynord	Missouri	Lower Monona Bend	9	2619.38	5632.55	223.00	5.48	N	26	I	0.0003	R,D	M	1.47	1.67
S. Maynord	Missouri	Blackbird Bend	10	4524.38	5632.55	209.25	5.15	N	21	I	0.0003	R,D	S	1.45	1.54
S. Maynord	Missouri	Tieville Bend	11	2381.25	4023.25	199.75	5.25	N	22	I	0.0003	R,D	M	1.42	1.69
de Vriend/Geldorf	Dommel	The Netherlands	1	16.00	47.60	5.88	0.50	N	74	I	0.0010	D	S	0.43	0.55
de Vriend/Geldorf	Dommel	The Netherlands	2	14.50	31.70	6.00	0.50	N	64	I	0.0010	D	S	0.42	0.61
Dietrich & Smith	Muddy Creek	Wyoming	1	8.00	25.00	4.00	0.40	N	67	S	0.0007	R,D	M	0.55	0.75
A.J. Odgaard	E. Nishnabotna	Iowa	1	233.00	560.00	48.00	2.05	N	47	R	0.0005	R,D	S	1.25	1.60

Explanation

N = Natural

R = Rough
I = Intermediate
S = Smooth

R = Ripples
D = Dunes
P = Plane

S = Straight
M = Meandering
B = Braided

TABLE 2 - BASIC DATA FOR TRAPEZOIDAL CHANNELS

RESEARCHER	SITE	BEND NUMBER	RADIUS OF CURVATURE (m)	BEND LENGTH (m)	WIDTH (m)	MEAN DEPTH (m)	OUTERBANK ANGLE (Degrees)	OUTERBANK ROUGHNESS ...S/I/R...	D50 (m)	BEDFORMS ...R;D;P...	APPROACH CHANNEL ...S/M/B...	AVERAGE VELOCITY (m/s)	DEPTH-AVE TOE VELOCITY (m/s)	SHEAR STRESS RATIO
A.J. Odgaard	Inst Hyd Res.	1	13.11	41.18	2.44	0.15	56	S	0.0003	R,D	S	0.45	0.55	
A.J. Odgaard	WES	1	13.11	41.17	2.44	0.10	34	S	0.0003	R,D	S	0.59	0.73	
WES	H.L.S.D.	1	15.24	23.93	6.76	0.78	27	I	0.0381	P	S	1.04	1.36	
WES	H.L.S.D.	2	15.24	35.91	6.70	0.77	27	I	0.0381	P	M	1.07	1.39	
WES	H.L.S.D.	3	15.24	23.92	6.72	0.77	27	I	0.0381	P	M	1.06	1.50	
WES	H.L.S.D.	1	8.05	14.06	2.69	0.14	27	I	0.0127	P	S	0.57	0.73	
WES	H.L.S.D.	2	8.05	14.06	2.69	0.14	27	I	0.0127	P	S	0.57	0.68	
D. Mueller	USBR	1	4.87	1.27	1.30	0.23	34	S	0.0001	P	S	0.34		1.33
D. Mueller	Uni. of Iowa	1	8.53	13.39	2.29	0.23	45	S	0.0001	P	S	0.53		1.30
D. Mueller	MIT	1	1.52	1.60	0.91	0.08	27	S	0.0001	P	S	0.41		2.00
D. Mueller	MIT	2	1.54	1.61	1.23	0.15	27	S	0.0001	P	S	0.36		2.80
Ippen & Drinker	MIT	4	1.50	1.60	1.22	0.11	27	S	0.0001	P	S	0.58		2.00
Ippen & Drinker	MIT	7	1.78	1.86	0.71	0.07	27	S	0.0001	P	S	0.43		1.75
Ben-Chie Yen	Univ. Iowa	1	8.53	13.40	2.05	0.10	45	S	0.0001	P	S	0.82	0.89	1.00
Ben-Chie Yen	Univ. Iowa	2	8.53	13.40	2.15	0.15	45	S	0.0001	P	S	0.69	0.71	1.00
Ippen & Drinker	MIT	1	1.78	1.86	0.61	0.08	27	S	0.0001	P	S	0.36	0.42	1.60
Explanation								R = Rough I = Intermediate S = Smooth	NOTE 0.0001 = Smooth	R = Ripples D = Dunes P = Plane	S = Straight M = Meandering B = Braided			

TABLE 3 - BASIC DATA FOR RECTANGULAR CHANNELS

RESEARCHER	SITE	BEND NUMBER	RADIUS OF CURVATURE (m)	BEND LENGTH (m)	WIDTH (m)	MEAN DEPTH (m)	OUTER BANK ANGLE (Degrees)	OUTER BANK ROUGHNESS ...S/I/R...	D50 (m)	BEDFORMS ...R;D;P...	APPROACH CHANNEL ...S/M/B...	AVERAGE VELOCITY (m/s)	DEPTH-AVE TOE VELOCITY (m/s)	SHEAR STRESS RATIO
Choudhary &	Benares, India	1	0.80	0.42	0.96	0.1920	90	S	0.0001	P	S			1.20
Narasimhan	Benares, India	2	0.80	0.84	0.96	0.19	90	S	0.0001	P	S			1.20
"	Benares, India	3	0.80	0.42	0.96	0.10	90	S	0.0001	P	S			1.10
"	Benares, India	4	0.80	0.84	0.96	0.10	90	S	0.0001	P	S			1.20
Varshney & Garde	Rookee, India	1	1.80	1.89	0.60	0.27	90	S	0.0020	P	S	0.37		2.36
"	Rookee, India	2	1.80	1.89	0.60	0.07	90	S	0.0020	P	S	0.54		2.46
"	Rookee, India	3	1.80	1.89	0.60	0.21	90	S	0.0020	P	S	0.35		2.46
Fox & Ball	Leeds, UK	1	1.07	3.35	0.31	0.15	90	S	0.0001	P	S	0.33	0.37	
Rozovski	USSR	1	0.80	2.51	0.80	0.06	90	S	0.0001	D	S	0.26	0.36	
Kikawa et al.	Japan	1	4.50	14.14	1.00	0.05	90	S	0.0009	D	S	0.40	0.52	
Kikawa et al.	Japan	2	4.50	14.14	1.00	0.06	90	S	0.0009	D	S	0.45	0.55	
Kikawa et al.	Japan	3	4.50	14.14	1.00	0.06	90	S	0.0009	D	S	0.48	0.60	
Struiksma et al.	Delft, Holland	1	12.00	29.32	1.50	0.08	90	S	0.0005	D	S	0.39	0.46	
Struiksma et al.	Delft, Holland	2	12.00	29.32	1.50	0.10	90	S	0.0005	D	S	0.41	0.48	
Hooke	Uppsala, Sweden	1	2.36	5.77	1.00	0.07	90	S	0.0003	P	S	0.28		2.00
Hooke	Uppsala, Sweden	2	2.36	5.77	1.00	0.10	90	S	0.0003	P	S	0.37		1.50
Hooke	Uppsala, Sweden	3	2.36	5.77	1.00	0.09	90	S	0.0003	P	S	0.38		1.50
Hooke	Uppsala, Sweden	4	2.36	5.77	1.00	0.13	90	S	0.0003	P	S	0.39		1.75
Bray & Ho	Fredrickton, Can	1	3.00	3.14	1.00	0.15	90	S	0.0001	P	S	0.55		1.60
Bray & Ho	Fredrickton, Can	5	3.00	3.14	0.67	0.10	90	S	0.0001	P	S	0.38		1.40
Bray & Ho	Fredrickton, Can	7	3.00	3.14	0.33	0.15	90	S	0.0001	P	S	0.38		1.60
Bray & Ho	Fredrickton, Can	9	3.00	3.14	0.33	0.05	90	S	0.0001	P	S	0.24		1.31
Onishi, Jain &	IIHR	1	8.53	13.41	2.34	0.13	90	S	0.0003	D	S	0.54	0.71	
Kennedy	IIHR	2	9.12	14.32	1.17	0.13	90	S	0.0003	D	S	0.54	0.61	
McCrea & Bray	Fredrickton, Can	1	3.00	3.14	1.00	0.20	90	S	0.0001	P	S	0.30	0.35	
McCrea & Bray	Fredrickton, Can	2	3.00	3.14	1.00	0.20	50	S	0.0001	P	S	0.30	0.35	
Nouh & Townsend	Calgary, Canada	1	0.90	0.71	0.30	0.04	90	S	0.0007	P	S			1.80
"	Calgary, Canada	2	0.90	0.94	0.30	0.04	90	S	0.0007	P	S			2.40
de Vriend & Koch	LFM	1	4.25	7.85	1.70	0.17	90	S	0.0001	P	S	0.66	0.81	
de Vriend & Koch	LFM	2	4.25	7.85	1.70	0.17	90	R	0.0400	P	S	0.60	0.75	
de Vriend & Koch	Delf Hydraulic Lab.	1	50.00	72.00	6.00	0.25	90	S	0.0001	P	S	0.41	0.45	
de Vriend & Koch	Delf Hydraulic Lab.	2	50.00	72.00	6.00	0.25	90	S	0.0001	P	S	0.40	0.47	
C. L. Yen	IIHR	1	8.53	13.40	2.34	0.12	90	S	0.0003	P	S	0.32	0.40	1.20
Hicks, Jin, & Stefler	Alberta University	A1	3.66	17.2	1.07	0.08	18	S	0.0001	P	S	0.44	0.56	
Hicks, Jin, & Stefler	Alberta University	B1	3.66	17.2	1.07	0.09	27	S	0.0001	P	S	0.46	0.55	

Explanation

R = Rough; I = Intermediate; S = Smooth

NOTE 0.0001 = Smooth

R = Ripples; D = Dunes; P = Plane

S = Straight; M = Meandering; B = Braided

The basic data were used to derive parameters of bend geometry and hydraulic roughness which could affect the pattern of flow through the bend. The derived data are listed in Tables 4, 5 and 6 for Natural Rivers, Trapezoidal Channels and Rectangular Channels respectively.

An important aspect of any experimentally based study is to identify the range of each variable observed. When applying relationships based on the experimental results, these ranges must set the limits to the applicability of the relations. It is highly speculative and very risky to apply any empirical relationship outside the range of data from which it has been developed and tested. The range of each of the variables is listed in Data Tables 7, 8 and 9 for Natural, Trapezoidal and Rectangular Channels, respectively.

TABLE 4 - DERIVED DATA FOR NATURAL RIVERS

RESEARCHER	RIVER	SITE	BEND NUMBER	Rc/W	L/W	W/d	d/D50	OUTERBANK ANGLE sin (angle)	OUTERBANK ROUGHNESS ...S/I/R...	BEDFORMS ...R;D;S;P...	APPROACH CHANNEL ...S/M/B...	Vtoe/Vbar
Markham/Thorne	Fall	Reach B	1	2.87	5.00	12.62	46.4	0.867	R	P	S	1.51
Thorne et al.	Fall	Reach A	1	0.82	1.52	16.45	78.4	0.967	R	P	M	1.40
Thorne et al.	Fall	Reach A	2	0.75	1.45	11.96	242.1	0.996	R	P	M	1.30
Thorne et al.	Fall	Reach A	3	0.88	2.12	10.31	73.8	0.94	R	P	S	1.55
Markham/Thorne	Roding	Loughton	1	1.75	5.50	9.23	100.0	0.87	R	P	S	1.19
C.R. Thorne	Fall	Reach 1	1	1.25	5.77	9.89	890.0	0.906	I	R,D	S	1.57
C.R. Thorne	Fall	Reach 1	2	1.27	4.53	16.06	660.0	0.899	I	R,D	M	1.28
D. Anthony	Fall	Reach 4	1	1.27	5.59	13.68	190.4	0.891	I	D	S	1.46
J.S. Bridge	South Esk	Glen Cova	1	2.92	5.00	18.85	677.8	0.848	I	R,D	S	1.44
N.G. Bhowmik	Kaskaski	Reach 1	1	7.92	8.72	10.11	1713.6	0.559	R	D	S	1.25
N.G. Bhowmik	Kaskaski	Reach 1	2	6.58	6.31	12.65	7180.0	0.707	R	R,D	M	1.10
N.G. Bhowmik	Kaskaski	Reach 1	3	3.76	5.63	9.05	4455.6	0.5	R	D	M	1.23
N.G. Bhowmik	Kaskaski	Reach 1	4	1.12	2.86	9.45	1129.4	0.719	R	D	M	1.29
N.G. Bhowmik	Kaskaski	Reach 1	5	0.80	2.14	11.47	610.5	0.848	R	D	S	1.35
N.G. Bhowmik	Kaskaski	Reach 2	2	7.83	10.41	14.25	655.8	0.875	R	D	S	1.36
N.G. Bhowmik	Kaskaski	Reach 2	3	1.94	6.34	12.80	1472.0	0.799	R	D	M	1.21
N.G. Bhowmik	Kaskaski	Reach 2	4	4.70	8.19	12.30	768.8	0.777	R	D	S	1.15
Bathurst/Thorne	Severn	Maes Mawr	1	3.80	1.64	38.46	20.5	0.985	R	P	S	1.04
Bathurst/Thorne	Severn	Rickety Bridge	1	4.84	3.57	10.46	13.8	1	R	P	S	1.19
S. Maynord	Missouri	Browers Bend	1	17.90	19.87	36.49	18500.0	0.454	I	R,D	M	1.11
S. Maynord	Missouri	Snyder Bend	2	16.23	21.78	36.27	18333.3	0.375	I	R,D	S	1.13
S. Maynord	Missouri	Glovers Point Bend	3	10.00	20.12	35.40	18833.3	0.391	I	R,D	S	1.28
S. Maynord	Missouri	Winnebago Bend	4	9.34	23.10	39.43	17666.7	0.469	I	R,D	M	1.15
S. Maynord	Missouri	Upper Omaha Mission	5	8.23	7.13	45.15	16666.7	0.423	I	R,D	M	1.19
S. Maynord	Missouri	Middle Omaha Mission	6	13.85	20.53	35.96	18166.7	0.375	I	R,D	M	1.26
S. Maynord	Missouri	Lower Omaha Mission	7	9.64	11.36	38.99	18166.7	0.469	I	R,D	M	1.11
S. Maynord	Missouri	Upper Monona Bend	8	9.26	6.95	46.02	16766.7	0.588	I	R,D	M	1.13
S. Maynord	Missouri	Lower Monona Bend	9	11.75	25.26	40.69	18266.7	0.438	I	R,D	M	1.14
S. Maynord	Missouri	Blackbird Bend	10	21.62	26.92	40.63	17166.7	0.358	I	R,D	S	1.06
S. Maynord	Missouri	Tieville Bend	11	11.92	20.14	38.05	17500.0	0.375	I	R,D	M	1.19
de Vriend/Geldorf	Dommel	The Netherlands	1	2.72	8.10	11.76	500.0	0.961	I	D	S	1.28
de Vriend/Geldorf	Dommel	The Netherlands	2	2.42	5.28	12.00	500.0	0.899	I	D	S	1.45
Dietrich & Smith	Muddy Creek	Wyoming	1	2.00	6.25	10.00	571.4	0.92	S	R,D	M	1.36
A.J. Odgaard	E. Nishnabotna	Iowa	1	4.85	11.67	23.41	4100.0	0.731	R	R,D	S	1.28

TABLE 5 - DERIVED DATA FOR TRAPEZOIDAL CHANNELS

RESEARCHER	CHANNEL	SITE	BEND NUMBER	Rc/W	L/W	W/d	d/D50	Vtoe/Vbar	SHEAR STRESS RATIO
A.J. Odgaard	Lab. Channel	Inst Hyd Res.	1	5.37	16.88	16.27	500.0	1.22	
A.J. Odgaard	Lab. Channel	WES	1	5.37	16.87	24.40	333.3	1.24	
WES	RFT (I)	H.L.S.D.	1	2.25	3.54	8.67	20.5	1.31	
WES	RFT (II)	H.L.S.D.	2	2.27	5.36	8.70	20.2	1.30	
WES	RFT (III)	H.L.S.D.	3	2.27	3.56	8.73	20.2	1.42	
WES	RFT (IV)	H.L.S.D.	1	2.99	5.23	19.21	11.0	1.28	
WES	RFT (V)	H.L.S.D.	2	2.99	5.23	19.21	11.0	1.19	
D. Mueller	Lab.Channel	USBR	1	3.75	0.98	5.70	2280.0		1.33
D. Mueller	Lab.Channel	Uni. of Iowa	1	3.72	5.85	10.00	2290.0		1.30
D. Mueller	Lab.Channel	MIT	1	1.67	1.76	11.38	800.0		2.00
D. Mueller	Lab.Channel	MIT	2	1.25	1.31	8.20	1500.0		2.80
Ippen & Drinker	Lab. Channel	MIT	4	1.23	1.31	10.70	1140.0		2.00
Ippen & Drinker	Lab. Channel	MIT	7	2.51	2.62	10.14	700.0		1.75
Ben-Chie Yen	Lab. Channel	Univ. Iowa	1	4.16	6.54	20.10	1020.0	1.09	1.00
Ben-Chie Yen	Lab. Channel	Univ. Iowa	2	3.97	6.23	14.83	1450.0	1.03	1.00
Ippen & Drinker	Lab. Channel	MIT	1	2.91	3.04	7.95	770.0	1.17	1.60

TABLE 6 - DERIVED DATA FOR RECTANGULAR CHANNELS

RESEARCHER	CHANNEL	SITE	BEND NUMBER	Rc/w	L/w	w/d	d/D50	BEDFORMS ...R;D;P...	Vtoe/Vbar	SHEAR STRESS RATIO
Choudhary &	Lab.Channel	Benares, India	1	0.83	0.4365	5.0000	1920.0	P		1.20
Narasimhan	Lab.Channel	Benares, India	2	0.83	0.87	5.00	1920.0	P		1.20
"	Lab.Channel	Benares, India	3	0.83	0.44	10.00	960.0	P		1.10
"	Lab.Channel	Benares, India	4	0.83	0.87	10.00	960.0	P		1.20
Varshney & Garde	U.P. Irrigation	Rookee, India	1	3.00	3.15	2.26	132.5	P		2.36
"	Research	Rookee, India	2	3.00	3.15	9.16	32.8	P		2.46
"	Institute	Rookee, India	3	3.00	3.15	2.85	105.2	P		2.46
Fox & Ball	Lab. Channel	Leeds, UK	1	3.51	10.98	2.00	1524.0	P	1.12	
Rozovski	IHHR	USSR	1	1.00	3.14	13.33	600.0	D	1.38	
Kikawa et al.	Lab. Channel	Japan	1	4.50	14.14	20.00	55.6	D	1.29	
Kikawa et al.	Lab. Channel	Japan	2	4.50	14.14	18.18	61.1	D	1.22	
Kikawa et al.	Lab. Channel	Japan	3	4.50	14.14	15.87	70.0	D	1.25	
Struiksma et al.	Lab. Channel	Delft, Holland	1	8.00	19.55	18.75	177.8	D	1.18	
Struiksma et al.	Lab. Channel	Delft, Holland	2	8.00	19.55	15.00	222.2	D	1.17	
Hooke	Lab. Channel	Uppsala, Sweden	1	2.36	5.77	13.70	243.3	P		2.00
Hooke	Lab. Channel	Uppsala, Sweden	2	2.36	5.77	10.53	316.7	P		1.50
Hooke	Lab. Channel	Uppsala, Sweden	3	2.36	5.77	10.87	306.7	P		1.50
Hooke	Lab. Channel	Uppsala, Sweden	4	2.36	5.77	7.81	426.7	P		1.75
Bray & Ho	Lab. Channel	Frederickton, Can	1	3.00	3.14	6.67	1500.0	P		1.60
Bray & Ho	Lab. Channel	Frederickton, Can	5	4.50	4.71	6.67	1000.0	P		1.40
Bray & Ho	Lab. Channel	Frederickton, Can	7	9.01	9.43	2.22	1500.0	P		1.60
Bray & Ho	Lab. Channel	Frederickton, Can	9	9.01	9.43	6.66	500.0	P		1.31
Onishi, Jain &	Lab. Channel	IIHR	1	3.65	5.73	18.00	520.0	D	1.31	
Kennedy	Lab. Channel	IIHR	2	7.79	12.24	9.00	520.0	D	1.13	
McCrea & Bray	Lab. Channel	New Brunswick	1	3.00	3.14	5.00	2000.0	P	1.17	
McCrea & Bray	Lab. Channel	New Brunswick	2	3.00	3.14	5.00	2000.0	P	1.17	
Nouh & Townsend	Lab. Channel	Calgary, Can	1	3.00	2.37	7.50	57.1	P		1.80
"	Lab. Channel	Calgary, Can	2	3.00	3.13	7.50	57.1	P		2.40
de Vriend & Koch	Lab. Channel	LFM	1	2.50	4.62	10.00	1700.0	P	1.23	
de Vriend & Koch	Lab. Channel	LFM	2	2.50	4.62	10.00	4.3	P	1.25	
de Vriend & Koch	Lab. Channel	Delf Hydraulic Lab.	1	8.33	12.00	24.00	2500.0	P	1.10	
de Vriend & Koch	Lab. Channel	Delf Hydraulic Lab.	2	8.33	12.00	24.00	2500.0	P	1.18	
C. L. Yen	Lab. Channel	IIHR	1	3.65	5.73	20.03	417.1	P	1.25	1.20
Hicks, Jin, & Stefler	Lab. Channel	Alberta University	A1	3.42	16.07	13.38	800.0	P	1.27	
Hicks, Jin, & Stefler	Lab. Channel	Alberta University	B1	3.42	16.07	12.30	870.0	P	1.20	

Table 7 - Range of Variables for Natural Channels

Measured Variables		
Variable	**Units**	**Range**
Radius of Curvature	meters	8 - 4,525
Bend Length	meters	16 - 5,633
Width	meters	4 - 232
Average Depth	meters	0.4 - 5.65
Outer Bank Angle	degrees	21 - 90
Outer Bank Roughness	- -	Rough-Intermediate
Median Bed Material Size	millimeters	0.3 - 63
Bedforms	- -	Plane - Dunes
Approach Channel	- -	Straight-Meandering
Average Velocity	meters/second	0.42 - 1.47
Depth-averaged Toe Velocity	meters/second	0.55 - 1.81
Derived Variables		
R/w	- -	0.75 - 21.6
L/w	- -	1.45 - 26.9
w/d	- -	9.05 - 46.1
d/D50	- -	13.8 - 18,833
Vtoe/Vavg	- -	1.04 - 1.57

Table 8 - Range of Variables for Trapezoidal Channels

Measured Variables		
Variable	**Units**	**Range**
Radius of Curvature	meters	1.5 - 15.24
Bend Length	meters	1.27 - 41.18
Width	meters	0.61 - 6.76
Average Depth	meters	0.07 - 0.78
Outer Bank Angle	degrees	27 - 56
Outer Bank Roughness	- -	Smooth-Intermediate
Median Bed Material Size	millimeters	Smooth - 38.1
Bedforms	- -	Plane-Dunes
Approach Channel	- -	Straight-Meandering
Average Velocity	meters/second	0.34 - 1.07
Depth-averaged Toe Velocity	meters/second	0.42 - 1.50

Derived Variables		
R/w	- -	1.23 - 4.16
L/w	- -	1.31 - 16.88
w/d	- -	5.70 - 24.40
d/D50	- -	11.0 - 2290
Vtoe/Vavg	- -	1.03 - 1.42
Ttoe/Tavg	- -	1.00 - 2.80

Table 9 - Range of Variables for Rectangular Channels

Measured Variables		
Variable	**Units**	**Range**
Radius of Curvature	meters	0.8 - 50
Bend Length	meters	0.42 - 72.0
Width	meters	0.30 - 6.00
Average Depth	meters	0.05 - 0.27
Outer Bank Angle	degrees	18 - 90
Outer Bank Roughness	- -	Rough-Smooth
Median Bed Material Size	millimeters	Smooth - 40
Bedforms	- -	Plane-Dunes
Approach Channel	- -	Straight
Average Velocity	meters/second	0.24 - 0.66
Depth-averaged Toe Velocity	meters/second	0.35 - 0.81
Derived Variables		
R/w	- -	0.83 - 9.01
L/w	- -	0.44 - 19.55
w/d	- -	2.22 - 24.0
d/D50	- -	4.3 - 2,500
Vtoe/Vavg	- -	1.10 - 1.38
Ttoe/Tavg	- -	1.20 - 2.46

Examination of Data

Before undertaking any advanced analysis or statistical treatment of data, it is important to examine the data carefully in the light of existing knowledge annd theory. This allows the researcher to identify expected and unexpected trends and relationships, and establishes the analytical framework for the formal treatment of the data. This, fairly lengthy, procedure is essential if the resulting relationships are to have physical as well as statistical significance.

The first step was to establish how the data collected in this study plotted in relation to the design curve developed by the US Army Engineer Waterways Experiment Station. Hence, a semi-logarithmic plot of (Rc/w) versus (Vtoe/Vavg) was produced for the Natural River data, with the WES design curve marked on (Fig. 3a). The design line does not pass through the points, but does form a good upper bound to the data with the exception of only three out of 34 points. Thus, it may be concluded that the WES design curve represents a reasonable, but rather conservative approach to the estimation of (Vtoe/Vavg) in natural channels. This is essential so that in the final design, the size of riprap specified is always on the safe side. A regression line through the scatter of the points for Vtoe/Vavg could be used, but this would require that a factor of safety be introduced in the relationship between the critical local velocity for entrainment and the size of stone used in a revettment. Present WES preference is to position the design line as an upper bound to the data, so that all of the zone of uncertainty is on one side of the line (Oswald, personal communication, March 1990).

However, there is considerable scatter in the data, and this deserves comment. Partly, it is a result of the methods used to collect the data. Usually, velocities were measured at a finite number of cross-sections around each bend. In some studies many sections were used (up to seven per bend), but in others only a few (less than three) were used. Outer bank velocities at intermediate points between sections were not measured. Consequently, there is no guarantee that the actual maximum outer bank in a bend would be observed in any study. Indeed, in studies with only a few sections, it is highly probable that the outer bank maximum velocity for a bend would not be measured. It is therefore to be expected that field data should plot either close to or below a line defining the maximum possible ratio of outer bank to average velocity. However, even for bends with multiple measured sections, the data often plot well below the WES line. This suggests that there may be further variables affecting the velocity ratio which are unaccounted for in the WES analysis.

Points for bends of very low Rc/w values reveal that the monotonic increase in Vtoe/ Vavg observed as Rc/w decreases may cease at an Rc/w of about 2. For Rc/w values less than 2, the data show a wide range of Vtoe/ Vavg values, but the velocity ratio never exceeds 1.6. This accords with other recent studies of bend flow in very tightly curved bends, which has shown that both outer bank scour pool depth and outer bank retreat rate may actually decrease with decreasing Rc/w for bends with Rc/w less than 2 (Biedenharn et al., 1989; Thorne, 1989). This is not unexpected theoretically, as there is a major discontinuity in the way the pattern of bend flow responds to increasing bend tightness at Rc/w of between 2 and 3 (Bagnold, 1960). Further data and analyses are required to confirm this tentative finding.

Fig. 3a **Natural Rivers**

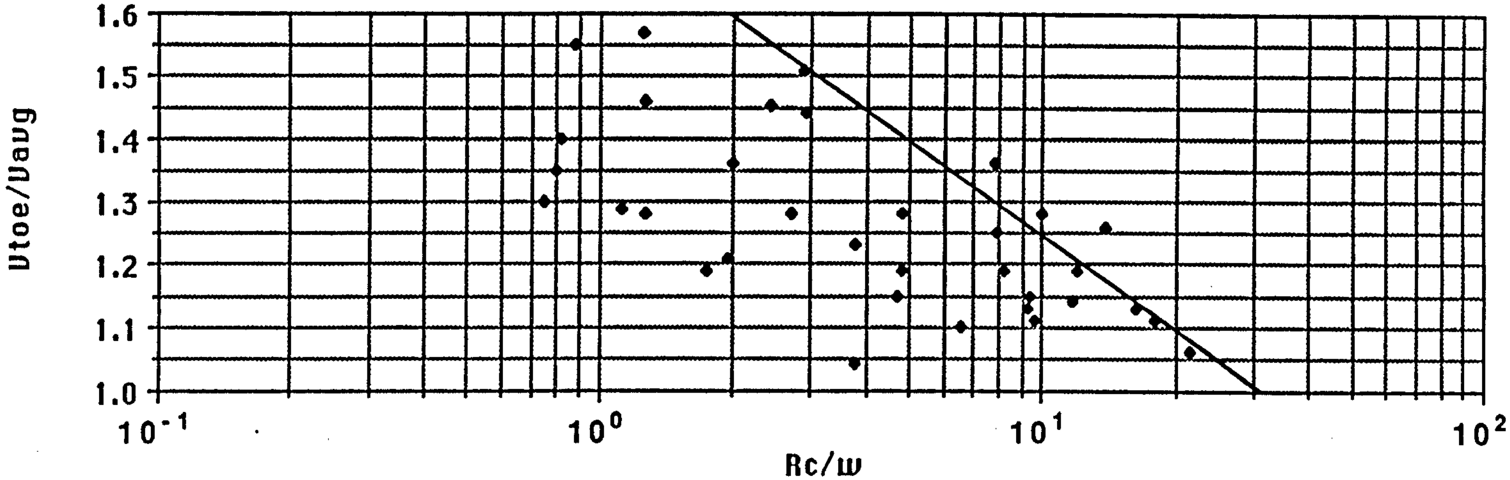


Fig. 3b **Trapezoidal Channels**

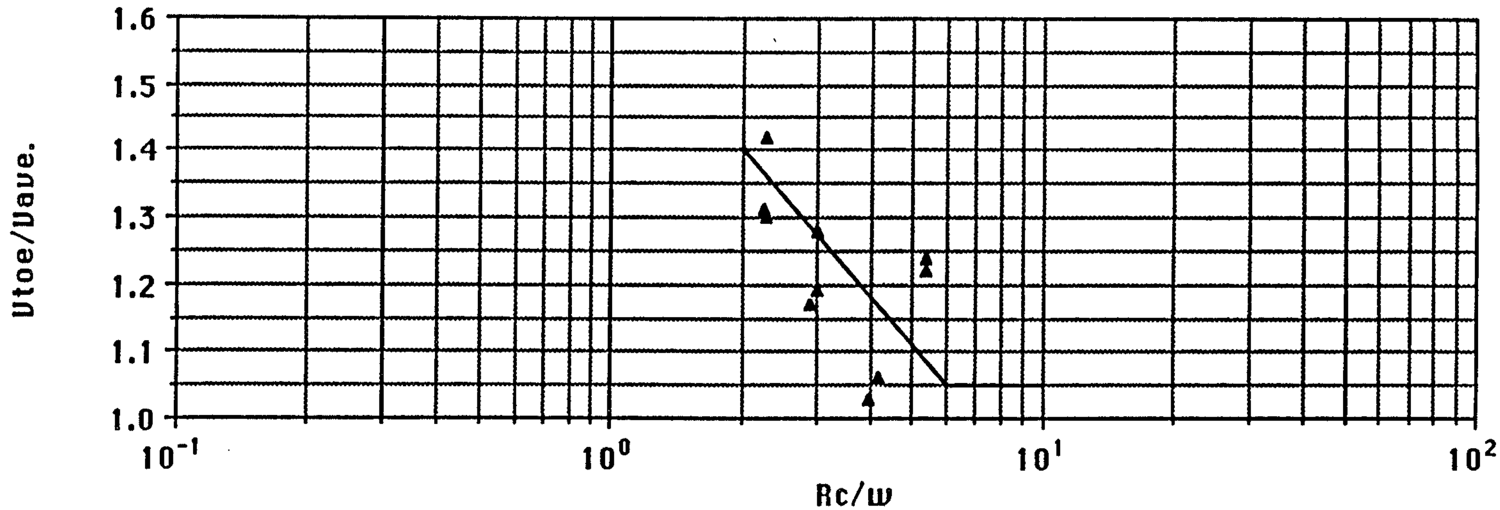
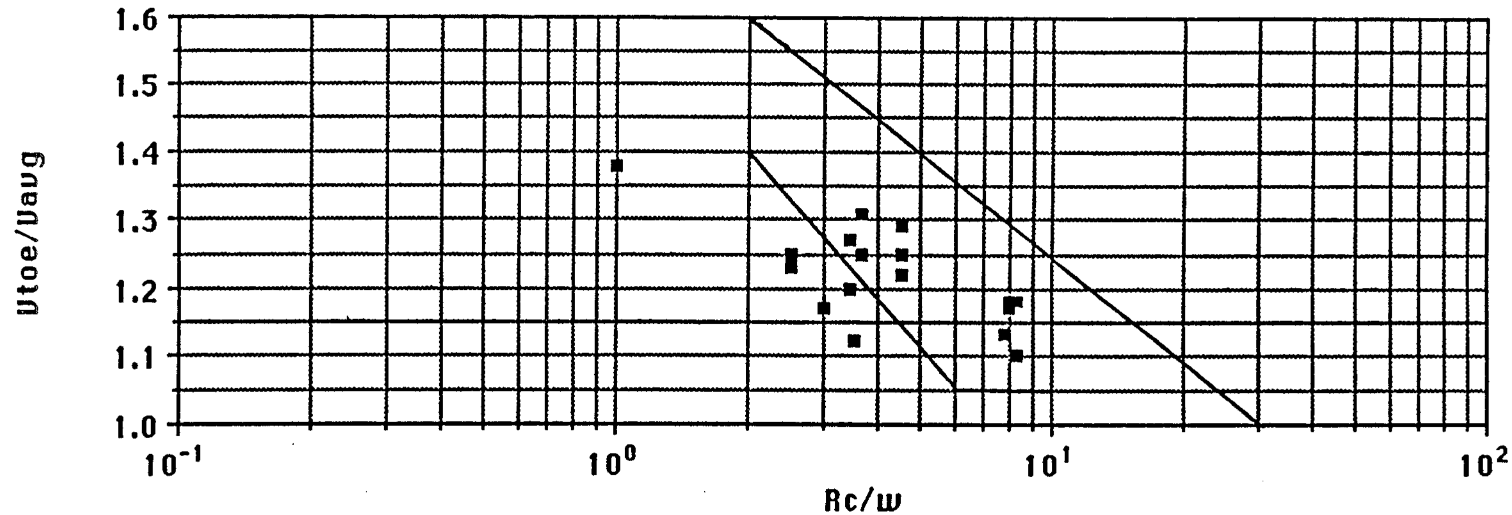


Fig 3c **Rectangular Channels**



It is concluded that the actual ratio of outer bank toe velocity to average velocity at a bend increases as the ratio of radius of curvature to width decreases, in bends with Rc/w greater than 2. In a natural channel the actual velocity ratio observed in the field is unlikely to exceed the value predicted from the WES design curve, but it is likely to be considerably lower under some circumstances. For very tight bends with Rc/w less than 2, a wide range of Vtoe/Vavg values is possible, but maximum values never exceed 1.6.

Effect of Channel Shape

Figure 3b shows the same plot for trapezoidal channels, again with the relevant WES design curve superimposed. The trend of the line is clearly correct, but the data tend to scatter about the line rather than lying near or below it as in the case of natural channels. Three out of ten points lie significantly above the line, suggesting that it might be prone to underestimating the actual ratio of toe to average velocity under some circumstances.

Figure 3c shows the same plot for rectangular channels. Both the lines for natural and trapezoidal channels are superimposed. The data tend to plot around the line for trapezoidal channels, eleven points lie above and six below the line. As the shape of a rectangular channel is something between trapezoidal and natural, the plotting position of the points is as expected. The plot suggests that Vtoe/Vavg values in rectangular channels are lower than those found in natural channels, but may be somewhat higher than those found in trapezoidal channels.

In order to establish which other variables influence the velocity ratio for a bend, separate semi-logarithmic graphs were plotted for further, different channel characteristics.

Effect of Bank Roughness

Figures 4a and 4b show the Rc/w versus Vtoe/Vavg relations for natural bends with intermediate roughness outer banks and rough outer banks, respectively. Examination of the plots shows complete overlap between the data clouds for the two bank types. This suggests that, for the range of bank roughness represented in the bends studied, the roughness of the outer bank did not materially affect the velocity ratio.

The banks of the laboratory flumes used to generate the data for trapezoidal and rectangular channels showed an insufficient range of roughness to allow separation of the data in this way.

Effect of Bedforms

Figures 5a, b and c show the Rc/w versus Vtoe/Vavg relations for natural bends with plane, ripple and dune, and dune bedforms, respectively. Examination of the plots shows complete overlap of the data clouds for the three bedforms, suggesting that in natural bends the bedform did not significantly affect the velocity ratio.

Fig. 4a Natural Rivers - Intermediate Roughness Outer Banks

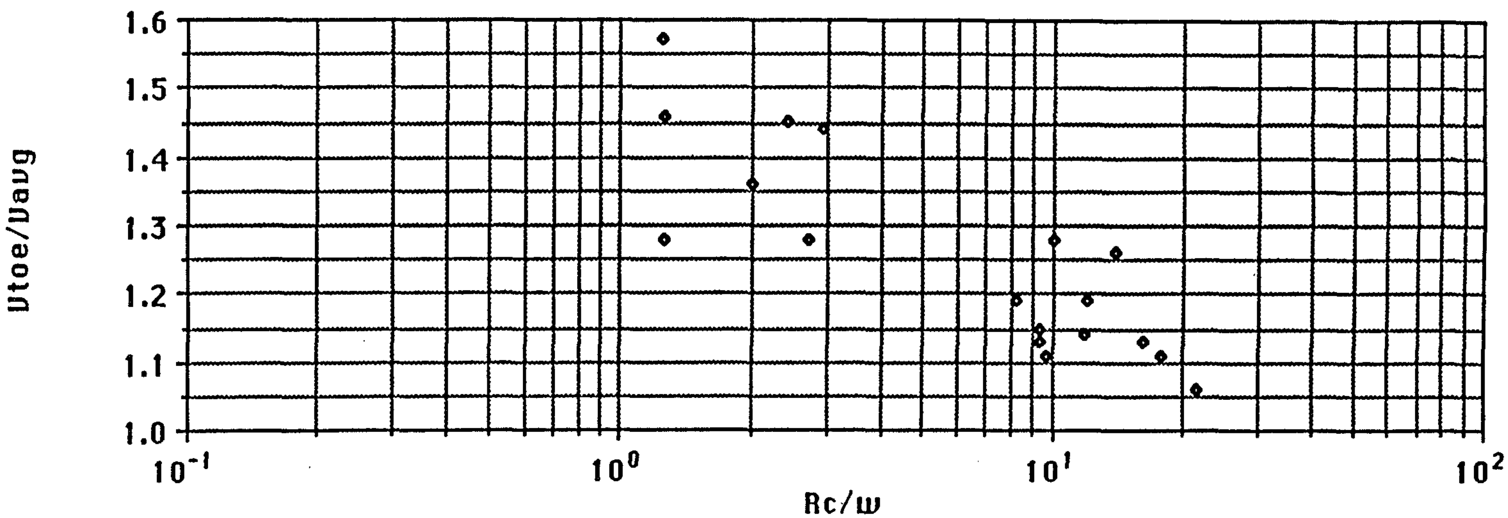


Fig. 4b Natural Rivers - Rough Outer Banks

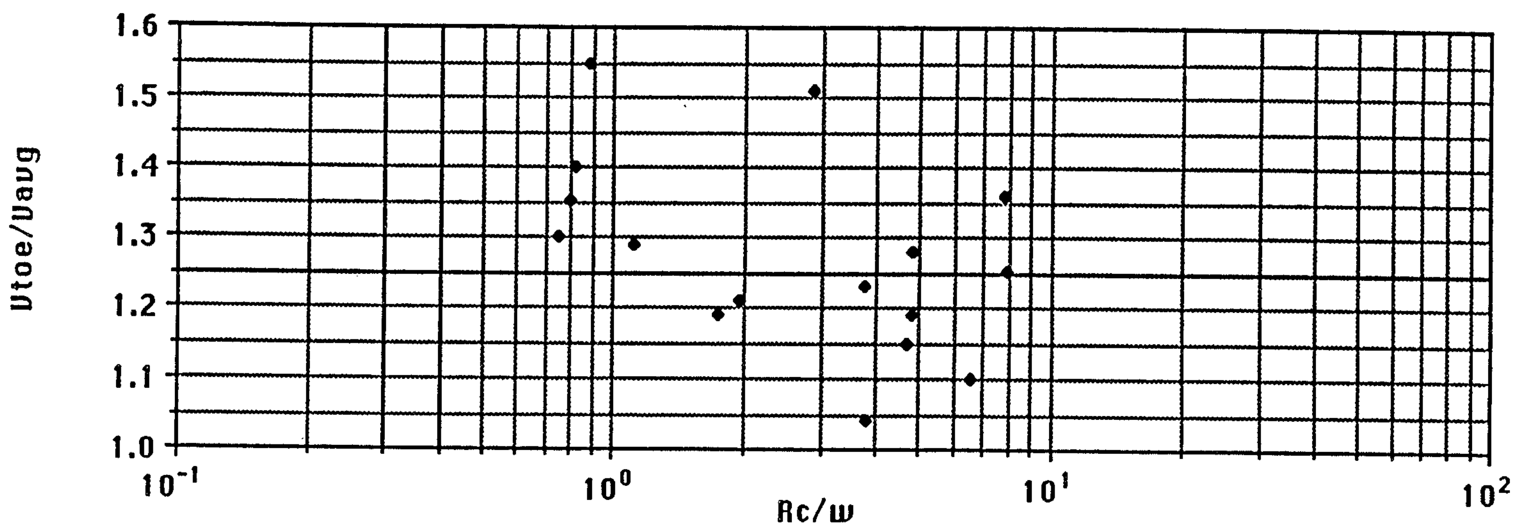


Fig. 5a Natural Rivers - Plane Beds

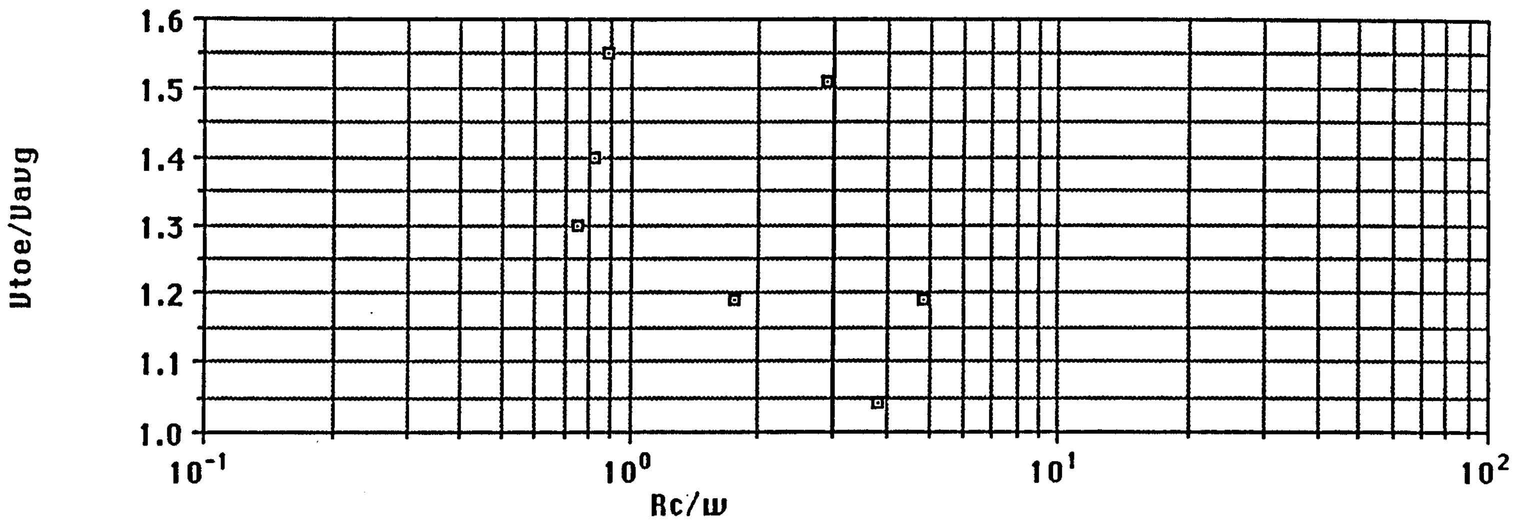


Fig. 5b Natural Rivers - Ripple and Dune Beds

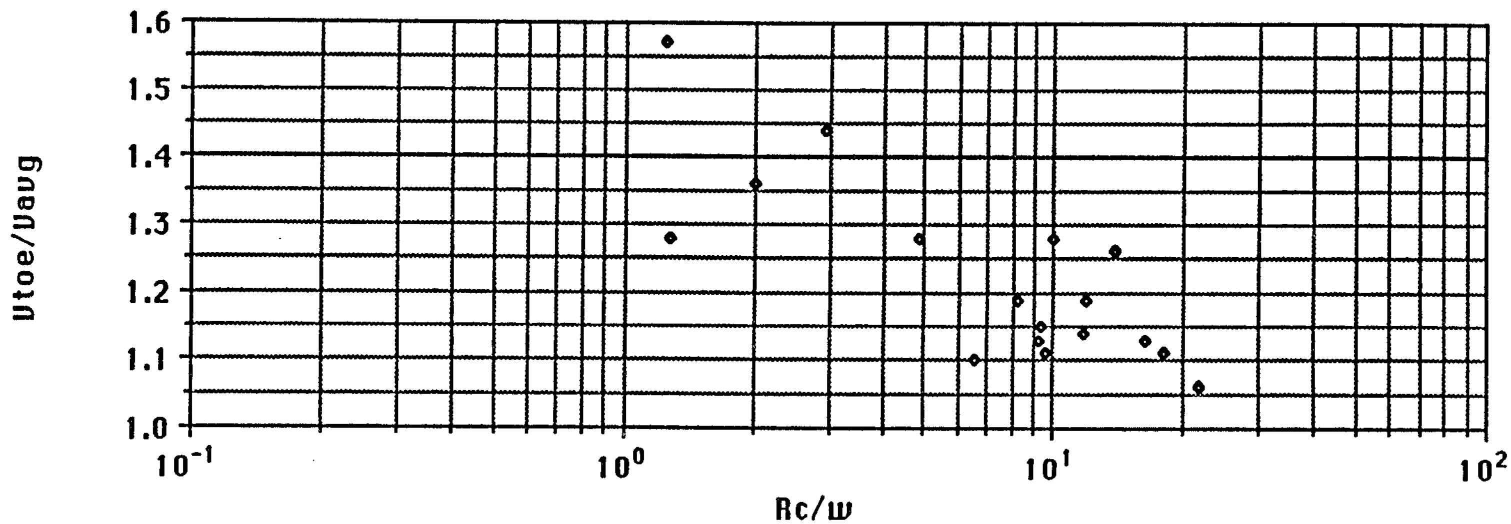


Fig. 5c Natural Rivers - Dune Beds