VERTICAL VELOCITY DISTRIBUTIONS IN SAND-BED ALLUVIAL RIVERS

BY

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THESIS

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ABSTRACT

An experimental study of flows over bedforms was conducted in two alluvial river systems; the Kankakee River and the Missouri River with the purposes of 1) evaluating the applicability of laboratory scale results to field-scale problems, 2) characterizing the spatially averaged (longitudinal) mean velocity profile to evaluate available velocity-distribution models, and 3) characterizing the spatially averaged Reynolds stress distribution and evaluating available shear-partitioning models. Three separate data sets were collected (two from the Missouri and one from the Kankakee Rivers) with detailed velocity data measured at numerous locations along bedforms. These data indicated flow separation in one of the Missouri River data sets. Local and spatially averaged velocity distributions were logarithmic for all data sets.

The large-river-scale data reflect similar flow characteristics to those of laboratory-scale flows. However, it is obvious that field-scale flows sometimes present bedform geometries that cannot be classified as equilibrium dunes, which are present in the laboratory-scale flume experiments. Also, at times, these bedform geometries could not be classified easily into other categories, such as ripples or bars. The wavelike response of the flow in the outer region, with velocity decreasing throughout the flow depth over bedform troughs, and vice-versa over bedform crests, is present in both field- and laboratory-scale flows. Turbulence production may be more appreciable in the outer region of a large river flow than for flume flows. Measured laboratory- and field-scale Reynolds stress distributions appear to support this conjecture. In general, the Reynolds stress distributions at laboratory- and field-scales are similar, with the both flow scales having the highest shear stresses in the zones of flow separation and along the shear layer.

The velocity-distribution models of Smith and McLean (1977) and Nelson and Smith (1989A) were evaluated using the field data from this study, as well as the field data of Smith and McLean (1977) and Kostascuk and Villard (1996). The Smith and McLean and Nelson and Smith models performed adequately when each was applied according to bedform type, with the Smith and McLean model working well for equilibrium dunes and the Nelson and Smith model working well for flows where form resistance is minimal (for example, elongated bedforms, gradual lee slopes, etc.).

In an effort to provide a simple field approach for estimating the reachwise spatially averaged vertical-velocity profile, the standard velocity-defect model also was evaluated, accounting for the wake effect through knowledge of the bulk Richardson number. The velocity-defect model mean flow velocities were within 2% of the measured values and estimated spatially averaged point velocities were within 10% for $z/H>0.1$. If sediment concentration cannot be estimated, the model performance decreases slightly, with vertically averaged mean velocity still accurate to within 2% for all but one data set (+3.7%), but point-velocity accuracies decreasing to +/- 10% for $z/H>0.3$.

Shear partition models of Einstein and Nelson-Smith were evaluated with the field data collected in this research. Einstein's method had an absolute average percent error of

11.3%, while the Nelson-Smith method had an absolute average percent error of 22.2% when the smaller bedforms were used as the geometry in the Nelson-Smith method. The Nelson-Smith method requires the estimation of bedform geometry. The Einstein method is recommended over that of the Nelson-Smith method based on both the better relative error estimates for the Einstein method and the need for bedform geometry in the Nelson-Smith method.

To Joanne…

An excellent wife, who can find? For her worth is far above jewels. Proverbs 31:10

To Rebecca, Amanda, Sophia, and Olivia…..

Behold, children are a gift of the Lord………How blessed is the man whose quiver is full of them……Psalms 127:3-5

“To God be the Glory”

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"Field studies with detailed measurements of not only dune characteristics but also flow and transport are valuable and daunting for the same reason: they indicate the complexity of the real problem, which, together with practical constraints on field measurements, make more difficult the analysis and interpretation of the data." ASCE Task Committee on Flow and Transport over Dunes (2002)

"From a practical point of view, it is very difficult to measure in the proximity of the bed" Garcia, 1989, p 7.11

"I had occasion to descend to the bottom in a current so swift as to require extraordinary means to sink the bell…The sand was drifting like a dense snowstorm at the bottom…At sixty feet below the surface I had found the bed of the river, for at least three feet in depth, a moving mass and so unstable that, in endeavoring to find a footing on it beneath my bell, my feet penetrated through it until I could feel, although standing erect, the sand rushing past my hands, driven by a current apparently as rapid as that on the surface. I could discover the sand in motion at least two feet below the surface of the bottom, and moving with a velocity diminishing in proportion to its depth." James Eads, circa 1842, discussing his salvage business on the Mississippi River and quoted in Rising Tide by John M. Barry (page 26)

TABLE OF CONTENTS

LIST OF FIGURES………………………………………………………………

xiv

LIST OF TABLES………………………………………………………………xxii

LIST OF SYMBOLS……………………………………………………………xxiv

CHAPTER 1. INTRODUCTION…………………………………………………1

1.1. Hydraulics of Sand-Bed Alluvial Rivers…………………………………1

1.2. Present Study…………………………………………………………11

1.2.1. *Research Needs and Motivation*………………………………11

1.2.2.*Goals and Objectives of Study*………………………………..14

CHAPTER 2. LITERATURE REVIEW AND THEORETICAL

BACKGROUND……………………………………………………16

2.1. Bedforms…………………………………………………………..16

2.1.1. *Origins of Bedforms*……………………………………..22

2.1.2. *Prediction of Bedform Type and Geometry*…………………..27

2.1.2.1. Prediction of Bedform Type…………………….…..28

2.1.2.2. Empirical Predictors of Bedform Geometry………...39

2.1.2.3. Analytic Predictors of Bedform Geometry…………47

2.2. Flow Over Bedforms…………………………………………………53

2.2.1. *Flow Resistance and Shear Partitioning Models*……………...57

2.2.2. *Velocity Profile Characterization*……………………..……68

2.2.2.1 Regions of Flow……………………………………...69

2.2.2.2 Derivations of Turbulent Velocity Relations from

Boundary Layer Theory……………………………71

2.2.2.3 Velocity-Defect Law…………………………………77

2.2.2.4 Wake Function………………………………………80

2.2.2.5 Other Alternative Velocity Models…………………..83

2.2.2.6 Added Complexity for Sand-Bed Rivers……………..84

2.3 Previous Field Scale Investigations……………………………….....88

CHAPTER 3. EXPERIMENTAL APPARATUS AND APPROACH………………96

3.1. Data-Collection Procedure……………………………………….....96

3.2. Instrumentation…………………………………………….…...101

3.2.1. *Acoustic Doppler Velocimeter*………………………………101

3.2.2. *Acoustic Doppler Current Profiler*…………………………...107

3.2.3. *Sediment Data Collection*……………………………………115

3.3. Design and Testing of Instrument Platform………………………....119

3.4 Description of Field Sites…………………………………………....125

3.4.1.*Kankakee River*………………….……………………………125

3.4.2. *Missouri River*…………………………………………………..127

CHAPTER 4. EXPERIMENTAL RESULTS: VELOCITY PROFILES…………...131

4.1. Overview of the Experiments…………………………………………..131

4.2. Overview of Data from Previous Studies………………………………147

4.3 Classification of Bedforms Present in Experiments……………………151

4.4 Structure of the Mean Velocity Profile…………………………………155

4.5. Spatially Averaged Velocity……………………………………...…173

4.6. Comparison of Field Data with Flume Data and Previous Studies…….181

4.7. Evaluation of Existing Models for Spatially Averaged Velocity………187

4.7.1. *Existing Models*…………………………………………….....188

4.7.2. *Evaluation of Models*……………………………………...203

4.8. Spatially Averaged Velocity-Defect Model……………………………210

4.9. Conclusions……………………………………………………………224

CHAPTER 5. EXPERIMENTAL RESULTS: SHEAR PARTITIONS …………..230

5.1. Overview………………………………………………………………230

5.2. Shear Stress Field Data…………………………………………………233

5.3. Evaluation of Available Shear Partition Models with Field Data……...245

5.4. Conclusions……………………………………………………………252

CHAPTER 6. SUMMARY AND CONCLUSIONS……………………………….255

6.1. Summary………………………………………………………………255

6.2. Conclusions……………………………………………………………258

6.2.1. *Similarity of Laboratory and Field Investigations*…………...258

6.2.2. *Spatially-Averaged Velocity Profiles*…………………….…..261

6.2.3. *Shear Stress Partitions*……………………………………..…262

6.2.4 *Recommendations for Future Research*………………………264

REFERENCES……………………………………………………………………..266

APPENDIX…………………………………………………………………………285

VITA………………………………………………………………………………..325

LIST OF FIGURES

FIGURE

1.1 Flow over a dune, δ is the internal boundary layer and b is the wake effect resulting in a momentum defect (from Nelson and others, 1993)….10

2.1 Forms of bed roughness in an alluvial channel (from Simons and Richardson, 1966)……………………………………………………18

2.2 Conceptual drawing of dunes (from Simons and others, 1965)…………..21

2.3 Evolution of eddies (from Yalin and da Silva, 2001)…………………….25

2.4 Bedform predictor from Simons and Richardson (1966)…………………29

2.5 Bedform predictor from Liu (1957)………………………………………30

2.6 Bedform predictor developed by Kennedy (1969) based on a potential flow model…………………………………………………………..…31

2.7 Bedform predictor proposed by Znamenskaya (1969) (from Raudkivi, 1990)…………………………………………………………..33

2.8 Bedform predictor proposed by Hill and others (1967) (from Raudkivi, 1990)…………………………………………………………..…34

2.9 Froude number versus H/D_{50} with indications of the type of bedform present for sands (from Vanoni,1974)……………………………………35

2.10 Bedform classification proposed by van Rijn (1984C)…………………..36

2.11 Prediction of dune steepness proposed by Yalin (1977A)……………….42

2.12 Prediction of ripple steepness proposed by Yalin (1977A)………………43

2.13 Bed form height predictor proposed by van Rijn (1984C)……………….45

2.14 Bed form steepness predictor proposed by van Rijn (1984C)……………45

2.15 Bed shear stress as a predictor of dune height as proposed by Fredsoe (1982)………………………………………………………………50

2.16 Bed shear stress as a predictor of dune steepness as proposed by Fredsoe(1982)……………………………………………………………….50

2.17 Comparison of theoretical and observed bedform shapes (from Haque and Mahmood, 1985)……………………………………….51

2.18 Non-dimensional pressure distribution in flow over a bedform (from Shen and others, 1990)…………………………………………….54

2.19 Observations of velocity distribution along a bedform plotted both in A) linear and B) log space by Nelson and others (1993)…………………55

2.20 Velocity profiles in a typical shear flow (Vanoni, 1975)…………………56

2.21 Observations of Reynold stress distribution along a bedform (from Nelson and others, 1993)………………………………………….56

2.22 Evaluation of W_0 from the velocity-defect law (from Julien, 1995)……..82

2.23 Bathymetric Data from the Mississippi River in Louisiana (from Carey and Keller, 1957)……………………………………………90

3.1 Boat anchored preparing to collect data on the Missouri River at St Charles, Missouri…………………………………………………….100

3.2 Modified P-61 platform with ADVs, compass/tilt/roll sensor, and sampler intake shown……………………………………………………...103

3.3 Stationarity analysis for streamwise mean velocity: MO-2, location 1, elevation =0.90 m above the bed……………………………………..104

3.4 Stationarity analysis for streamwise mean velocity: MO-2, location 3, elevation =0.154 m above the bed……………………………………104

3.5 Stationarity analysis for average covariance of streamwise and vertical velocity fluctuations: MO-2, location 1, elevation =0.90 m above the bed…………………………………………………………………105

3.6 Stationarity analysis for average covariance of streamwise and vertical velocity fluctuations: MO-2, location 4, elevation =0.82 m above the bed……………………………………………………………….....105

3.7 Stationarity analysis for average covariance of streamwise and vertical velocity fluctuations for MO-1, location 1, elevation =6.09 m above the bed……………………………………………………….…….106

3.8 Stationarity analysis for streamwise turbulence intensity for MO-2, location 4, elevation =0.82 m above the bed…………………………….106

3.9 Stationarity analysis for streamwise turbulence intensity for MO-1, location 1, elevation =6.09 m above the bed…………………………….107

3.10 RD Instruments 600 kHz Rio Grande™ ADCP…………………………108

3.11 ADCP and ADV velocity profiles……………………………………….110

3.12 ADCP and ADV mean velocity data for MO-2, location 1……………..111

3.13 Mean velocity data plotted in defect form……………………………….111

3.14 Reynolds shear stresses for selected MO-2 locations……………………114

3.15 ADV and ADCP Reynolds stress comparison…………………………..115

3.16 ADCP backscatter compared with measured sediment concentrations A) total suspended-sediment concentration, B) suspended-sand concentration…………………………………………………………….117

3.17 Optical backscatter readings compared and measured suspended-sediment concentration, Wabash River near Cayuga, Indiana……………………………………………………………...………118

3.18 Bed material size distribution for the Missouri River St. Charles and the Kankakee River at the State Line……………………………………118

3.19 Conceptual sketch of the near-bed data collection platform (looking upstream)………………………………………………………119

3.20 Instrument platform used for data collection in San Francisco Bay (Cheng and others, 2000)……………………………………………….120

3.21 Prototype of beta version of the data-collection platform for this research………………………………………………………….120

3.22 Overhead view of large tilting flume at the Ven Te Chow Hydrosystems Laboratory……………………………………….….…..121

3.23 Modified P-61 platform with ADV positioned in center of large tilting flume…………………………..…………………………….122

3.24 Mounting for upstream ADV…………………………………………..123

3.25 Ambient ADV velocity and P-61 platform ADV velocity…………….124

3.26 Plan view of the Kankakee River at the Illinois-Indiana State Line…...126

3.27 Kankakee River looking upstream along study reach…………………127

3.28 Plan view of the Missouri River at St Charles, Missouri……………...129

3.29 Missouri River (A) looking downstream through study reach; (B) looking from right bank to left bank…………………………..….…130

4.1 A) Locations for detailed velocity data collection in KANK-1 and B) typical cross section through the sampled reach……………………..…134

4.2 ADCP output from the Kankakee River measurements June 5, 2002, in A) water mode 5 and B) water mode 1 for the 1200 kHz RDI Rio Grande Workhorse ADCP…………………………………….…135

4.3 Streamwise velocity observations for KANK-1 at locations 7-21…….136

4.4 A) Locations for detailed velocity data collection in MO-1 and B) cross section (looking downstream) of the channel downstream of the detailed velocity data collection reach……………………………..139

4.5 Three-dimensional view of the bedforms for the Missouri River at St Charles on June 18, 2002 …………………………………..…140

4.6 ADCP reported depth and the depths from the Fathometer survey for MO-1……………………………………………………………141

4.7 Time series data from the lower ADV for MO-1, location 5………….142

4.8 Time-averaged mean velocity profile for MO-1, location 2…………..143

4.9 Streamwise velocity observations for MO-1, locations 4-16………..…144

4.10 A) Locations for detailed velocity data collection for MO-2 and B) cross section (looking downstream) of the channel downstream of the detailed velocity data collection reach……………………………..146

4.11 Streamwise velocity observations for MO-2 at locations 1-15 (note: location 11 is omitted for clarity)…………………………….…147

4.12 Bedform geometry of case 3 experiment from Lyn (1993)…………..…..148

4.13 Bedform geometry of experiment from Bennett and Best (1995)….…149

4.14 MO-2 velocity profiles at the crest and in the lee of the crest………..157

4.15 KANK-1 velocity profiles at the crest and in the lee of the crest…….158

4.16 MO-1 velocity profiles at the crest and in the lee of the crest………..159

4.17 Definition sketch of flow and bedforms from Lyn (1993)…………...162

4.18 MO-2 velocity profiles for locations 6 – 9…………………………...163

4.19 KANK-1 data plotted in velocity-defect form…………………….….166

4.20 KANK-1 data plotted in velocity-defect form with bulk shear velocity as the scaling parameter…………………………………….….166

4.21 KANK-1 data plotted in velocity-defect form with local shear velocity as the scaling parameter…………………..……………....167

4.22 MO-1 data plotted in velocity-defect form with bulk shear velocity as the scaling parameter………………………………….….….….167

4.23 MO-1 data plotted in velocity-defect form with local shear velocity as the scaling parameter…………………………………….….…..168

4.24 MO-2 data plotted in velocity-defect form with bulk shear velocity as the scaling parameter……………………………………..….…168

4.25 MO-2 data plotted in defect form with local shear velocity as the scaling parameter……………………………………….….…..169

4.26 All local velocity data collected in KANK-1, MO-1, and MO-2 plotted in velocity-defect form and scaled by the local shear velocity……………………………………………………………169

4.27 All local velocity data collected in KANK-1, MO-1, and MO-2 plotted in velocity-defect form and scaled by the bulk shear velocity……………………………………………………………170

4.28 Streamwise turbulent fluctuations for MO-2………………………...171

4.29 Variation of Coles wake coefficient with distance along the dune for all experiments……………………………………………...172

4.30 Spatially-averaged velocity profile for A) KANK-1, B) MO-1 and C) MO-2…………………………………………….….….…..175

4.31 Friction factor diagrams (from Brownlie, 1981)…………………..….178

4.32 Log-linear dimensionless velocity plot……………………………180

4.33 Spatially averaged velocity data plotted in velocity-defect form…….180

4.34 Laboratory and field data considered in this research plotted in velocity-defect form……………………………………………….182

4.35 Laboratory and selected field data collected in this research plotted in velocity-defect form……………………………………….182

4.36 Laboratory and selected field data plotted in log-linear form with composite roughness height as the similarity parameter……………..183

4.37 Laboratory and field data plotted in log-linear form…………………183

4.38 Smith and McLean (1977) data plotted in log-linear form…………...185

4.39 Kostaschuk and Villard (1996) data plotted in log-linear form……..185

4.40 Local velocity data collected near the bedform crests plotted in velocity-defect form………………………………………………..…186

4.41 Local velocity data collected in the bedform trough plotted in velocity-defect form………………………………………………..…187

4.42 Comparison of the full model of Smith and McLean (1977) and a simplified log-linear version using the parameters of the Smith and McLean (1977) model…………………………………..…….191

4.43 Velocity profiles for clear water and capacity suspensions of 0.210 mm sand (from Coleman, 1986)……………………..……..192

4.44 Spatially averaged flow over a dune, (from Fedele and Garcia, 2001)……………………………………………………………200

4.45 Comparison of all field data with results from three velocity distribution models…………………………………………………..205

4.46 Spatially averaged velocity profile from Smith and McLean (1977) 69-W1 data set …………………………………………………206

4.47 Velocity profiles estimated by the Nelson and Smith (1989A) model with different estimates of $(z_0)_1$ (0.005 cm is the estimate of $(z_0)_1$ given by the Nelson and Smith (1989A) model and 1.12 cm is the estimate of $(z_0)_1$ given by the Smith and

McLean (1977) model, but used in the Nelson and Smith (1989A) model)……………………………………………………….207

4.48 A) Observed and modeled velocities for the Smith and McLean (1977) model, and B) percent error by dimensionless depth…………208

4.49 A) Observed and modeled velocities for the Nelson and Smith (1989A) model, and B) percent error by dimensionless depth……….209

4.50 Coles wake parameter as a function of the ratio of the bedform height to flow depth……………………………………………………..215

4.51 Coles wake parameter as a function of the ratio of the bedform height to dune length……………………………………………………….215

4.52 Coles wake parameter as a function of the bedform symmetry ratio…216

4.53 Coles wake parameter as a function of the gross flow Richardson number…………………………………………………………..…......216

4.54 Observed and velocity-defect modeled velocity profiles for MO-2 data………………………………………………………………………218

4.55 Observed and velocity-defect modeled velocity profiles for Smith and McLean (1977) 69-W1 data……………………………..……….219

4.56 Observed and velocity-defect modeled velocity profiles for Kostaschuk and Villard (1996) June 29 data…………………..…….219

4.57 Observed and modeled velocity for the velocity-defect model using the Coles wake parameter relation…………………………..…220

4.58 Velocity-defect model error as a function of dimensionless elevation above the bed………………………………………………221

4.59 Observed and modeled velocities (with the Coles wake parameter neglected) for all field data………………………………………..222

4.60 Velocity-defect model error (with the Coles wake parameter neglected) as a function of the dimensionless elevation above the bed………………………………………………………….….223

5.1 Evolution of the shear stress distribution as proposed by Fedele and Garcia (2001)……………………………………………………231

5.2 Measurements of Reynolds stress over a laboratory dune (from

Nelson and others,1993)……………………………………….………..232

5.3 Reynolds stress measurements from MO-2, at locations 1-15, with location 11 omitted………………………………………………..234

5.4 Reynolds stress measurements for 0<x≤ 50 meters of the MO-2 profile, showing locations 1-5……………………………….……234

5.5 Reynolds stress measurements for 50≤x≤100 meters of the MO-2 profile, showing locations 6-8……………………………………..235

5.6 Reynolds stress measurements for 100≤x≤160 meters of the MO-2 profile, showing locations 9-15, except location 11………………….235

5.7 Spatial average of the Reynolds stresses for the KANK-1 data by averaging along lines of equal distance from the bed…………….239

5.8 Spatial average of the Reynolds stresses for the MO-2 data by averaging along lines of equal distance from the bed……………..239

5.9 Dimensionless spatially averaged shear stress and elevation………...240

5.10 Spatial average of the Reynolds stress for the Bennett and Best flume data by averaging along lines of equal distance above the mean bed elevation (from Bennett and Best, 1995)………………..…244

5.11 Spatial average of the Reynolds stresses for the MO-2 data by averaging along lines of equal distance above the mean bed elevation…………………………………………………….……..244

LIST OF TABLES

TABLE

2.1 Classification of bedforms and other information (from Graf,1971)…17

2.2 Summary description of bedforms and configurations (from Vanoni,1975 and ASCE, 1966)…………………………………….....19

2.3 Ratio of Nikuradse equivalent grain roughness size and sediment size for open-channel flows (from Yen,1992, p.120) ……………..……60

4.1 General data for experiments KANK-1 MO-1, and MO-2………..132

4.2 General data for flume experiments in the literature considered in this research………………………………………………………....149

4.3 General data for field experiments conducted by Smith and McLean (1977) ……………………………………………….……150

4.4 General data for field experiments conducted by Kostaschuk and Villard (1996)……………………..…………………………...151

4.5 Predicted bedforms from selected methods in the literature……..…155

4.6 Data for experiment KANK-1……………………………….……..160

4.7 Data for experiment MO-1…………………………………………160

4.8 Data for experiment MO-2……………………………………….…161

4.9 Roughness estimates for KANK-1, MO-1, and MO-2…………..……179

4.10 Bottommost region roughness parameter estimated by the models of Smith and McLean (1977) and Nelson and Smith (1989A)…………………………………………………………..207

4.11 Mean velocities computed by the simplified velocity-defect model for the associated Coles wake parameter used in the model………..221

5.1 Shear stress partition values for the MO-1 and MO-2 data…………240

5.2 Grain-shear stress computed by the shear-partition methods of Einstein (1950) and Nelson-Smith (collectively from Smith and McLean, 1977; Wiberg and Nelson, 1992; and Nelson and others, 1993)…………………………………………..……….250

5.3 Form-shear stress computed by the shear partition methods of Einstein (1950) and Nelson-Smith (collectively from Smith and McLean, 1977; Wiberg and Nelson, 1992; and Nelson and others, 1993)……………………………………………………….250

5.4 Estimated drag coefficients………………………………………….251

LIST OF SYMBOLS

a_0	constant from the work of Smith and McLean (1977)
A	area
A	constant in the Garcia and Parker(1991) entrainment function = $1.3X10^{-7}$
A’	portion of the area attributable to grain shear
A”	portion of the area attributable to form shear
b	elevation above the bed for which a reference concentration is known
B	channel width
c	volumetric suspended-sediment concentration
c_b	concentration at elevation z = b above the bed
c_m	sediment discharge concentration of the flow (Vanoni (1975, p 85) defines it as “*the concentration which, when multiplied by the flow rate, will give the total sediment discharge of the flow*”)
C	Chezy’s roughness coefficient
C	constant of integration
C_1	constant =0.25 for Kennedy and Odgaard (1981) work
C_d	drag coefficient
C_f	frictional resistance coefficient used in $\tau_0 = \rho C_f U^2$
C_{fs}	frictional resistance coefficient attributable to grain resistance
C_n	proportionality constant
D	pipe diameter
D	sediment grain size
D_{50}	median grain size
D_{65},d_{65}	grain size in which 65% of the total sample is finer
D_{90}	grain size in which 90% of the total sample is finer
D_f	form drag
D_*	dimensionless sediment diameter---$R_{ep}^{2/3}$
Es	Entrainment rate of sediment into suspension
f	Darcy-Weisbach friction factor
f’	Darcy-Weisbach grain shear friction factor
f”	Darcy-Weisbach form drag friction factor
f_0	rigid-flat-bed Darcy-Weisbach friction factor $f_0 = 8 \Big/ \left\{6.25 + 2.5\ln\left(H \big/ 2.5D_{50}\right)\right\}^2$
Fr	Froude number---$\dfrac{U}{\sqrt{gH}}$
F_t	limiting Froude number for beginning of the transition regime-- $2.716\left(\dfrac{H}{D_{50}}\right)^{-0.25}$

F_u	limiting Froude number for beginning of upper regime-- $4.785\left(\frac{H}{D_{50}}\right)^{-0.27}$
H	depth of flow
<H>	spatially averaged reach-wise flow depth
H'	portion of the depth attributable to grain shear
H"	portion of the depth attributable to form drag
H_{cr}	depth at which incipient motion takes place
H_d	bedform height (i.e., dune or ripple height)
H_d/λ	bedform steepness
j	δ/H
K_n	Manning equation units parameter, K_n=1.0 for metric and 1.49 for English units
K	eddy viscosity (used in Smith and McLean (1977) derivation)
k	bedform wave number-- $2\pi/\lambda$ (Richards, 1980), Kennedy (1963)
k	dimensionless bedform wave number--- $2\pi H/\lambda$
k_s	equivalent roughness height of the grains
k_c	composite roughness height
k_n	Nikuradse roughness height (see Schlichting, 1979, p 620)
L_L	length of lee side of dune
L_s	length of stoss side of dune
L_L/L_s	dune (or bedform) symmetry ratio
n	Manning's roughness coefficient
N_*	$\frac{u_* D_{50}}{\nu}\frac{U}{\sqrt{gRD_{50}}}$
p	pressure; bed porosity
q	unit discharge
Q	water discharge
q_b	bedload
q_s	suspended-sediment load
R_h	hydraulic radius
R	submerged specific gravity--- $\frac{\rho_s - \rho}{\rho}$
R_h'	portion of the hydraulic radius attributable to grain shear
R_h"	portion of the hydraulic radius attributable to form shear
Re	Reynolds number--- UH/ν
Rep	$\frac{\sqrt{RgD}D}{\nu}$
Re_*	$\frac{u_* D_{50}}{\nu}$

R_g	$\frac{\sqrt{gD}D}{\nu}$
R_i	gradient Richardson number--- $\left[\frac{-(\rho_s-\rho)g}{\rho}\frac{\partial c}{\partial z}\right]\left(\frac{\partial u}{\partial z}\right)^{-2}$
R_{ig}	bulk flow Richardson number--- $\frac{gH(\rho_s-\rho)}{\langle\rho\rangle U_{\max}^2}$
S	water surface slope
S_0	bed slope
S_e	energy slope
T	transport stage parameter -- $\frac{u_*'^2-u_{*cr}^2}{u_{*cr}^2}$; water temperature
u	streamwise local mean velocity at a point
u'	streamwise velocity fluctuation
U	streamwise vertically averaged mean velocity
U_b	slip velocity
U_m	maximum velocity in a vertical
U_r	reference velocity for form drag closure
$\rho\overline{u'w'}$	Reynolds stress
u_*	bed shear velocity, $u_*=\sqrt{\frac{\tau_0}{\rho}}$
u_{*cr}	critical bed shear velocity
u'_*	bed grain shear velocity
u''_*	bed form shear velocity
u_{*T}	bulk (or reach-averaged) bed shear velocity computed from either 1) slope of the spatially averaged velocity profile, or 2) square root of the product of g, H, and S (in this report, method 1 is used unless otherwise noted)
u_{*L}	local bed shear velocity
$(u_*)_n$	shear velocity for region n (n is also taken to be the bottommost region)
v	transverse local mean velocity at a point
v'	transverse velocity fluctuation
ν_s or v_s	fall velocity (note the equation editor makes the symbol for v appear like the greek letter Nu (ν)
w	vertical local mean velocity at a point
w'	vertical velocity fluctuation
W_0	Coles wake coefficient
X	distance from the previous bedform crest
x	distance along the streamwise axis
y	distance from the water surface along the vertical axis
z	distance from the bed along the vertical axis
z_N	roughness length parameter computed from the work of Nikuradse
z_0	roughness length parameter

$(z_0)_n$	roughness length parameter for region n of the flow (n is also taken to be the bottommost region)
$(z_0)_{n+1}$	roughness length parameter for region n+1 of the flow
$(z_0)_1$	roughness length parameter of bottommost region
$(z_*)_{n,n+1}$	matching elevation between region n and n+1
z'	physical location of the boundary layer at which u=0 (Chen, 1991)
Z_R	Rouse number, $Z_R = \dfrac{v_s}{\kappa u_*}$
Zu	relation in the Garcia and Parker (1991) entrainment relation , $Z_u = \dfrac{u'_*}{v_s} R_{ep}^{0.6}$
α	constant, =5 for Kennedy and Odgaard (1981) work; ratio of eddy diffusivity of mass to that of momentum
α_0	constant of proportionality = 22.8
α_1	empirical constant ≈ 0.077 for the work of Smith and McLean (1989A)
β	constant of proportionality for the roughness parameter (equation 2.67)
β	constant in the Smith and McLean (1977) derivation
γ	unit weight of water
γ_D	$\left[\dfrac{\tau_{n+1}}{\tau_n}\right]^{1/2} = \left[1 + \dfrac{C_d}{2\kappa^2}\dfrac{H_d}{\lambda}\left(\ln\dfrac{H_d}{(z_0)_n} - 1\right)^2\right]^{1/2}$
δ_b	bedload-layer height
δ_L	laminar sublayer height
δ_v	height of the viscous sublayer ---≈ $11.6\,\nu/u_*$
δ	lag distance-- $\dfrac{\varepsilon U_b}{v_s^2}$, which is a phase shift between the local sediment transport rate and the local mean velocity
Δh_z	relative piezometric head
$\left(\dfrac{\Delta U}{u_*}\right)_S$	velocity profile difference due to the influence of suspended sediment (Coleman, 1986)
ε	dimensionless height =z/H; eddy viscosity
ε_e	Fedele and Garcia's (2001) equilibrium level
ε_s	equivalent sand grain diameter in the Moody diagram
η	proportionality constant; dune length coefficient (Julien and Klaassen, 1995)
ξ	proportionality constant
κ	von Karman's constant =0.41
λ	bedform wavelength or simply bedform length
μ_t	dynamic eddy viscosity
μ	dynamic viscosity
ρ	fluid density
$\langle\rho\rangle$	vertically averaged density

ρ_s	sediment density
θ	bed shear stress at the top of the dune (Fredsoe, 1982)
θ_S	angle between horizontal and stoss side of bedform
θ_L	angle between horizontal and lee side of bedform
τ	shear stress
τ_t	shear stress due to turbulence
τ_v	shear stress due to viscous effects
τ_s	bed shear stress attributable to grain (skin) shear stress
τ_f	bed shear stress attributable to form drag
τ_*	Shield's dimensionless shear stress-- $\frac{\tau_0}{\rho RgD}$
τ'_*	Shield's dimensionless grain shear stress-- $\frac{\tau'_0}{\rho RgD}$
τ'_0	bed shear stress attributable to grain shear (skin friction shear stress)
τ''_0	bed shear stress attributable to form drag (form shear stress)
τ_0	total shear stress
τ_n	grain shear stress in derivation of velocity models in Chapter 4
τ_{n+1}	total shear stress in derivation of velocity models in Chapter 4
τ_{cr}	critical shear stress
τ_v	turbulent shear stress
τ_v	viscous shear stress
ν	kinematic viscosity
ν_t	kinematic eddy viscosity
ξ	dune height coefficient (Julien and Klaassen, 1995)
ϕ	angle of friction of the bed material (sand ≈20˚ to 30˚)
Φ_b	dimensionless bedload sediment transport-- $\frac{q_b}{\sqrt{RgD^3}}$
Φ_s	dimensionless suspended-sediment transport-- $\frac{q_s}{\sqrt{RgD^3}}$
ψ'	$\frac{\rho_s - \rho}{\rho}\frac{D}{R'_h S_0}$