RIVER MECHANICS

SECOND EDITION

The second edition of Julien's textbook presents an analysis of rivers, from mountain streams to estuaries. The book is rooted in fundamental principles to promote sound engineering practice. State-of-the-art methods are presented to underline theory and engineering applications. River mechanics blends the dual concepts of water conveyance and sediment transport. Like the first edition, this textbook contains ample details on river equilibrium, river dynamics, bank stabilization, and river engineering. Complementary chapters also cover the physical and mathematical modeling of rivers. As well as being completely updated throughout, three new chapters have been added on watershed dynamics, hillslope stability, and stream restoration. Throughout the text, hundreds of examples, exercises, problems, and case studies assist the reader in learning the essential concepts of river engineering. The textbook is very well illustrated to enhance advanced student learning, while researchers and practitioners will find the book to be an invaluable reference.

Pierre Y. Julien is Professor of Civil and Environmental Engineering at Colorado State University. He has 35 years of professional engineering experience in the fields of hydraulics and river sedimentation. Julien has authored more than 500 scientific contributions, including two textbooks (the first edition of *River Mechanics*, and *Erosion and Sedimentation* (Cambridge University Press 2010, second edition)), 25 book chapters and manuals, 185 refereed journal articles, and 230 professional presentations and conference papers. He has delivered 20 keynote addresses and guided more than 130 graduate students to completion of their engineering degrees. He is the recipient of the Hans Albert Einstein Award of the American Society of Civil Engineers (ASCE), delivered the Hunter Rouse Lecture of the Environmental and Water Resources Institute (ASCE) in 2015, and is a former editor for the ASCE *Journal of Hydraulic Engineering*.

"This elegantly written book covers the major topics associated with water flow and sediment transport in rivers. It thoughtfully guides readers through descriptions and formulations of key physical processes, and offers many illustrations and worked examples to aid understanding. The book is a comprehensive companion to the author's book *Erosion and Sedimentation*, which focuses on alluvial sediment transport in rivers."
—Robert Ettema, *Colorado State University*

"As an engineering professional facing the challenges of sediment transport, I found the new edition of *River Mechanics* to be a great reference and a very useful resource. Its presentation of material has been substantially revised and expanded, including several new chapters. I especially liked the expanded treatment of watershed processes and new material on stream restoration. *River Mechanics* stands on its own and is even more useful in tandem with Pierre Julien's other book *Erosion and Sedimentation* as its companion. Having been familiar with the first edition from my days in graduate school, this new edition will undoubtedly prove to be an indispensable resource for students and practitioners alike."
—Mark Velleux, *HDR*

"A book in river engineering taking the interested reader from its sources to the estuary, painted with concise problem statements and solved by adequate engineering methods and techniques. Prof. Julien's second edition can be fully recommended to graduate students, researches and practicing engineers in the fields of river basins, river mechanics, river flows, river stability, river equilibrium, river models, and river restoration. Prof. Julien should be praised for his integral approach, his technical formulation and his updated presentation involving both problems in practice and exercises of the complicated topic."
—Willi Hager, *ETH Zurich*

"A rare must-read on modern river mechanics that covers the subject not only comprehensively and rigorously but also inspirationally. The author's philosophy 'from observations to physical understanding to mathematical modelling and numerical simulations' underpins every topic in the book, making it very clear and complete. Undoubtedly, this text will quickly become a benchmark source equally important to students, engineers and researchers. It will also be noteworthy to geoscientists and stream ecologists working at the borders between their disciplines and engineering. A genuine pleasure to read!"
—Vladimir Nikora FRSE, *University of Aberdeen*

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Dedicated to my deceased mother Yolande and my brother Michel

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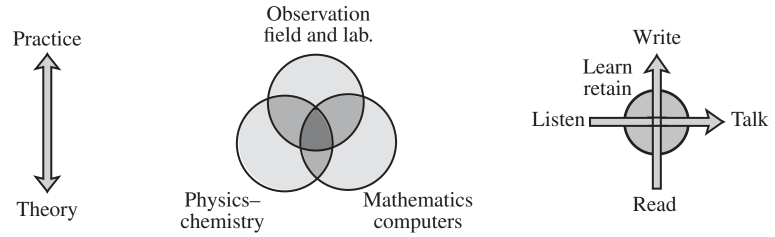
Preface

Water is essential to sustain life and rivers are truly fascinating. Most prosperous cities are located near river confluences and river engineers must design structures to draw benefits from the fluvial system for developing societies. Ideally, scientists should develop new methods to improve engineering design, while practitioners must understand why certain structures work and others fail. Fundamentally, river mechanics requires understanding of hydrodynamic forces governing the motion of water and sediment in complex river systems. Additionally, the fluvial network must seek equilibrium in its ability to carry water and transport sediment through dynamic river systems. Nowadays, river engineers are concerned not only about urban drainage, flood control, and water supply, but also about water quality, contamination, and aquatic habitat. This textbook broadens this perspective by integrating knowledge of climatology, hydrology, and geomorphology.

This textbook has been prepared for engineers and scientists developing a broad-based technical expertise in river mechanics. It has been specifically designed for graduate students, for scholars actively pursuing scientific research, and for practitioners keeping up with recent developments in river engineering. The prerequisites for reading it and making use of it are simply a basic knowledge of undergraduate fluid mechanics and of partial differential equations. The textbook *Erosion and Sedimentation* from Cambridge University Press serves as prerequisite material for the graduate course, River Mechanics, that I have taught at Colorado State University over the past three decades.

My teaching philosophy has been detailed in my recent Hunter Rouse lecture (Julien, 2017). Sketch I.1 illustrates the key points that I seek to develop among my graduate students and postdoctoral advisees.



Sketch I.1. Professional development in river engineering

First, the essential complementarity of theory and practice cannot be overemphasized. Theory can best enhance engineering applications when the fundamental understanding has been grounded in practical observations. Second, there is a need to develop three main poles, where observations from field and laboratories lead to physical understanding, prior to mathematical calculations. Expertise is developed by expanding the overlapping areas of these three poles. Finally, while the processes of listening and reading are essential to the ability to learn and retain new knowledge, my teaching emphasizes also the need to develop verbal and written communication skills. The ability to express dynamic thinking is a tremendous asset for any successful professional career.

Rather than being a voluminous encyclopedia, this textbook scrutinizes selected methods which meet pedagogical objectives. There is sufficient material for a 45-h graduate-level course. Beside basic theory and lecture material, the chapters of this book contain various exercises and problems, data sets and examples, computer problems, and case studies. They illustrate specific aspects of the profession from theoretical derivations, through exercises and problems, to practical solutions with the analysis of case studies. Most problems can be solved with a few algebraic equations; others require the use of computers. No specific computer code or language is required. Instead of promoting the use of commercial software packages, I stimulate students' creativity and originality in developing their own computer programs. Throughout the book, a solid diamond (♦) denotes equations and problems of particular significance; double diamond (♦♦) denotes the most important.

The book covers topics essentially from the mountains to the oceans:

Chapter 1 outlines the physical properties of water and sediment;
Chapter 2 reviews the governing equations of motion and sediment transport;
Chapter 3 describes river basins in terms of the source of water and sediment;
Chapter 4 looks at river basin dynamics;
Chapter 5 treats the steady-flow conditions in canals and rivers;

Chapter 6 delves into flood-wave propagation in rivers;
Chapter 7 introduces some numerical methods used to solve river engineering problems;
Chapter 8 copes with hillslope and riverbank stability;
Chapter 9 deals with riverbank protection measures;
Chapter 10 delineates the hydraulic geometry and equilibrium in alluvial rivers;
Chapter 11 explains the concepts of river dynamics and response;
Chapter 12 focuses on physical modeling techniques;
Chapter 13 provides essential knowledge on stream restoration;
Chapter 14 presents several river engineering techniques; and
Chapter 15 covers waves and tides in river estuaries.

My teaching has been greatly inspired by Drs. Marcel Frenette, Daryl B. Simons, Hunter Rouse, Yvon Ouellet, E. V. Richardson, Jean Louis Verrette, Steven R. Abt, Jose D. Salas, Richard Eykholt, HsiehWen Shen, Jim Ruff, Carl F. Nordin, Jean Rousselle, and Stan Schumm, as well as many others. They have greatly influenced my professional development and university teaching since 1979. I am also thankful to Drs. Phil Combs, Drew Baird, and Patrick O'Brien for sharing their practical expertise in river engineering. This book would not have been the same without contributions and suggestions from a couple of generations of graduate students at Colorado State University. They helped me tailor this textbook to meet their needs under the constraints of quality, concision, and affordability. Jean Parent patiently drafted all the figures. Finally, it has been a renewed pleasure to collaborate with Matt Lloyd, Esther Migueliz, and the Cambridge University Press production staff.

Notation

Symbols

a_x, a_y, a_z	Cartesian acceleration
a_r, a_θ, a_z	cylindrical accelerations
a	reference elevation
a	pier width
a_{cent}	centrifugal acceleration
a_{cor}	Coriolis acceleration
a_{i}	incremental cross-section area
a_{j-1}, a_{j+1}	upstream/downstream boundary coefficients of the Leonard scheme
a_t	partial watershed area
a_Θ	projection of the submerged weight into the embankment plane
$\bar{a}$	wave amplitude
a, b	coefficients of the resistance equation
a, b, $\hat{a}$, $\hat{b}$	transform coefficients for duration curves
A, B	coefficient and exponent of the sediment rating curve
A	surface area
A_a	error amplitude factor
A_{sb}	surface area of a settling basin
A_t	watershed drainage area
$\tilde{A}$, $\tilde{B}$	wave coefficients
b_r	river-bend coefficient
B	base channel width
BCF	bioconcentration factor
c	wave celerity
c^*	dimensionless celerity

c_G	group celerity
c_u	undrained cohesion
C	Chézy coefficient
C	sediment concentration
C_a	reference concentration
$\hat{C}$	cropping management factor
C_{fl}	Courant–Friedrichs–Lewy condition
C_k	grid dispersion number
C_{0i}	upstream sediment concentration
C_r	runoff coefficient
$C_u = u\Delta t/\Delta x$	Courant number
C_v, C_w, C_{ppm}, $C_{\mathrm{mg/l}}$	sediment concentration by volume, weight, parts per million, and milligrams per liter
d_{10}, d_{50}	particle size distribution, % finer by weight
d_m	effective riprap size
d_s	particle size
d_*	dimensionless particle diameter
D	pipe/culvert diameter
D	headcut height
D_d	degree-days
D_p	drop height of a grade-control structure
D_x	oxygen deficit
DO	dissolved oxygen content
e	void ratio
E	specific energy
E	gross erosion
E_{tons}	expected soil loss in tons
$\hat{E}$	soil loss per unit area
$\tilde{E}$	total energy of a wave
$E(\ )$	exceedance probability
ΔE	specific energy lost in a hydraulic jump
f	Darcy–Weisbach friction factor
f_l	Lacey silt factor
$f(t)$	infiltration rate
F	force
$\tilde{F}$	fetch length of wind waves
F_B	buoyancy force
F_c	centrifugal force
F_D	drag force

F_g	gravitational force
F_h	hydrodynamic force
F_i	inertial force
F_L	lift force
F_M	momentum force
F_p	pressure force
F_s	shear force in a bend
F_S	submerged weight of a particle
$F_{Vf} = V/\sqrt{gL_f}$	fish Froude number
F_w	weight of water
F_W	weight of a particle
$F(\ )$	nonexceedance probability
$F_n(z)$	standard normal distribution
$F(t)$	cumulative infiltration
$F_a(t)$	actual cumulative infiltration
$F_p(t)$	potential cumulative infiltration
Fr	Froude number
g	gravitational acceleration
G	specific gravity of sediment
Gr	gradation coefficient
G_u	universal gravitation constant
h	flow depth
h_c	critical flow depth
h_d	downstream flow depth
h_n	normal flow depth
h_p	pressure head at the wetting front
h_r	rainfall depth
h_s	cumulative snowmelt
h_t	tailwater depth
h_u	upstream flow depth
h_w	partial elevation drop on a watershed
Δh	local change in flow depth
H	Bernoulli sum
ΔH	energy loss over a meander wavelength
H_c	critical hillslope soil thickness
$H_o(\theta_m)$	Struve function
$\tilde{H}_s = 2\tilde{a}$	wave height
H_w	elevation drop on a watershed
i	rainfall intensity

i_b	riverbed infiltration rate
i_e	excess rainfall intensity
i_f	snowmelt rate
i_{30}	maximum 30-min rainfall intensity
j	space index
$J_0(\theta_m)$	zeroth-order Bessel function of the first kind
k	decay coefficient
k_0	resistance parameter for laminar overland flow
k_s	surface roughness
k_s'	grain roughness height
k_t	total resistance to laminar overland flow
$\tilde{k}$	wave number
K	saturated hydraulic conductivity
K	conveyance coefficient
$\hat{K}$	soil erodibility factor
K_1, K_2	coefficients of the pier scour equation
K_b	ratio of maximum shear stress in a bend to a straight channel
K_c	riprap coefficient
K_d	dispersion coefficient
$\mathrm{K_d}$	flood-wave diffusivity
$\mathrm{K_d}$	soil–water partition coefficient or ratio of sorbed to dissolved metals
$\overline{\mathrm{KE}}$	average kinetic energy per unit area
$K_G(T)$	frequency factor of the Gumbel distribution
K_{num}	numerical dispersion coefficient
K_{oc}	soil–water partition coefficient normalized to organic carbons
K_{ow}	octanol–water partition coefficient
K_p	plunging jet coefficient
$K_p(\gamma)$	frequency factor of the log-Pearson III distribution
K_S	ratio of the sediment volume
K_{sj}	submerged jet coefficient
$\Delta l = a/R$	mean annual migration rate
l_1 to l_4	moment arms
l_c, l_d	moment arms in radial stability of river bends
L	sinuous river length
L	field runoff length
L_a	abutment length

LC_{50}	lethal concentration resulting in 50% mortality
L_f	depth of the wetting front
L_0	normalized channel length
L_p	pier length
L_r	river length
L_r	length ratio
L_{sb}	settling-basin length
$\hat{L}$	slope-length factor
L_f	fish length
L_M	runoff-model grid-cell size
L_R	grid size of rainfall precipitation
L_S	correlation length of a storm
L_W	length scale of a watershed
L_Δ	length of arrested saline wedge
m	exponent of the resistance equation
m_E	mass of the Earth
m_M	mass of the Moon
m_s	sediment mass eroded from a single storm
M	mass
M	specific momentum
M	snowmelt rate
M_f	melt factor
M_1, M_2	first and second moments of a distribution
M, N	particle-stability coefficients
M/N	ratio of lift to drag moments of force
n	Manning coefficient n
$\vec{n}$	normal vector pointing outside of the control volume
$\tilde{n}$	wave number index
N	number of points per wavelength
N	number of storms
$N_0(\theta_m)$	Neumann function, or the zeroth-order Bessel Y function
$O(\ )$	order of an approximation
p	pressure
$p(\ )$	probability density function
p_{cl}	mean annual percentage lateral migration rate
p_0	porosity
p_{0e}	effective porosity

p_{0i}	initial water content
p_{0r}	residual water content
Δp_c	fraction of material coarser than d_{sc}
Δp_i	sediment size fraction
Δp_0	change in water content at the wetting front
P	wetted perimeter
$P(\,)$	probability
ΔP	power loss in a hydraulic jump
$\hat{P}$	conservation practice factor
$\tilde{P}$	total power of a wave
PCB	polychlorinated biphenyls
$\overline{\mathrm{PE}}$	average potential energy per unit surface area
P_0	power loss
P_Δ	grid Peclet number
q	unit discharge
q_{bv}	unit sediment discharge by volume
$q_{bv}^* = q_{bv}/\omega_0 d_s$	dimensionless unit sediment discharge
q_l	lateral unit discharge
q_m	maximum unit discharge
q_s	unit sediment discharge
q_{sj+1}, q_{sj}	upstream and downstream unit sediment discharge
q_t	total unit sediment discharge
Q	river discharge
Q_{bv}	bed sediment discharge by volume
Q_p	peak discharge
Q_s	sediment discharge
r	radial coordinate
r^*	dimensionless radius of curvature
r, θ, z	cylindrical coordinate system r lateral, θ downstream, and z upward
r_Q	discharge ratio
R	risk
R	radius of curvature of a river
$\hat{R}$	rainfall-erosivity factor
ΔR_e	excess rainfall
R_{E}	radius of the Earth
Re	Reynolds number
$\mathrm{Re}_* = u_* d_s/\nu$	grain shear Reynolds number
R_h	hydraulic radius

R_m	minimum radius of curvature of a channel
$Ro = \omega/\kappa u_*$	Rouse number
S	slope
$\hat{S}$	slope-steepness factor
S_D	specific degradation
S_{DR}	sediment delivery ratio
S_e	effective saturation
S_0, S_f, S_w	bed, friction, and water-surface slopes
S_{0x}, S_{0y}	bed-slope components in x and y
S_r, S_{wr}	radial water-surface slope
S_r^*	dimensionless radial slope
SF	safety factor
t	time
t	trapezoidal section parameter
Δt	time increment
Δt_s	time increment for sediment
t_a	cumulative time with positive air temperature
t_e	time to equilibrium
t_f	cumulative duration of snowmelt
t_f	fish swimming duration
t_r	rainfall duration
$t_r^* = t_r/\bar{t}_r$	normalized storm duration
t_t	transversal mixing time
t_v	vertical mixing time
T	period of return of extreme events
T	wave period
T°	temperature
T_{50}	time for half the channel-width change
T_E	trap efficiency
T_s	windstorm duration
u, v	velocity along a vertical profile
$\bar{u}$	average flow velocity
u_*	shear velocity
u_{*c}	critical shear velocity
U_f	fish swimming velocity
U_w	wind speed
v_h	migration rate of headcuts
v_s	local velocity against the stone
v_x, v_y, v_z	local velocity components

V	mean flow velocity
V_c	critical velocity
V_x, V_y, V_z	Cartesian mean flow velocities in x, y, and z
V_Δ	densimetric velocity
V_θ	downstream velocity in cylindrical coordinates
$\forall$	volume
$\forall_v, \forall_t$	volume of voids and total volume
W	channel width
W	weight of soil per unit width
W, W_0, W_e	active, initial and equilibrium channel width
W_m	meander width
W_0	overland plane width
x, y, z	coordinates usually x downstream, y lateral, and z upward
x_r, y_r, z_r	length ratios for hydraulic models
$X_{\max}$	downstream distance with the maximum oxygen deficit
Δx	grid spacing
X	runoff length
X_c	reach length
X_e	equilibrium runoff length
$X_{\max}$	maximum endurance fish swimming distance
y_d, y_u	downstream and upstream wave amplitude
Y	sediment yield
z_b	bed elevation
z_w	water-surface elevation
z^*	dimensionless depth
Δz	scour depth

Greek Symbols

α	coefficient of the stage–discharge relationship
α, β	parameters of the gamma distribution
α_b	deflection angle of barges
α_e	Coriolis energy correction factor
$\tilde{\alpha} = 2\pi/N$	phase angle
β	exponent of the stage–discharge relationship
β	bed particle-motion angle
β_m	momentum correction factor

γ	specific weight of water
γ	skewness coefficient
γ_m	specific weight of a water–sediment mixture
γ_{md}	dry specific weight of a water–sediment mixture
γ_s	specific weight of sediment
$\Gamma = \sqrt{1 + 4kK/U^2}$	dimensionless settling parameter
$\Gamma(x)$	gamma function
δ	angle between streamline and particle direction
$\delta_L = \ln(y_d/y_u)$	wave amplification over length L_0
ξ	ratio of exceedance probabilities
$\xi_r = W_r/h_r$	channel width–depth ratio
$\tilde{\xi}$	wave displacement in the x direction
η	sideslope stability number
$\tilde{\eta}$	wave surface elevation
$\zeta_{\tilde{n}}^k$	Fourier coefficients
κ	von Kármán constant
λ	streamline deviation angle
λ	wavelength
λ_f	snowmelt intensity
$\lambda_r = t_r/t_e$	hydrograph equilibrium number
λ_s	significant wavelength
Λ	meander wavelength
μ	dynamic viscosity of water
ν	kinematic viscosity of water
φ	angle of repose of bed material
ϕ	latitude
Φ	potential function for waves
ρ	mass density of water
ρ_m	mass density of a water–sediment mixture
ρ_{md}	dry mass density of a water–sediment mixture
ρ_s	mass density of sediment
ρ_{sea}	mass density of seawater
$\Delta\rho$	mass density difference
$\Pi = \ln[-\ln E(x)]$	double logarithm of exceedance probability
ω	settling velocity
ω_E	angular velocity of the Earth
Ω	sinuosity
Ω_R	ratio of centrifugal force to shear force in bends
θ	downstream orientation of channel flow

θ	angular coordinate
θ_c	critical angle of the failure plane
θ_j	jet angle measured from the horizontal
θ_m	maximum orientation of channel flow
θ_p	flow orientation angle against a pier
θ_r	raindrop angle
θ_0, Θ_0	downstream bed angle
Θ_1	sideslope angle
$\Theta = (t - t_r)/t_e$	dimensionless time
σ	stress components
σ	standard deviation
$\sigma = 2\pi L_0/\lambda$	dimensionless wave number
σ'	effective stress
σ_g	gradation coefficient
σ_x, σ_y, σ_z	normal stresses (negative pressure)
$\sigma_{\Delta t}$	standard deviation of dispersed material
σ_θ	normal stress on a plane at an angle θ from the principal stresses
$\tilde{\sigma}$	angular frequency of surface waves
τ	shear stress
τ_0, τ_b	bed shear stress
τ_{0x}, τ_{0y}	downstream and lateral bed shear stresses
τ_{bn}	bed shear stress at a normal depth
τ_c	critical shear stress
τ_f	failure shear strength of the soil
τ_r	radial shear stress
τ_r^*	dimensionless radial shear stress
τ_s	side shear stress
τ_{sc}	critical shear stress on a sideslope
τ_w	wind shear stress
τ_{zx}	shear stress in the x direction in a plane perpendicular to z
τ_*	Shields parameter
τ_{*c}	critical value of the Shields parameter
τ_θ	tangential stress on a plane at an angle θ from the principal stresses
$\psi = q/i_eL$	dimensionless discharge
Ψ	reduced variable

Superscripts and Diacritics

$\tilde{n}$	wave properties
$\hat{C}$	parameters of the universal soil-loss equation
$\bar{e}$	average value
h^k	time index k

Subscripts

a_r, a_θ	cylindrical coordinate components
a_x, a_z	Cartesian components
n_o, n_c	roughness values for overbank and main channel
τ_c	critical shear stress
h_{j+1}	space index at $j + 1$
L_m, Q_m	model value
L_p, Q_p	prototype value
L_r, Q_r	similitude scaling ratio
K_1, K_2, K_3	correction factors of the CSU scour equation
$W_{1/2}$, $h_{1/2}$, $S_{1/2}$	width, depth, and slope for half the discharge
t_{63}, X_{63}	time and distance scale for 63% of the sediment to deposit
ρ_m, γ_m	properties of a water–sediment mixture
ρ_{md}, γ_{md}	properties of a dry water–sediment mixture
ρ_s, γ_s	sediment properties