Essentials of Hydraulics

Written for a one-semester course in hydraulics, this concise textbook is rooted in the fundamental principles of fluid mechanics and aims to promote sound hydraulic engineering practice. Basic methods are presented to underline the theory and engineering applications, and examples and problems build in complexity as students work their way through the textbook. Abundant worked examples and calculations, real-world case studies and revision exercises, as well as precisely crafted end-of-chapter exercises, ensure students learn exactly what they need in order to consolidate their knowledge and progress in their career. Students learn to solve pipe networks, optimize pumping systems, design pumps and turbines, solve differential equations for gradually varied flow and unsteady flow, and gain knowledge of hydraulic structures such as spillways, gates, valves, and culverts. An essential textbook for intermediate to advanced undergraduate and graduate students in civil and environmental engineering.

Pierre Y. Julien is Professor of Civil and Environmental Engineering at Colorado State University. He has 40 years of experience in the fields of hydraulics, sedimentation, and river engineering. He has authored over 600 scientific contributions including two textbooks, 35 book chapters and manuals, 195 refereed articles, and over 250 conference papers and presentations. He has delivered 25 keynote addresses world-wide, taught 20 short courses, and has guided 40 Ph.D. and over 100 Master’s students to graduation. His other two textbooks are *Erosion and Sedimentation* (second edition, 2010, Cambridge University Press) and *River Mechanics* (second edition, 2018, Cambridge University Press).

"I was lucky to be Pierre's Ph.D. student at Colorado State University many years ago. I took several courses from him and was deeply influenced by his teaching style and methods. I am more than happy to see the publication of his *Essentials of Hydraulics* so that the rest of the world of civil engineering students have a chance to learn from this great teacher and scholar."
Junke Guo, University of Nebraska–Lincoln

"*Essential of Hydraulics* by Professor P. Y. Julien is an excellent and well-needed addition to the literature on hydraulic engineering. The textbook encompasses all subject areas of hydraulics with clarity, and provides an in-depth understanding of the theoretical aspects by using detailed step-by-step worked examples. In addition, the plethora of exercises and problems provide a solid pedagogical tool for mastering the material. The textbook is suitable for undergraduate and graduate students, but also for engineers practicing in the general area of hydraulics. Based on my 30 years of academic experience in hydraulic engineering, I fully appreciate and unequivocally endorse this textbook."
Panagiotis (Pete) D. Scarlatos, Florida Atlantic University

"This handily focused and lucidly written textbook presents the indispensable information needed for a course on civil engineering hydraulics. The textbook's author writes from his extensive experience teaching hydraulics, and draws on his considerable insights into the practical hydraulics issues often faced by civil engineers."
Robert Ettema, Colorado State University

"An excellent reference for a course in hydraulics covering fundamental principles in pipe flow, pumps, and open channel flow. With numerous examples, this textbook will support learning very effectively in an undergraduate course, or serve as review of hydraulics for a graduate course with exposure to more advanced topics."
Paola Passalacqua, University of Texas at Austin

"This is an excellent textbook for learning and teaching the fundamentals of hydraulics and their applications in the fields of civil and environmental engineering. The topics covered in the book are comprehensive. The examples of numerical calculation help undergraduate and graduate students to better understand the fundamental concepts, and the problems are well designed with different levels of challenge and importance."
Ming Ye, Florida State University

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Pierre Y. Julien
Colorado State University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University’s mission by disseminating knowledge in the pursuit of
education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/highereducation/isbn/9781316513095
DOI: 10.1017/9781108907446

First published 2022

Printed in the United Kingdom by TJ Books Limited, Padstow, Cornwall, 2022

A catalogue record for this publication is available from the British Library.

ISBN 978-1-316-51309-5 Hardback
ISBN 978-1-108-81630-4 Paperback

Additional resources for this publication at www.cambridge.org/julien-hydraulics

To my father Guy,
and
to all engineers working in developing countries

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Preface

Water sustains life and engineers supply drinking water to a growing world population. Meeting this daunting challenge requires a proper understanding of hydraulic engineering. Hydraulics is an integral part of the curriculum for all civil and environmental engineers. Water flows naturally in river systems and the propagation of large floods can be devastating. In controlling floods through dams and multiple hydraulic structures, engineers have developed techniques to generate hydropower and distribute water through open channels, culverts and pipe networks. The principles governing the motion of water include conservation of mass, momentum and energy, as well as resistance to flow. These governing equations constitute essential knowledge for the understanding of the motion of fluids in pipes and open channels. This textbook demonstrates the benefits of mastering these governing principles. Fundamentally, hydraulic engineering requires an understanding of hydrodynamic forces governing the motion of water in closed conduits and open channels. Engineers apply these fundamental concepts to meet the practical needs of society. These needs include flood control, water distribution systems for agriculture and water supply, hydropower production and sustainable development of water resources.

This textbook prepares engineers through understanding fundamental concepts and problem solving. 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. Rather than a voluminous encyclopedia, this textbook scrutinizes selected and proven methods meeting pedagogical objectives. The prerequisites required of the reader include basic knowledge of engineering dynamics, fluid mechanics and differential equations. Besides basic theory and lecture material, the chapters of this book contain numerous examples and solved problems, several data sets, computer problems and case studies. They illustrate specific aspects of the profession from theoretical derivations to practical solutions with the analysis of typical problems. The key to successfully mastering the material from this book is to solve problems. Most problems can be solved with algebraic equations while a few require the use of computers. No specific computer code or language is required. Instead of promoting the use of commercial software packages, student creativity and originality is stimulated by developing their own spreadsheets and computer programs. Throughout the book, a solid diamond (♦) denotes examples and problems of particular significance, double diamond (♦♦) denotes the most important and/or difficult.

This textbook proceeds from closed conduits to open channels as follows:
Chapter 1 describes the physical properties of water and hydrostatics;
Chapter 2 reviews the motion of water in pipes;
Chapter 3 derives the governing equations describing the motion of water;
Chapter 4 guides the design of pumping systems;
Chapter 5 treats the topic of hydropower generation from turbines;

Chapter 6 delves into the compressibility effects of water in pipes;
Chapter 7 presents fundamental methods for unsteady flow in pipes;
Chapter 8 focuses on steady open-channel flow;
Chapter 9 deals with rapidly varied open-channel flow;
Chapter 10 delineates backwater curves and gradually varied open-channel flows;
Chapter 11 broaches the advanced topic of unsteady flow in open channels;
Chapter 12 copes with more complex flows through culverts;
Chapter 13 introduces different types of spillways and gates;
Chapter 14 outlines broad-based concepts in hydrology;
Chapter 15 summarizes the fundamentals of geohydrology; and
Chapter 16 covers essential knowledge of groundwater.

There is more than sufficient material for a 45-hour undergraduate-level course. On a three-hour per week basis, the core material can be subdivided into four parts (four weeks each) with the possibility for monthly mid-term exams. The first part covers hydrostatics and flow in pipes (Chapters 1–3). The unique aspect of this section is to solve pipe networks. The second part focuses on hydro-machinery with pumps and turbines (Chapters 4–6). The unique skill being developed is the optimization of a pipe and pump system. The third part covers open-channel flows (Chapters 8–10). This section uniquely presents methods to obtain synthetic knowledge and analytical solutions, besides the numerical solution of differential equations for backwater profiles. The last section deals with hydraulic structures (Chapters 12–13). This shorter and more descriptive section leads to a comprehensive final exam. One unique aspect of this last section is to introduce practical engineering issues and professional ethics. The end of the semester is also convenient for broader guest lectures from practitioners.

Graduate and honor students will gain advanced knowledge of unsteady flow in pipes (Chapter 7) and in open channels (Chapter 11). In preparation for graduate studies, additional knowledge of hydraulics is provided along complementary concepts in hydrology (Chapter 14), geohydrology (Chapter 15) and groundwater (Chapter 16). All these chapters can support teaching in a quarter system. My preference for presenting pipes before open channels is rooted in the fact that pipes have constant cross sections which makes the geometry simpler to handle. It is also possible to reverse the teaching order and follow the sequence: hydrology, open channels, pipes and hydro-machinery.

This book benefitted from my teaching experience at university level since the late 1970s. The suggestions of a couple of generations of undergraduate students helped tailor the content to meet their needs under the constraints of quality, concision and affordability. I am grateful to Drs. Jai Hong Lee, Joon Hak Lee and Seong Joon Byeon who helped me prepare earlier versions of lecture notes for the students of hydraulic engineering at Colorado State University. Jean Parent deserves all the credit for patiently drafting all the figures. It has been a renewed pleasure to collaborate with Matt Lloyd, Jane Adams, Rachel Norridge, Zoë Lewin and the Cambridge University Press production staff.

Notation

Symbols

a	acceleration
a_x, a_y, a_z	Cartesian acceleration
a_s	seismic acceleration
A	surface area
A	activity of a clay
A_T	surge tank area
A_t	watershed drainage area
B	(base) channel width
B	wicket-gate height, turbine-blade height
c	wave celerity
c	damping coefficient
c'	wave celerity in an elastic pipe
c_v	consolidation coefficient
C	resistance coefficient
C, C_D	discharge coefficient
C	runoff coefficient
C_c	orifice coefficient
C_C	consolidation coefficient
C_g	volumetric gas concentration in water
C_G	Venturi geometric coefficient
C_H, C_Q	pump head and discharge dimensionless parameters
C_s	seismic coefficient
C_v	coefficient of variation
C_V	Venturi coefficient
C_Δ	triangular weir discharge coefficient
$C_\$$	cost function
CMP	corrugated metal pipe
d, w	opening height of a Tainter gate
d_{10}, d_{50}	particle size distribution, % finer by weight
d_s	particle size
D, d	pipe/culvert diameter
D	scour depth below a flip-bucket spillway

D_1, D_2	upstream and downstream flow depths of a stilling basin
DC	downstream control
e, e_m, e_p	efficiency of pumps
e	pipe thickness
e	void ratio
E	specific energy
E_w	water modulus of elasticity
E_p	pipe modulus of elasticity
EGL	energy grade line, EGL $=$ HGL $+ V^2/2g$
ΔE	elevation gain for pumps
ΔE	specific energy lost in a hydraulic jump
f	Darcy–Weisbach friction factor
f_d, f_n	damped and natural frequency of oscillations
F	force
F	network frequency
F	future value
F_h	hydrostatic force
F_H, F_V, W	horizontal, vertical and weight forces
Fr	Froude number
g	gravitational acceleration
G	specific gravity of sediment
h	flow depth
Δh	flow depth increment
h_b	block height of baffled chutes
h_c	critical flow depth
h_c	capillary rise
h_d, h_u	downstream and upstream flow depths
h_f	friction loss in pipes
h_n	normal flow depth
h_t	tailwater depth
h_v	vapor head
h_1 *to* h_4	various sizes of stilling basins

Δh	local change in flow depth
H	Bernoulli sum, or flow depth
H_D	design head of a spillway
H_0, H_a	initial and added pressure head
HDPE	high-density polyethylene
HGL	hydraulic grade line, also piezometric line
ΔH	energy loss
i, i_r	rainfall intensity
i	annual interest rate
i	gradient of the groundwater surface
i_b	riverbed infiltration rate
i_c	critical groundwater gradient for boiling sands
$\bar{I}$	area moment of inertia about the center of gravity
I_0	area moment of inertia about axis 0
k	pipe conveyance coefficient ($h_f = k\ Q^2$)
k	open-channel conveyance coefficient ($Q = k\ S_f^{1/2}$)
k	constant of a spring–mass system
k	number of occurrences
k	intrinsic permeability coefficient
k_1, h_1/D	culvert inlet control parameters
k_s, ε	surface roughness
K	pipe loss coefficient ($h_f = K\ V^2/2g$)
K	conveyance coefficient
K	permeability coefficient
K	flood diffusion (dispersion) coefficient
K	saturated hydraulic conductivity ($V = K\ i$)
K_b	pipe bend coefficient
K_C	pipe contraction coefficient
K_e	pipe or culvert entrance coefficient
K_E	pipe expansion coefficient
K_f, K_f'	ratio of horizontal to vertical normal stresses
$K_G(T)$	frequency factor of the Gumbel distribution
L	pipe, spillway or weir length
L_e	equivalent pipe length for minor losses
L_F	loading factor for pipe trenches
L_j	length of hydraulic jump
L_{II}, L_{III}, L_{IV}	lengths of stilling basins
L_r	river length
LL	liquid limit
m	Manning equation unit coefficient ($m = 1.49$ in customary units, $m = 1$ in SI units)
M, m	mass
M_s, M_w, M_t	mass of solids, water and total
M	specific momentum
M_0	moment of force about 0
n	Manning roughness coefficient
n	porosity of a soil
n	number of independent trials
n	number of years
N	rotational speed
N	dimensionless parameter in Allievi's formula
N	normal force
N	number of years in a sample
N_p, N_s	number of potential and streamlines
N_{rpm}	number of rotations per minute
N_s	specific speed of a pump, or turbine
N_{sq}	specific speed for turbines in SI units
NPSH	net positive suction head
p	pressure
p_{atm}	atmospheric pressure
p_{rel}	relative pressure
p_{abs}	absolute pressure
p	probability of occurrence
p, q	average and half-difference soil pressure
p_0	number of poles in a generator
p_0	porosity
p_v	vapor pressure
P	power
P	wetted perimeter
P	present value
P	flow depth at the spillway crest
P_k	binomial probability distribution
P_{kW}, P_{hp}	power in kilowatt and horsepower
PI	plasticity index
PL	plastic limit

P	probability
Δp	pressure increase from a water hammer
ΔP	power loss in a hydraulic jump
q	unit discharge
q_l	lateral inflow unit discharge
Q	discharge
Q_{gpm}, Q_{cfs}, Q_{cms}	discharge in gallons per minute, ft^3/s and m^3/s
r, R	radius
R	reaction force
R	manometer reading
R	hydrologic risk
R	repeated uniform annual amount
Re	Reynolds number
R_h	hydraulic radius
RCP	reinforced concrete pipe
s_u	subsidence
S	slope
S	surge-tank water elevation
S	degree of saturation
S_F	safety factor
S_0, S_f, S_w	bed, friction and water-surface slope
S_y	specific yield of an aquifer
S_{XY}	sign of pipe flow (+ clockwise from X to Y)
S_3	three-edge pipe-bearing strength
t	time
t	trapezoidal section parameter (H:V)
Δt, Δx	time and space increment
t_C	time of pipe closure
t_e	watershed time to equilibrium
t_r	rainfall duration
T	torque
T	tension, and surface tension
T	surge-tank oscillation period
T	period of return of extreme events

T	trench width
T	transmissivity of an aquifer
T	dimensionless consolidation time
T°	temperature
T_n, T_d	natural and damped period of oscillations
u	pore pressure in a soil
U, $U_{\%}$	consolidation percentage
UC	upstream control
v_p	plate velocity
v_x, v_y	local velocity components
V	mean flow velocity
V_r, V_t	radial and tangential velocity
$\forall$	volume
$\forall_v$, $\forall_t$	volume of voids and total volume
w, d	opening height of a Tainter gate
w	water content of a soil
W	channel surface width
W	weight
W_T	throat width of a Parshall flume
$W(u)$	Theis integral
x, y, z	coordinates usually x downstream, y lateral, and z upward
x, y	coordinates of an ogee spillway
x_b	flip-bucket launching distance
Δx, Δy, Δz	infinitesimal fluid element
Δx, Δy	infinitesimal distance and flow depth in backwater calculations
X_{max}	maximum elevation without cavitation
y	open-channel flow depth
y_b	flip-bucket launching height
y_c	critical flow depth
y_{cp}	center of pressure
y_n	normal flow depth
z_b	bed elevation
z_{max}	maximum successive flow oscillations
z_t	turbine elevation above the tailrace

Greek Symbols

α	angle of failure in the p-q diagram
α	flip bucket launching angle
α, β	coefficient and exponent of the stage discharge relationship
α_s	ratio of seismic acceleration to gravity
β	turbine-blade angle
γ	specific weight of water
ε	surface roughness
θ	angular coordinate
ζ	dimensionless damping coefficient
$\kappa - \varepsilon, \kappa - \omega$	turbulence models
μ	dynamic viscosity of water
υ	kinematic viscosity of water
ξ, η	orthogonal functions for potential and streamlines in groundwater
ρ, ρ_w	mass density of water
ρ_d	dry mass density of a water–sediment mixture
ρ_g	mass density of gas or air
ρ_m, ρ_t	total mass density of a water–sediment mixture
ρ_s	mass density of solid
ρ_{sat}	mass density of a saturated soil
σ	turbine cavitation index
σ	standard deviation
σ	applied stresses in a soil
σ'	effective stress in a soil
σ_g	gradation coefficient
σ_p	pipe tension
ϕ	turbine speed ratio
ϕ	dimensionless turbulent flow oscillations
ϕ, ϕ'	internal friction angle, and effective internal friction angle
ϕ, φ	groundwater potential and streamlines
φ	oscillation phase angle
τ, σ	tangential and normal shear stresses
ω	turbine (angular) rotational speed
ω_n, ω_d	natural and damped circular frequency of oscillations
$\Omega = 1 - \mathrm{Fr}^2$	coefficient of the diffusive-wave equation

Superscripts and Diacriticals

$\bar{e}$	average value
$x, \dot{x}$ *and* $\ddot{x}$.	position, velocity and acceleration, e.g. spring–mass system
$\forall$	volume

Subscripts

a_x, a_y, a_z	Cartesian components
y_n, y_c	normal and critical flow depths
ρ_s, γ_s	solid properties