

PRINCIPLES OF FLUID FLOW
AND
SURFACE WAVES
IN
RIVERS, ESTUARIES, SEAS AND OCEANS
(Edition 2011)

Leo C. van Rijn



Universiteit Utrecht

Physical Geography



Other publications:

Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas by Leo C. van Rijn, 1993 and 2006 (update)

*Principles of Coastal Morphology,
by Leo C. van Rijn, 1998*

*Principles of Sedimentation and Erosion Engineering in Rivers, Estuaries and Coastal Seas
by Leo C. van Rijn, 2005*

Manual Sediment Transport Measurements in Rivers, Estuaries and Coastal Seas by Leo C. van Rijn, 2007 (update)

**Aqua Publications
The Netherlands
(WWW.AQUAPUBLICATIONS.NL)**

PRINCIPLES OF FLUID FLOW
AND
SURFACE WAVES
IN
RIVERS, ESTUARIES, SEAS AND OCEANS
(Edition 2011)

Leo C. van Rijn

Professor Fluid Mechanics and Sediment Transport
University of Utrecht, The Netherlands (1987-2011)

Senior Hydraulic Engineer, Deltares/Delft Hydraulics
Delft, The Netherlands (1975-2011)



AQUA PUBLICATIONS

Published in The Netherlands

- first published 1990 (Bound Edition)

- last update 2011 (Bound Edition)

Aqua Publications

The Netherlands

(WWW.AQUAPUBLICATIONS.NL)

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG, THE NETHERLANDS

Rijn, Leo C. van

Principles of fluid flow and surface waves in rivers, estuaries, seas and oceans

Author: Leo C. van Rijn

Publisher: Aqua Publications (www.aquapublications.nl)

ISBN: 978-90-79755-02-8

NUR: 929, mechanics

Subject headings: Fluid mechanics

Photographs Cover

Yangtze river, China

Egmond coast, The Netherlands

Ocean wave, Hawaii

Copyright 2011 by Aqua Publications

All rights reserved. No part of this publication may be reproduced in any form or by any means without the prior written permission of the publisher.

FOR THOSE WHO LIKE WATER

**PRINCIPLES OF FLUID FLOW AND SURFACE WAVES
IN RIVERS, ESTUARIES, SEAS AND OCEANS**

LIST OF CONTENTS

1. INTRODUCTION	Page
1.1 Historical background.....	1.1
1.2 Definitions.....	1.6
1.3 Types of flow.....	1.7
1.4 Symbols and units.....	1.8
2. FLUID PROPERTIES	Page
2.1 Introduction.....	2.1
2.2 Density.....	2.1
2.3 Viscosity.....	2.2
2.4 Compressibility or elasticity.....	2.4
2.5 Surface tension.....	2.4
2.6 Examples and problems.....	2.8
3. FLUID STATICS	Page
3.1 Introduction.....	3.1
3.2 Isotropy.....	3.1
3.3 Hydrostatic pressure.....	3.2
3.4 Curved surfaces.....	3.6
3.5 Buoyancy.....	3.6
3.6 Examples and problems.....	3.7
4. FLUID KINEMATICS	Page
4.1 Introduction.....	4.1
4.2 Streamlines and streamtubes.....	4.1
4.3 Stream function.....	4.3
4.4 Accelerations.....	4.5
4.5 Deformations.....	4.8
4.6 Vorticity.....	4.10

5. FLUID DYNAMICS	Page
5.1 Introduction.....	5.1
5.2 Equation of continuity (mass balance).....	5.2
5.3 Momentum balance.....	5.6
5.3.1 Second law of Newton.....	5.6
5.3.2 Momentum and energy passing a section.....	5.6
5.3.3 Application of momentum balance.....	5.9
5.4 Equations of motion.....	5.11
5.4.1 Forces on fluid elements.....	5.11
5.4.2 Euler equations.....	5.12
5.4.3 Bernoulli equation.....	5.13
5.4.4 Navier-Stokes equations.....	5.25
5.4.5 Reynolds equations.....	5.26
5.5 Subcritical and supercritical flow.....	5.33
5.5.1 Propagation velocity of an elementary wave.....	5.33
5.5.2 Critical flow and critical depth.....	5.34
5.6 Work and power.....	5.37
5.7 Examples and problems.....	5.39

6. STEADY UNIFORM FLOW	Page
6.1 Introduction.....	6.1
6.2 Fluid forces and shear stresses.....	6.2
6.3 Velocity distribution in laminar boundary layer.....	6.3
6.3.1 Introduction.....	6.3
6.3.2 Velocity profile in laminar flow.....	6.4
6.4 Velocity distributions in turbulent boundary layer.....	6.4
6.4.1 Smooth and rough bottoms.....	6.4
6.4.2 Turbulent logarithmic sublayer.....	6.7
6.4.3 Viscous sublayer.....	6.10
6.4.4 Transition sublayer.....	6.10
6.4.5 Outer sublayer.....	6.11
6.4.6 General velocity distribution for smooth and rough flow.....	6.12
6.4.7 Velocity distribution in transverse direction (secondary flow).....	6.15
6.5 Flow resistance formulae.....	6.16
6.5.1 Chézy formula.....	6.16
6.5.2 Chézy-coefficient.....	6.16
6.5.3 Manning formula.....	6.19
6.5.4 Flow resistance of trapezoidal channels.....	6.21
6.5.5 Flow resistance of compound channels.....	6.31
6.5.6 Flow resistance in pipes.....	6.43
6.6 Secondary flow.....	6.47
6.7 Examples and problems.....	6.52
6.8 References.....	6.62

7. STEADY NON-UNIFORM FLOW

Page

7.1 Introduction.....	7.1
7.2 Potential flow.....	7.1
7.2.1 Introduction.....	7.1
7.2.2 Two-dimensional potential flow.....	7.1
7.2.3 Flow nets.....	7.3
7.2.4 Application: Potential flow through a duct.....	7.4
7.3 Gradually varied turbulent flow.....	7.6
7.3.1 Introduction.....	7.6
7.3.2 Bélanger equation.....	7.6
7.3.3 Classification of water surface curves.....	7.8
7.3.4 Analytical computation of water surface curves.....	7.17
7.3.5 Numerical computation of water surface curves.....	7.21
7.4 Rapidly varied turbulent flow.....	7.24
7.4.1 Introduction.....	7.24
7.4.2 Carnot equation for decelerated flow.....	7.25
7.4.3 Hydraulic jump.....	7.26
7.4.4 Flow in a duct.....	7.29
7.4.5 Broad-crested weir.....	7.30
7.4.6 Narrow-crested weir.....	7.32
7.4.7 Sharp-crested weir.....	7.32
7.4.8 Under-water opening.....	7.33
7.4.9 Curved accelerating flow.....	7.34
7.4.10 Free overfall.....	7.40
7.4.11 Velocity profiles in rapidly varied flow.....	7.47
7.5 Flow over a channel.....	7.49
7.5.1 Channel parallel to current.....	7.49
7.5.2 Channel perpendicular to current.....	7.50
7.5.3 Channel oblique to current.....	7.52
7.6 Curved flow in river bends.....	7.57
7.7 Fluid forces on a body.....	7.61
7.7.1 Introduction.....	7.61
7.7.2 Drag force.....	7.62
7.7.3 Lift force.....	7.64
7.8 Examples and problems.....	7.65
7.9 References.....	7.77

8. NON-STEADY FLOW: LONG FREE SURFACE WAVES	Page
8.1 Introduction.....	8.1
8.2 Basic equations.....	8.3
8.2.1 Equations of continuity and motion.....	8.3
8.2.2 Scale analysis.....	8.8
8.2.3 Character of long waves.....	8.9
8.2.4 Eulerian or Lagrangian approach.....	8.10
8.3 Progressive wave.....	8.12
8.3.1 Basic equation.....	8.12
8.3.2 Phenomena affecting wave propagation.....	8.19
8.4 Standing wave.....	8.25
8.4.1 Open basin.....	8.25
8.4.2 Closed basin.....	8.28
8.5 Translation waves.....	8.30
8.6 River flood waves.....	8.35
8.6.1 Dynamic wave model.....	8.35
8.6.2 Diffusive wave model.....	8.36
8.6.3 Kinematic wave model.....	8.39
8.6.4 Discharge-water depth relationship.....	8.42
8.7 Tidal wave generation.....	8.43
8.7.1 Introduction.....	8.43
8.7.2 Tide generating forces.....	8.44
8.7.3 Tidal analysis and prediction.....	8.49
8.7.4 Tidal constituents and classification.....	8.51
8.7.5 Coriolis force.....	8.53
8.8 Tides in oceans and coastal seas.....	8.56
8.8.1 Basic equations.....	8.56
8.8.2 Kelvin waves.....	8.57
8.8.3 Enclosed seas.....	8.60
8.8.4 Coastal shelf seas.....	8.62
8.9 Tides in estuaries.....	8.73
8.9.1 Definitions and characteristics.....	8.73
8.9.2 Analytical solution of energy flux equation for prismatic and converging channels.....	8.89
8.9.3 Analytical solution of tidal wave equations in prismatic channel (constant width and depth).....	8.97
8.9.4 Analytical solution of tidal wave equations in converging channel (constant depth).....	8.111
8.9.5 Numerical and analytical solution of tidal wave equations in prismatic and converging channels.....	8.128
8.9.6 Non-linear effects and tidal asymmetry.....	8.153
8.10 Density-induced flow in estuaries and along coasts.....	8.168
8.10.1 Types of stratifications.....	8.168
8.10.2 Basic equations.....	8.171
8.10.3 Salinity intrusion in tideless channels (arrested salt wedge).....	8.183
8.10.4 General characteristics and basic equations of salinity distributions in tidal conditions.....	8.184
8.10.5 Salinity distribution and salt intrusion in prismatic tidal channels.....	8.198
8.10.6 Salinity distribution and salt intrusion in converging tidal channels.....	8.210
8.10.7 Computed salinity distributions in prismatic and converging tidal channels.....	8.215
8.10.8 Exchange currents.....	8.219
8.10.9 Internal long waves in coastal seas.....	8.226
8.10.10 Influence of fresh river discharge on coastal flows.....	8.227

8. NON-STEADY FLOW: LONG FREE SURFACE WAVES (continued) **Page**

8.11 Wind-induced currents and storm surge in seas and oceans.....	8.229
8.11.1 Wind-induced currents.....	8.229
8.11.2 Water level rise by onshore wind (storm surge).....	8.232
8.11.3 Wind-induced velocities and water level variations by longshore wind.....	8.235
8.11.4 Water level variations by oblique wind.....	8.243
8.11.5 Upwelling and downwelling near coast.....	8.243
8.11.6 Ocean circulation.....	8.244
8.12 References.....	8.246

9. NON-STEADY FLOW: SHORT FREE SURFACE WAVES **Page**

9.1 Introduction.....	9.1
9.2 Linear and non-linear wave theory.....	9.3
9.2.1 Bernoulli equation for unsteady flow.....	9.3
9.2.2 Linear small amplitude wave theory.....	9.4
9.3 Linear wave properties.....	9.8
9.3.1 Introduction.....	9.8
9.3.2 Dispersion relationship.....	9.9
9.3.3 Fluid particle velocities.....	9.16
9.3.4 Fluid particle displacements.....	9.20
9.3.5 Fluid pressure.....	9.21
9.3.6 Standing waves.....	9.23
9.4 Non-linear waves.....	9.24
9.4.1 Non-linear small amplitude wave theory.....	9.24
9.4.2 Non-linear effects: mass transport in non-breaking waves.....	9.39
9.5 Irregular waves (random waves).....	9.47
9.5.1 Introduction.....	9.47
9.5.2 Characteristic wave parameters.....	9.47
9.5.3 Rayleigh wave height distribution.....	9.48
9.5.4 Wave spectra.....	9.52
9.5.5 Wave measurements.....	9.59
9.5.6 Dominant wave height and direction.....	9.59
9.5.7 Example irregular waves.....	9.61
9.6 Wave boundary layer dynamics.....	9.62
9.6.1 Definitions.....	9.62
9.6.2 Velocity and shear-stress distribution in oscillatory flow.....	9.64
9.6.3 Bed-shear stress and friction in oscillatory flow.....	9.74
9.6.4 Wave energy dissipation in oscillatory flow.....	9.80
9.6.5 Wave current interaction.....	9.81
9.6.6 Bed-shear stress in combined current and waves.....	9.89
9.7 Wave energy and energy transfer (based on linear wave theory).....	9.94
9.7.1 Potential and kinetic energy.....	9.94
9.7.2 Energy transfer and flux.....	9.95
9.7.3 Wave group velocity.....	9.96
9.7.4 Wave front velocity.....	9.98
9.8 Wave reflection.....	9.100
9.9 Wave shoaling.....	9.102
9.9.1 Energy flux balance.....	9.102
9.9.2 Influence of bottom friction.....	9.104
9.9.3 Influence of currents.....	9.106

9. NON-STEADY FLOW: SHORT FREE SURFACE WAVES (continued)	Page
9.10 Wave refraction.....	9.108
9.10.1 Definitions.....	9.108
9.10.2 Constant wave period.....	9.109
9.10.3 Refraction equation and energy flux equation.....	9.109
9.10.4 Depth contours parallel to straight coastline.....	9.111
9.10.5 Gradually varying depth contours.....	9.114
9.10.6 Wave trapping.....	9.116
9.11 Wave diffraction.....	9.117
9.11.1 Wave diffraction processes.....	9.117
9.11.2 Long-crested monochromatic waves.....	9.118
9.11.3 Multi-directional waves.....	9.123
9.12 Wave breaking.....	9.130
9.12.1 Limiting steepness.....	9.130
9.12.2 Limiting wave height on a horizontal bed.....	9.130
9.12.3 Limiting wave height on a sloping bed.....	9.131
9.12.4 Energy dissipation by a breaking wave.....	9.144
9.12.5 Water depth at breaker line.....	9.147
9.12.6 Wave run-up in the swash zone.....	9.148
9.13 Wave-induced water level variations (set down and set up).....	9.157
9.13.1 Introduction.....	9.157
9.13.2 Radiation stress.....	9.157
9.13.3 Wave set-down in non-breaking waves.....	9.165
9.13.4 Wave set-up in breaking waves.....	9.167
9.14 Wave-induced cross-shore currents.....	9.169
9.14.1 Basic processes.....	9.169
9.14.2 Mean flows (Eulerian streaming) in shoaling waves over a horizontal bottom.....	9.169
9.14.3 Mean flows (Eulerian streaming) in shoaling waves over a sloping bottom.....	9.191
9.14.4 Mean flows in breaking waves over a sloping bottom.....	9.195
9.15 Wave-induced longshore currents.....	9.213
9.15.1 Basic processes.....	9.213
9.15.2 Outside the breaker zone.....	9.213
9.15.3 Inside the breaker zone.....	9.214
9.15.4 Effects of breaker bars in surf zone on longshore and cross-shore currents.....	9.222
9.16 Low frequency waves.....	9.235
9.16.1 Low-frequency processes.....	9.235
9.16.2 Bound long waves.....	9.236
9.16.3 Surf beat.....	9.238
9.16.4 Edge waves.....	9.239
9.16.5 Experimental data.....	9.242
9.17 Wave models.....	9.243
9.17.1 Basic equations.....	9.243
9.17.2 One-dimensional cross-shore models.....	9.245
9.17.3 Two-dimensional models for combined refraction, diffraction, shoaling and dissipation.....	9.256
9.17.4 Two-dimensional models for combined refraction, shoaling and dissipation.....	9.260
9.17.5 Wave growth models.....	9.266
9.18 References.....	9.268

APPENDICES

APPENDIX A: BASIC FORMULAE		Page
A1	Basics	A1
A2	River flow.....	A1
A3	Long surface waves.....	A2
A4	Short surface waves.....	A3
APPENDIX B: MATHEMATICS IN FLUID MECHANICS		Page
B1	Notation	B1
B2	Functions.....	B2
B3	Derivatives and differentiation.....	B7
B4	Scalars and vectors.....	B11
B5	Integration.....	B14
B6	Numerical integration.....	B16
B7	Power series.....	B17
B8	Linear systems and matrices.....	B18
B9	Complex numbers.....	B19
B10	Differential equations.....	B26
B11	Equations of motion and rotation.....	B39
B12	Propagation of errors.....	B40
B13	Curvature.....	B41
APPENDIX C: TURBULENCE		Page
C1	Characterization of turbulence.....	C1
C2	Origin of turbulence.....	C1
C3	Types of turbulence.....	C1
C4	Turbulence intensity and energy.....	C2
C5	Turbulence length scales.....	C3
C6	Structure of turbulent boundary layers.....	C4
C7	Turbulent stresses and its modelling.....	C5
APPENDIX D: METHOD OF CHARACTERISTICS		Page
D1	Equations.....	D1
D2	Numerical approach.....	D3
D3	Graphical approach.....	D3
APPENDIX E: ANALYTICAL SOLUTION METHOD FOR LINEARIZED FLOW EQUATIONS		Page
E1	Prismatic channels.....	E1
E2	Converging channels.....	E9
APPENDIX F: NUMERICAL SOLUTION METHOD FOR FLOW EQUATIONS		Page
F1	Introduction.....	F1
F2	Types of differential equations.....	F1
F3	Finite-difference method.....	F1
F4	Finite-elements method.....	F4
F5	One dimensional flow.....	F4
F6	Two dimensional horizontal flow.....	F5
F7	Two dimensional vertical flow.....	F7
APPENDIX G: MODEL SCALING LAWS		Page
G1	Definitions.....	G1
G2	Derivation of basic scaling laws.....	G1
G3	River flow.....	G2
G4	Tidal and density-induced waves (long surface waves).....	G3
G5	Short surface waves.....	G4
G6	Practical rules.....	G5

SUBJECT INDEX

A.....	S1
B.....	S1
C.....	S1
D.....	S1
E.....	S2
F.....	S2
G.....	S2
H.....	S2
I.....	S3
J.....	S3
K.....	S3
L.....	S3
M.....	S3
N.....	S3
O.....	S4
P.....	S4
Q.....	S4
R.....	S4
S.....	S5
T.....	S6
U.....	S7
V.....	S7
W.....	S7
X.....	S7
Y.....	S7
Z.....	S7

PREFACE 1

This book reflects a one-year lecture course of fluid flow and surface waves for physical geographers of the University of Utrecht in The Netherlands. The book deals essentially with the basic principles of fluid mechanics in rivers, estuaries, seas and oceans.

The early Chapters 2, 3 and 4 cover the field of fluid properties, hydrostatics and kinematics. Chapter 5 on fluid dynamics describes the momentum equations of Euler, Bernoulli, Navier-Stokes and finally Reynolds, who introduced a time-averaging method to deal with turbulent flow. Chapter 6 deals with steady uniform flow in rivers. Phenomena like subcritical and supercritical flow, smooth and rough flow, boundary layer flow and flow resistance are explained. Work and power related to fluid dynamics are also explained.

Chapter 7 presents steady non-uniform flow in rivers giving information of potential flow, gradually varied and rapidly varied flow, curved flow and flow-induced forces (drag and lift).

The last two Chapters 8 and 9 deal with non-steady flow related to long and short surface waves.

Long wave phenomena like progressive waves, standing waves, translation waves, river flood waves, tidal waves, density-induced-waves and storm surge waves are described in detail.

Basic short wave properties are presented in Chapter 9. Phenomena like shoaling, refraction, diffraction and breaking are explained. Phenomena of the wave boundary layer and its effect on a current are also presented. The generation of longshore currents inside the surf zone is described. Finally, random waves are explained. The book ends with Appendices on basic formulae, mathematics, turbulence, methods to solve the flow equations and model scaling laws.

Basic knowledge of mathematics (especially differential equations) is required to understand the derivation of the equations of continuity and motion which appear throughout the text. To fresh up the readers memory, the most essential information of mathematics with respect to fluid mechanics is presented in Appendix B.

The book has been written with a view to sediment transport and morphology. Both fields of work are described extensively in: "Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas" and "Principles of Coastal Morphology".

The author hopes that the present book will serve as a useful tool for scientists, engineers and students in civil engineering, earth sciences, physical geography and oceanography.

Professor Leo C. van Rijn, 1993, 2011

PREFACE 2

In his long career as a researcher, Professor Leo van Rijn has given a major boost to sediment transport research. The transport formulae he derived are used all over the world and many researchers and professionals are familiar with his books on coastal sediment transport and morphology. Moreover, he has led a number of landmark research programs, national as well as international, with sediment transport as a common denominator.

On top of this, he has tested his knowledge and trained a large number of young colleagues in a wide range of practical application projects, all with a sediment transport component. He has done this first under the umbrella of WL|Delft Hydraulics, and after the merger of WL into Deltares in 2008 under the umbrella of Deltares. Many clients have profited from his sometimes unconventional views and insights.

But this is not his only career. He also serves since many years as a professor at Utrecht University, training generations of students in Physical Geography with his courses and exercises in hydrodynamics and sediment transport. Without exaggerating, one may claim that he has brought these courses and exercises to a substantially higher level.

Now that he is about to retire, Leo has found the time for an extensive write-up of his course material on coastal hydrodynamics, enriched with many insights he has gathered over the years. The result is this impressive book, which in my opinion is a must for every researcher in coastal dynamics. It gives an almost complete overview of the aspects of hydrodynamics that are necessary to understand coastal dynamics.

Thorough knowledge of the water motion due to waves and currents on a coast, including their complex interactions, is indispensable to understand how a coast behaves. This knowledge ranges from classical textbook material through to state-of-the-art research results.

Maybe the greatest value of this book lies in the fact that it covers this entire range. This makes it a goldmine to people entering this fascinating field, be it students or young professionals, and an invaluable reference to the more experienced. I congratulate Leo with this laudable initiative. Deltares is proud to have had him among its staff and happy to have been able to support the production of this book.

Professor Huib de Vriend

Director Science Deltares, Delft, The Netherlands, 2011

Acknowledgements

The author wishes to acknowledge the Deltares Organization and the Department of Physical Geography of the University of Utrecht for providing the financial means to publish this 2011 Edition on the occasion of my retirement.

I am also grateful to the following copyright holders for permission to reproduce figures: Dr. M. de Vries and Mr. C. Verspuy of Delft Technical University, Mr. R. Thabet of Delft Hydraulics, American Society of Civil Engineers, MacMillan Press, Pitman Press and Longman Group.

Ocean tides are periodic rises and falls in the level of the sea, and are formed by the gravitational attraction of the Moon and Sun on the water in the ocean. Although the Moon is much smaller than the Sun, it has a greater gravitational attraction for the Earth because the Moon is much closer to Earth. Lunar Tides. Water responds to the Moon's gravitational force by flowing toward it, making a bulge on the surface of the ocean. On the side of Earth facing the Moon, gravitational force is applied to water particles toward the Moon. This type of constructive interference can also occur as tides flow into an estuary against an outflowing current. Standing waves, termed tidal bores, will form and progress upstream at heights of several feet. Principles of Fluid Flow and Surface Waves in Rivers, Estuaries, Seas and Oceans consists of 881 pages and figures and contains all details of fluid mechanics in rivers, estuaries, seas and oceans. Principles of Fluid Flow and Surface Waves in Rivers, Estuaries, Seas and Oceans can be used as a basic text book for students and as a practical reference book for graduates in civil engineering, earth sciences, physical geography and oceanography. 1. introduction 2. fluid properties 3. fluid statics 4. fluid kinematics 5. fluid dynamics 6. steady uniform flow 7. steady non-uniform flow 8. non-steady flow: long free surface waves 9. non-steady flow: short free surface waves. Principles of fluid flow and surface waves in rivers, estuaries, seas and oceans. List of contents. 1. introduction. The book deals essentially with the basic principles of fluid mechanics in rivers, estuaries, seas and oceans. The early Chapters 2, 3 and 4 cover the field of fluid properties, hydrostatics and kinematics. Chapter 5 on fluid dynamics describes the momentum equations of Euler, Bernoulli, Navier-Stokes and finally Reynolds, who introduced a time-averaging method to deal with turbulent flow. Chapter 6 deals with steady uniform flow in rivers. Phenomena like subcritical and supercritical flow, smooth and rough flow, boundary layer flow and flow resistance are explained. Work and power related to fluid Subjects. Fluid mechanics, Hydrodynamics, Rivers. There's no description for this book yet. Can you add one? Edition Notes. Includes bibliographical references. Waves. Ocean Literacy Principles: OLP 1: The earth has one big ocean with many features. OLP 1.C. Water waves are generally caused by winds, and they can transfer energy over long distances across ocean basins. Activities: Activity: Watching Waves. Further Investigations: Circulation in Marginal Seas and Estuaries. Atmospheric Effects. Introduction to Atmospheric Effects.