Hydrology

Second Edition

Wilfried Brutsaert has revised and updated his classic textbook to take into account recent developments, while retaining the rigor and structure of the previous edition to introduce the fundamental principles of hydrology. New topics include the response of the global water cycle to climate change, the land-surface energy-budget closure, snow melt, groundwater trends and statistical surface variability with disturbed atmospheric boundary layers. Hydrologic phenomena are dealt with at the spatial and temporal scales at which they occur in nature. The physics and mathematics necessary to describe these phenomena are introduced and developed: readers will require a working knowledge of calculus and basic fluid mechanics. This classroom-tested textbook – based on the author's long-running course at Cornell – is invaluable for entry-level courses in hydrology directed at advanced undergraduate and graduate students in physical science and engineering. In addition, it is also a great reference text for practising scientists and engineers.

Professor Wilfried Brutsaert has been active in education and research for over fifty years at Cornell University, where he has taught courses in hydrology, fluid mechanics, groundwater, and atmospheric boundary layer physics. He has been widely recognized for his research and has received many awards, including the Bowie Medal and the Horton Medal from the American Geophysical Union; the Charney Medal and Honorary Membership from the American Meteorological Society; and the International Award and Honorary Membership from the Japan Society of Hydrology and Water Resources. He was awarded a "Doctor Honoris Causa" title at Ghent University, and he was the recipient of the Prince Sultan Bin Abdulaziz International Prize for Water. Most notably, in 2022 he was awarded the Stockholm Water Prize (sometimes described as the Nobel Prize for water). He is a member of the U.S. National Academy of Engineering. Professor Brutsaert was President of the Hydrology Section of the American Geophysical Union, served as a Council member of the American Meteorological Society, and as Section Chair of the National Academy of Engineering. He is also the author of the book *Evaporation into the Atmosphere* (1982, Springer).

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An Introduction

Second Edition

Wilfried Brutsaert
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Preface to Second Edition

The first edition of this book was well received in the hydrologic community. It was even translated in several languages, namely Japanese, Albanian, Macedonian and most recently Chinese. In essence, this new edition is an updated version of the original, with clarifications and corrections and with inclusion of several additional sections. These new or greatly modified sections address physical phenomena in hydrology that have received continued or even increased attention during the past two decades. Briefly, these additions are about aspects of the global water cycle response to climate change (Section 1.3), land-surface energy-budget closure (Sections 2.6 and 4.2.1), statistical surface variability with disturbed atmospheric boundary layers (Section 2.7), atmospheric rivers and precipitation (Section 3.2.6), energetics of snow melt (Section 3.5), complementarity between actual evaporation and atmospheric evaporative demand (Section 4.3.3), the Schreiber-Oldekop hypothesis, aka the Budyko framework (Section (4.4.2), drying of soil (Section 9.6.2), base-flow decline rate (Section 10.6.3), groundwater storage changes (Section 10.6.4), simulation of subsurface storm flow to identify old and new water (Section 11.2.2), and long-term relationships between runoff and precipitation (Section 12.5).

Like in the first edition, the material is presented in two formats. The more basic material, which consists of topics fit for a first reading and covered in regular courses, is shown in standard type. More advanced topics and elaborations for further reading or research are presented in a slightly smaller type against a grey background to indicate them.

To facilitate the preparation of courses with this book, prospective teachers can request from the publisher an example syllabus outlining sections that may be covered in a first course in hydrology during a 42-lecture semester. Similarly, a solutions manual for the problems listed at the end of each chapter can also be provided to prospective teachers.

Wilfried Brutsaert, 2023

Preface to First Edition

Water in its different forms has always been a source of wonder, curiosity and practical concern for humans everywhere. The goal of this book is to present a coherent introduction to some of the concepts and relationships needed to describe the distribution and transport of water in the natural environment. Thus it is an attempt to provide a more thorough understanding, and to connect the major paradigms that bear upon the hydrologic cycle, that is the never-ending circulation of water over the continents of the Earth.

Continental water transport processes take place above, on and below the Earth's land surfaces. Accordingly, in Part I, water is considered as it passes through the lower atmosphere; this part consists of a general description of atmospheric transport in Chapter 2, followed by the application of these concepts to precipitation and evaporation in Chapters 3 and 4, respectively. In Part II, water transport on the Earth's surface is dealt with; this part consists of a general description of the hydraulics of free surface flow in Chapter 5, which is then applied to overland runoff and streamflow routing in rivers in Chapters 6 and 7, respectively. Water below the surface is the subject of Part III; again, a general introduction to flow in porous materials in Chapter 8 is followed by applications to phenomena involving infiltration and capillary rise in Chapter 9, and groundwater drainage and baseflow in Chapter 10. Part IV is devoted to flow phenomena, mostly fluvial runoff, in response to precipitation at the catchment and river basin scales, which result from the combination of flows both above and below the Earth's surface, already treated at smaller scales separately in Parts II and III. Various interactions of these flow phenomena and the major paradigms regarding the subscale mechanisms are described in Chapter 11. This is followed by a treatment of the available parameterizations in Chapter 12. In Chapter 13 the fourth part of the book concludes with a brief description of some of the more common statistical concepts that are useful in the analysis of hydrologic data. Finally, as an afterword, Chapter 14 closes the book with a brief history of the ideas on the water cycle, which over the centuries evolved to our present understanding; Santayana's dictum may be a bit worn by now, but several recent reinventions of the hydrologic wheel could have been avoided, if the past had been better remembered.

These transport phenomena in the hydrologic cycle on land are treated at spatial and temporal scales, at which they are commonly encountered in everyday life and at which they are tractable with presently available data. Hydrology is a physical science, and the language of physics is mathematics. Accordingly, plausible assumptions are introduced and the mathematical formulations and parameterizations are derived, which describe the more relevant mechanisms involved in the different phases of the continental hydrologic cycle. The resulting equations are then examined and, if possible, solved for certain prototype situations and boundary conditions. The motivation for this is, first, to gain a better understanding of their structure and underlying assumptions, and of the physics they are intended to represent; and second, to provide the basis and background for more complex modeling exercises, simulations and predictions in practical applications.

The subject material covered in this book grew out of the lecture notes for my courses in hydrology and related topics in the School of Civil and Environmental Engineering, at Cornell University. I have not tried to cover all possible angles and points of view of the subject matter. Rather, I have followed a line of thought, which over the years I have come to find effective in conveying a broad understanding of the more important phenomena, and in stimulating further inquiry in the subject. Similarly, no attempt has been made to compile

a complete bibliography. But the references that are listed refer to other works, so that it should be possible to trace back the more important developments.

As its subtitle indicates, this book is intended as an introduction; as such, it should be suitable as a textbook for an entry-level course in hydrology directed at advanced seniors and beginning graduate students in engineering and physical science, who have a working knowledge of calculus and basic fluid mechanics. The book contains much more material than can reasonably be covered in a first course. Thus it will depend on the objectives of the course, and on the orientation and level of the students, which specific topics should be selected for coverage. Naturally, the instructor should be the ultimate judge in this. However, to facilitate this selection, the text is printed in two different type formats. The main subject matter, which in the experience of the author can be suggested for inclusion in a first course, is presented in regular type. An effort has been made to lay out this part of the text in such a way that the student should be able to grasp the material with little or no reliance on the more advanced sections. For certain topics, clarification by an experienced instructor in the lectures will undoubtedly be helpful. Subject matter of a more advanced or specialized nature is printed as indented text in a slightly smaller type and with a grey rule on the left-hand side of the page. This material is intended either as optional or explanatory reading for the first course, or as subject matter to be covered in a second and more advanced course. Sections of this second type of material have also been used as major portions in more specialized courses, namely in Groundwater Hydrology (Chapters 8, 9 and 10) and in Boundary Layer Meteorology (Chapters 2, 3 and 4) at Cornell.

The book is intended mainly for students of hydrology; it should, however, also be more broadly of interest to professional scientists and engineers, who are active in environmental matters, meteorology, agronomy, geology, climatology, oceanology, glaciology and other Earth sciences, and who wish to study some of the underlying concepts of hydrology, relevant to their discipline. In addition, it is hoped that the book will be of use to workers in fluid dynamics, who want to become acquainted with applications to some intriguing and fascinating phenomena in nature.

Wilfried Brutsaert, 2005

Ter nagedachtenis van mijn ouders Godelieve S. G. Bostijn (-B.) en Daniel P. C. Brutsaert
妻 トヨに捧 げる
And to the life of Siska, Hendrik, Erika and Karl