Ecohydrology of Water-Controlled Ecosystems

Soil Moisture and Plant Dynamics

Understanding of the systems that control the circulation of water between atmosphere, soil, and plant life is clearly important for a general understanding of the hydrologic cycle and the way that ecosystems operate and survive. *Ecohydrology of Water-Controlled Ecosystems: Soil Moisture and Plant Dynamics* addresses the connections between the hydrologic cycle and plant ecosystems, with special emphasis on arid and semi-arid climates.

This book presents a quantitative understanding of the impacts of soil moisture on ecosystem dynamics using a probabilistic framework. It investigates the vegetation response to water stress (drought), the hydrologic control of cycles of soil nutrients, and the dynamics of plant competition for water. The book also offers insights into processes closely related to soil moisture dynamics, such as soil–atmosphere interaction and soil gas emissions. This modern and important topic is treated by building suitable mathematical models of the physics involved and then applying them to study the ecosystem structure and its response to rainfall and climate forcing in different parts of the world, including savannas, grasslands, and forests.

The book will appeal to advanced students and researchers from a large range of disciplines, including environmental science, hydrology, ecology, earth science, civil and environmental engineering, agriculture, and atmospheric science.

Ignacio Rodríguez-Iturbe is Theodora Shelton Pitney Professor of Environmental Sciences and Professor of Civil and Environmental Engineering at Princeton University. Professor Rodríguez-Iturbe is the author of over 200 research papers and several books, including *Fractal River Basins: Chance and Self-Organization* with Andrea Rinaldo (Cambridge, 1997). A member of the US National Academy of Engineers, and many other academies throughout the world, he is the winner of numerous national and international awards including the Stockholm Water Prize, the Horton and Macelwane Medals of the American

Geophysical Union, the Langbein Lecture (also AGU), the Huber Prize and V. T. Chow Award (American Society of Civil Engineering), the Horton Lecture (American Meteorological Society), the Premio Mexico, and the Premio Nacional de Ciencias de Venezuela.

Amilcare Porporato is Associate Professor of Civil and Environmental Engineering at Duke University. He is the author of more than 50 research papers. He received the Arturo Parisatti International Prize, awarded by the Istituto Veneto di Scienze, Lettere e Arti. He has been a research associate in the Civil Engineering, Environmental and Water Resources Division at Texas A&M University and the Department of Civil Engineering at Princeton University. He was chairman of the last two Ecohydrology sessions of the American Geophysical Union Spring Meeting.

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Como siempre, para Mercedes
I. R.-I.

A Sandra
A. P.

Contents

Foreword

Merging beauty with importance!

Among the numerous and diverse subjects within the geosciences, hydrologic science is arguably the fastest evolving discipline. Born from chapters and appendices of standard hydraulics and agricultural science textbooks, hydrology went through its first metamorphism 40 years ago to become a prominent science dealing with the physical laws that govern water movement within watersheds. A second metamorphism occurred in the last 30 years with the realization that water is among the primary controlling factors of the Earth's climate, and thus, the coexistence of all three physical states and the cycling among them became a research priority. Over the past ten years, however, a third metamorphism has started to develop and is primarily motivated by the recognition that the water cycle strongly influences element cycling such as nitrogen and carbon. Within the terrestrial biosphere, water availability regulates the growth of plants and controls the rate of nitrogen uptake and carbon assimilation. Hence, the interaction between the hydrologic cycle and vegetation received simultaneous attention within the climate, hydrologic, and ecological communities. *Ecohydrology* is the emerging discipline that concentrates on the cycling of water and other elements within the context of the Earth's biological productivity, the subject of this book.

From its birth, ecohydrology bifurcated early on into a phase that is primarily observational and focused on a plant's response to its microclimate (primarily spear-headed by ecologists) and a phase that focused on detailed water flow models combined with plant models of varying complexity (primarily spear-headed by hydrologists). The trajectory of ecohydrology following this bifurcation was brief and predictable – increases in observational cataloging and increases in model complexity with little intersections amongst these two trajectories. Enter Ignacio Rodríguez-Iturbe and

Amilcare Porporato – who promoted low-dimensional models that offer simplicity in interpreting physical and biological processes within the context of field experiments yet retain much of the inherent system nonlinearity. As such, this text draws upon the ripening fruits of nonlinear science, the wealth of stochastic precipitation models that formed the initial growth phase of hydrologic sciences, and the probabilistic treatment that shaped molecular physics some 80 years ago – now re-introduced into the hydrologic consciousness.

The text, composed of 11 chapters, addresses six themes central to water-controlled ecosystems. By no means can 11 chapters cover the entire depth and breadth of ecohydrology and give justice to all the literature on the topic. The authors chose to focus primarily on the propagation of stochastic rainfall patterns within the nonlinear component of the soil–plant–atmosphere continuum. The thrust is primarily devoted to how stochasticity in precipitation produces different modes of variability and how these modes affect ecosystem structure and function. The first five chapters deal with the stochastic treatment of soil moisture and its impact on plant water stress (*theme 1*). The sixth chapter introduces the coupled water and carbon uptake by plants and their interaction with the atmospheric boundary layer (*theme 2*). The seventh chapter is a preliminary treatise on plant strategies and water use – using a binary classification of extensive and intensive plant users of soil moisture (*theme 3*). Chapters 8 and 9 revisit the soil moisture dynamics with emphasis on scaling in space and time (*theme 4*). Longer-term soil moisture dynamics ranging from seasonal to interannual and spatial scaling from point-processes to hill-slope are developed. Chapter 10 introduces the connection between cycles of soil organic matter and nutrients, with particular emphasis on carbon and nitrogen (*theme 5*). Chapter 11 charts a new direction to the connection between spatio-temporal patterns of precipitation and vegetation structure. The emergence of spatially organized patterns in vegetation is explored via the methods developed in the previous chapters in the context of cellular automaton (*theme 6*) among others. The book includes numerous examples and draws upon published datasets from a wide range of water-controlled ecosystems in three continents.

Ignacio Rodríguez-Iturbe's hallmark statement (using a charming Venezuelan accent) in seminars is "we don't study . . . because it is *important* but because it is *beautiful*." Ironically, he ended up drafting a book with Amilcare Porporato whose impact on ecohydrology is probably comparable to the impact of Robert May's landmark papers on population dynamics some 25 years ago. Judging this statement must wait for the future. For now, it is a privilege to commend the following pages to individual readers and to the broad scientific community.

Gabriel Katul, Professor of Hydrology and Environmental Fluid Mechanics, Nicholas School of the Environment and Earth Sciences, Duke University

Preface

The last decade has seen a reformulation of the disciplinary basis of hydrology, which will be even more accentuated during the years ahead, with a dramatic increase of the intimate links between hydrology and the life sciences. We are convinced that the role of the hydrologic cycle throughout a wide range of temporal and spatial scales will be seen as a keystone in some of the most crucial areas related to biocomplexity, biodiversity, and the nature of the environment.

This book deals with the spatial and temporal linkages between hydrologic and ecological dynamics. It is a book on ecohydrology, which we define as the science that seeks to describe the hydrologic mechanisms that underlie ecological patterns and processes. The interplay between climate, soil, and vegetation is central to hydrology itself and it is crucially influenced by the scale at which the phenomena are studied as well as by the physiological characteristics of the vegetation, the pedology of the soil, and the type of climate. Ecohydrology is a key component of what are loosely called biogeosciences, in reference to the interrelationship among the biological, geophysical, and geochemical approaches to understand the earth system. Hydrologic phenomena play a commanding role in this field and hydrologically oriented research has much to contribute towards what surely will be one of the most exciting scientific frontiers of the first part of the twenty-first century.

As Peter S. Eagleson has eloquently said:

> We need to get away from a view of hydrology as a purely physical science. Life on earth also has to be a self-evident part of the discipline. In particular, I am thinking of vegetation and its powerful interactive relationship with the atmosphere, at both a local and a global level. In attempting to get the full picture, we must not be afraid to express the role of plants in our mathematical equations.
>
> *(Interview with Peter Hanneberg, in Our Struggle for Water, Stockholm: Stockholm International Water Institute, 2000.)*

This statement describes well the core question that this book attempts to study; namely, how can we develop a geographically and temporally broad understanding of the dynamic coupling between biological and hydrological processes in natural systems? Within this framework we then focus on water-controlled ecosystems and the relationship between their hydrologic and vegetation dynamics. Thus, for example, one will intuitively accept that plant biomass production depends not only on the total rainfall during the growing season but also on the intermittency and magnitude of the rainfall events. Nevertheless, to quantitatively model the linkage between soil moisture dynamics and carbon assimilation accounting for the stochasticity of rainfall is a challenging problem which requires extensive simplification of very complex processes of a physical and biological nature. The dynamics of soil moisture, transpiration, and carbon assimilation takes place at the hourly time scale with soil, plant, and atmospheric boundary layer characteristics affecting the diurnal course of photosynthesis and transpiration. The linkage of this complex dynamics with climate fluctuations and/or changes in aspects such as ecosystem structure requires temporally upscaling the hourly processes. Any attempt to do this necessarily needs a simplified analytical description of the dynamics involved.

The disciplinary reformulation of hydrology which the above implies is inserted in a new intellectual frontier for the environmental sciences. Lars Hedin et al. (2002) have defined this frontier as "the natural convergence of the historically distinct disciplines of biology and physical science. This disciplinary convergence will over the next several decades transform our understanding of basic processes that control the stability and sustainability of natural environmental systems. The ensuing findings will have extraordinary implications for our abilities to predict and manage how humans impact the health of ecosystems across local, regional, and global scales. Such knowledge is a critical component of a safe, sustainable, and prosperous future."

As the title of the book implies, soil moisture is considered as the crucial link between hydrologic and biogeochemical processes. This key role is described throughout the book in terms of its controlling influence on transpiration, runoff generation, carbon assimilation, and nutrient absorption by plants among many other phenomena. Through its impact on these and other processes, soil moisture is the central hydrologic variable synthesizing the interaction between climate, soil, and vegetation. Its temporal and spatial dynamics are at the heart of ecohydrology.

The challenges that we have mentioned are part of what Roger Newton (1993) so beautifully describes in his book *What Makes Nature Tick?*: "Science at the most fundamental level is very far from being merely an efficient enumeration of experimental facts and empirical rules, nor is its structure simply determined by induction from observations. To think of it only as an orderly collection of intriguing and useful bits of information is to misunderstand its cultural value and its fascination altogether. Science is, in fact, an intricate edifice erected from complex, imaginative designs in which esthetics is a more powerful incentive than utility. Beauty, finally, comprises its greatest intellectual appeal." The simplifying assumptions made in different parts of the analysis can obviously be criticized as naive and/or incomplete from many different points of view. This is always the case when attempting to model nature and even more so with the type of dynamics that is the subject of this book. Nevertheless, we are convinced that it is through necessarily simplistic models with a strong esthetic incentive that general principles and an illuminating quantitative framework of analysis are laid out to facilitate progress in enormously complex problems.

The subject and results of this book are by no means exhaustive or conclusive since ecohydrology has been experiencing major scientific advances in recent years, and this will undoubtedly continue, even more so, in the years ahead. Nevertheless, we believe it is an appropriate moment to present some of the results with a unifying perspective and through a coherent framework, hopefully facilitating in this manner future work on these topics.

We owe recognition to institutions and individuals. Princeton University, Politecnico di Torino and, more recently for one of us, Duke University have provided a most supportive environment that has enabled our close collaboration, even when we were continents apart. To these institutions, our grateful thanks. Peter S. Eagleson from MIT has been a source of friendship and guidance for I. R.-I. for 30 years. More recently, his path-breaking work on ecohydrology has been an inspiration for us in attempting to work in this area. Rafael L. Bras, from MIT, Andrea Rinaldo, from the University of Padova, and Juan Valdes, from the University of Arizona have been, for many years, very special friends and close companions in science for I. R.-I. Luca Ridolfi, from Politecnico di Torino, has been a source of invaluable support and close friendship for A. P. from his days as a student, and more recently a friend and coworker for I. R.-I. The trust and support of Luigi Butera and Sebastiano T. Sordo and the friendly help of Roberto Revelli, from Politecnico di Torino, were important to A. P. during his stay at Princeton University. David R. Cox (Oxford) and Valerie Isham (University College, London) have also been a source of personal and professional support for which we are very grateful.

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Michael A. Celia has been a close friend for I. R.-I. for years. More recently he has also been a close research collaborator who has contributed enormously to the efforts of this book. Special thanks for all this and also to him and Eric F. Wood for the close daily companionship during our academic life in Princeton.

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