



Water Resilience for Human Prosperity

Johan Rockström • Malin Falkenmark

Carl Folke • Mats Lannerstad

Jennie Barron • Elin Enfors

Line Gordon • Jens Heinke

Holger Hoff • Claudia Pahl-Wostl

CAMBRIDGE

Water Resilience for Human Prosperity

Johan Rockström

Stockholm Resilience Centre, Stockholm University

Malin Falkenmark

Stockholm Resilience Centre, Stockholm University and Stockholm International Water Institute

Carl Folke

Stockholm Resilience Centre, Stockholm University and the Beijer Institute of Ecological Economics of the Royal Swedish Academy of Sciences

Mats Lannerstad

Stockholm Environment Institute and International Livestock Research Institute

Jennie Barron

Stockholm Environment Institute

Elin Enfors

Stockholm Resilience Centre, Stockholm University

Line Gordon

Stockholm Resilience Centre, Stockholm University

Jens Heinke

Potsdam Institute for Climate Impact Research and International Livestock Research Institute

Holger Hoff

Stockholm Environment Institute and Potsdam Institute for Climate Impact Research

Claudia Pahl-Wostl

Institute for Environmental Systems Research at the University of Osnabrück



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Published in the United States of America by Cambridge University Press, New York

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/9781107024199

© Johan Rockström, Malin Falkenmark, Carl Folke, Mats Lannerstad, Jennie Barron, Elin Enfors, Line Gordon, Jens Heinke, Holger Hoff and Claudia Pahl-Wostl 2014

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2014

Printed in Spain by Grafos SA, Arte sobre papel

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

Library of Congress Cataloguing in Publication data

Water resilience for human prosperity / Johan Rockström, Malin Falkenmark, Carl Folke
pages cm

ISBN 978-1-107-02419-9 (Hardback)

1. Water-History. 2. Water supply-History. 3. Drinking water-History. I. Rockström, Johan.
GB659.6.W38 2014

333.91-dc23 2013028561

ISBN 978-1-107-02419-9 Hardback

Additional resources for this publication at www.cambridge.org/9781107024199

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Water Resilience for Human Prosperity

Humanity has entered a new geological era, the Anthropocene, where the world's human population now constitutes the largest driving force of changes to the biosphere. Emerging water challenges require new system thinking and ideas for governance and management of water resources in the context of rapid global change.

This book presents a new resilience-based approach to water resources, addressing their role for global sustainability. Topics covered include the risks of unexpected change; human impacts and dependence on global water; the prospects for feeding the world's population by 2050; and a pathway for the future. The book's innovative and integrated approach links green and blue freshwater (the rainfed soil moisture supporting plant growth and the liquid water in rivers and aquifers) with terrestrial and aquatic ecosystem functions and use. It also links changes arising from land-use alteration with the impacts of those changes on social-ecological systems and ecosystem services.

Based on recent scientific advancements on integrated water resources research, global environmental changes and ecosystem services, the key focus is on building social-ecological resilience – the ability to persist, adapt and transform – in a future where we can expect more frequent water-related shocks and stresses. This is an important, state-of-the-art resource for academic researchers and water resource professionals, and also a key reference for graduate students studying water resource governance and management.

Johan Rockström is a Professor in Water Systems and Global Sustainability at Stockholm University. He is the Director of the Stockholm Resilience Centre (SRC), former Executive Director of the Stockholm Environment Institute (SEI), and a leading international scientist on global sustainability. He has more than 15 years' experience of research on agriculture, water resources and ecosystem services, and over 100 research publications and several books, in the fields of global environmental change; resilience and sustainability; agricultural water management; global water resources; and food production. He serves as an advisor to several international organizations and governments, and sits on international committees including the EU Commission Resource Efficiency Platform (the leadership council of the United Nations Sustainable Development Solutions Network, SDSN). He co-chaired the design process of Future Earth, a new initiative by the International Council for Science (ICSU), and serves as the chair of the Water, Land and Ecosystems program of CGIAR.

Malin Falkenmark is currently with the SRC, Stockholm University, and the Stockholm International Water Institute (SIWI). She is a future-oriented scientist and a pioneer of interdisciplinary environmental and water research. Her deepest interests lie in the linkages between land/water/ecosystems, particularly as they relate to water scarcity, regional similarities and differences, and their policy implications. She has introduced three broadly used concepts: the water scarcity indicator, the concepts of green and blue water, and hydrosolidarity. Professor Falkenmark has held several high level posts on international boards and committees, and has received several international awards, including the Rachel Carson Prize and the Volvo Environmental Prize.

Carl Folke is Professor in Natural Resource Management, founder and Science Director of the SRC, and Director of the Beijer Institute of Ecological Economics of the Royal Swedish Academy of Sciences. He is a leading researcher on social-ecological systems and resilience, sustainability science and ecological economics, and co-founder of the Resilience Alliance. Dr Folke's work focuses on the essential role of life-support ecosystems, ecosystem services and biodiversity and their governance, emphasising that people are part of and fundamentally dependent on the capacity of the biosphere to sustain development. He has published some 180 research papers, numerous book chapters and 12 books. He serves as scientific advisor to international research institutes, organisations and other actors in science, policy and practice.

Mats Lannerstad is a Research Fellow at the SEI and a Scientist at the International Livestock Research Institute (ILRI). His research is centred on natural resource use in the global food system, with particular focus on freshwater requirements for food security on multiple scales and pathways towards a sustainable intensification in food production. Two key areas are the dietary change towards more animal-source foods following rising affluence and urbanisation, and the linkages between livestock production and the use of different water sources. Dr Lannerstad has authored 15 peer-reviewed publications, three books/book chapters and numerous research reports.

Jennie Barron is a Research Leader at SEI and a researcher at the SRC. Her research applies a systems approach to farm and landscape agricultural development trajectories, to improve productivity, livelihoods, food security and ecosystems services, and to advise on opportunities for action and investment. She works in local, national and international partnerships in sub-Saharan Africa and South Asia. Dr Barron has written or co-authored more than 25 peer-reviewed publications, and developed various outreach communications and research for development and policy at local, national and international levels.

Elin Enfors is a Researcher at the SRC. Her main interest concerns pathways to transformation in agro-ecosystems, with a special focus on how ecosystem services generated in these systems can contribute to poverty alleviation. She has a background in systems ecology, with extensive experience of field research from Africa, and a keen interest in participatory research.

Line Gordon is an Associate Professor and Deputy Science Director at the SRC and leads the Landscape research theme. Her research centres on interactions among freshwater resources, ecosystem services and food production, with a focus on how resilience thinking can enable better management of these resources. Dr. Gordon has published over 20 peer-reviewed papers and book chapters in a wide range of journals. She has extensive international experience, and is conducting transdisciplinary research with a strong interest in the interface of science and society.

Jens Heinke is a Research Fellow and doctoral candidate at Potsdam Institute for Climate Impact Research (PIK), and a Scientist at the ILRI. He primarily works with the Lund-Potsdam-Jena dynamic global vegetation model (LPJ), as both a developer and analyst. His research is focussed on global change impacts on the water cycle with an emphasis on water resources, food production and livestock production. He also works on mapping and understanding the flows and linkages in the global food system, and is the author or co-author of more than 20 scientific papers and several research reports.

Holger Hoff is Senior Research Fellow at the SEI and PIK. His research focus is on climate impacts and adaptation in water, agriculture and ecosystems, and integrated water and natural resource management, across scales up to the global level. He works primarily in the Middle East and North Africa, sub-Saharan Africa and South Asia regions, and at PIK he currently works on sustainability boundaries of water and land use. Mr Hoff co-coordinates the Nexus Initiative at SEI, using WEAP and other nexus tools, and is the author of more than 30 peer-reviewed publications, several book chapters and numerous research reports and policy papers.

Claudia Pahl-Wostl is Professor for resources management and Director of the Institute for Environmental Systems Research at the University of Osnabrück, Germany. Her major research interests are adaptive governance and management of water resources, social and societal learning and their role in transformation processes towards sustainability, global water governance and multi-level governance systems and conceptual and methodological frameworks to analyse social-ecological systems. She has authored numerous papers in peer-reviewed journals, chapters in edited books, policy briefs and popular reports, and has also edited three books and twelve special issues in peer reviewed journals.

Contributors

These authors contributed the informative boxes on particular issues found throughout this volume.

Göran Berndes

Chalmers University of Technology

Petra Döll

University of Frankfurt

Ellen M. Douglas

University of Massachusetts, Boston

Ruud J. van der Ent

Delft University of Technology

Lance Gunderson

Emory University

Elke Herrfahrdt-Pähle

German Development Institute

Eloise Kendy

The Nature Conservancy

Yuanhong Li

Gansu Research Institute for Water Conservancy (GRIWAC)

Michael E. McClain

UNESCO-IHE Institute for Water Education

Denis Mpairwe

Makerere University

Jay O’Keeffe

Rhodes University

Donald Peden

International Livestock Research Institute (ILRI)

Marcela Quintero

International Centre for Tropical Agriculture (CIAT)

Wilhelm Ripl

Technical University of Berlin (Professor Emeritus)

Hubert H.G. Savenije

Delft University of Technology

Bridget Scanlon

University of Texas at Austin

Maja Schlüter

Stockholm Resilience Centre

Jan Sendzimir

University of Natural Resources and Applied Life Science, Vienna (BOKU)

Will Steffen

The Australian National University and Climate Commissioner, Australia

Alain Vidal

CGIAR Challenge Program on Water and Food

Brian Walker

Commonwealth Scientific Industrial Research Organisation (CSIRO)

Qiang Zhu

Gansu Research Institute for Water Conservancy (GRIWAC)

Preface

Why yet another book on water? Partial thinking and sectoral approaches have dominated resource and environmental management for too long, and this is also true for freshwater. Perspectives are rapidly changing, however, expanding on the conventional perception of freshwater as 'blue water' – a natural resource to be extracted from rivers and groundwater for households, industry, irrigation and economic production. Integrated water resource management (IWRM), although still predominantly concerned with the blue water branch of the water cycle, has extended the focus to interacting sectors in catchments. More recently, water vapour or 'green water' has increased focus in the policy arena on issues such as rainfed agriculture. The role of freshwater in ecosystem services, both terrestrial and aquatic, is now on the agenda, as well as work on their water trade-offs or in relation to water-related tipping points in dynamic landscapes. New approaches are emerging, such as adaptive water governance of landscapes and catchments.

The biosphere – the sphere of life – is the living part of the outermost layer of our rocky planet – the part of the Earth's crust, oceans and atmosphere where life dwells. It is the global life-support system that integrates all living beings and their relationships. Life on Earth interacts in myriad ways with the chemistry of the atmosphere, the circulation of the oceans and the water cycle, including solid water in polar and permafrost regions, to form favourable conditions for life on Earth. People and societies are integrated parts of the biosphere, dependent on its functioning and life support.

Water plays a key role in the operation of the biosphere, from the level of the cell to the dynamics of the atmosphere. The water cycle functions as the bloodstream of the biosphere. Like any organism, humans have evolved with water, benefitting from its many functions and the mineral salts it carries. Water is required for soil formation and is critical to

the production of the food we eat. Continents are connected by rainfall patterns, it provides climate-regulating services and plays a central role in extreme events such as floods, storms and droughts. On the blue planet, the water cycle is clearly essential to our existence and a precondition for our evolution.

It is now apparent that humanity has become a major force in the dynamics of the biosphere, shaping it not only locally and regionally but also globally, and leaving a significant imprint on the operation of the biosphere as a whole. Drivers of change such as rising human numbers, urbanisation, migration patterns, emerging markets, the diffusion of new technologies and social innovations can combine with sudden events such as floods, fires, pandemics, rapid shifts in fuel prices and volatile financial markets to trigger tipping points. The global social-ecological system is complex and dynamic, and subject to unexpected, often rapid, changes – not as exceptions but increasingly as the rule. Such changes play out in cascading fashion in a world where everyone is in everyone else's backyard. Thresholds and tipping points are now part of the furniture.

This new situation – the Anthropocene – calls for a fundamental shift in perspectives and world views, reconnecting development and progress to the capacity of the biosphere and its water cycle to sustain society and prosperity. This reconnection is linked to the insight that humanity has been prospering from a stability that is exceptional in the history of the Earth. The past 10 000 years, the Holocene geological epoch, was an era during which agriculture and human civilisations emerged and flourished. Many take the favourable Holocene conditions for granted. In our view, a greater appreciation is needed of water as part of biosphere dynamics and resilience. Hence the call for a broader water perspective that connects the local with the global. Resilience, in the way we approach it, is about persistence in the face of change, having the capacity to continually adapt to complex dynamics,

and to develop in order to get out of traps and even transform and shift into new development pathways. The capacity of the biosphere and the water bloodstream sets the framework for such pathways – the planetary boundaries for prosperous societal development.

It is in this context that we have written this book – to take on the challenge of expanding mindsets towards water as the bloodstream of the biosphere of which people are an embedded part. In the globally interconnected world, humanity is critically dependent on the capacity of the biosphere to support our way of life, and the way we have organised societies, technologies and economies. The water bloodstream approach is not just an ethical stand. It is about prosperity and ultimately about survival. It is also about biosphere stewardship and innovation for sustainable development for humanity.

We have written this book in search of a deeper understanding of the new water dynamics in the globally integrated system of people and nature, to put forward new conceptual systems, perspectives, hypotheses and findings. We believe that science has a responsibility to search for a better understanding of

the new challenges facing humanity, and to explore pathways for a sustainable world. We describe and analyse the role of water in the biosphere and how it relates to human actions and well-being from the global to the local levels, and we introduce new concepts such as water resilience and water stewardship in the new Anthropocene era. Striving for water stewardship and a resilient biosphere is not about preserving the status quo or circumventing change. It is about having the capacity to deal with change, turning crises into opportunities and shifting into sustainable pathways.

Resilience thinking encourages us to anticipate, experiment, adapt and transform. Water resilience and water stewardship are about strengthening the resilience of social–ecological systems to deal with changing conditions, and finding ways to live in prosperity in the Anthropocene era. This will require an appreciation of the critical role of water in the operation of the biosphere for human well-being. We hope this book will inspire people in this direction.

*Carl Folke, Malin Falkenmark
and Johan Rockström*

Introduction to the book

Scope of the book

This book aims at synthesising our current state of knowledge and probing the key area of how recent insights from social–ecological systems and resilience research influence our understanding of water resource governance and management in a world subject to rapid global environmental change. It advances a proposed new framework on ‘water resilience’ as an integral part of sustainable water resource management. We have a focus on ecosystem services in productive landscapes, especially food production (and bioresources), seen from the perspective of land, water, ecosystem interactions and resilience building. Focus is on water resources from local to global scale, exploring dynamic interactions between sectors, components of the Earth system and scales. The book will therefore only briefly address water quality issues. The water resource focus of the book includes water flows from the local water balance to the global hydrological cycle – i.e. the governance and management of precipitation, vapour flows, as well as surface and sub-surface runoff flows and resources. It is, furthermore, global in scope, even though a particular focus is set on the regions of the world facing the most challenging future in terms of water resource scarcity and water resilience challenges related to current and future global environmental change. This means that a particular focus is given to the semi-arid and dry sub-humid tropical savannah regions of the world.

The water and ecosystems focus of the book, places the emphasis on the relations between freshwater and the living systems in the biosphere. The book thus takes as a starting point the role of water resources in the generation of ecosystem functions and services from terrestrial and aquatic ecosystems, and how these define the resilience of ecosystems; how human interactions with water impact on

ecosystem and resilience; and how innovative water governance and management principles can be applied to human challenges in an era of rapid global changes. In essence we attempt to advance a social–ecological systems approach to water resilience for human prosperity in the Anthropocene.

The book thereby does not focus on water in marine ecosystems, and does not explore the important role of water for resource use (e.g. in mining) nor for domestic and urban water supply and water for industrial purposes. This said, the book obviously takes an integrated perspective on the trade-offs between water use for living systems and other resource and social uses. Our special focus on water and food in a changing world is justified by the fact that no human sector consumes so much freshwater as bioresources for food, energy and biomass, which raises, apart from trade-offs between different water needs, the challenge of how to build water resilient *food production* in the world.

Target audience

The book is targeted at graduate/post-graduate students, water resource professionals and senior water planners, and is therefore a book targeting higher education, which can also inform key water professionals in different sectors from agriculture and environment to industry and river basin planning.

We allow ourselves to be relatively detailed and in-depth, and quite technical where needed, while trying to reach a broader professional audience. We want to explain and give examples related to complex issues ranging from vapour shift, water-induced regime shifts, moisture feedback, water resilience, etc. The text is interspersed with a set of *boxes*, authored by invited water scientists looking deeper into a number of issues discussed or referred to in the main text.

Book sections

The book is divided into four parts.

Part I. A new perspective

Chapter 1 is an overview and framing chapter on the emerging challenge of water resilience in the Anthropocene. It explains the crucial roles played by water in the life-support systems on Earth in an era of rapid global and regional change. It discusses different disturbance regimes and the emerging threats and dilemmas, and highlights potential thresholds of critical concern. It explains the core roles of water in sustaining a desired 'Holocene-like' state on Planet Earth, and the risk for human-induced water thresholds. It also explains three core roles of water for resilience. The chapter furthermore highlights the central role of water partitioning changes, motivating special focus on foreseeable future land-use alterations, in particular future human use of bioresources, especially implications of feeding a growing humanity.

Part II. Living in a human-dominated world

Chapter 2 offers an overview of past human alterations to the Earth system and the main drivers of change. It highlights climate change in particular, as it interacts profoundly with the planet's global water cycle. It demonstrates the socially driven connectivity between different global regions, and human-generated impacts on the Earth System. It stresses that humanity is now living in the new Anthropocene, a new geological epoch where humanity constitutes a quasi-geological force of planetary change, at risk of and approaching various water-related tipping points.

Chapter 3 analyses the options for safe global pathways towards sustainable water development and the dangers to be avoided in the form of water-related thresholds, rigidity and poverty traps. It addresses water's involvement in abrupt, unexpected regime shifts in social-ecological systems. Resilience is characterised by the existence of reinforcing processes and stabilising feedbacks. Water's many different roles in the life-support system mean that it is profoundly involved in the processes of and responses to regime shifts, as both a state variable and a control variable.

Chapter 4 examines human dependence on the global water system (GWS), and the role of water as the bloodstream of the biosphere. It highlights

human-generated changes in the system, including a number of remote water-related connections between regions (so-called teleconnections) such as trade-related virtual water flows. Resilience-related changes are summarised including land-use change and its implications for green-blue water partitioning; climate change, noting that aridification can reduce resilience to droughts; growing water demands; and groundwater overexploitation. It stresses that basin closure represents a critical threshold beyond which new processes and interactions are triggered.

Part III. Food production globally: in hotspot regions and in the landscape

Chapter 5 analyses the challenge of feeding a growing humanity from a water perspective. It describes the growing food demand up to 2050, considering population increase, average per capita food supply levels, and changed composition of animal and vegetal source foods in food supply. Country-level assessments of food water requirements are given for different scenarios, including climate change, irrigation development, water productivity improvements, alternative dietary options and reduced food losses. The chapter highlights the need for large-scale virtual water transfer through expanded food trade. Food supply is examined from a dynamic perspective in terms of the ability to cope with shocks and change, and the adaptability and social-ecological resilience required.

Chapter 6 analyses the large and rising social-ecological challenge in the water-poor savannah zone with rapidly increasing populations and demands for water. What are the implications of food supply efforts, and the implementation difficulties in these regional hotspot regions? The chapter clarifies that, contrary to popular beliefs, this zone has a substantial (and untapped) agro-hydrological potential. Rather than facing absolute lack in water, the challenge is the huge fluctuations in rainfall and the large amount of water lost to the farming system through evaporation, runoff and drainage. Water resilience strategies involve practices for dry-spell mitigation, using, e.g. water harvesting systems.

Chapter 7 focuses on basin-level challenges and the meso-scale perspective, which is where land-use changes can aggregate and affect ecosystem services, and consequently livelihood and development opportunities, and ecosystem sustainability. Agriculture, which is itself an ecosystem service provider, is

primarily a way to manage particular benefits from ecosystems, but other ecosystem services may be affected. Three landscapes are analysed in terms of landscape multifunctionality, exemplifying common development trends and emerging upstream–downstream conflicts of interest.

Part IV. Governance and pathways

Chapter 8 addresses the challenge of water governance of landscapes and basins for resilience, sustainability and human well-being. Integrated governance of land and water resources for the generation of ecosystem services, safeguarding development and avoiding crossing critical thresholds, is at the heart of this analysis, integrating global dynamics, the necessity of water governance that ‘safeguards rainfall and wetness in landscapes’. We focus on the blue–green water partitioning, the blue–green trade-off between upstream and downstream activities and strategies for stabilising moisture feedbacks (the source of future rainfall). The chapter highlights governance challenges and transformations needed.

Chapter 9 concludes by addressing insights and pathways for a world transition towards sustainability by adopting a social–ecological systems approach to IWRM. It describes the evolution of water governance and management from a largely blue water focused paradigm from the early 1970s until the early 1990s, which has served humanity quite well in a world of relative water abundance, but which, now, under pressures of growing human demands, water use and the recognition of shifts in water supply and risks of thresholds due to global environmental change, necessitates a new integrated green–blue water paradigm. It summarises the new insights in terms of what we have learnt on water and resilience, and highlights the grand global challenge of feeding a world population within a safe operating space of planetary boundaries. It also notes that the current water governance

paradigm of managing for a stable and predictable supply of water is ill-prepared to deal with the new reality of having to adapt to unavoidable changes.

The four-step resilience chain

As is noted in the Preface, we have written this book in search of a deeper understanding of the new water dynamics in the globally integrated system of people and nature, and to put forward new conceptual systems, perspectives, hypotheses and findings. We believe that science has a responsibility to search for a better understanding of the new challenges facing humanity, and to explore pathways for a sustainable world. All the different chapters analyse the role of water in the biosphere, and how it relates human actions and well-being to the global to local levels. New concepts are introduced, such as water resilience and water stewardship.

Striving for sustainable water stewardship and a resilient biosphere is not about preserving the status quo or circumventing change. It is about having the capacity to deal with change, turning crises into opportunities and shifting on to sustainable pathways. Special emphasis is put on the world’s most water-dependent sector – agriculture.

Governing and managing water for resilience encompasses a range of actions from mitigation to resilience building, adaptation and transformation. The figure below shows these actions in a schematic way, indicating the interconnected challenges facing global water resource management. The range of actions along this ‘change continuum’ includes mitigation to reduce human pressures on the Earth System, building the resilience of Earth System components, adaptation to materialised responses and transformation after regime shifts in social–ecological systems.

Every chapter opens with a short *resilience-oriented ingress*, clarifying how it relates to the above sequence of stages in resilience thinking. The reader

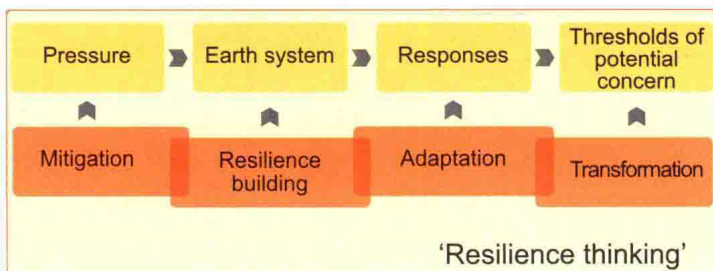


Figure 1.1 The challenges facing the world in the Anthropocene, from a range of pressures to impacts on the Earth System, influence responses from societies and the possibilities of passing thresholds that change social–ecological systems. The chain of actions to build resilience for global sustainability includes mitigation, local resilience building, adaptation and transformation.

will find key components of the different steps in the resilience chain exemplified in the different chapters.

Pressure	Chapters 2, 4, 5, 6: drivers of change, land-use change, feeding humanity, water supply, energy supply, industrial production, urbanisation, technological development and international trade
Earth system	Chapters 2 and 4: land productivity, Holocene equilibrium, GWS, ecosystem functions, biodiversity
Responses	Chapters 2, 5, 6: land degradation, CO ₂ -enrichment, water stress, aquifer overexploitation, virtual water flows, megafires, traps, migration, famine
Thresholds/ tipping points	Chapters 1, 3, 4, 9: desertification, savannisation, salinisation, monsoon weakening, basin closure, aquifer depletion, thresholds of potential concern
Regime shifts	Chapters 1 and 3: Anthropocene dynamics, ecosystem shifts, unproductive land, biodiversity loss, poverty traps, rigidity traps
Resilience building	Chapters 1, 3, 6, 7, 8, 9: land stewardship, moisture feedback, balanced water uses, secured partitioning, environmental flow, planetary boundaries, vital ecosystem functions and services, upstream–downstream trade-offs

Authorship

This book is a result of a joint collaborative effort among all authors. The book was written by synthesising recent research, advancing new insights through a series of author workshops and a distributed responsibility for different chapters among co-authors. The lead authorship responsibility was shared as follows: Chapter 1, lead author Johan Rockström; Chapter 2, lead author Holger Hoff; Chapter 3, lead author Line Gordon; Chapter 4, lead author Holger Hoff; Chapter 5, co-lead authors Mats Lannerstad and Malin Falkenmark, data modelling and analysis Jens Heinke; Chapter 6, lead author Elin Enfors; Chapter 7, lead author Jennie Barron; Chapter 8, co-lead authors Carl Folke and Claudia Pahl-Wostl; Chapter 9, lead author Johan Rockström. Johan Rockström and Carl Folke led the effort together with Malin Falkenmark in distilling key messages and structuring the line of argument on water-related resilience thinking throughout the book.

Production staff

Mats Lannerstad

Book project manager

Jens Heinke

Modelling and data analysis

Hugo Ahlenius, Nordpil

Illustrations and production coordination

Andrew Mash

Language and sub-editing

Acknowledgements

We wish to thank colleagues at the Stockholm Resilience Centre (SRC), Beijer Institute of Ecological Economics of the Royal Swedish Academy of Sciences, the Potsdam Institute for Climate Impact Research and the Stockholm Environment Institute (SEI) for the stimulating discussions during the advancement of this book.

We are grateful to several donors and projects, without which this book could not have been written. Core funding was provided by Mistra, through its support to the Stockholm Resilience Centre, and from the Swedish Research Council Formas, through its Centre of Excellence grant to SRC and SEI. We also appreciate the support from the Kjell and Märta Beijer Foundation, which enabled the engagement of Beijer Institute colleagues, the Ebba och Sven Schwartz Stiftelse and the Swedish International Development Cooperation Agency (SIDA).

The authors greatly appreciate the contributions made by colleagues in the form of the informative boxes on particular issues found throughout this volume: Göran Berndes, Petra Döll, Ellen M. Douglas, Ruud van der Ent, Lance Gunderson, Elke Herrfahrdt-Pähle, Eloise Kendy, Yuanhong Li, Michael E. McClain, Denis Mpairwe, Jay O'Keeffe, Donald Peden, Marcela Quintero, Wilhelm Ripl, Hubert Savenije, Bridget Scanlon, Maja Schlüter, Jan Sendzimir, Will Steffen, Alain Vidal, Brian Walker and Qiang Zhu.

Many research colleagues have contributed significantly to our thinking in this book. We thank

you all collectively, but would like to particularly mention Patrick Keys who assisted in development of several figures and the conceptual thinking; Howard Cambridge, SEI, ran the Nariale water balances in SWAT; Kausal Garg, ICRISAT, kindly developed additional maps for the Kothapally case study, and Philippe Cecchi, IRD UMR G-eau, has provided invaluable understanding of the Nariale catchment development, including providing land-use data over time. Charles Batchelor, independent consultant, kindly shared the case data from Rajasthan, India. Thanks to Dieter Gerten, the leading scientist at the Potsdam Institute on the LPJ model (used for all global estimates of green-blue water flows), and to several water scientists for dialogues stimulating and triggering the writing of this book (in particular, Hubert Savenije, Sandra Postel, Tony Allan, Charles Vörösmarty, Joseph Alcamo, Gretchen Daily, Suhas Wani, Theib Oweis, David Molden and Vladimir Smakhtin).

We greatly appreciate the enthusiasm and deep commitment to the realisation of this book shown by all these contributors.

Special thanks to Hugo Ahlenius for preparing all the figures and tables and leading the final stretch in organising the manuscript for submission, Mats Lanerstad for the management of this highly interactive book project, and to the language editor Andrew Mash, for your invaluable contributions. Without your tireless efforts we would not have been able to finalise this book.

Contents

<i>List of Contributors</i>	xiii
<i>Preface</i>	xv
<i>Introduction to the book</i>	xvii
<i>Acknowledgements</i>	xxi

Part I – A new perspective

1 The role played by water in the biosphere	3
1.1 The fundamental role of water in sustaining life on Earth	3
1.1.1 Water as a strategic agent in building resilience in our societies	3
Box 1.1 Water: the mysterious basis of life	4
1.1.2 Towards sustainable stewardship of freshwater on a planet with finite resources	5
1.2 Water in the era of the great acceleration of human enterprise	6
1.2.1 Humans as an integrated part of the Earth System	7
1.2.2 Acceleration of human enterprise since the 1950s	8
1.2.3 Water concern across a wider range of scales	9
1.2.4 Regime shifts between multiple states	13
1.2.5 The role of water in sustaining a desired state on Earth	16
1.2.6 Human dependence on water for life support	18
1.3 Recognising the boundaries of water use	19
1.3.1 A safe operating space for humanity in the Anthropocene era	20
1.3.2 Humanity approaching planetary boundaries	21
1.3.3 Water is closely interrelated with seven of the nine boundaries	22
1.3.4 The need to consider a sustainable global level of water use	23
Box 1.2 Water: a planetary boundary	25

1.4 The role of water in social–ecological resilience	28
1.4.1 The role of water resources in the resilience of social–ecological systems	29
1.4.2 Water as a control variable of resilience	30
1.4.3 Water as a state variable of resilience	30
1.4.4 Water as a driving variable of future change	30
1.5 Water resilience	31
1.5.1 Facing changes in space and time: addressing efficiency versus redundancy in water resilience	32
1.5.2 Water resilience and surprise feedbacks: linking development, global change and agriculture	33
1.6 A new conceptual framework: water resilience for human prosperity in the Anthropocene era	35
1.6.1 Key insights contributing to a water resilience framework	35
1.6.2 Integration of a green–blue water paradigm with resilience thinking	36
1.6.3 An overarching framework on water resilience for global sustainability and human prosperity	37
1.6.4 The focus of the book: freshwater and the living systems of the biosphere	39
Summary	39
The role played by water in sustaining life on Earth	39
The role of water for resilience	40
Safe operating space	40
Building blocks for the new water agenda	40
References	41

Part II – Living in a human-dominated world

2 Human modification of the Earth System 47

2.1 Humans have altered the Earth System through multiple drivers of change 47

- 2.1.1 Demographic trends 47
- 2.1.2 Economic development 49
- 2.1.3 Urbanisation 50
- 2.1.4 Technological development 50
- 2.1.5 Trade: a decoupling of production and consumption 51
- 2.1.6 Decoupling of production and consumption through foreign direct investment 52
- 2.1.7 Climate change 52
- 2.1.8 Political interactions: national and international policies 53

2.2 Interacting anthropogenic drivers, impacts and feedbacks in the Earth System 55

- 2.2.1 Land conversion and the implications for carbon stocks 55
- 2.2.2 Agricultural expansion and intensification 56
- Box 2.1 Bioenergy and water 57
- 2.2.3 Alterations of ecosystems, ecosystem services and primary productivity 60
- 2.2.4 Alterations of biogeochemical cycles, including water 61

2.3 We now live in the Anthropocene era, and are approaching various water-related tipping points 62

Summary 62

- Human pressures on the Earth System 62
- Earth System responses 63
- An era of significant human influence 63

References 64

3 Balancing on a threshold of alternate development paths: regime shift, traps and transformations 69

- 3.1 Rapid, accelerating and surprising changes in the Anthropocene era 69
- 3.2 What are regime shifts? 70

3.3 Regime shifts can happen across the whole hydrological cycle 71

- 3.3.1 Land use and climate are important drivers of water-related regime shifts at different scales 74
- 3.3.2 Water can be both a control and a state variable in these shifts 74
- 3.3.3 Different regime shifts are more common in some parts of the world 75

3.4 Regime shifts involve both social and ecological processes 77

- 3.4.1 Gradual change in the biophysical domain causes a regime shift in the social domain 78
- 3.4.2 A regime shift in one domain can cascade to other domains 78
- Box 3.1 Water management and resilience in the Goulburn–Broken Catchment, Australia 78
- 3.4.3 Regime shifts may also involve truly linked social–ecological systems 80

3.5 Enhancing resilience in the face of regime shifts 82

- 3.5.1 Focus on slow variables 82
- 3.5.2 Predicting thresholds is important but difficult 82
- 3.5.3 Building resilience through diversity and spatial heterogeneity 83
- 3.5.4 Understanding landscape dynamics 83
- 3.5.5 Managing the spatial disconnects between causes and effects of change 83

3.6 Traps: highly resilient but undesirable situations 84

- Box 3.2 Re-greening the Uganda ‘Cattle Corridor’ 84
- Box 3.3 Restoring ecosystem services in the Andes 86
- 3.6.1 Poverty traps: running on the treadmill with no returns 87
- 3.6.2 Rigidity traps: where past successes are the failures of tomorrow 88
- 3.6.3 A need for transformation: when you are in a hole, stop digging 89

Summary 89

- The role of water in regime shifts 89

- Water-related disturbances and feedbacks 90
- Building resilience to regime shifts 90
- Traps and how to get out of them 90

References 91

4 Crucial functioning of and human dependence on the global water system 95

4.1 The role of water as the bloodstream of the biosphere 95

- 4.1.1 Water sustains all ecosystem services on which humans depend 96

Box 4.1 Water has shaped the face of our planet 97

4.2 The Global Water System as part of the Earth System 100

- 4.2.1 Remote water connections between regions 101

Box 4.2 Irrigation impacts on water and energy budgets 103

- 4.2.2 Remote water connections between regions 103

Box 4.3 Land surface feedbacks and tipping points across scales in the Mediterranean 106

Box 4.4 The origin and fate of atmospheric moisture over continents 109

4.3 Changes, interactions, feedbacks, teleconnections and resilience in the Global Water System 110

- 4.3.1 Land-use change, water and resilience 111

- 4.3.2 Climate change, water and resilience 112

Box 4.5 Coping with a chaotic climate in Australia 114

- 4.3.3 Increasing water demands and resilience 114

Box 4.6 Groundwater use and groundwater stress today and in the future 116

Box 4.7 Sustaining flows in the world's rivers 118

- 4.3.4 Virtual water flows and resilience 120

Box 4.8 A tale of two plains: the consequences of groundwater depletion in the US Central High Plains and the North China Plain 121

4.4 Water-related indicators for water security and food security 125

4.5 Comparative analysis of water scarcity in a number of large river basins 127

- 4.5.1 Water-basin characteristics 127

- 4.5.2 Basin dependence on virtual water imports 128

- 4.5.3 Basin dependence on atmospheric moisture inflow 129

- 4.5.4 Socio-economic factors in water and food security 130

- 4.5.5 Basin dynamics 131

- 4.5.6 Concluding overview 131

Summary 133

The water cycle and vegetation 133

Teleconnections 133

Changes, interactions and feedbacks 133

Planetary and local freshwater boundaries 134

Regional water scarcity exposure 134

References 134

Part III – Food production globally: in hotspot regions and in the landscape

5 Food production: a mega water challenge 143

5.1 Food demand trajectories and water preconditions 143

- 5.1.1 Hunger alleviation and population increase: two strong driving forces at work 143

- 5.1.2 Dietary improvements increase per capita food requirements 146

- 5.1.3 Consumptive water use in agricultural production 149

- 5.1.4 Large yield and water productivity gaps to close 150

- 5.1.5 Consumptive water use depends on diet, food losses and water productivity 151

5.2 Consumptive food water requirements by 2050 153

- 5.2.1 What can be achieved on current cropland? 153