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978-1-107-02419-9 — Water Resilience for Human Prosperity
Johan Rockström , Malin Falkenmark , Carl Folke , Mats Lannerstad , Jennie Barron ,
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Part I

A new perspective

The rainforest of Borneo is one of the greatest biodiversity hotspots in the world, but is under threat from deforestation and conversion to oil palm plantations. This leads to a drier open landscape with higher risk of severe forest fires, and lower moisture feedback, with implications for local regional rainfall.

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Chapter 1

The role played by water in the biosphere

The future of humanity will depend on our capacity to govern and manage water in ways that build resilience in an era of rapid global change and growing indications of large-scale, undesirable risks caused by the unsustainable exploitation of ecosystems. We define this strategic domain of global sustainability as 'water resilience', i.e. the role of water in achieving social–ecological resilience in support of sustainable development in the world. The chapter presents the new conceptual framework for reconnecting our societies to the biosphere and introduces the focus of the book: freshwater and the living systems of the biosphere.

1.1 The fundamental role of water in sustaining life on Earth

Water is understood, and has been for centuries, as a fundamental component of human well-being and socio-economic development. This insight dates back to the ancient water civilisations in human history, ranging from the Mesopotamian irrigation societies of the early years of the Holocene geological era, some 8000 years ago, to the great water-engineering feats of the Egyptian, Maya, Chinese and Roman empires, all the way through to sophisticated local contemporary water societies such as the Bali water temples and the intricate Dutch water-control boards. Nonetheless, there is ample evidence to suggest that we have reached a new situation in which our current way of governing and managing freshwater is becoming obsolete in relation to the social and environmental challenges facing humanity in the coming 50 years.

1.1.1 Water as a strategic agent in building resilience in our societies

We need to rethink how we govern and manage freshwater resources. The purpose of this book is to present a new freshwater paradigm, which originates from several strands of scientific advances and empirical developments. These include, in short, the insights that:

1. humanity may be approaching a point of planetary water overshoot, i.e. that water use will exceed sustainable boundaries at the planetary scale;
2. the social and economic demands for freshwater, driven predominantly by food production, exceed what we can sustainably supply with current policies and practices;
3. we have reached a globalised phase of sustainability in which accelerated global environmental change – ranging from climate change to loss of biodiversity – undermines the ability of the planet to supply freshwater in a way that is conducive to human development on a planet which will have at least nine billion people by 2050;
4. there is increasing evidence of the role of water in sustaining the resilience of ecosystems and thereby access to and the use of natural capital, which is key to our development and our ability to avoid undesirable, rapid and irreversible tipping points in social and ecological systems;
5. water needs to be actively governed in order to sustain terrestrial and aquatic ecosystem functions and services as well as the direct supply of freshwater for societies;
6. water is intimately linked essentially to all other biophysical processes on the planet that regulate the functioning of the Earth System and thereby its ability to support human development – from the generation of biomass to the regulation of climate; and
7. water, at any given location in the world, can no longer be governed and managed without an active understanding of the drivers of and impacts on other spatial and temporal scales, from the local to the global, for now and the decades and centuries to come.

What emerges is a deeper understanding of the fundamental role played by water in sustaining the living biosphere on Earth (Falkenmark and Chapman, 1989), as well as the role of water as a key driver of change (IPCC, 2007) and as a strategic agent in building resilience in our societies (Falkenmark and Folke, 2003). The above insights are currently maturing in the scientific world, at a time of increased social, economic and ecological turbulence across the globe. We are seeing increasing evidence of abrupt changes and undesirable social feedback – of financial and social crises moving from the local to the regional and the global scales – but there is also evidence of a similar globalisation of environmental change, generating unexpected interactions between social and ecological changes, posing new challenges for human development. Water plays a central role in this new era of social, economic and ecological globalisation.

This book is written in the context of the new water-related turbulence in the world. We address the question of how the governance and management of water need to change to enable a transition to global sustainability that meets human needs for water and water-dependent ecosystem services (such as food, medicine and bioenergy) while building resilience to unavoidable change.

The new social–ecological global water complex is central to our understanding of the threats to human development, and key to identifying new ways of transforming water governance and management in a direction that supports human development in the future. It is an interesting and challenging paradox that as we realise the growing and excessive human pressures on finite freshwater resources on the planet, we also better understand our total dependence on freshwater not only for food, industry and the domestic water supply, but also for the generation of fundamental or essential ecological functions and services in terrestrial and aquatic ecosystems, which in turn form the basis for social–ecological resilience.

Box 1.1 Water: the mysterious basis of life

Wilhelm Ripl, Technical University of Berlin (Professor Emeritus)

One dazzling property of water – its ability to determine the lifespan of structures at several different levels of organisation and of the water cycle – is linked to its chemical dissipative property: the partial dissociation of water into protons and electrons. Its molecular structure, with an angle of about 105° between the two hydrogen atoms and the oxygen atom, helps to make water a polar agent and the most abundant solvent on Earth for salts and even organic compounds. When salts are dissolved, anions and cations are evenly distributed in the solvent water. Water molecules show paramagnetic properties, and ionic solutions show electric properties.

Water reacts with carbon dioxide to form carbohydrate radicals that in turn combine to polymerise into glucose. This reaction system reacts with nitrogen ions and continues reacting to give long-chained fibre structures of, e.g. cellulose or, say, starch. Preferentially, molecules containing carbon and nitrogen form long-chained complex molecules with hydrogen and oxygen.

Water plays crucial roles as a transportation, reaction and cooling medium in self-organising ecosystems. According to Odum (1969), ecosystem development is a two-phase process. In the establishment phase, pioneer plants prove to be the most efficient at utilising nutrients and water for rapid reproduction, and thus cover the available empty surface or space. When the available space is filled and limitations occur, a change in strategy is forced by negative feedback. The maintenance phase takes over in which assemblages that develop matter-recycling capabilities, characteristic of 'mature' ecosystems, appear. In the maintenance phase, ecosystems are analogous to organisms designed in a cellular way, and are known as dissipative ecological units (DEUs). Five functionally defined components are necessary to form such a unit (see Figure 1.b1.1): (1) three types of organism – green plants (primary producers), bacteria and fungi (decomposers) and the food chain (all kind of animals as grazers and predators of all kinds of organisms, opening up space for growth and reproduction, and keeping the system efficient); and (2) two non-living components – dead organic debris, which serves as a stock of energy, nutrients and minerals, and water, which serves as the cooling, transportation and reactive medium.

The green plant usually has a double function: as a source of energy for all kinds of organisms and as an active water pump, sucking water through the roots to the leaves and maintaining the process of transpiration which is coupled to the photosynthetic processes in the root zones by way of feedback. Evapotranspiration coupled with net production reduces the amount of water in the soil zone capillaries and gives air access to the debris layer, enhancing the activity of decomposers and providing

Box 1.1 (*cont.*)

mineralised nutrients for the production process just at the time when they are needed – and almost without energy, nutrient or mineral losses.

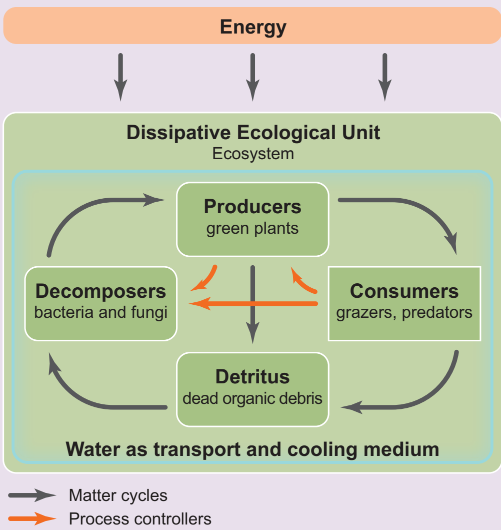

Figure 1.b1.1 Water as a transportation, reaction and cooling medium, and the Dissipative Ecological Unit (DEU) (Ripl and Hildmann, 2000).

Water is not only the bloodstream of the landscape – as has been stated insightfully over the decades – it is also the bloodstream of human societies and of the human enterprise on Earth. It is, of course, late in the day to be deepening and widening our understanding of the role of water in human development. We have reached a precarious situation for humanity, with large and growing demands for water in the world, occurring in an era of rapid global environmental change, which could trigger a serious undermining of freshwater availability in the future. This is a challenging predicament. In a situation where we face a tougher and tougher battle to secure freshwater for immediate human needs in an increasingly populated world, we now need to incorporate into our thinking, policy and practice the need to secure and be active stewards of freshwater flows to sustain ecosystem services and resilience outside the traditional water sector. We thus face the urgency of meeting rapidly rising social needs for water, while simultaneously safeguarding an increasingly large proportion of freshwater resources for ecosystem services and resilience. This includes freshwater to sustain biodiversity, carbon sequestration in soils and the ability of landscapes to buffer storm flows to avoid disastrous floods. Simply put, at a time when we may be running short of freshwater to sustain the traditional 'economic water sectors' – agriculture, industry and domestic needs – we are increasingly realising the need to secure water for ecosystems not for their preservation, but for our ability to prosper in the future.

1.1.2 Towards sustainable stewardship of freshwater on a planet with finite resources

Significant advances on several scientific fronts have contributed to the insight that we need to develop a new integrated paradigm on the governance and management of water resources. Several components of a new approach to water and development either already exist or are advancing rapidly, including, for example, the management of environmental water flow in aquatic ecosystems, the integration of climate change impacts on water resources at 'governing' scales (e.g. river basins) and advances in frameworks for managing land-based ecosystems to regulate water flows (e.g. managing forests and the spatial configuration of rivers and wetlands).

There have also been significant scientific advances across disciplines that converge towards a social–ecological approach to integrated land and water resource management from the local to the global scale. These include, for example, water resources research focused more actively on the role of evapotranspiration in generating ecosystem functions and services (Enfors, 2013; Jansson *et al.*, 1999; Liquete *et al.*, 2011; Rockström *et al.*, 1999), a growing recognition of water-induced thresholds (Gordon *et al.*, 2008), the role of freshwater in terrestrial ecosystems (Poff *et al.*, 1997; Poff and Zimmerman, 2009; Richter *et al.*, 1997), research on IWRM, broadened out to a stronger focus on land and water (de Vries and de Boer, 2010; Duda, 2003), a stronger integration of water and land management into Earth System science (Canadell *et al.*, 2007; Lambin and Geist, 2006) particularly on climate change and water (Alcamo and Henrichs, 2002; Bogardi *et al.*, 2012), a deeper focus on the role of water in complex system dynamics and tipping points in ecosystems (Scheffer *et al.*, 2001), advances in institutional research focused on the need for adaptive co-management across scales to address the complex and intertwined challenges of water,

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ecosystems and development (Pahl-Wostl *et al.*, 2012) and managing common pool resources and property rights (Cole and Ostrom, 2011).

Our task in this book is to integrate these strands in order to put forward a social–ecological resilience-based approach to the way we understand and approach water resources and human development in an era of rapid global change. To achieve this, water resource governance and management needs its own paradigm shift, away from a focus on securing freshwater supply and minimising the negative impacts on freshwater resources, to a broader perspective on freshwater in social–ecological systems for ecosystem services and resilience, in order to avoid undesirable feedback and promote adaptive capacity and desirable transformations.

The purpose is not only to develop a new approach to sustainable water use. It is also to establish the foundations for an approach to water governance and management which recognises that the expected increase in water turbulence in the world, triggered by abrupt shifts in water flows, and rising risks of water-related regional or global traumas, arising from shifts in the stability and functioning of the biosphere, cannot be addressed with truncated approaches to water.

We build this approach on the different strands of advances across the social and natural sciences related to water resources. This is not a blueprint. It should rather be seen as an effort to draw logical conclusions from the latest science on water resources and how water relates to global change, resilience, ecosystem services and development. From these, we propose a framework – to be further explored and advanced by scientists, in education and by water professionals – for how to proceed towards the sustainable stewardship of freshwater on a planet with finite resources, which has entered a new geological epoch – the Anthropocene, or the global phase of human pressure on Planet Earth.

1.2 Water in the era of the great acceleration of human enterprise

The water situation is becoming increasingly precarious. The number of hungry people in the world remains stubbornly high, approaching a staggering 1 billion (FAO, 2012a). The planet is more or less committed to another 2 billion inhabitants by 2050 (UN DESA, 2011). Just to meet the basic food requirements of the currently malnourished and the unavoidable growth in the world's population will require an increase in world food production of a staggering 50–70% (Godfray *et al.*, 2010; McIntyre *et al.*, 2009; Tilman *et al.*, 2011). Furthermore, the world is experiencing unprecedented levels of growth in the new global middle class, predicted to rise from less than 2 billion to over 4 billion in the next 30 years (Kharas, 2010), driven by developments in China, South Asia and Latin America in particular. This causes rapid shifts away from vegetable-based diets to water-greedy meat-dominated diets.

This increasing wealth and demand for food is potentially the most dramatic trend in terms of the impact on freshwater resources in the future. Food production – and particularly livestock production in terms of the amount of water input per unit calorie output – is by far the largest direct water-consuming sector in society. To produce – using current agricultural practice – an adequate diet for an adult requires in the order of 1300 m^3 of freshwater per person per year, which equates to 3.5 to 4 m^3 of freshwater per person per day, or 80 to 90% of total freshwater use per person, i.e. some five times higher than water for domestic and industrial purposes. It is estimated that annual world food production consumes 5100 km^3/year of freshwater (see Chapter 5 in this volume). Recent assessments of the additional water required by 2050 for all forms of food production to lift people out of hunger and feed the growing world population amount to 1500–4000 km^3 per year (McIntyre *et al.*, 2009). This on a planet where a significant number of the larger rivers in the world, such as the Colorado river, the Rio Grande and the Yellow river, run dry before they reach the ocean, due to the overuse of freshwater, primarily for irrigation (Molle and Wester, 2009).

Despite remarkable success stories in terms of the accelerated exploitation of freshwater on Earth through massive water-engineering feats –the world has over 6000 km^3 of storage capacity for water behind large dams – we know that approximately half the world population of ~7 billion people already faces various degrees of water scarcity, with 30% facing severe stress (Kummu *et al.*, 2010). As shown in Figure 1.1 various indicators of water infrastructure show an accelerated pace of expansion over the past 100 years. Despite this remarkable expansion, which has come at a very high cost for the environment, the world is far from keeping pace with growing human water shortages, and the overuse of runoff water is

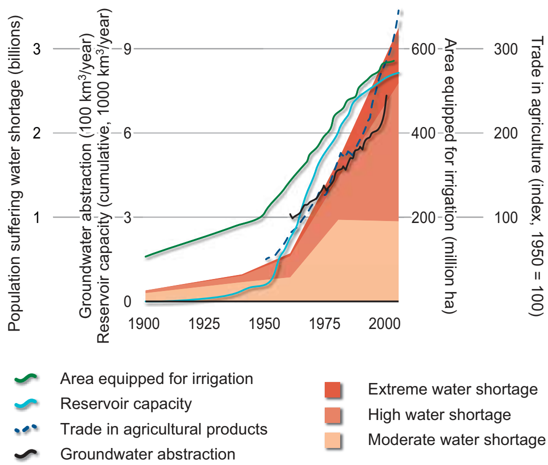

Figure 1.1 Population facing water shortage, using the Falkenmark index of average per capita blue water availability in each country. < 500 m^3/year means absolute or extreme water shortage; 500–1000 m^3/year per capita is severe or high water shortage; and 1000–1700 m^3/ year per capita is moderate water shortage. The lines provide several indicators of water infrastructure development in the world, ranging from reservoirs to abstraction of groundwater (adapted from Kummu *et al.*, 2010, based on Chao *et al.*, 2008; Freydank and Siebert, 2008; Wada *et al.*, 2010; WTO, 2012).

undermining the ability of aquatic freshwater ecosystems to fulfil crucial ecosystem functions and services (Millennium Ecosystem Assessment, 2005). This is an absolutely critical point. Furthermore, human-induced climate change undermines the availability of freshwater in many regions, and will increase the frequency and magnitude of extreme events such as droughts and floods (IPCC, 2007).

To these water-related drivers must now be added the interacting complexity of social and environmental systems on the local to the global scale, which directly influence the availability and use of freshwater. This requires a deeper integration of the human dimensions of water resource development, the role of freshwater in global change processes – ranging from climate change to biodiversity loss and global trade flows – and the role of water in building social and ecological resilience to various shocks and disturbances.

1.2.1 Humans as an integrated part of the Earth System

The availability of water at the river basin, regional and global levels has long been regarded as predefined – a given, predictable volume that oscillates within a relatively narrow natural variability, which can be estimated based on empirical measurements of runoff in major rivers. Moreover, this is thought to change only slowly, in incremental and therefore controllable ways. This is the basis of water resource governance and management. This water-centric, 'mono-scale' approach, always depicted by stable water resource data – as hydrographs of base flow and total runoff for the major river basins world – fails to recognise that the availability of water changes rapidly according to a broad set of social–ecological drivers. These range from rates of local land degradation or regional deforestation in rainforests, which affect moisture feedback and therefore rainfall patterns, to the impacts on water availability of climate change and air pollution.

A key message of this book is that humans are an integral part of the Earth System, and water availability for human needs is intimately connected to dynamic changes in the biophysical systems of the Earth. Water cannot therefore be dealt with in isolation from land management, climate mitigation, ecosystem stewardship, air pollution abatement and other key social and economic activity that exploits natural capital at different scales. Water determines the outcome of essentially all the processes on Earth that matter for human well-being, from food production to the temperature of the atmosphere. In turn, water is affected by essentially all the environmental processes influenced by humans, from loss of biodiversity to emissions of greenhouse gases.

This is what makes the governance and management of freshwater so challenging – well beyond the conventional, truncated approach to water resource management and development. Water is a determining factor behind the functioning, structure and stability of the biophysical systems on Earth, all of which are being put under tremendous stress by human beings. Water does this by regulating the climate system – as the most important greenhouse gas. It is a prerequisite for all biomass growth and therefore all living species on Earth, and also sets the pace of the global cycles of carbon, nitrogen and phosphorus, is an agent for transportation and a solvent of chemical compounds. At the same time, water delivers human well-being, beyond the usual focus on the conventional domestic, industrial and agricultural sectors of water supply, by generating ecosystem functions and services from terrestrial and aquatic water use and providing the basis for social–ecological resilience.

This means, paradoxically, that a book on integrated water resources logically starts outside of the hydrosphere, by focusing on the trends and dynamics, in relation to water, of the other systems on Earth, covering the biosphere, the atmosphere, the stratosphere and the cryosphere.

1.2.2 Acceleration of human enterprise since the 1950s

What makes the current global water situation so different from the past is that the Earth has entered a new geological era, the Anthropocene, in which humanity constitutes the major driving force of planetary change (Crutzen, 2002a, b; Crutzen and Steffen, 2003; Crutzen and Stoermer, 2000). There is evidence to suggest that humanity has become the driving force behind abrupt changes on a par with or even greater than (particularly in terms of pace) natural geophysical forces, such as the position of the planet in relation to the Sun, and geological events, such as earthquakes and volcanic eruptions. There is also evidence that we have reached a point of human-induced global ecological overshoot on a planet with finite resources (Ewing *et al*., 2010; Loh *et al*., 2005).

These two facts together completely change the agenda for sustainable development. The United Nations Conference on Environment and Development (UNCED) process in Rio in 1992 made tremendous progress in pursuit of sustainable development through the conceptual advances in 'Our Common Future' (Brundtland, 1987) and the development and publication of its implementation plan, Agenda 21, in 1992 saw the birth of the three leading United Nations conventions on the environment (the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD) and the Convention on Biodiversity). Nonetheless, the dominant way in which nations choose to address environmental problems remains embedded in a sectoral and largely local to regional approach, aimed at minimising environmental impacts while securing social and economic development. It is important to remember that the sectoral approach to sustainable development that evolved out of the UNCED process also had a big influence on the water resource agenda. Thus, framed by the UNCED process, the Dublin principles for IWRM were born in 1991 (International Conference on Water and the Environment, 1992). The IWRM was framed around a set of basic principles: water has an economic value and its competing uses should be recognised as an economic good; water should be recognised as a scarce and vulnerable resource; the need for participatory approaches to water resource management; and the key role played by women in water management. These focused on managing runoff for societal purposes, i.e. a heavily runoff or blue water-centric approach to the governance and management of water, and one moreover that is disconnected from cross-scale interactions.

Now the situation has changed. Major scientific advances since 1992 clearly show that we are not only in the Anthropocene era, but have reached a globalised phase of sustainable development in which the aggregate effects of all local uses of natural capital directly influence environment processes at the regional to global scales. Water is no exception. That this globalised phase of humanity affects our life-support systems – of which water is the most fundamental – was recognised in the run-up to the United Nations Rio+20 Earth Summit, which took place in Rio de Janeiro in June 2012, where the world gathered 20 years after the UNCED conference and 40 years after the Stockholm conference on environment and development. The UN Secretary-General, Ban Ki-Moon, established a Global Sustainability Panel, which delivered a pre-Rio+20 report, 'Resilient people, resilient planet: a future worth choosing', which was the 'Brundtland equivalent' of the 2012 summit. The report concluded that the current world development paradigm is not sustainable, and that the risk of unacceptable tipping points in the Earth System, due to human-induced global environmental change, needs to be recognised and integrated into our development paradigm. The Rio+20 summit decided to transform the Millennium Development Goals (MDGs) into a set of global Sustainable Development Goals (SDGs), with the aim of addressing social and economic development in the context of global sustainability.

The most important evidence of humanity having entered the Anthropocene epoch was published in 2004 in a synthesis of Earth System science by the International Geo-Biosphere Program (IBGP) (Steffen *et al*., 2004). We refer specifically to this publication not only because it is such a scientific achievement, but also as a reminder of the timing. It is important to remember that it was only in 2004 that we were presented for the first time with an integrated synthesis of the state of the planet under anthropogenic pressures.

This integrated analysis shows a convincing trend of accelerated impacts on biophysical systems on Earth due to human pressures. It is not, as is often portrayed, only carbon dioxide emissions that have increased in an exponential way since the industrial revolution in the mid-eighteenth century. In fact, a broad range of the biophysical processes that constitute the basis for human development show the same classic 'hockey-stick' pattern of rise over the past century and millennium. Figure 1.2 shows how the trends for all the processes accelerate in the mid-1950s. This is now defined as the point of the great acceleration of human enterprise. It seems increasingly clear that 10 years after the end of World War II, there were enough people on the planet – a mere 3 billion – and a large enough proportion benefiting from the upscaling of industrialised society to create, for the first time in human history, an ecological imprint on Planet Earth. This is all the more remarkable because not only were we few compared to today, but only a minority of the inhabitants of the planet were the predominant source of the escalation in environmental problems. It was the rich minority, amounting to around 20% of the world population, who benefited from fossil-fuel-based industrialisation. There are empirical datasets covering essentially all the environment processes that generate human wealth, including emissions of greenhouse gases, interference with the global nutrient cycles of nitrogen and phosphorus, air pollution, deforestation, land degradation, overfishing and loss of biodiversity.

The social drivers generating this accelerated change, not surprisingly, show a similarly accelerated trend of change since the mid-1950s (Figure 1.2). The situation for water follows a similar pattern. The social driving forces behind pressures on finite freshwater resources are largely the same as for the Earth System as a whole, including population growth, the expansion of agriculture, consumption patterns, the globalisation of trade, and the growth of transport and energy use. The global drivers and observable impacts on systems directly related to water also show an accelerating negative trend over the past 60 years (Figure 1.3).

In sum, the operation of the global water cycle has also entered the Anthropocene era (Meybeck, 2003), and human pressures are now the dominant force determining the functioning and distribution of the global freshwater system. This includes both global-scale changes in river flows (Oki and Kanae, 2006; Shiklomanov, 1998; Shiklomanov, 2000) and shifts in vapour flows from land-use change (Gordon *et al.*, 2008). The challenge is to recognise the water implications of this human expropriation of natural capital from the Earth System. In natural capital we include both the non-living, abiotic, and the living, biotic, components of the Earth System, i.e. both finite natural resources, such as fossil energy sources, phosphorus, land and freshwater, and the living biosphere – all the living species in our landscapes and seascapes. The water implications of the human use of natural capital can be expressed under three broad headings, which are explored in-depth in this book:

- Human pressure on finite freshwater resources threatens the future ability to provision key ecosystem services, such as food, a biological gene pool, bioenergy and key ecosystem functions such as pollination and climate regulation.
- We are at risk of hitting hard-wired biophysical thresholds on a regional and planetary scale, which could induce abrupt changes in the functioning of the Earth System. Freshwater is at the heart of this concern.
- Freshwater is both a driver of change – through changes in freshwater flows and water availability affecting global change processes – and a victim of change, affected by global social–ecological change, e.g. through climate-change-induced shifts in rainfall patterns.

Freshwater determines the quality and quantity of all terrestrial and aquatic ecosystem services in human societies, and is therefore an, or even *the*, underlying determinant of social and economic growth.

Water also presents a strong social dynamic, where the impacts of human pressures on finite water resources are a reflection not only of an increasing global population, but also of a rapid increase in relative per capita water use, which in turn is a reflection of increased human wealth. This is demonstrated by the fact that freshwater withdrawals increased almost twice as fast as population growth, which increased exponentially, over the past 100 years (Lundqvist, 2000).

1.2.3 Water concern across a wider range of scales

The Anthropocene era, in which water is being impacted by a large number of global social and ecological change processes, while at the same time

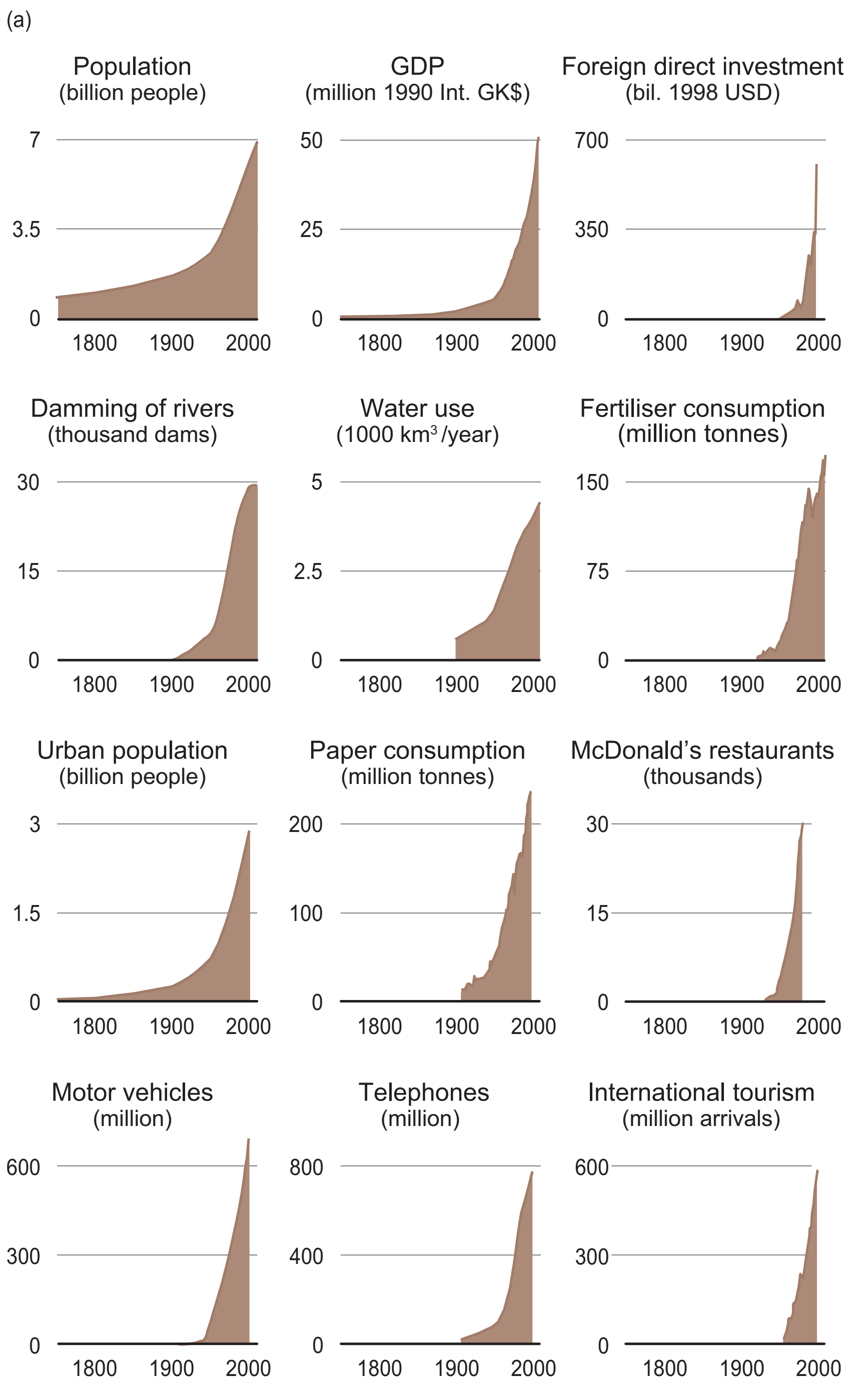

Figure 1.2 Processes affected by human change in the great acceleration of human enterprise. (a) The development of key social processes, such as population growth, water use, and consumption of various resources and goods. (b) The implications of the exponential rise in human pressures on the Earth System, for key environmental processes ranging from atmospheric concentration of greenhouse gases to loss of biodiversity (adapted from Steffen *et al.*, 2004).