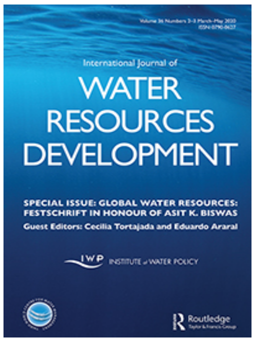

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Water resilience and human life support - global outlook for the next half century

Malin Falkenmark

Stockholm Resilience Centre, Stockholm, Sweden

ABSTRACT
This article highlights green and blue water functions in the densely tied global water network, stabilizing the life support system and generating ecosystems and ecological services. Essential water challenges of the next half century are analyzed, identifying low-latitude dryland vulnerability and sharpening hydro-social water constraints. Attention is drawn to global warming, and the crucial roles of water and agriculture in stabilizing Holocene climate below a fatal warming of +2 °C or more. The article ends with a hydro-climatic, hydro-social and hydro-ecological outlook on how to principally navigate a resilient life support system stressed by climate change, population growth and increasing demands.

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Green-blue water; water functions; climate change; land use; dryland agriculture; water constraints

> Water permeates life on Earth. Water is essential as an enabler and sustainer both of life such as plants, animals, and humans, and of human civilization. The concern for this fundamental truth in fact increased after NASA's Mars missions. One of its conclusions was the urgent need to pay increased interest to the importance of the water cycle for life on this Planet – the only planet where water can exist in liquid form. (International Water Resources Association, 1991)

Introduction: Why?

Considering the global water situation towards the next half century, Rockström et al. (2014) stress that 'two giants collide – water demand from nine billion people and water impacts from a rapidly growing economy'. Ability to successfully approach this challenge will demand a broader water paradigm, connecting as essential components (1) green water in the soil with blue water in rivers and aquifers, and (2) land and water integration. A key strategy will be to build resilience and sustain rainfall, by *inter alia* sustaining forested areas as critical zones for moisture feedback. Stewardship of the landscape has to be seen as the core strategy. Water is not only the bloodstream of the biosphere, but also the key to resilience in social-ecological systems.

In this situation, a core question for the next generation to raise is how further future stresses, caused by ongoing climate change, continued population growth, increasing human demands and intensified land use change, will continue to disturb the life support system and how the interactions between water flows, water functions and roles, and

CONTACT Malin Falkenmark malin.falkenmark@su.se

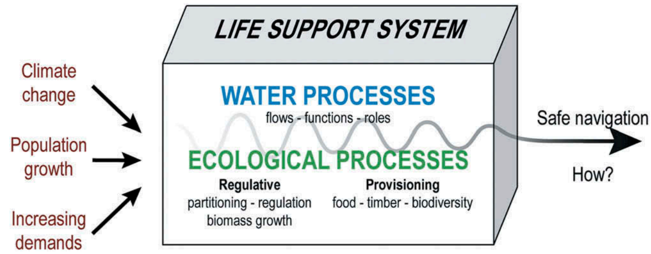


Figure 1. An expanded way to think about water as part of the life-supporting system. Diagram by the author.

relevant ecological processes like food production, timber production and biodiversity will be reflected in the life support system.

Critical questions worth focusing on, will be how to keep the planet in the present favourable Holocene-like conditions with a relatively stable climate, and how to achieve this by safe navigation of the life support system (Figure 1). What transformations will be needed? What shifts in governance approaches in terms of scope, scale, and speed will be required? *How* can that be done? And how closely will the UN's Sustainable Development Agenda reach this overarching goal?

The aim of this article is to identify some of the most essential components of the answers sought for the core questions raised in Figure 1. We will consider where the current understanding of the planet's biological playing field, of its many green and blue water functions and its different ecological processes, will lead. We will at the same time try to identify essential near-future constraints in both the green and the blue water realms. The time horizon will be the next half century.

Water: core of the life support system

Earth is the only planet in the solar system where liquid water makes life possible. The other planets are either too hot (like Venus) or too cold (like Mars). And while the energy transformations from ice to liquid and from liquid to vapour are essential for spreading solar heat across the surface of the Earth, one of the three core green water functions is to keep the Earth's temperature 30 °C warmer than it would be without H_2O as a key compound characterizing this planet. Water determines all processes on Earth of importance for human well-being, but is at the same time itself affected by all environmental processes influenced by human activities (Rockström et al., 2014).

Water's hidden roles and functions

As the core component of the global life support system, water is active in terms of having both water flows (playing different water roles) and water functions, together constituting the global bloodstream. In a recent article, Stockholm Resilience Centre scholars analyzed these hidden roles and core functions of water in the life support system (Falkenmark, Wang-Erlandsson, & Rockström, 2019). During circulation, water plays three roles: in its *controlling* role, it is a key in sustaining all life, generating ecosystem services and functions in both terrestrial and aquatic systems; in its *state* role, it is a victim of change, responding for example to land-use change and pollution; and in its *driving* role, it may cause social shocks by floods and droughts, or as a driver of conflict. These three roles exist simultaneously and interact dynamically.

There is also a dense interaction with the land through which water passes, together generating the life support system. Through this interaction, a set of water functions are active in transfer of human water uses and activities, as a rule causing water partitioning effects. There is a long series of such *core water functions*, active around the water cycle (Figure 2). The water-cycle circulation, together with the dense system interaction, stabilizes the life support system, making it water resilient.

Green water functions are three: *regulatory*, involving all the functions of soil moisture, evaporation and transpiration flows to regulate the Earth's energy balance and climate system through for instance carbon sequestration and water's ability as a greenhouse gas; *productive,* such as evaporation and transpiration to sustain food, biomass and bioenergy production; and *moisture feedback*, regulating the water cycle over land by evaporation. Water also has five different *blue water functions*: water for societal *supply*, available to be withdrawn; water as a *carrier* of nutrients and pollution, and for transport; water as *state*, involving the function of water masses and storages; the *productive* function, for irrigation

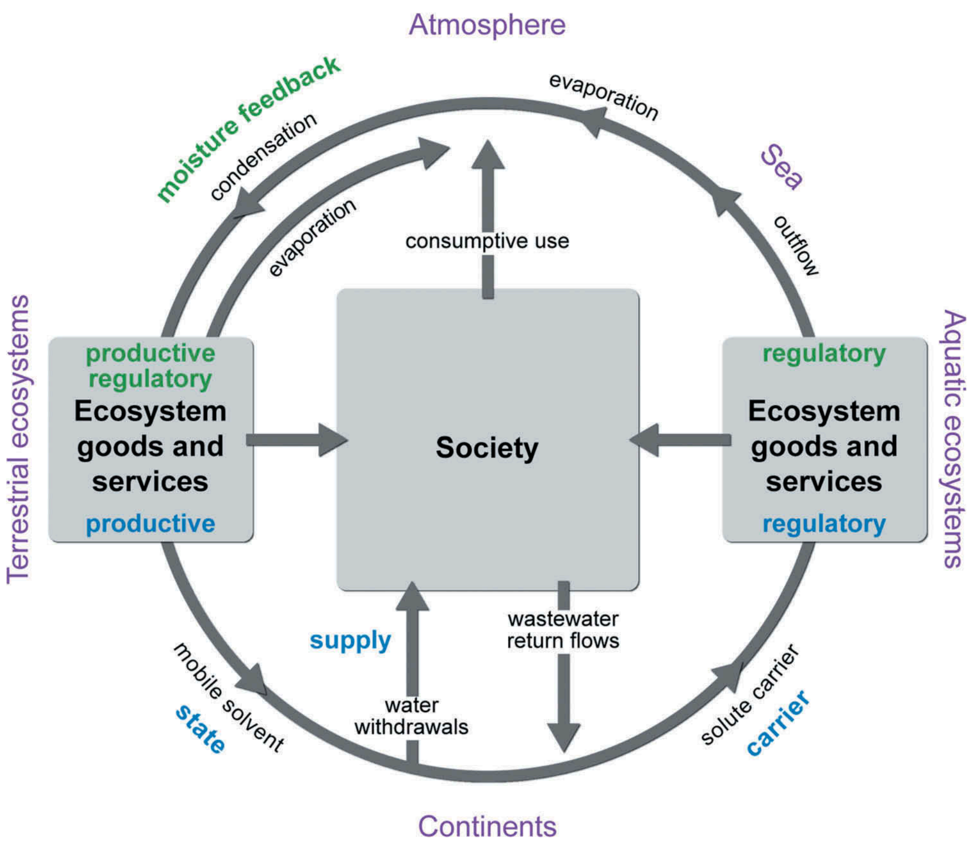


Figure 2. Water functions appear in many different positions in the water bloodstream. *Source*: Falkenmark et al. (2019).

to produce food, and water to sustain aquatic growth; and the *control* function, regulating the Earth's energy balance, sea levels and geological processes, such as subsidence.

Together, all these water flows, roles and core functions profoundly interact with the land system, forming a dense interactive network. This network constitutes the life support system of humanity, and is active through two kinds of ecosystem services: *regulating* ecosystem services, such as weather dynamics, albedo, carbon sequestration, land and aquatic habitats and water flow partitioning; and *provisioning* ecosystem services, such as provision of food, timber and energy. This intricate global system thus forms a densely tied water-related network, crucial for building the water resilience of ecosystems, and essential for the ability to generate ecosystem services.

Dense interaction with ecosystems

Human land-use activities tend to generate water partitioning phenomena, disturbing human roles and functions and contributing to a rich variety of typical ecosystem disturbances. Water flow alterations change water roles and functions, reflected in ecosystem degradation. Over time, such processes will modify ecosystems in a variety of ways. A rich archive of historical evidence shows that past land and water mismanagement has been degrading water functions (Falkenmark et al., 2019). The result is a long array of partial degradation in terms of severe ecosystem collapses and regime shifts. Desertification may develop after dryland crusting; groundwater rise and waterlogging may develop after alterations in the root zone; savannization may develop as a result of altered evapotranspiration reducing atmospheric water vapour and its condensation into new rainfall; monsoon change may develop in regions where large-scale irrigated agriculture has been increasing evapotranspiration; aquifer depletion may develop where groundwater withdrawals have been larger than natural groundwater recharge; and eutrophication may develop in systems overloaded with nutrients. Water-related societal problems may build up step by step, eroding water resilience. Recent cases are the Somalian drought, the Cape Town water crisis, and the Arab Spring / Syrian conflict. In the end societies may even collapse, as did the ancient Mesopotamian and Mayan civilizations. Such degradations humanity will have to live with, persist in, adapt to or transform.

Global life support system

Still, today, the dominant worldview tends to disconnect human progress and economic growth from fundamental interaction with the biosphere (Rockström et al., 2014; Rockström, Falkenmark, Lannerstad, & Karlberg, 2012). The sustainability agenda for humanity must urgently shift towards seeing people and nature as interdependent systems, in which much stronger emphasis is placed on managing water for social-ecological resilience and sustainability.

Thus, the twin objectives of global water resilience and human development require modernized water thinking, acknowledging that water is, as stressed by Rockström et al. (2014), the most important greenhouse gas and a prerequisite for all biomass growth. It sets the pace of global cycles of carbon, nitrogen and phosphorus; it is an agent of transportation and a solvent of chemicals; and it provides the basis for social-ecological resilience. The global life support system, the central role of water in both ecosystems and society, and the intricate linkages between the components make a system approach essential.

Awareness is required of the risk for global change in response to links between driving forces and potential tipping elements, of relevance for long-term land use planning. Such tipping elements may originate from three types of driving forces (Rockström et al., 2014): water-use driven (water crowding), land-use-change driven (food production, deforestation, afforestation), and climate driven (global warming, droughts, floods).

Without planetary stewardship for water resilience, it is difficult to see how the world can eradicate poverty and hunger, two of the Sustainable Development Goals. This makes understanding water's profound involvement in the interlinkages between societies, ecosystems and the Earth System (Folke, 2003; Rockström et al., 2012) essential. Water resilience, i.e. safeguarding a well-functioning water bloodstream, is a central prerequisite for global sustainability (Falkenmark et al., 2019). At the core of the life support system are the functions of both blue and the green water and the ecosystem services generated by their interaction with the land they pass through, in other words the water, land and ecosystem processes in landscapes. (Figure 3). Manoeuvring this system to achieve human well-being involves governance and management of its components and of the social transformations involved, to secure provision of ecological services and social-ecological resilience.

This system approach involves a switch from our past conceptualization of 'the environment' (Falkenmark, 2008) – a negative approach – to highlight its constructive components, i.e. the ecosystem services that form its core. Over time, the scale of water

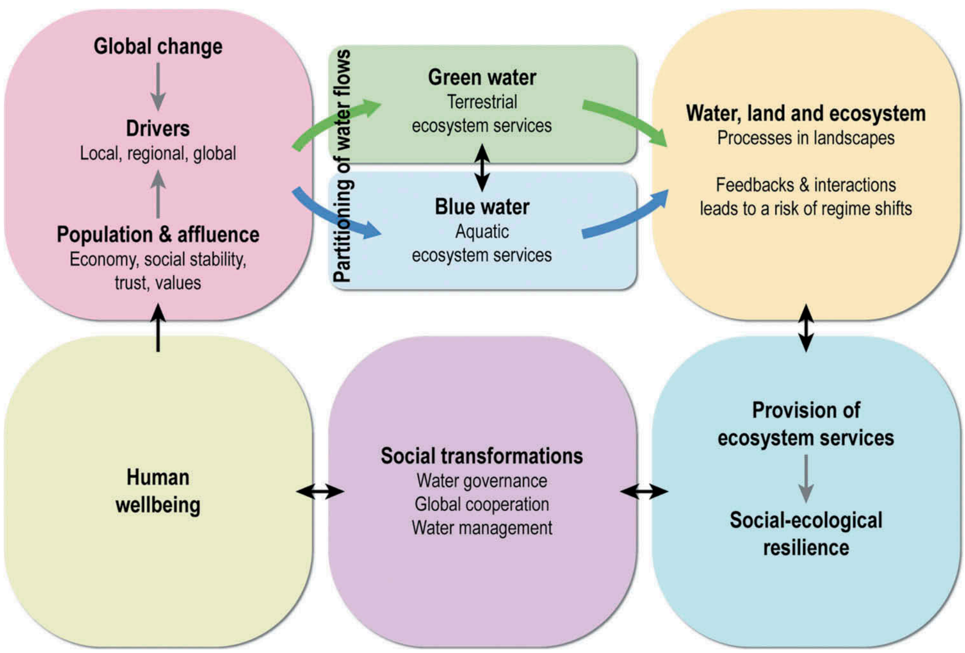


Figure 3. Interconnectedness of social drivers and processes in the landscape, where blue and green water interact with land and ecosystems in producing goods and services to secure human well-being. Adapted from Rockström et al. (2012).

impacts has increased with human activities such as withdrawals, land use change, air pollution and climate change (Rockström et al., 2014). Rainfall patterns, such as the monsoon, have changed. The function of large-scale biophysical systems, such as the tropical rainforests, has also changed.

In other words, the key is to shift from yesterday's focus on how to reduce the environmental impacts of human activities towards what is required to connect our societies with the biosphere supporting them. What is needed is a transition towards development of a safe, just, stable and resilient society within the biospheric playing field provided by the Earth System.

After this deep dive into the details of how water is active in generating ecosystems as an important component of generating resilience, we will now dive into two broad water-related problem areas: the giant task of learning to master the atmospheric water interaction of vast tropical drylands, inhabited by a rapidly expanding population of poor farmers; and the foreseeable challenge of securing household water supply in broad arid regions with multiplying populations.

Dryland water interaction with the atmosphere

Water-based categorization of landscape types

Agriculture is the largest water user on the planet, and the largest shaper of landscapes (Rockström et al., 2014). The two water functions involving the largest global amounts of water are both green: productive function (biomass) and moisture feedback (Falkenmark et al., 2019). In view of the global importance of arid lands for many millions of people, Weiskel et al. (2014) developed a water-related categorization of landscape types, based on the dominant horizontal and vertical inflows and outflows of water through a landscape unit (Figure 4). Input to landscapes is rainfall and/or inflow. In humid regions, landscapes are dominated by blue outflows (river flow), in drylands by vertical green water flows (rainfall and evaporation). There, development has to take a different form depending on green water practices, protecting or restoring green water storages in terms of soil moisture, and managing green water flow, i.e. precipitation and evaporation.

Sink region vulnerability

Agricultural and land use decisions involve direct impacts on vertical water flows, i.e. the amounts of water that enter and leave the atmosphere. Keys (2016) showed that the removal of vegetation in Mato Grosso, Brazil, altered the amount of rainfall over the land downwind, and even the seasonality of the rainfall. Such moisture-recycling-related findings imply that vegetation changes in one location may cause large changes far away in rainfall, soil moisture, crop production and even blue water flows (Figure 5).

Upwind land cover is critical to sustain precipitation in water-stressed downwind areas and allow agricultural production there. This link between upwind land use and downwind rainfall is especially relevant in drylands, where water is a limiting factor for agricultural production, since most rain evaporates before reaching a river, so that irrigation is difficult. Water-stressed areas are water constrained, and semiarid areas with aridity index P/EP (quotient between precipitation P and potential evaporation EP)

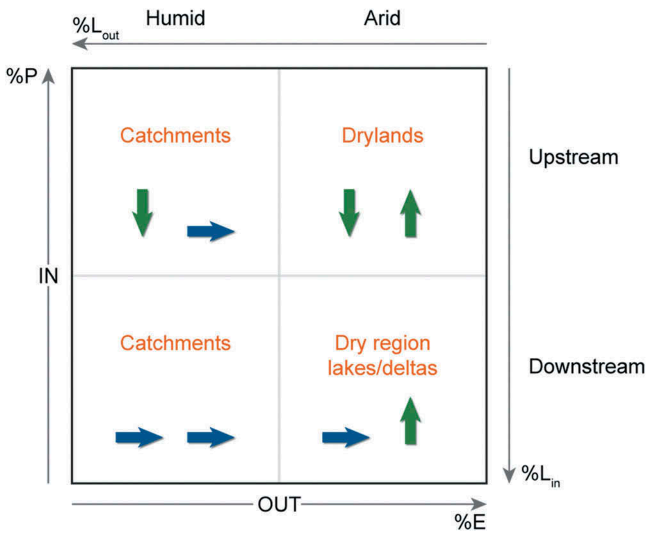


Figure 4. Categorization of hydroclimatic landscape situations based on composition of water inflow and outflow. Axes show percentage of vertical inflow and outflow components, respectively. P= precipitation; E = evaporation; L_{in} = river inflow; L_{out} = river outflow. Adapted from Weiskel et al. (2014).

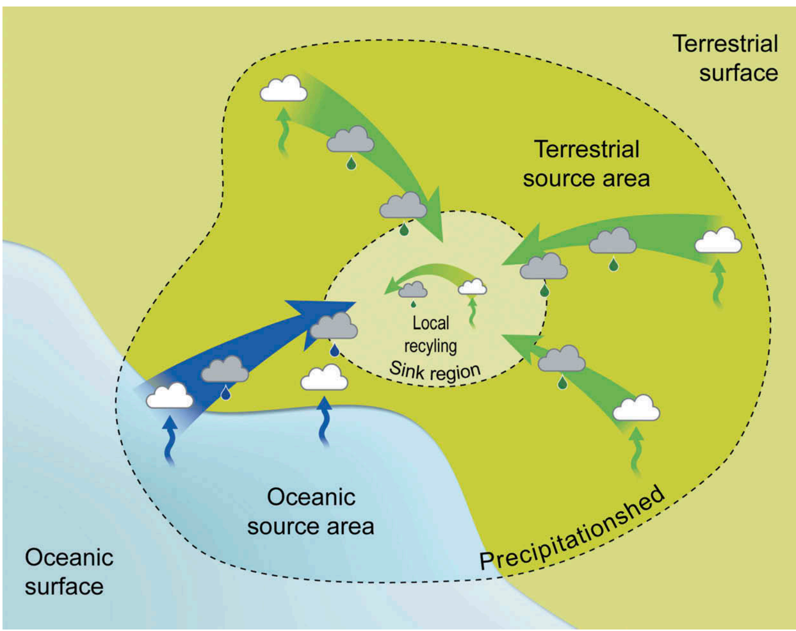


Figure 5. Precipitationshed and sink regions with rainfed agriculture. *Source*: Keys (2016).

less than 0.5 are therefore highly vulnerable to reductions in rainfall due to land use change. Keys et al. (2012) found that such water-constrained areas occupy 50% of the earth's land surface. Dryland rainfed agriculture is therefore particularly susceptible to even small changes in precipitation.

The concept of the precipitationshed indicates how upwind terrestrial evaporation *source* areas contribute moisture for precipitation to downwind *sink* regions. Keys (2016) identified seven terrestrial, water-constrained, recycling-dependent sink regions with 500–600 mm rainfall and vulnerable to upwind land use change. Many of these areas are also priority areas for global development. Two of Keys's seven cases have particular interest because of size and population: the Sahel and north and east China. In the western Sahel there is high local recycling and no absolute contribution from the nearby Sahara at present, but greater future evaporation in the Sahara might have large effect on precipitation in the Sahel. The precipitationshed is vast, containing 83 countries and more than 900 million people. The Chinese sink regions have the highest vulnerability of the seven regions, due to many potentially evaporation-altering land cover changes: expanded urbanization as well as irrigated cropland, deforestation in both East and South-East Asia and afforestation in northern China. They also have the largest populations, with eastern China exceeding 2 billion.

Keys's analysis suggests that the food security of some of the most water-constrained rainfed agricultural regions could be very sensitive to distant land use changes. Although until now Integrated Water Resource Management (IWRM) has been used primarily for holistic management of runoff (blue) resources, the importance of moisture feedback (green) would make IWRM appropriate for landscape management as well.

As a base for societal water supply, blue raw water, although harvested from river runoff or groundwater, basically originates from precipitation, which has its source in land evapotranspiration elsewhere. In special cases, therefore, drought may severely complicate a city's raw water supply. Many megacities (population over 10 million) are on the leeward side of a continent, where the prevailing winds have passed over land, and therefore find themselves in a vulnerable situation (Keys, 2016), since much of their raw water depends on terrestrial moisture recycling. The most vulnerable are eight terrestrial-moisture-recycling-dependent cities (including Shanghai, Sao Paolo, Buenos Aires, Karachi and Kinshasa), where around half of the water supply originates from precipitation over upwind land areas.

The arid-zone Achilles' heel

Achieving Sustainable Development Goal 2 (to end hunger and achieve food security) will require massive, continent-scale efforts to secure food for the population, which for only semiarid and dry sub-humid regions is likely to approach 900 million by 2030 (Figure 6). About 40% of sub-Saharan Africa is semi-arid or dry sub-humid; climate change and ecosystem degradation are creating major water shocks on a continent with a population projected to grow from 1 billion to up to 3 billion in this century. Based on an overview of green and blue water resources in Africa (Schuol, Abbaspour, Yang, Srinivasan, & Zehnder, 2008), and on the particular blue water geography in sub-Saharan Africa (Vörösmarty, Douglas, Green, & Revenga, 2005), it is not surprising that agriculture remains mostly rainfed. And as a consequence of the aridity, there is only limited irrigation – in the drylands, most rain evaporates before reaching a river – and most sub-Saharan agriculture is rainfed subsistence agriculture with very low yields.

The drought proneness seriously complicates crop production (Falkenmark & Rockström, 2006; Rockström & Falkenmark, 2000), both the interannual droughts, which

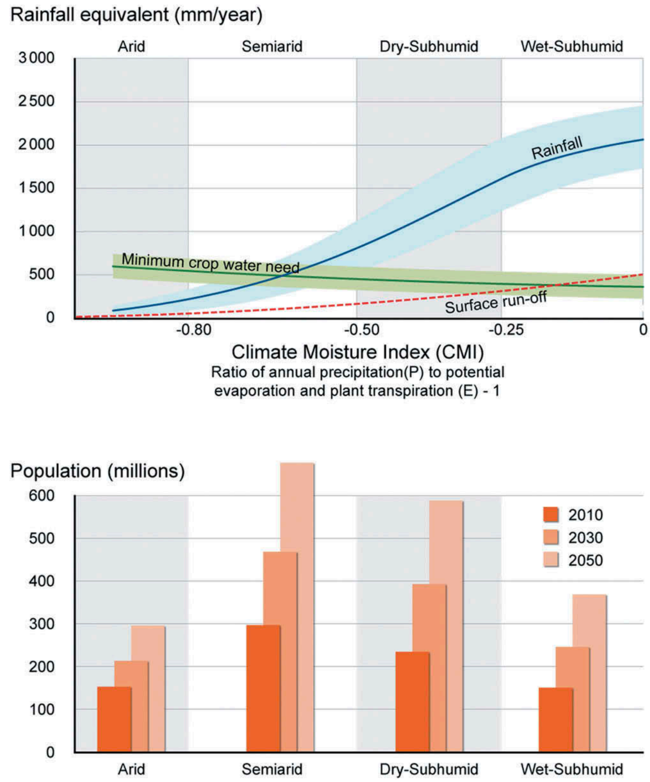


Figure 6. Hydroclimate and food production prospects in African savanna landscapes. Upper: Precipitation compared to crop water requirement ±1 standard deviation in arid, semiarid and sub-humid zones. Lower: population in 2010, 2030 and 2050. *Source*: Falkenmark and Rockström (2015).

are becoming both more serious and more frequent in response to the ongoing climate change, and the frequent dry spells, with many days or even weeks without any rain during the rainy season. During such dry spells roots are damaged, reducing their capacity to absorb green water for the production of crop biomass. As a consequence, yields become extremely low, typically of the order of only 1 t/ha out of a hydro-climatically possible yield of 7 t/ha (Garg, Karlberg, Barron, Wani, & Rockström, 2012).

In contrast to the irrigation-based Asian Green Revolution, a better idea to upgrade rainfed agriculture in dryland sub-Saharan Africa is a particular African Green Revolution (SIWI, 2016). An attractive possibility is to make better use of the rain by *vapour shift*, which helps the roots take up more of the infiltrated water in the soil and protects them from drought damage during dry spells. This can be done by small-scale supplementary irrigation during dry spells, with rainfall harvested during rainstorms and stored in small local dams. An African Green Revolution would thus involve three parallel green-water dimensions, combining blue water strategies with farming systems that operate on green water in rainfed systems (Bill and Melinda Gates Foundation, 2006; Dile, Karlberg, Temesgen, & Rockström, 2013) in a sustainable 'triply green revolution' (Rockström et al., 2014): maximized use of green water for radically increased production; adequate attention to protection of critical ecosystem services, increasing sustainability; and in the long term improving the ability of landscapes to safeguard water resilience, i.e. the capacity to regenerate rainfall by moisture feedback and wetness in landscapes for ecological functions.

'Triply green' thus means a green water, green production, and green sustainability revolution. There are three key implications of the vapour shift for overall water management (Keys & Falkenmark, 2019): minimal impacts on the hydrological environment means more water can be used for biomass production for human use; minimal reliance on blue water means more can easily be used for other purposes; and the vapour shift means that more green water can support crop diversification, allowing both subsistence food production and some cash-crop production for sale on market.

Vulnerability to upwind land use change

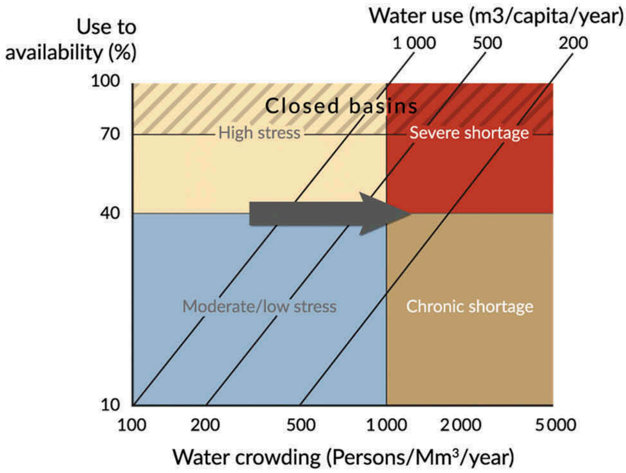
Development of large drought-prone regions with rain-dominated lands will be critical in the present poverty- and hunger-ridden global zones. African dryland developers have their focus on vertical water flows and are working to overcome the climatic challenge of limited and variable precipitation by seeking ways to secure effective rootzone water uptake through protective irrigation with harvested rainfall. Vapour shift is becoming a dominant component of agricultural development. Managers in more developed dryland regions have started to direct their vertical water flow focus on the origin of rainfall in terms in upwind land use, especially its dependence on land use changes there. Seven such recycling-dependent regions with only 500 mm of annual rainfall, including eastern China and the Sahel, are particularly vulnerable to upwind land use changes. A large part of the water supply of many megacities is also vulnerable to upwind land use changes (Keys et al., 2012).

Hydro-social perspective

Hidden challenges of the near future

With the increasing scale of socio-ecological drivers, blue water availability may rapidly change in response to land use change, local land use degradation, moisture feedback altering rainfall patterns, and in response to climate change. Oki and Kanae (2006) stressed that increasing population pressure is a growing challenge, and that more than two billion people live in highly water-stressed areas because of the uneven blue water distribution in time and space. Increasing population-driven water scarcity generates water crowding (Falkenmark & Widstrand, 1992; Kummu & Porkka, 2016), whereas economic development increases demand-driven water scarcity, so-called water stress. Climate change is expected to accelerate water circulation and therefore slow down the population-driven increase in water stress, but seasonality changes and increasingly severe extreme events may reduce this effect (Oki & Kanae, 2006). Figure 7(a) shows a blue water scarcity matrix, distinguishing between water stress (use-to-availability ratio) and water crowding (the inverse of per capita availability). The matrix identifies five different situations in terms of water use as related to water crowding and environmental priority/closed basins.

(a)



(b)

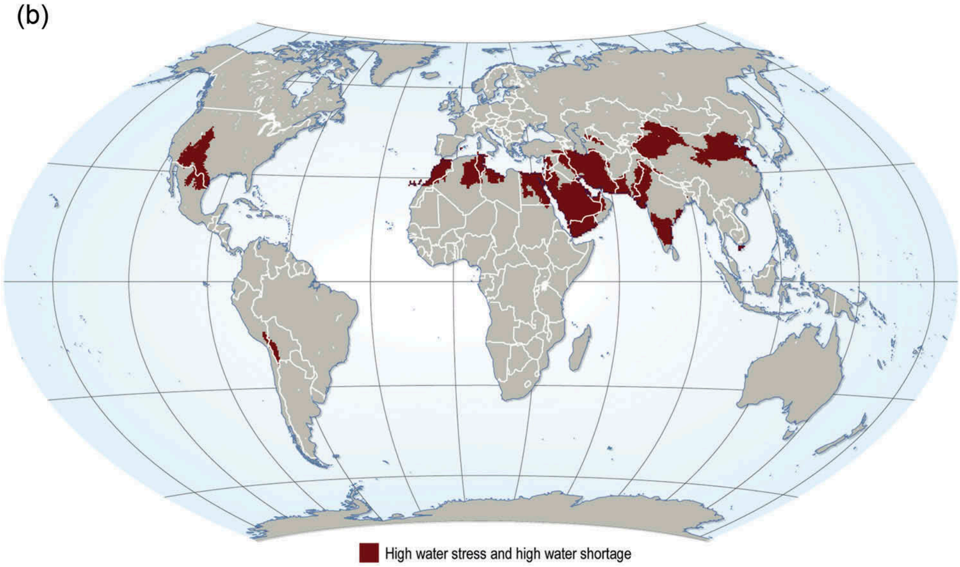


Figure 7. Water stress and scarcity. (a) Two modes of blue water scarcity. The vertical axis represents the water mobilization ratio: water accessible for use. The mobilization ratio reaches a peak at the amount necessary for aquatic ecosystem health (ecological flow, here 70%). The horizontal axis shows water crowding (people per million m^3/y of water flow), or the number of people jointly dependent on and polluting each unit of water. The large arrow indicates the effect of population growth. *Source*: Falkenmark, Jägerskog, & Schneider (2014). (b) Areas of both high water stress (use-to-availability above 40%) and chronic water shortage (water crowding beyond 1000 people per million m^3 per year) in 2000–2010. Adapted from Kummu and Porkka (2016).

In 2005, the most vulnerable situation, with more than 40% of the available water already in use, and more than 1000 people per million m^3 per year, included 1.13 billion people. The most critical geographical region in terms of this severe water shortage includes the Middle East and North Africa, and Central Asia (Figure 7(b)). These are also regions with transnational river basins and continuing population growth, driven by both high fertility and extended life expectancy (Kummu & Porkka, 2016).

The world therefore now finds itself in a situation where growing populations in many basins are approaching increasingly severe water constraints. More than 10 years ago, around 1 billion experienced severe water scarcity, and the increasing population pressure since then has been continuously reducing their possible water demand limit towards 200 m^3 per person per year – a level that Hillel Shuval, Israel, 20 years ago, considered the minimum for an industrialized country in a dry climate (Lundqvist & Gleick, 1997).

Such water-short basins have therefore been approaching a water use level where basin-scale economic planning will be urgently required for adaptation of the water supply to shrinking blue water availability. Basically, two types of water availability need to be balanced: water for food production (rainwater in the soil, green water) and water for municipal and industrial water supply (liquid, blue water). One pathway may be increasing reliance on green water in the soil for food production, improved by rainwater harvesting, and later increasing dependence on 'virtual water' (in food imports). As per capita availability shrinks further, a shift in thinking towards water reuse and desalination will be necessary.

Blue and green water sharing options

In future equitable and reasonable sharing in large river basins must be based on a preliminary understanding of the basic water resource constraints of a basin, in terms of both blue water constraints on water supply and green water constraints on food production:

- What degree of food security do the green water conditions provide: secure rainfed agriculture, dependence on irrigation support, or the necessity of food imports?
- To what degree do the blue water crowding constraints allow irrigation?

Some principal conclusions may be drawn by building on earlier work on water scarcity (Falkenmark & Xia, 2012). The answers to the two questions above can be derived from Figure 8(a), relating green and blue water availability. The next clarification needed refers to the blue water constraints within in the severe-shortage window, clarified in Figure 8(b), showing water allocation component as a function of blue water availability. Highest priority is given to municipal/industrial water supply, and second priority to protection of environmental flow (assumed to remain 30% of river flow). Irrigation withdrawal is possible only at higher availability levels and has to be maximized to limit consumptive water use (Rockström et al., 2012).

As mentioned, the region where water scarcity is most severe is the Middle East and North Africa, a global hot spot of unsustainable water use. Future water security options in that region have been analyzed by the World Bank (FAO/World Bank, 2018), considering reallocation of blue water from rural to urban users and from agriculture to industry.

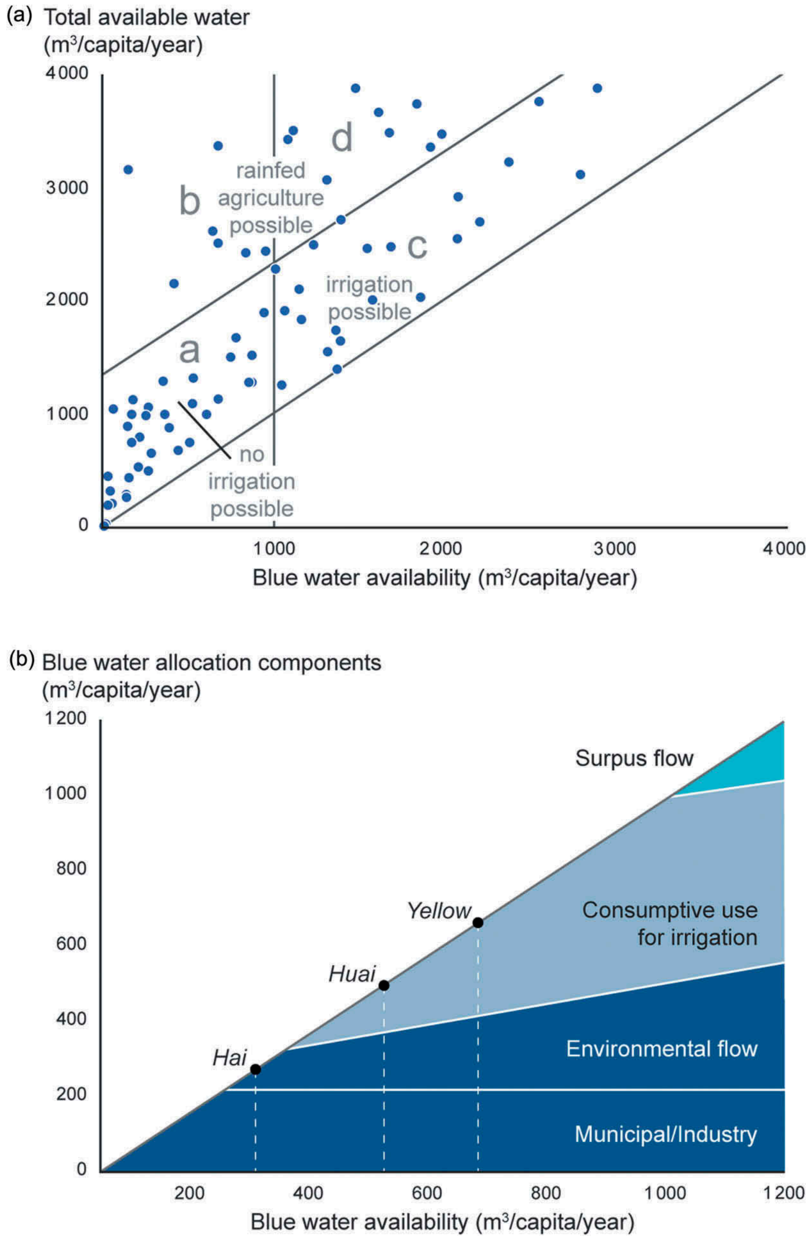


Figure 8. Food security and water supply. (a) Water availability constrains food security options. Enough green water for self-sufficient rainfed agriculture is available above the upper sloping line (areas *b* and *d*). Enough blue water for irrigation exists beyond the vertical line (area *c*). Inside area *a*, both green and blue water shortage implies dependence on food imports (adapted from Rockström, Karlberg, & Falkenmark, 2011). (b) Theoretically available water supply options, assuming 200 m^3 per person per year for municipal/industrial use, using the three Chinese rivers Hai, Huai, and Yellow (based on Falkenmark and Xia, 2012).

Water-scarcity-based vulnerability function

Intensifying water shortages in north-east China have vulnerability considerations, including analyses of the entire Hai River basin (Shi, Xia, Gippel, Chen, & Hong, 2017; Xia, Qiu, & Yuanyuan, 2012). The authors there introduce a water resources vulnerability function, dependent on the quotient of *sensitivity* and *adaptability*. The sensitivity of a water resources system is the sensitivity of annual runoff to precipitation change. Adaptability refers to adaptation strategies, integrated socio-economic capacity, and ability to tackle water stress (expressed as an exponential function of water stress [use-to-availability ratio], stress barrier, actual water crowding, and per capita water use). For the Hai basin analysis, vulnerability was rated from not fragile to extremely fragile, based on thresholds of water stress, water crowding and per capita water use in preparation for river basin agreements negotiations. For the very water-scarce Hai basin, the concept of 'water fragility' was tested through an index-based method, quantitatively evaluating water resources vulnerability and comparing different sub-basins (Shi et al., 2017).

Hydro-social water constraints now in view

Two perspectives have been highlighted in the approaching hydro-social water constraints which are expected to add complexity to water resources management in the coming half century. One is the ongoing population growth in water-constrained regions, especially those already developing high-level blue-water stress. There, long-term water supply planning – especially for mega-cities – will be essential for at least two central reasons: hydro-social constraints on sustainable development with safe municipal and industrial water supply; and implications of limits on irrigation possibilities. Implications of the importance of upstream–downstream cooperation have been illustrated both in the Middle East and North Africa and in the large rivers of north-east China (the Hai, Huai, and Yellow).

The other is the limitations originating in the origin of the rainfall that feeds the river basin and therefore further threatens the water resource. The large rivers in north-east China are examples of vulnerable rivers in a sink region, with a high proportion of their precipitation originating in upwind terrestrial evaporation in Siberia (Keys et al., 2012) and vulnerable to upwind use change in inner Asia (Gleeson et al., 2019).

Future outlook

Short overview

This article has clarified water's basic roles and functions in the life support system, not only as a generator of ecosystem services like food and energy, but also as a critical agent of change, for instance as a greenhouse gas, a regulator of temperature, and a victim of change through shocks related to global warming, like droughts and floods. Water is therefore a key in supporting life. On the continents, all its different functions and roles form one integrated framework with the land system. Water is also associated with shifts in social-ecological systems, as water functions cross tipping points. Recent research has also clarified the intense interaction between land and atmosphere, with profound implications for both plant growth (including food) and precipitation patterns, with their international dependence. The increased understanding of the importance of land use for water conditions, in terms of both water partitioning change (Keys et al., 2012) and the dependence of downwind rainfall on upwind land use, is a new dimension of fundamental importance, not only for future water planning, management and governance but also for long-term climate change mitigation.

Some current challenges and constraints regarding both green and blue water were also highlighted. The great population stress on drylands, especially in sub-Saharan Africa, makes food production a critical land use. The vulnerability of savanna landscapes to invisible water in the sky, i.e. rain and upwind evaporation rather than river flow, will have to be a new component in future dryland management. Vapour shift – turning large unproductive evaporation losses into productive transpiration –together with fertilization, will considerably increase crop yields, provided that root damage during dry spells can be avoided through supplementary irrigation, based on rainwater harvesting.

The world is rapidly approaching an era where water crowding will make technical shifts essential, avoiding throughflow as a basic philosophy for societal water supply. The land–atmosphere link makes mega-city water supply particularly vulnerable during drought periods. Water pollution abatement in highly polluted river systems, which is especially severe with high levels of water crowding, is an essential goal for water management.

How to navigate

After this short overview of water's crucial roles and functions in the life support system – the biological playing field for human activities – we will be seeking answers to the core question of this article: How to navigate to secure a sound and decent life for humanity in the next half century within the goals of the Paris Agreement, given further stresses on the life support system and the importance of securing a resilient water bloodstream that can secure safe land/water/ecosystem interaction. Safe navigation will depend on answering questions such as: What transformations will be needed? What shifts in governance approaches, in terms of scope, scale and speed, will be required? *How* can that be done? And how closely will the UN's Sustainable Development Agenda reach its overarching goal? Three perspectives will be essential: hydro-climatic, hydro-ecological, and hydro-social.

Future hydro-social stresses on the life support system will primarily originate from the combination of population growth, increasing water demands and foreseen climate change. Most population growth is expected to occur in Africa (Sturgis, 2014), where UN projections indicate that population might even quadruple before the end of this century (Gerland et al., 2014; United Nations, 2015). The rising demand will be policy dependent, but another 1 billion to 2 billion people may be expected in the coming half century, challenging the Sustainable Development Goals, which have been analyzed within the UN system (Vörösmarty et al., 2018).

Hydro-climatic management will have to be guided by the Paris Agreement to limit global warming to 1.5–2 °C, the amount seen as essential to avoid further tipping of the climate. Recent research in Earth System dynamics (Steffen et al., 2018) has clarified the risks involved in crossing the +2 °C limit; these results stress the fundamental importance of the Earth System remaining in the Holocene state. It is increasingly clear that allowing the global average temperature to rise by more than 2 °C might push the Earth System into even warmer conditions with a widely different biosphere. Even a 2 °C global warming might be enough to lock the climate onto a new Hothouse Earth era, with temperatures similar to those of several million years ago. The bio-geophysical processes involved would then be difficult or impossible to slow down or reverse. In other words, such a development would have catastrophic consequences for human civilization as we know it.

The risk of a Hothouse Earth scenario shows the importance of very conscious climate mitigation activities, making humanity planet stewards to keep the Earth System in Holocene conditions. In other words, mitigation will have to be a core component of navigation activities in the next half century. It will be not only essential but extremely urgent. And a core component of this urgent climate stabilization will be wise, water-resilient land use. In particular, agricultural production will be a characteristic land use activity to safeguard the Holocene climate. This will involve enhancing biosphere carbon sinks and increasing soil CO_2 uptake through intensified biomass production. Improved and expanded agricultural production will necessitate expanded control and management of freshwater functions.

Finally, a crucial component of hydro-ecological management will be adequate attention to the potential effects of land use change, especially on water flow, since the most visible manifestation of climate change will be seen in the hydrological lens: floods, droughts and sea-level rise. Also, green water phenomena will be linking land use and atmospheric water, and may trigger an under-studied interplay of ecological, biophysical and social feedbacks. As stressed by Rockström et al. (2014), 'The stability of fresh water flows has in the Holocene period played a fundamental role in enabling this human development.'

Many global and regional ecosystems are already approaching tipping points in terms of severe degradation of water, land and ecosystem services, threatening future human living conditions (Falkenmark et al., 2019). Tipping phenomena can be leading to erosion of water resilience and possibilities of ecosystem recovery, and can be water-related (groundwater collapse, river depletion), land use related (deforestation, land mismanagement, salinization) or climate change related (global warming, rainfall regime change, saltwater intrusion, sea level rise, sharpening droughts and floods) (Rockström et al., 2014).

The particular importance of the required climate stability of agricultural land use pinpoints the crucial involvement of the three green water functions. In the Holocene climate, water vapour is a powerful climate-regulating greenhouse gas, providing the basis for biomass growth, and thereby also regulating also carbon fluxes. One key strategy will be to sustain rainfall by treating forested areas as critical zones for moisture feedback. Research will be essential to clarify how to navigate in order to remain in the Holocene climate, by identifying available manoeuvring space, to secure the resilience of social-ecological systems.

This understanding has generated efforts, starting in the early 2000s, to identify the biospheric playing field of humanity in terms of finding a safe operating space for a set of key components. In the first-generation analysis of planetary freshwater boundaries (Rockström et al., 2014), the water boundary was developed by identifying maximum blue-water consumptive use, causing river depletion and undermining freshwater ecosystems.

A recent upgrade towards a second generation (Gleeson et al., 2019) was based on considering freshwater core functions in search of a set of sub-boundaries, which are now open for quantification of six sub-boundaries. Human activities in the landscape involve unavoidable water partitioning alteration, which suggests the question of at what stage such alterations are too large to allow Holocene conditions. Many water partitioning changes originate from land use change and therefore alteration of evapotranspiration (increasing food production), in other words increasing consumptive use.

A shift in thinking

Returning now to the question, where does the current more profound understanding of the close and tightly linked interaction between water and the life support system lead, and how can it be navigated? It will be critical to focus on what shifts will be needed in the management of the planet. Vital components of the navigation approach that is needed address both current problems, failures and oversights, and emerging long-term problems. Both land use and water use will be essential.

When it comes to blue water, attention is drawn to approaching water security problems, which call for awareness of increasing hydro-social fragility, foreseen from the expected combination of climate change, population growth and increasing water demand, especially in low-latitude regions. The increasing irrigation dependence that might follow from the rising importance of agriculture to balance temperature rise will further increase the stress on blue-water resources. Water pollution, as a large-scale hindrance to water usability, is another water management challenge of increasing importance for future socio-economic development and industrialization, especially in water-scarce regions with dense populations and therefore low access to dilution water.

Economic development and population growth have resulted in growing water scarcity, both demand-driven and population-driven (Gerland et al., 2014). The water crowding in the Middle East and North Africa and part of Central Asia will demand careful water use planning for social-economic development, taking an integrated approach to municipal and industrial water supply as opposed to irrigation needs. Special attention will be needed to secure mega-city water supplies.

A fundamental challenge will be hydro-climatic management, i.e. moderating temperature fluctuations to secure Holocene conditions in terms of remaining below 2 °C of global warming. In other words, attention to land use, and skilful attention to green water functions in terms of transpiration and energy flows, will be crucial. Reducing forest destruction will be essential, to reduce current net emissions from deforestation and land-use changes, today a sizable contribution to global CO_2 emissions. Wise land use is necessary, supporting subsurface carbon sequestration and CO_2 mitigation by safeguarding both sustainable management of tropical rainforests and water-secured agricultural development.

For hydro-ecological reasons, attention will also be needed to land use change and disturbance, and the possible risk of emergence of tipping-point situations, for instance from deforestation, which may complicate recovery (Runyan, D'Odorico, & Lawrence, 2012). Green water's increasingly dominant roles and functions in the life support system have deepened understanding of water's profound involvement in supporting terrestrial ecosystems. This represents a call for awareness of the core role that future land use change and therefore further water partitioning changes will have to play in moderating climate change. Land-use-oriented planning will be essential for regional food security.

The unfinished problems of mega-scale water pollution and the lack of successful approaches to overcoming other essential environmental problems imply the need to replace the increasingly outdated dichotomy between economic development and environmental protection. Constructive solutions are being sought in the ongoing planning for the Sustainable Development Goals (Vörösmarty et al., 2018), introducing a new ecosystem-based water security, by which all 17 of these goals can be addressed in a unitary way. A twenty-first-century approach to the world's water problems is currently under development, with water-related ecosystem services as a core concept, seeking responses to all the different Sustainable Development Goals in terms of a combination of nature-based components and technical components.

Final remarks

The missing answers for 'How to navigate?' will be built out of three groups of activities:

- *Hydro-climatic*: safeguarding the Holocene climate, relying on green water functions and therefore wise land use, supporting carbon sequestration and CO_2 mitigation by safeguarding sustainable management of tropical rainforests and water-secured agricultural development;
- *Hydro-social*: this has two parts. For water supply, modernizing and upgrading rural supply; expanding urban and industrial water supply in response to the enormous wave of mega-city development; constructively responding to groundwater depletion; recirculating and reusing wastewater; finding new technical approaches to high water stress and chronic water crowding; and producing new raw water through desalination. For water management, taking a practical and realistic approach with attention to basin scale, management complexity, and upstream–downstream relations.
- *Hydro-ecological*: developing the concepts of water-related ecosystem services and ecosystem-based water security; forest conservation and restoration; seeing the particular importance of agricultural production for global food security; launching a potential 'triply green revolution' in the vast drylands; and understanding sink area vulnerability to upwind land use changes.

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