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Understanding of water resilience in the Anthropocene

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ABSTRACT

Water is indispensable for Earth resilience and sustainable development. The capacity of social-ecological systems to deal with shocks, adapting to changing conditions and transforming in situations of crisis are fundamentally dependent on the functions of water to e.g., regulate the Earth's climate, support biomass production, and supply water resources for human societies. However, massive, inter-connected, human interference involving climate forcing, water withdrawal, dam constructions, and land-use change have significantly disturbed these water functions and induced regime shifts in social-ecological systems. In many cases, changes in core water functions have pushed systems beyond tipping points and led to fundamental shifts in system feedback. Examples of such transgressions, where water has played a critical role, are collapse of aquatic systems beyond water quality and quantity thresholds, desertification due to soil and ecosystem degradation, and tropical forest dieback associated with self-amplifying moisture and carbon feedbacks. Here, we aggregate the volumes and flows of water involved in water functions globally, and review the evidence of freshwater related linear collapse and non-linear tipping points in ecological and social systems through the lens of resilience theory. Based on the literature review, we synthesize the role of water in mediating different types of ecosystem regime shifts, and generalize the process by which life support systems are at risk of collapsing due to loss of water functions. We conclude that water plays a fundamental role in providing social-ecological resilience, and suggest that further research is needed to understand how the erosion of water resilience at local and regional scale may potentially interact, cascade, or amplify through the complex, globally hyper-connected networks of the Anthropocene.

1. Introduction

Humanity has entered a new geological Epoch, the Anthropocene, where humans constitute the largest driver of environmental change at the planetary scale (Crutzen, 2002; Steffen et al., 2015) This includes human pressure on the hydrological cycle, which occur across all scales, from local watershed and water tables, to river basins and regional climate systems. There is ample evidence of human induced deterioration of water quantity and quality related to environmental degradation over the past century, in particular since the advent of the great acceleration of the modern human industrialized societies in the mid-1950s (Kummu et al., 2016; Wada et al., 2011). Future water prospects are uncertain, with four million people facing severe water scarcity at one month per year already today (Mekonnen and Hoekstra, 2016) and water-related risks listed among the top five global impact risks by the World Economic Forum for the past consecutive seven years (World Economic Forum, 2018).

With climate change and intensifying human activities, scientific interest in freshwater functions has broadened, in view of their roles not only for economic and social development, but for sustaining the Earth's life support system itself (Rockström et al., 2012). Particularly, there is mounting evidence that rising human pressures on the Earth system trigger shifts in interactions (between environmental processes and systems, e.g., the hydrological cycle and its interactions with the biosphere), feedbacks and potentially triggering tipping points (Gordon et al., 2008; Rockström et al., 2014). At the local to regional scale, social-ecological systems crossing water induced tipping points include e.g., aquatic ecosystem collapse, desertification, and savannization (see Sect 2). At the planetary scale, Earth resilience defines the capacity of biophysical processes and systems on Earth to sustain feedbacks and interactions that enable the Earth system to remain in its current inter-glacial state. Vital for Earth Resilience are key

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biophysical tipping elements in the Earth system (e.g., Botero et al., 2014; Lenton et al., 2008; Lenton and Williams, 2013; Reyer et al., 2015), among others the Amazon rainforest, the Indian monsoon, and the Sahara, which are all crucially dependent on the water cycle.

System tipping points may, however, not only occur in the ecological and biophysical realm, but also in the societal realm. For example, in the recent past, water wars have been heatedly debated (Gleick, 1993). However, while most recent research appears to agree that direct conflicts and wars are not fought over shared water resources in rivers and lakes (Allan, 1997; Brochmann and Gleditsch, 2012), the debate is still ongoing on the links between e.g., water scarcity, agriculture failure, and migration (Miletto et al., 2017), and droughts and societal collapse (Aimers and Hodell, 2011).

A growing evidence base on abrupt changes due to social and environmental interactions and reinforcing feedbacks, urges attention to the risk of water-induced tipping points in social- ecological systems across scales. This offers an opportunity to deepen our understanding of how water-induced system tipping points and collapse emerge. Here, the application of resilience theory may offer a perspective for understanding the processes and underlying conditions that lead up to unwelcome surprises.

The overall aim of this paper is to provide a synthesized and conceptual understanding of the processes through which water-induced tipping points are crossed and collapse occur in ecological and social-ecological systems, based on documented evidence and through the lens of water resilience, including fundamental water functions and roles (Falkenmark, 2017; Rockström et al., 2014). Specifically, we present evidence of a set of biophysical water-related tipping points in systems, discuss their geopolitical and social aspects, and discuss the evidence of a number of life support system changes that have shaken societies in the past.

2. Water resilience: theory, concepts, and definitions

2.1. Resilience theory

Resilience is defined as the ability of a system to cope with disturbance without crossing tipping points into a new stability domain, to adapt to change, and transform into a new state following a regime shift (tipping into a new social-ecological equilibrium) (Folke et al., 2010). Water resilience can be defined as the role of water (see Section 2.2) in safeguarding and sustaining a particular desired state of a social-ecological system, ranging from sustaining the state of ecosystems and biomes, to the stability of regional weather and climate systems, and the ability of the hydrological cycle to maintain stable water supply for societies and ultimately the state of the biosphere and the Earth system (through moisture feedback, climate forcing, and regulating biomass growth in terrestrial ecosystems). In principle, we distinguish between two types of system collapse (Fig. 1):

- **Non-linear collapse/shift:** crossing of a tipping point resulting in a state change, from one (semi)equilibrium state (characterised by one set of negative feedbacks) to another (characterized by a new set of self-reinforcing, positive feedbacks), that is often impossible or difficult to reverse due to hysteresis effect; and
- **Linear collapse**: gradual change of water properties that causes the collapse of a system without any shift from one mix of feedbacks to another, and that has limited or no hysteresis effect.

A typical example of a non-linear tipping point is the evidence of the biophysical existence of a state shift between rainforest and savanna (Fig. 1a, c), strongly related to water resilience. As precipitation declines past a certain threshold (triggered e.g., by climate change and deforestation reducing moisture feedback dynamics and raises the dryness of the air due to higher vapor pressure deficit as forest density is reduced), the rainforest cannot be sustained and will irreversibly transition into a savanna (Hirota et al., 2011). The transition from a dense to a scarce tree canopy increases evaporation from land, reduces the moisture recycling, and increases fire risks, which are feedbacks (Fig. 1c) that help maintain the savanna system (Staal et al., 2015; Zemp et al., 2017). Thus, the precipitation threshold required to transition from savanna to rainforest is much higher than the level that lead to a savannization of the forest system. This difference in threshold level depending on state shift direction is by definition the hysteresis effect. In some circumstances, a transition can be irreversible, such as in the case of species extinctions.

Linear collapse, on the other hand, can be exemplified by river depletion (Fig. 1b, d), which can cause a river to dry up without self-amplifying feedbacks, since the water level can in principle be restored in a linear fashion. However, it is important to clearly define the system and water variable considered. Related social systems such as riverine fishing communities can tip non-linearly with hysteresis effect, and much better fishing conditions can be required to attract people to resume fishing than was required for the activities to be abandoned.

Central to these two definitions of system state shift are, thus, the *shift* or *absence of shift* in feedbacks in the considered system and the degree of *hysteresis*. While the distinction between non-linear tipping dynamics and linear collapse appears clear-cut in theory, a varying degree of hysteresis in real-world systems means that it is not always possible to cleanly categorize all system collapse in this way. To further clarify the role and function of water for resilience, see Sections 2.2 and 2.3, and definitions in Table 1.

2.2. The three roles of water for system resilience

Water is inherently intertwined with all processes of a social-ecological system, and we distinguish between three central roles of water relative to the system of consideration: as control, state, and driving variable (Fig. 2) (Rockström et al., 2014).

As control variable, water is the “source” of resilience, or one of the regulating factors behind the state of a system, through the generation of ecosystem services and functions in both terrestrial and aquatic systems. Being the bloodstream of the biosphere, water is key in sustaining all life on Earth. As state variable, water is the “victim” of change, being subject to external changes, for example land-use change and pollution. As driving variable, water is the “agent” of change, affecting resilience by changes in spatial and temporal distribution of water flows and stock, e.g., due to hydrological impacts of climate change.

These three roles of water flow into each other, and can exist simultaneously and interact dynamically. For example, deforestation disturbs the water cycle (i.e., water becomes the “victim” of change), which in turn might lead to disruptive flooding and decrease in moisture feedback (i.e., water becomes the “agent” of change) that fails in delivering water dependent biomass growth and sustain biodiversity beyond those directly affected by the initial deforestation (i.e., water as “source” of resilience, i.e., a control variable).

2.3. Water functions in the fresh water system

The water cycle involves a broad set of core functions, together crucial for biophysical stability and determinants of water resilience (Falkenmark, 2017; Rockström et al., 2014). These functions are active in different segments of the water cycle (Fig. 3) in terres-

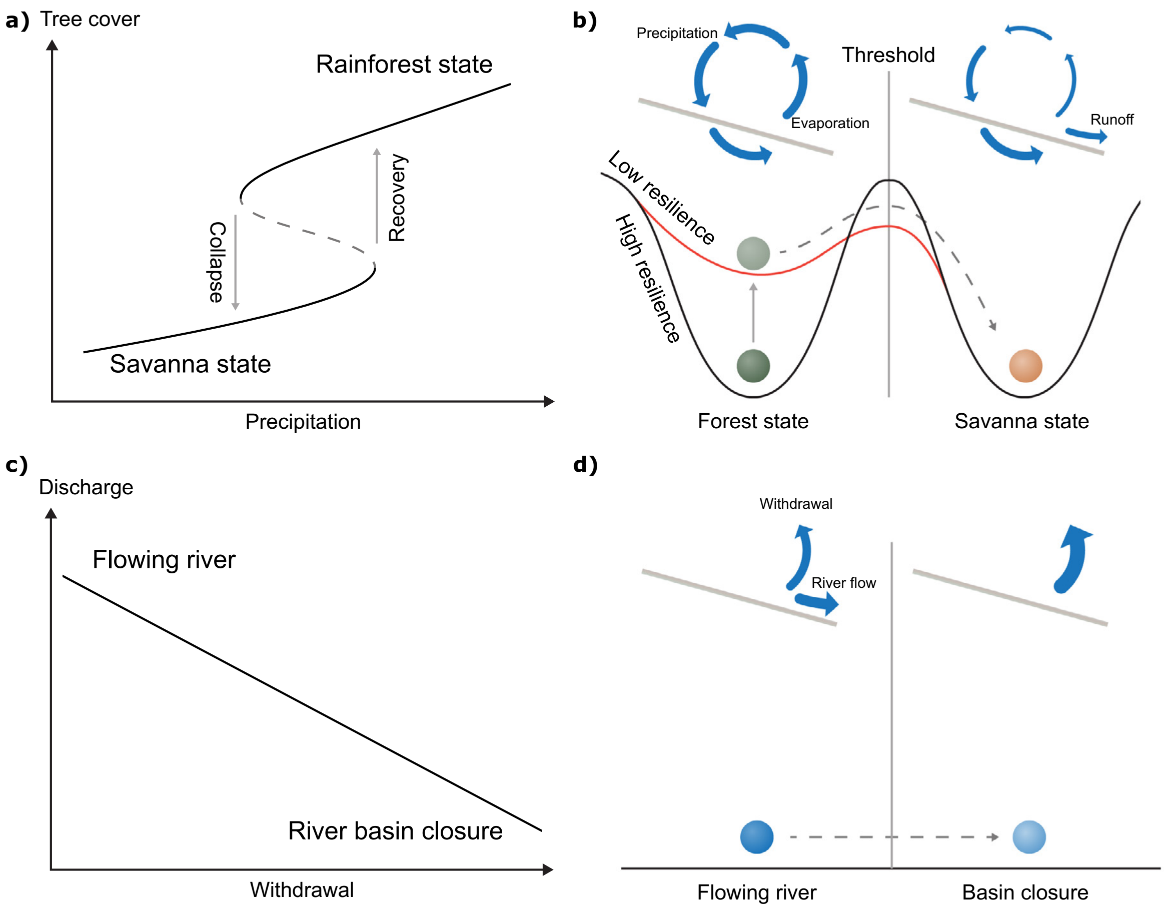


Fig. 1. Two types of system collapse: (a, b) non-linear tipping dynamics illustrated through rainforest to savanna shift, (c, d) linear collapse of riverine system illustrated through gradual decrease in river flows. Rainforest that is deforested has a lower resilience due to a reduction in moisture recycling and precipitation. Below a certain level of precipitation, rainforest can no longer be sustained and collapses to the new stable state of savanna. A higher precipitation level is required for the rainforest to recover due to hysteresis effect.

Table 1
Brief explanations of key terms used in this paper.

Term	Explanation
Green water	Green water flows include evaporation and transpiration. Green water stocks include soil moisture.
Blue water	Blue water flows include river and groundwater flows. Blue water stocks include rivers, lakes, aquifers, and wetlands.
Resilience	The ability of a system to cope with disturbance, to adapt to change, and transform into a new state following regime shift.
Regime shift	Large, abrupt, persistent changes in the structure and function of a system.
Tipping point	A point at which feedbacks shift direction establishing a new state of a system (a new basin of attraction).
Feedback	A positive feedback reinforces a change, while a negatve feedback decreases it.
Water functions	Ways water support the resilience of the biosphere and human society.
Control variable	The role of water for generating resilience and ecosystem functions. Water as “source” of resilience.
State variable	The role of water as being affected by other external drivers. Water as “victim” of change.
Driving variable	Changes in water that affect other systems. Water as “driver” of change.

trial and aquatic ecosystems, in the atmosphere, and in direct interaction with human society. While water functions can overlap with water-related “ecosystem services”, the key of the water functions lies in their role to provide resilience, and not just benefits.

We identified three *green water functions*:

1. *regulatory*, which involves the function of air moisture, soil moisture, water in living matter, and evaporation and transpiration flows to regulate the Earth’s energy balance and climate system at local to global scale through carbon sequestration (Jackson et al., 2005), cloud formation, albedo regulation, latent heat release and temperature regulator (Miralles et al., 2014), atmospheric boundary layer development, convective conditions (Guillod et al., 2015), as well as water vapor’s ability to trap heat as a greenhouse gas;
2. *productive,* which involves the function of evaporation to sustain food and bioenergy production, as well as biomass growth (Novák and van Genuchten, 2008);
3. *moisture feedback,* which involves the function of recycled evaporation to regulate the water cycle over land (Salati et al., 1979; van der Ent et al., 2010);

and five *blue water functions*

4. *water for supply*, which involves the function of withdrawn water used for water supply in society (Wada et al., 2014);

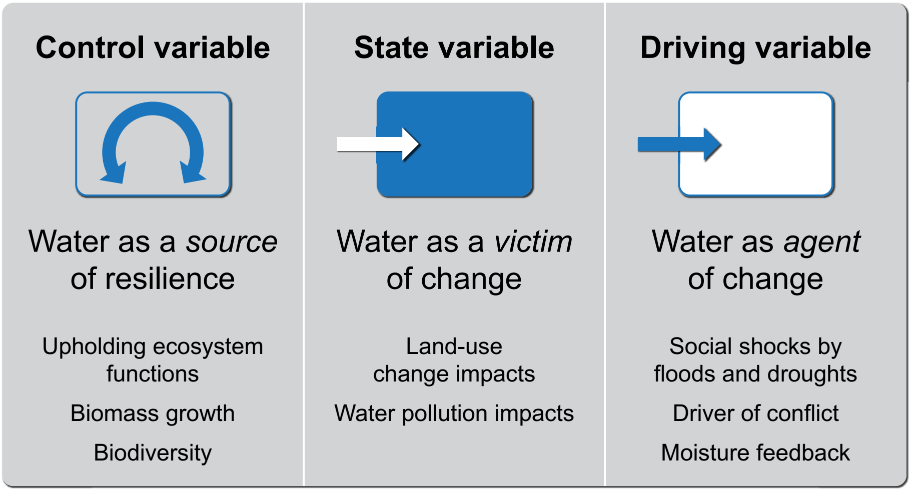


Fig. 2. The role of water in social-ecological resilience, where blue color denotes water, and grey refer to other variables or systems. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

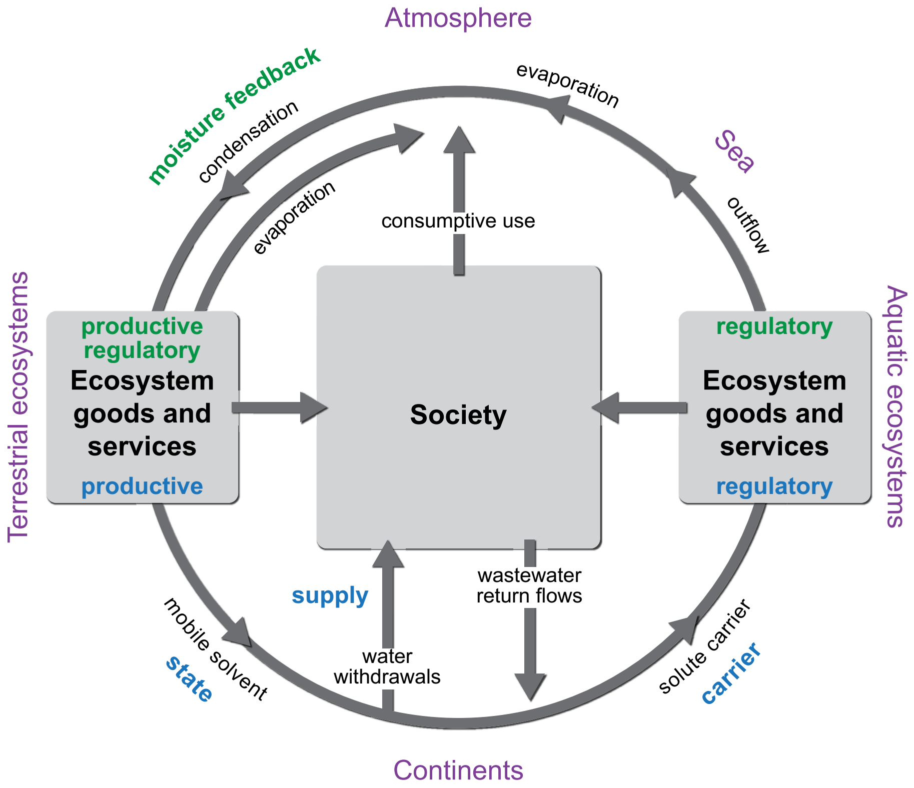


Fig. 3. Example of water functions appear in different positions of the water cycle.

5. *carrier/chemical load*, which involves the function of river flows and base flows to carry nutrients and pollution;
6. *state*, which involves the function of lakes, wetlands, groundwater, reservoirs, and river water volumes to uphold the aquatic state;
7. *productive*, which involves the function of withdrawn water used for irrigation in agriculture to produce food (Jägermeyr et al., 2016); and lakes, wetlands, and river water volumes to sustain aquatic biomass growth; and
8. *regulatory/control*, which involves the function of river flows and base flows to regulate aquatic ecosystems; wetlands, groundwater, glaciers, and permafrost volumes regulate the Earth's energy balance and climate through albedo regulation and carbon storage; groundwater (Wada et al., 2016) and glaciers (Hirabayashi et al., 2010) regulate sea levels and geological processes such as subsidence.

The various ways the different water stocks and flows serve as water functions are listed in Tables 2 and 3, and range from direct

Table 2
Overview of functions of green water stocks and flows.

	Green water stocks			Green water flows		
	Air moisture	Soil moisture	Living matter	Evaporation		
				All	Recycled evaporation	Transpiration
Regulatory	Cloud formation (albedo, precipitation, weather patterns), GHG, wet deposition of nitrogen and pollutants	Carbon storage, albedo, heat wave, lateral water flows	Albedo (in leaves and exposure to soil), soil quality, surface resistance and winds	Latent heat and Bowen ratio, temperature		Carbon sequestration
Productive						Biomass production
Moisture feedback					Precipitation	

Table 3
Overview of functions of blue water stocks and flows.

	Blue water stocks				Blue water flows		
	Surface water	Groundwater	Glaciers	Permafrost	Withdr. water		Runoff
					All	Transpiration use	
Supply					Societal use		
Carrier							Nutrient, pollution transport
State	Aquatic state	Aquatic state				.	
Productive	Aquatic biomass prod.	Groundwater dependent biomass prod.				Agri. prod	
Regulatory	Carbon storage, nutrient and pollutant trapping, lateral water flows	Geological processes, carbon storage, sea level	Albedo, carbon storage, geol. proc., sea level	Carbon storage, geological processes, nutrient and pollutant storage			Aquatic ecosystem

link to the water cycle, to indirect interaction with the climate system through vegetation, such as albedo and carbon cycle regulation. While the tables do not to show interactions, the water stocks, flows, functions, and processes are massively interlinked and can interact in complex ways. For example, beyond direct contribution to climate regulation through carbon storage and albedo, soil moisture is also a key determinant of evaporation, and has an important influence on precipitation patterns and water state in living matter. Sometimes, the feedbacks in different water compartments can be both positive and negative, and thus, cancel out impacts on certain water functions. For example, while drying soil may increase reflectance, water stress in plants may cause reduced reflection in leaves and increased exposure to soil that undo those effects (Teuling and Seneviratne (2008)). Due to these complex interactions, the attribution of water functions to different stocks and flows in these tables should be seen only as a method to pinpoint key processes. In reality, all water stocks, flows, and functions are intimately connected.

Through the eight water functions, freshwater flows and stocks are fundamental determinants of the state of ecosystems and biomes in the biosphere, and the stability and feedbacks in Earth system regulating systems, such as the climate system and global cycles of nutrients. Importantly, water is not only a determinant of the ability of social-ecological systems to deal with shocks, adapting to changing conditions, and transforming in situations of crisis, i.e., what defines resilience (Folke, 2006). Water is also a primary driver of amplified and more frequent shocks and stresses as a result of human global environmental change. In this sense, water is both friend and foe, in the pursuit of resilience for sustainable development in the Anthropocene.

As evident from the overview in Table 2 and 3, water stocks and flows often serve more than one function and are profoundly active in driving the life support system. We aggregate water stocks and flows at the global scale from the literature (see Table S1) to provide an overview of quantity of water involved in the eight different green and blue water functions. This exercise (Fig. 4) shows that blue water functions together involve much larger volumes of water (groundwater, surface water, ice) than those of green water (soil moisture, air moisture, living matter). In terms of flows, by contrast, the green water function for regulating the Earth's energy and climate system involves the largest water flows (terrestrial evaporation). Compared with precipitation over land, green water functions involve 1.0–1.7 times as much water flows, and blue water 0.6–1.0 times. Together, green and blue water functions involve water flows amounting to 1.6–2.7 times the precipitation flow, despite the conservative way of accounting for water functions that ignore indirect and cascading effects. Thus, this neatly highlights the inherently multi-functional role of water.

3. Evidence of water-related non-linear tipping and linear collapse

3.1. Ecological and biophysical collapse

Literature offers a broad overview of cases where resilience has undergone erosion. This section synthesizes examples of water related biophysical regime shifts that have either been observed or suggested by theories or modelling studies around the world (Table 4). Importantly, we show how each evidence of regime shift

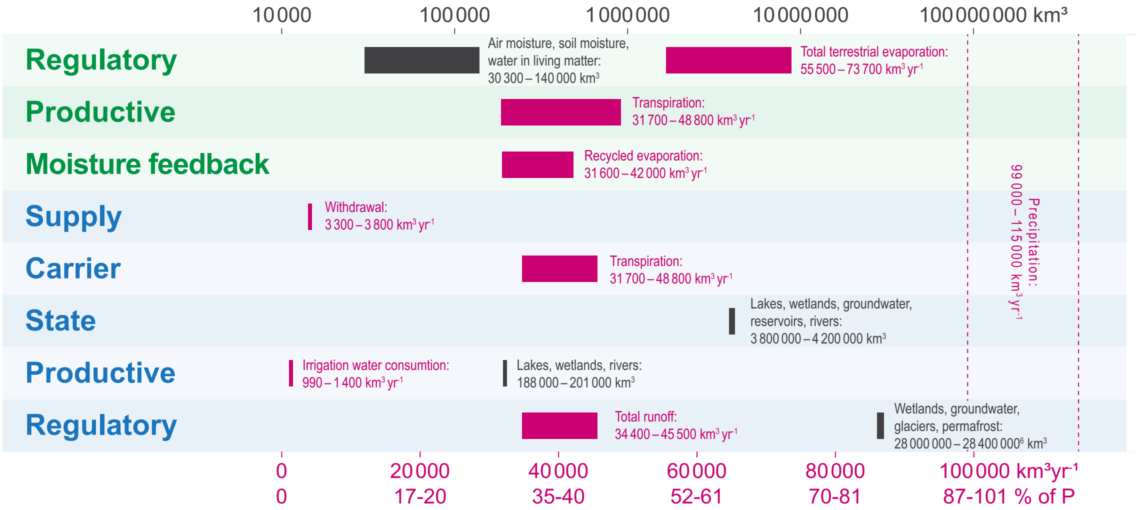


Fig. 4. Global estimates of flows and volumes of water functions.

is linked to key water functions, as well as the resilience and feedback processes involved.

This overview shows the diversity of water related tipping points and collapses, in terms of human interference, spatial scale, temporal scale, location, reversibility, and system perturbed. It is clear that many of the local and regional scale biophysical resilience erosion processes and mechanisms are well understood by the scientific community. The most serious regime shifts related to full-scale Amazon forest dieback and total glaciers meltdown are well-understood through theories and modelling. The perhaps most elusive feedbacks are the ones potentially occurring in societies. For example, while loss in water supply to societies can in principle be considered a linear process in the biophysical system (i.e., water supply can be re-instated as soon as water is available), potential thresholds in the society towards e.g., upheaval, migration, and financial collapse are complex and context specific, and have generally been challenging to attribute to changes in any specific variables.

Social feedback mechanisms can, moreover, mediate regime shift in an ecological or biophysical system. These social feedback are context-dependent, and not necessarily tied to a specific type of water resilience function perturbation. Social feedback modifications may operate from individual to global scale, and include a wide range of aspects (Müller-Hansen et al., 2017; Wada et al., 2017), such as social norms, cultural values, laws and regulations, implementation (Castilla-Rho et al., 2017), behavioral patterns (Chen et al., 2012), traditions, risk levels (Benchekroun and Long, 2014), uncertainty (de Zeeuw and Zemel, 2012), institutions (Galaz, 2005), technology, markets, knowledge (Micklin, 1988), and learning (Pahl-Wostl, 2006).

A wealth of studies explore social feedback in resource sharing context to understand the “tragedy of the commons” (Hardin, 1968) and the conditions required to govern the commons (Ostrom, 1990). Commonly, these relate to the *blue* water resilience functions *Supply*, *Carrier*, *State*, *Productive, and Regulatory* and the *green* water resilience function *Productive* at the local to regional scale. Few studies have yet explored the social dynamics of *green* water resilience function *Moisture feedback* (Keys and Wang-Erlandsson, 2018). Indirect relation to *green* water resilience function *Regulatory* can be found in studies that address for example global climate (Barrett, 2013; Nkuiya, 2015), or land management (Meyfroidt et al., 2018).

3.2. Social collapse

The evidence that water has multiple functions (Tables 2 and 3) regulating the state and the resilience of biophysical systems, combined with mounting evidence of water related, and induced tipping points as water resilience is lost (Table 4), raises the major question of what implications loss of water resilience and crossing water tipping points have on societies?

Table 5 illustrates a set of evidences and risks for social tipping points and collapsed civilizations. Failure has been generated in different ways: in most cases triggered by severe drought years. All show disastrous effects on management failures that lead to societal problems generated by biophysical collapses.

4. Water resilience processes in social-ecological systems

In this section, we summarise, and interpret the evidences presented in Section 3, and discuss the general pattern that emerge. State shifts in ecological and biophysical systems related to water often involve more than one water function and role. Disturbances in water functions might occur simultaneously, interact, or cascade. Accordingly, the role of water for inducing regime shifts or linear collapse shifts between being a control, state and driving variable.

4.1. Water functions mediate ecosystem tipping and collapse

Based on Table 4, Fig. 5 illustrates the general way water mediate in ecosystem collapse through its eight functions (Section 2.3) and three roles (Section 2.2) at the local to regional scale. For example:

1. salinization, which is primarily induced by irrigation using salinized water (blue carrier function, driving variable) and moisture feedback (green moisture feedback function, state variable), and secondarily by regulation of soil moisture (green regulatory, control), and thirdly by loss in biomass production (green productive, control);
2. savannization, which is primarily induced by deforestation and climate change (green moisture feedback, driving), secondly through decrease in biomass production (green productive,

Table 4
Evidence of biophysical water tipping points and linear collapse.

Water functions (primary system perturbed)	Resilience erosion (primary human interference)	Feedback modification (Type of collapse in the ecological/biophysical system, see Section 2.1)	Regime shift evidence (Observed tipping in **bold**; theoretical or simulated tipping in *cursive*)
Regulatory/ productive (land, climate)	Land degradation (dryland mismanagement)	Crusting causing radical decrease in infiltration capacity, plummeting the land system into a vicious cycle of increasingly drier conditions (Tipping)	**Sahel** (Mbow et al., 2015)**; Loesss plateau, China** (Zhao et al., 2013)**.**
	Ecological change due to changed rainfall regime (climate change)	Positive self-sustaining feedback loop of climate change, leading to unreliable rainfall patterns, decreased biomass, carbon release and further climate change. (Tipping)	**Abrupt weakening of Indian monsoon** (Dixit et al., 2014); **Drought induced boreal forest dieback in western Canada** (Michaelian et al., 2011)**;**
	Hydrological extremes (carbon emissions)	Increase in hydrological extremes, forest dieback, carbon sequestration loss. (Potentially self-amplying feedback loop through deforestation, although further research is need to fully understand the overall feedback wil the green water cycle in terms of e.g., cloud, albedo, and water use efficiency.)	**Response of the US forest to climate change induced drought** (Hanson and Weltzin, 2008)**;** *climate change induced Amazon dieback* (Cox et al., 2004; Malhi et al., 2009)**.**
	Heat wave (climate change)	Positive feedback loop of soil moisture deficit, sensible heat, atomspheric boundary layer growth, warm air entrainment, and further build-up of heat. (Tipping within the scale of the heat wave event)	**Escalation of high temperatures in European mega heat-waves** (Miralles et al., 2014)
Productive (land)	Water logging induced reduction in crop production (irrigation)	Water logging can interact syngergistically with salinization (Linear, or tipping in interaction with salinization)	**Water logging in Australia** (McFarlane and Williamson, 2002)
Moisture feedback (land, climate)	Deforestation drastic rainfall change (deforestation)	Positive self-sustaining feedback loop of deforestation leading to decreased rainfall (potentially drought and fire), decreaed biomass, decreased evapotranspiration, and further decreased rainfall. (Tipping)	*Tropical forest to savanna* (Hirota et al., 2011; Staver et al., 2011; Zemp et al., 2017)**;**
Supply (society)	Loss in river water supply (water withdrawal)	(Linear biophysical response)	Ogallala aquifer depletion has economic impacts (Terrell et al., 2002). Global water scarcity (Kummu et al., 2016)
	Loss in groundwater supply (water withdrawal)	(Linear biophysical response)	**India** (Rodell et al., 2009); **High Plains, US** (Steward et al., 2013; Steward and Allen, 2016);
	Loss in melt water supply (climate change)	(Linear biophysical response)	**Loss in stable water supply downstream the Andes** (Baraer et al., 2012; Vergara et al., 2007);
	Loss in irrigation water supply (water withdrawal)	(Linear biophysical response)	**Loss in agricultural irrigation supply Aral Sea** (Micklin et al., 2014) **India** (Rodell et al., 2009); **High Plains, US** (Steward et al., 2013; Steward and Allen, 2016);
Carrier (water body)	Eutrophication (agricultural fertilization)	Nutrient excess causes algae bloom, biomass degradation by bacteria, and subsequent oxygen depletion that prevents the lake from regaining organisms to consume nutrients and recovering. (Tipping)	**Hypoxia Lake Erie** (Arend et al., 2011; Zhou et al., 2015)**; Ecosystem change in Lake Victoria** (Hecky et al., 2010)**.**
	Pollution (industrial contamination)	Loss of biodiversity and structural change in biological community (Tipping in the ecological system)	**Industrial contamination of fresh major lakes in China** (Ma et al., 2013)**; Non-point agricultural pollution of waterways in China** (Sun et al., 2012)**; TBT induced regime shift in shallow lakes** (Sayer et al., 2006)
	Salinization of terrestrial systems (irrigation)	Salt accumulation causes self-reinforcing cycle of biomass production loss, soil organic carbon loss, and erosion. Irrigation induced mobilisation of salt. Potential social feedback. (Tipping in the biophysical and ecological systems)	**Irrigation in Greece** (Pisinaras et al., 2010)**; Irrigation in Mexico** (Endo et al., 2011)**; Irrigation in NW China** (Li et al., 2008)**; Australia** (Anderies et al., 2006) **1.1 GHa land is salt affected globally** (Wicke et al., 2011)
	Salinization and alkalization of freshwater (agriculture, land clearing, mining, road salt)	Ecosystem regime shift through e.g., favoring of physiologically tolerant species, structural changes in ecosystem communities, riparian vegetation loss affects nutrient cycling and light (that shift the system from heterotrophic to autotrophic) etc. (Tipping in the ecological system)	**Salinization and alkalinization of fresh water in the USA** (Kaushal et al., 2018, 2005); **Salinization wetlands worldwide** (Herbert et al., 2015); **Salinization of rivers** (Cañedo-Argüelles et al., 2013)
State (water body)	River basin closure (surface water withdrawal)	Prevention of migration, decline in water quality, loss of species (Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	Observed and projected: **Colorado river** (Castle et al., 2014); **Yellow river** (Yang and Jia, 2008); river basin closure (Molle et al., 2010).
	Aquifer collapse (water withdrawal)	Salt water intrusion and subsidence resulting from aquifer collapse may prevent future recharge and recovery. (Potentially tipping)	Observed and projected groundwater depletion **India** (Rodell et al., 2009); **High Plains, US** (Steward et al., 2013; Steward and Allen, 2016); **salt intrusion in coastal aquifers** (Mazi et al., 2013). **Global depletion** (Wada et al., 2010).
	Glacier retreat (human induced climate change)	Retreat of glaciers decreases albedo, leading to temperature rise, and further glacier melting. Melt water also increases the speed of glacier retreat. (Tipping)	Observed and projected: **Himalaya glacier retreat** (Bolch et al., 2012; Kargel et al., 2011; Kulkarni et al., 2007);
	Lake depletion (water withdrawal)	Water quality decline, species loss, biological community collapse (Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	**Aral Sea** (Micklin et al., 2014)

(*continued on next page*)

Table 4 (*continued*)

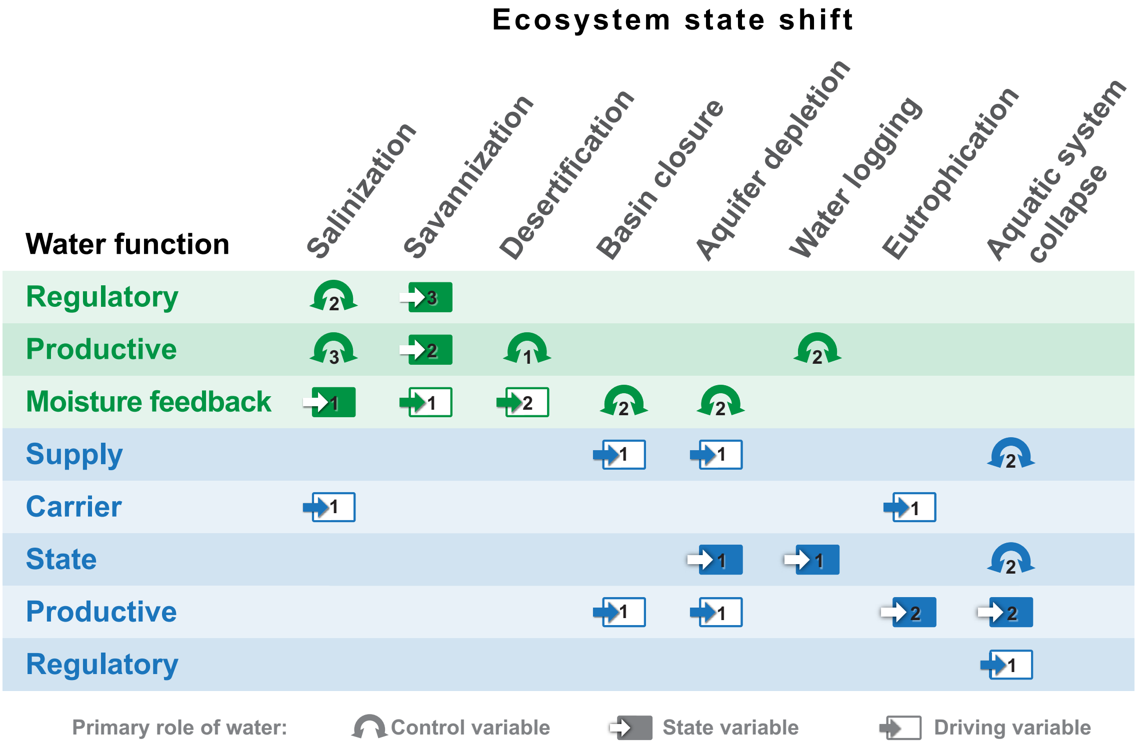
Water functions (primary system perturbed)	Resilience erosion (primary human interference)	Feedback modification (Type of collapse in the ecological/biophysical system, see Section 2.1)	Regime shift evidence (Observed tipping in **bold**; theoretical or simulated tipping in *cursive*)
Productive (water body)	Loss in fishery, crop yields, biodiversity (water withdrawal)	(Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	**Loss in biodiversity, fishery, agricultural production around Aral Sea** (Micklin et al., 2014);
Regulatory/control (water body)	Regional climate change (water withdrawal)	(Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	**Dust storm and desert climate around Aral Sea** (Micklin et al., 2014);
	Flooding (human induced climate change)	(Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	**Glacial retreat** (Hoffmann and Weggenmann, 2013)
	Ecosystem collapse due to unnatural flow regimes (dams and reservoirs)	Loss of flow variation. (Linear in terms of biophysical feedbacks, tipping possible in the ecological system)	**Dolphin population dependence on natural flows in the Gangetic basin** (Choudhary et al., 2012); **Global flow regulation and fragmentation** (Nilsson et al., 2005);

Table 5
Evidence and hypotheses of water related social collapse.

Collapse casedetrimental human activity (reference)	Biophysical manifestation	Social collapse category (collapse type, see Sect. 2.1)
Antique Arab civilization • large-scale Mesopotamian agriculture • Euphrates-Tigris basin • 762 – 1258 AD • (Cowen, 1999)	• agricultural land degradation • salinization • canals silt-choked • deathblow=flood-generatedshift of river courses	• water supply collapse • agricultural system collapse • socio-economic collapse of rich Arab culture(time of Sheherazade) • Iraq remained desert >600 yrs (linear collapse)
Maya civilization • advanced civilization • 19 million people • 800's or 900's AD • (Aimers and Hodell, 2011; Kuil et al., 2016; Oglesby et al., 2010; Turner and Sabloff, 2012)	• deforestation • reduced precipitation • severe drought period • erosion, soil degradation	• crop failure • collapsing life support system • abandoning of cities/archeological evidence • sudden collapse of sophisticated civilization (non-linear tipping)
US dust bowl • US Midwest (23 states) • agricultural development • 1930's • (Cook et al., 2009; Schubert et al., 2004)	• plowing deep-rooted prairie grass • severe series of drought years • soil erosion • land desertification • dust storms	• agricultural degradation with implications for moisture feedback and reduced soil water holding capacity, • worsened effects of Economic Depression • socioeconomic degradation (non-linear tipping)
Aral Sea region • large-scale irrigation upstream and downstream • 1930's – 1980's (?) • (Micklin et al., 2014; Micklin, 1988)	• consumptive water use • river depletion • lowered lake water level • water and land salinization • salt+dust flow from bare lake bottom	• regional trade losses • water supply collapse • health effects • societal collapse (non-linear tipping)
Syrian conflict/Arab spring • rapid population growth • 2006-ongoing • (Gleick, 2014)	• extreme 5-yr drought 2006- 2011 • reduced river inflow fr Turkey • climate change stresses(?) • irrigation development • salinization	• agricultural collapse • rural water shortages • water supply disturbance • food insecurity for > 1 million people • mass migration • unemployment • political tensions, revolution • social unrest (non-linear tipping)

state), and thirdly through impact on the climate system through albedo, carbon, and circulation feedback (green regulatory, state);

3. desertification, which is primarily induced by overgrazing (green productive, control), and secondarily through decline in moisture feedback (green moisture feedback, driving);
4. river basin closure, which is primarily induced by unsustainable surface water withdrawal (blue supply, driving), ability to support biomass growth (blue productive, driving), and secondarily through moisture feedback as evaporation decreases (green moisture feedback, control);
5. aquifer depletion, which is primarily induced by unsustainable groundwater withdrawal (blue supply, driving), decline in water volumes (blue state, state), ability to support biomass growth (blue productive, driving), and secondarily through moisture feedback as evaporation decreases (green moisture feedback, control);
6. water logging, which is primarily induced by water being accumulated in the soil (blue state, state), and which has secondary effects on the biomass production (green productive, control, although irrigation or groundwater caused water logging could be considered as affecting the "blue" productive function);



Water function	Salinization	Savannization	Desertification	Basin closure	Aquifer depletion	Water logging	Eutrophication	Aquatic system collapse
Regulatory	↷2	■3						
Productive	↷3	■2	↷1			↷2		
Moisture feedback	■1	□1	□2	↷2	↷2			
Supply				□1	□1			↷2
Carrier	□1						□1	
State					■1	■1		↷2
Productive				□1	□1		■2	■2
Regulatory								□1

Primary role of water: ↷ Control variable ■ State variable □ Driving variable

Fig. 5. The role and function of water in ecosystem collapse. The numbers refer to the general sequence of the water related processes in mediating the ecosystem state shift.

7. eutrophication, which is primarily induced by nutrient overload from agricultural fertilization (blue carrier, driving), secondarily by shift in type of ecological biomass supported by the ecosystem (blue productive, state);
8. aquatic system collapse, which is primarily induced by dams and reservoirs that disrupt flow variation (blue regulatory, driving), secondarily by demand in water for societal supply (blue supply, state), biomass production (blue productive, state), and change in water volumes (blue state, control).

Fig. 5 is a conceptualization of key processes useful for system understanding in generalized cases, and specific cases might have more diverse causes and interactions. A benefit of breaking down the roles and functions of water is how clearly it shows that water issues have profound implications and can be critically impacted by systems and sectors well beyond the traditional notion of a water sector that directly deals with visible liquid water. In addition, many climate, land-surface, and hydrological models struggle to adequately reflect observed ecosystem regime shifts, and may benefit from a systematic understanding of how water function disturbance and feedbacks may or may not be well-represented in the model. Finally, system understanding of the biophysical and ecological processes is fundamental for understanding the often much more elusive, complex, and context-specific feedbacks in societal systems, as we will discuss in the next section.

4.2. Life support systems changes can shake societies

A rich archive of historic evidence shows how water scarcity and deterioration of water quality has contributed to the decline of ancient Empires, such as the Maya, the Mesopotamian irrigation societies, and the Antique Arab civilization (Section 3.2). There is rising indicative evidence of how deterioration of fundamental water functions for life support systems—such as the collapse of food systems due to prolonged droughts (which very likely amplified by Anthropogenic global warming) has contributed to accelerate and potentially accentuate human conflicts and national instability, such as the Arab Spring and the Syrian War (Gleick, 2014).

In more general terms, land mismanagement may contribute to social system collapse by altering the terrestrial ecosystem to which the population has become used. Especially vulnerable have been irrigated civilizations in dry climate regions, where the agriculture has included unsustainable components. Contributing causes of agricultural civilization's collapses include salinization, water logging, choking canals, soil fertility decline, etc. The processes may be slow, with progressive increase in salinization or water logging for which there is no remedy in sight. Societal problems may build up step by step, as illustrated by the Arab spring, but finally have grown in size and complexity to a level, impossible to compensate by countermeasures.

Social collapse is, thus, a result of multiple interacting processes, ranging across geopolitics, economics, values, weak states and environmental shifts—in simple terms when deterioration of natural, economic and human capital manifests itself in collapse in human security, rule of law and ultimately conflict. At first, resilience is eroded in the social-economic system, hydrological system, and other biophysical systems through anthropogenic or natural disturbance of slow, underlying variables. As resilience is eroded, it becomes more likely for a shock to manifest, that potentially triggers a non-linear regime shift or linear collapse in the biosphere and the society. We attempt to illustrate this general social collapse process in Fig. 6a.

In a more tangible example, we interpret the Syrian crisis through the resilience lens in Fig. 6b. In the slow undercurrents of the societal, land, and climate system, it is clear that resilience was low due to political instability, land degradation, and climate change that affected the local hydrological regime. As drought triggered crop failure in the low-resilient system, people abandoned their rural land and migrated to cities where political tensions

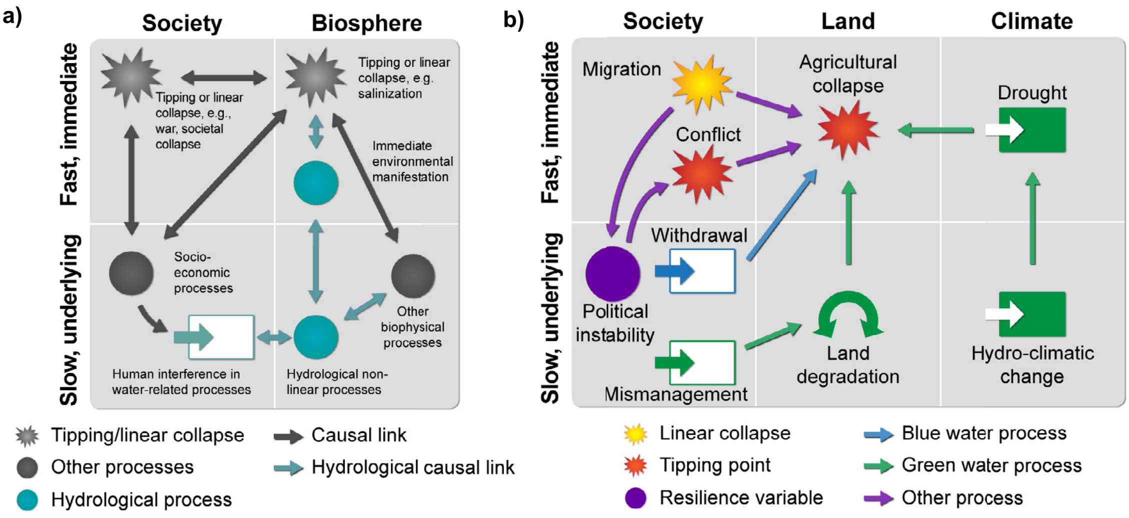


Fig. 6. Water related process sequence towards environmental and social crossing of tipping points, in (a) general case, and (b) specific case of the Syrian conflict.

and instability reached new highs and contributed to the break-out of the civil war.

Clearly, the societal collapse illustrated in these examples involve feedback with the ecological and biophysical systems in which the societies fundamentally are embedded and rely on. This shows both a risk and an opportunity for management and governance of natural systems. A resilient biophysical system reduces the risks for the society to cross the threshold towards collapse, and a non-resilient natural system can influence and in worst case trigger avoidable societal failures. While the ancient case studies of societal collapse are limited to the regional scale, regional agricultural collapse or failure in our modern era are compensated by for instance food import, which may delay realization of resilience problems, but potentially also risk larger scale of collapse if resilience erosion affects e.g., an entire trade network.

Emerging disciplines of hydro-sociology and socio-hydrology are evidence of the recognised need to study coupled co-evolving human-water systems (Sivapalan et al., 2012). Further, consideration of social resilience or hydrological resilience alone is distinctly different from consideration of their resilience of a coupled socio-hydrological system (Mao et al., 2017).

4.3. Building water resilience in the Anthropocene

In Anthropocene, the role of water for human development and sustainability has expanded in scope, scale, and speed, placing water resilience at the core of integrated water resource management. *Scope*: water resilience is no longer just about water, they link to climate change, dietary choice, trade, consumption, and more. When in the past, water management effectively meant blue water management, water managers of today need to consider vastly cross-sectoral implications and green-blue water interactions. *Scale*: water issues have gone global. In the past, water were studied at the catchment scale, lake scale, or community scale, but global scale drivers of climate and land-use change is effectively mediating with the water cycle by melting glaciers, changing rainfall patterns, increasing drought risks, rising sea levels etc. Water solutions now also need to be sought at the global scale and inter-connectivity between scales need to be at the forefront. *Speed*: changes in the water cycle and changes in the society are rapid and surprising, competing with the hard and soft infrastructure development pace and societal learning and response rate, and requiring societies to think, plan, and adapt proactively.

Building water resilience in the Anthropocene necessitates a paradigm shift from traditional blue water focused management to adaptive water management (Pahl-Wostl, 2007) that takes into account interactions between green and blue water, and the full water cycle, relying on empirically derived resilience building principles: maintain diversity, manage connectivity, manage slow variables and feedbacks, foster complex adaptive systems thinking, encourage learning, broaden participation, and promote polycentric governance (Biggs et al., 2015). New tools to build resilience have emerged, including resilience assessment and resilience planning (Sellberg et al., 2018), that need to be further developed and employed in various contexts. The water resilience functions identified in this paper have the further potential to be explored in terms of their usefulness for management and policy, beyond the water sector.

5. Conclusions and future outlook

Water is behind all ecological goods and services from the biosphere that make human life on Earth possible. Water is not only a generator of ecosystem services, like food and energy, it is also a critical agent of change, e.g., functioning as a greenhouse gas and a regulator of temperature on Earth, and a victim of change, e.g., through shocks like droughts and floods caused by global warming. In this paper we put a further emphasis on the role of water as the bloodstream of the biosphere, and thus key in sustaining all life on Earth, by integrating all different functions of water into one integrated framework, namely water resilience. Water resilience defines the role of water in regulating the state of ecosystems, biomes and the Earth system through interactions and feedbacks of water related ecological functions. In this paper we provide comprehensive evidence that water is associated with state-shifts in social-ecological systems, as water functions cross critical tipping points, pointing at the importance of understanding the role of water as a source of resilience. Its functioning is essential for Earth system resilience and sustainable development.

We distinguish between eight parallel water functions and show the massive scale of the water flows and stocks by which they contribute to the functioning of components of the Earth System. *Green water-related flows* and stocks uphold three of these systems: the energy and climate system, biomass production, and moisture feedback and hydrological recirculation; and *blue water flows and stocks uphold five systems:* related to societal water supply, the nutrient and pollution transport, the aquatic state of blue freshwater bodies and resources, and the regulation of aquatic ecosystems and climate. We clarify the profound role played by water flows as a function multiplier: water flows corresponding up to 170% of the annual flow of terrestrial precipitation contribute to green water functions (>100% means the same precipitation contribute to several functions), and up to 100% to blue water functions. All freshwater stocks serve fundamental functions for regulating the Earth's climate and aquatic ecosystems.

Human interference with green and blue water functions is considerable and examples of hydrologically coupled ecological system tipping points associated with non-linear change are ample in literature. A broad overview of cases provide evidence of erosion of water resilience in biophysical water-related systems with tipping points. In most cases multiple water functions are active in the loss of water resilience: salinization, savannization, deforestation, desertification, river basin closure, aquifer depletion, water logging, eutrophication, aquatic system collapse. The cases include several regional scale ecological systems and biomes (savannas, aquatic ecosystems, Amazon rainforest, Indian monsoon, and the Sahara desert).

Water functions are linked also to societal collapse, as evident in historical as well as modern time cases. We provide mounting evidence of risks of crossing social tipping points as water-related resilience is lost, resulting in collapse of civilization, degraded human security, loss of rules of law, and amplified conflicts. Most of these cases were triggered by severe drought events, salinization, water logging, choking canals and soil fertility decline, hitting agricultural civilizations. Land and water mismanagement alter the function and state of terrestrial ecosystems, slowly or step by step until no remedy is in view. The identified cases exemplify erosion of water resilience, both through gradual system decline (Antique Arab civilization) and regime shifts (Maya civilization, US dust bowl, Aral Sea region, Arab spring/Syrian conflict).

Regime shifts in the past have occurred at the local to regional scale, but with the dawn of the Anthropocene, we now need to consider the risk of human induced regime shifts at the planetary scale (Rockström et al., 2009; Steffen et al., 2018, 2015). In future research, it will be important to better understand how loss of water resilience at the local scale may influence Earth system resilience as a whole through for example cumulative, integrative, and cascading processes. The most visible manifestation of climate change is displayed through the hydrological lens – in the form of e.g., floods, droughts, and sea-level rise – that may trigger an understudied interplay of ecological, biophysical and social feedbacks. At the same time, uncertainty prevails in climate model predictions of Earth's future climate associated e.g., with clouds – the water in the sky, and the dynamics of biosphere carbon feedbacks, related directly to water resilience. Thus, the role of water for future Earth system resilience will be essential to clarify.

Human interference in all water functions, green as well as blue, is modifying life support systems on Earth. How will further global stresses, caused by for instance ongoing climate change, global population growth, and increasing human demands, continue to disturb the Earth's life support system with its profound interactions between water flows, functions and roles on the one hand, and on the other essential ecological processes such as food production, timber production and biodiversity? And what risks will this involve? In view of the strong driving forces in the Anthropocene, the complex interactions with social-economic phenomena need special attention. Modern time teleconnections such as trade and migration, can put some relief to water induced social stress and impacts of displacement. However, this may also temporarily mask resilience loss at the global scale.

Finally, the new understanding of water's critical roles for building resilience of the Earth's life support system will lead to new types of questions: what management-related navigation options for the life support systems on Earth will there exist, to safeguard human wellbeing along realistic pathways that can keep the planet in the present favorable Holocene-like state, with its relatively stable climate? What transformations will be critical? What shifts in governance approaches in terms of scopes, scales, and speed will be essential? And how can they be achieved? We challenge the scientific community to integrate water resilience thinking when exploring these grand challenges for humanity's future on Earth.

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Conflict of interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2018.100009.

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