A conceptual framework for assessing socio-hydrological resilience under change

Feng Mao[1], Julian Clark[1], Timothy Karpouzoglou[2], Art Dewulf[2], Wouter Buytaert[3, 4], and David
5   Hannah[1]

[1] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

[2] Public Administration and Policy Group, Wageningen University, Wageningen, Netherlands

[3] Department of Civil and Environmental Engineering, Imperial College London, London, UK

10   [4] Grantham Institute for Climate Change and the Environment, Imperial College London, London, UK

Correspondence to: Feng Mao (f.mao@bham.ac.uk)

Abstract. Despite growing interest in resilience, there is still significant scope for increasing its conceptual clarity and
15   practical relevance in socio-hydrological contexts. Specifically, questions of how socio-hydrological systems respond to and
cope with perturbations and how these connect to resilience remain unanswered. In this paper, we propose a novel
conceptual framework for understanding and assessing resilience in coupled socio-hydrological systems. Taking a systems
perspective, we argue resilience is a set of systematic properties with three dimensions: *absorptive, adaptive* and
transformative, and contend that socio-hydrological systems can be viewed as various forms of human-water couplings,
20   reflecting different aspects of these interactions. We propose a framework consisting of two parts. The first part addresses
the identity of socio-hydrological resilience, answering questions such as 'resilience of what in relation to what'. We identify
three framings of resilience for different types of human-water systems and subsystems: (1) the *water subsystem,*
highlighting *hydrological resilience* to anthropogenic hazards; (2) the *human subsystem,* foregrounding *social resilience* to
hydrological hazards; and (3) the *coupled human-water system,* exhibiting *socio-hydrological resilience*. We argue that these
25   three system types and resiliences afford new insights into the evaluation of different water management challenges. The
first two types address hydrological and social states, while the third type emphasises the feedbacks and interactions between
human and water components within complex systems subject to internal or external disturbances. In the second part, we
focus on resilience management and develop the notion of the 'resilience canvas', a novel heuristic device to identify

possible pathways and to facilitate the design of bespoke strategies for enhancing resilience in the socio-hydrological context. The 'resilience canvas' is constructed by combining absorptive and adaptive capacities as two axes. At the corners of the resulting two-dimensional space are four quadrants which we conceptualise as representing resilient, vulnerable, susceptible, and resistant system states. To address projected change-induced uncertainties, we recommend effort is now focused on shifting socio-hydrological systems from resistant towards resilient status. In sum, the novel framework proposed here clarifies the ambiguity inherent in socio-hydrological resilience, and provides a viable basis for further theoretical and practical development.

Keywords: water, adaptive management, socio-hydrological system, pathway, resilience

1 Introduction

There is now great interest in understanding human-water relationships from a complexity perspective. One example is the field of 'hydro-sociology' (Linton and Budds, 2014; Sivakumar, 2012), emphasising social scientific and humanities approaches to understanding the interactions between humans and water. Similarly, Sivapalan et al. (2012, 2014) have foregrounded the human role in the water cycle by establishing 'socio-hydrology' as a perspective to understand modification and changing patterns of water use in the Anthropocene. While presenting hydrological complexity from different viewpoints, both approaches highlight the interrelationship of human and water systems as one prone to instability. Shifting hazard regimes and altering external conditions caused by human-induced change means dealing with uncertainties, and the prospect of system degradation to undesired states and/or collapse. This opens up questions of how socio-hydrological systems respond to perturbations and future management uncertainties, making it opportune to explore the concept of resilience in socio-hydrological contexts.

Since its introduction in the 1970s, the idea of resilience has evolved from a descriptive notion to a normative concept with broad and often ambiguous meanings (Brand and Jax, 2007; Olsson et al., 2015; Weichselgartner and Kelman, 2015). Some authors have observed this lack of conceptual clarity hinders the application of resilience thinking (Strunz, 2012), raising questions of how to apply the concept to socio-hydrological systems. In the coupled human-water context, resilience is now used in many different ways, such as hydrological resilience, aquatic ecological resilience, community and urban resilience to hydrological disasters, and resilience of water cycles (Rockström et al., 2014). Yet these applications do not always capture the essence of socio-hydrological dynamics or lend support to inter-disciplinary resilience research. We argue that this is because of our limited understanding of human-water couplings and hence the type of resilience that adheres to systems, as much as it is a product of lack of clarity in analysing systematic change. As a result, system identities need defining before examination is undertaken of their intrinsic resilience types (Cumming et al., 2005).

Our aim here is to propose a conceptual framework for understanding and managing resilience in socio-hydrological contexts. The paper's structure is as follows. First, we examine the relationship between resilience, system type and capacities, and characterise resilience as a set of *absorptive, adaptive* and *transformative* properties. Secondly, we classify three types of human-water couplings and their associated resilience forms. Within this classification, we propose studying

5   socio-hydrological resilience, and explain how this differs from the existing notions of hydrological and social resilience. We proceed to argue socio-hydrological systems and subsystems and their attendant resilience dynamics can be characterised using the conceptual toolkit of ecosystem services, as this approach effectively classifies dominant processes of human-water interactions already. Thirdly, we show how to implement the new concept of socio-hydrological resilience. To do so, we develop the notion of a 'resilience canvas' as a means of specifying pathways to specific socio-hydrological resilience states.

10   To enhance system capacity to face future uncertainties, we suggest that a concerted shift is now required to move from resistance to resilient water management.

2 Resilience, systems and capacities

The concept of resilience has many definitions, and is routinely used in multiple fields in widely contrasting contexts (Brand and Jax, 2007). Our aim here is not to describe this variety, but instead to characterise how resilience is interpreted in order

15   to clarify its relationship to other concepts especially systemic capacities and properties (Anderies et al., 2004; Klein et al., 2003; Plummer and Armitage, 2007). Resilience can be understood as a set of systemic *absorptive, adaptive* and *transformative* capacities (Walker et al., 2004, 2009). A clear understanding of the overall system is thus an essential precursor to any evaluation of its resilience (Carpenter et al., 2001). A system refers to a set of interacting components forming a complex whole, which is delineated by its boundaries, surrounded by its environment, and characterised by its

20   structures and functions (Backlund, 2000; Limburg et al., 2002). However, many socio-hydrological systems have ambiguous boundaries, making it difficult to examine resilience properties. So for example referring to 'the system' may mean components or parts of the whole human-water interaction, such as the water subsystem with anthropogenic drivers, or to the human subsystem with hydrological drivers, or may refer to the *socio-hydrological* system, which emphasises the feedbacks and interactions between human and water processes in a balanced and integrated perspective.

25   Once the system type, or 'resilience of what in relation to what', is defined, it clarifies what aspects are being examined, what key indicators of system state need to be established, and what possible desired state is sought (Carpenter et al., 2001; Mao and Richards, 2012). It also helps to identify the drivers of system state, and ultimately what shapes the resilience process. Resilience in this context is mainly driven by two factors – hazards and external conditions, often referred to as 'fast' and 'slow' variables (Walker et al., 2012). Hazards are threats to a system, usually comprising short-term perturbations

(Gómez-Baggethun et al., 2012; Kuo et al., 2012; Turner et al., 2003) such as diffuse pollution, land-use change, drought and flooding. External conditions or controlling variables include changing climate altering the influence of legal and socio-cultural contexts, and the role of science and technology on the *stability landscape* which is used as a metaphor to describe the resilient process of systems (Dent et al., 2002; Scheffer et al., 2001). Systems can shift from one position to another, and

5 make large, abrupt, long-lasting changes to system structure and function (Biggs et al., 2009). Resilience management seeks both to reduce hazards to prevent the system shifting to an undesirable position (e.g. degradation of ecosystems and living standards), and to move the system toward a desired position. The stability landscape itself can also alter because of change in slow variables. This resilience process is usually represented as a bifurcation diagram, showing system state as a ball moving between equilibrium positions (Scheffer et al., 2001, see Fig. 1).

10 Thinking through how *absorptive, adaptive* and *transformative* capacities feature in these diagrams opens up new possibilities for understanding systematic and resilience properties (Walker et al., 2004, 2009). Based on Fig. 1a, the interrelation between three resilience capacities is portrayed in Fig. 1b. Absorptive capacity equates to the original concept of resilience: that is, the capacity of absorbing disturbance while retaining essential structures and functions (Adger et al., 2005; Cumming et al., 2005; Holling, 1973). It is represented as the size (e.g. width) of the equilibrium region (Walker et al.,

15 2004). This capacity is closely connected with the notion of sensitivity (McGlade et al., 2008; Yan and Xu, 2010).

Adaptive capacity is usually defined as the systemic capability to respond to perturbation from a changing environment by adjustment and alteration. If absorptive capacity describes system tolerance to change in structure and function under existing conditions, then adaptive capacity denotes how much this absorptivity can increase in response to external change and to change-induced uncertainties in the future (Engle, 2011; Gallopín, 2006; Smit and Wandel, 2006). It also determines

20 resilience by moving the tipping point and making the desired attraction basins wider or deeper, although it does not necessarily lead to improved system state (Walker et al., 2004, see red dotted line in Fig. 1b). Adaptive capacity arises from two sources, i.e. biological or anthropogenic (Engle, 2011; Lindner et al., 2010). From a biological viewpoint, adaptation refers to the response of organisms to their environment at the genetic, individual and/or ecosystem scale (Engle, 2011; Hoffmann and Sgrò, 2011; Krimbas, 2004). This underlies redundancy and natural selection, which drive evolution

25 (Krimbas, 2004; Lindner et al., 2010). In a social-ecological system however, humans often play dominant roles in creating adaptive capacity (Folke et al., 2010; Walker et al., 2004). For example, Gupta et al. (2010) summarise six dimensions of institutional adaptive capacity: variety and diversity of problem framing and solving, learning capacity, room for autonomous change, leadership, resources and fair governance.

Lastly transformative capacity, or transformability, refers to the human's ability to change the stability landscape or even

30 create a new system by means such as introducing new components or new ways of living, when existing ecological, economic or social structures are untenable (Folke et al., 2010; Walker et al., 2004). Transformations aim to navigate the

systematic transitions from an undesired stability landscape to a new, desired state (Folke et al., 2010, see Fig. 1b; Walker et al., 2009). Proactive transformation may be attempted if change in external conditions is so great that incremental improvement through adaptive capacity is inadequate to meet managerial goals (Bene et al., 2014; Ernstson et al., 2010).

3 A typology of human-water couplings and resilience framings

The importance of using resilience in the coupled human-water context is increasingly evident in both academic and public policy fields, ranging from aquatic ecosystem conservation (Khamis et al., 2013; Sala et al., 2000) to hydrological risk management (Adger et al., 2005; Hallegatte et al., 2013), and sustainable water use and development (Pahl-Wostl et al., 2013; Vorosmarty et al., 2000). We identify three types of human-water couplings with their own intrinsic resilience framings: (1) the *water subsystem,* with hydrological resilience to anthropogenic hazards; (2) the *human subsystem,* with social resilience to hydrological hazards; and (3) the *social-hydrological system,* with socio-hydrological resilience (Fig. 2). The former two types focus on intrinsic hazard-subsystem relations, while the latter covers these subsystem relations and broader and more iterative interplay between them.

3.1 Water subsystem with anthropogenic hazards

Resilience was advanced initially as a phenomenon of freshwater ecosystems to explain the dramatic change in aquatic ecosystem triggered by anthropogenic disturbances (Table 1), such as algal blooms caused by human nutrient enrichment and fish population collapses triggered by overharvesting (Holling, 1973). Based on these cases, this type of coupling describes a particular aspect of human-water interactions, focused on water subsystems and anthropogenic activities or human-induced change as large scale external factors shaping water subsystems. However, from this perspective the human subsystem and its attendant hydrological hazards are not the main emphasis.

Resilience has since been used in a wide range of water subsystems, such as lakes, rivers, and oceans (Dudgeon et al., 2006; e.g. Gibbs, 2009; Hoegh-Guldberg et al., 2008; Willis et al., 2010), where hydrological conditions can be measured by surrogate indicators such those described by Holling (1973), or through examining other biotic or abiotic components. This coupling model is primarily used in aquatic ecosystem conservation and management, with the implicit goal of maintaining subsystem equilibrium or restoring it to a desired historical state. Climate change or increased human hazards may degrade aquatic ecosystems or propel them to irreversible undesired end-states (O'Reilly et al., 2003; Sala et al., 2000), prompting resilience management (Mace, 2014). For example, climate change and ocean acidification together with local anthropogenic stress decrease sea water quality, alter community structure and diversity, change species distribution and might even push ecosystems such as coral reef to functional collapse (Carpenter et al., 2008; Doney et al., 2012; Hoegh-Guldberg and Bruno, 2010). In such cases aquatic organisms (e.g. macroinvertebrates and macrophytes) can be used for biological monitoring to assess adverse human impacts on species and ecosystems (e.g. Miller et al., 2007; Ozkan et al., 2010). Ecological indicators

have been developed for river basin management in many regions of the world (Bunn et al., 2010; Josefsson and Baaner, 2011). Attention has also been paid to resilience of hydrological aspects of water systems under climate change, extreme weather and alteration in land cover (Harder et al., 2015; Peterson et al., 2012). Better understanding of multiple steady hydrological states and the process interaction of switching between states can inform adaptive water management (Botter et al., 2013).

3.2 Human subsystem with hydrological hazards

The second type of coupling is the human subsystem with hydrological hazards (Table 1). Here hydrological components are not considered as a system, but as impacts on human activities. Although hydrological hazard may be caused or increased by human activities, or its impacts on human society may be exacerbated by inadequate management or responses (Van Loon et al., 2016), emphasis on resilience from this perspective is on how hydrological hazards change human subsystems, and how human societies respond to these hazards, rather than how water subsystems are changed by human activities. This human-hydrological coupling is commonly applied in disaster management (Kelman et al., 2015; Sudmeier-Rieux, 2014), where resilience is derived from capacity building within human systems to better cope with more frequent hydrological shocks (for example, those induced by climate change; Adger et al., 2005; Aerts et al., 2014; Dahm, 2014).

Human subsystems have many facets and their state is described through numerous indicators and disciplinary approaches. Similarly, resilience understandings vary widely. Meerow et al (2016) describe human subsystems as complex arrangements of processes and phenomena at many different scales and levels. Reviewing 675 articles on resilience, Ostadtaghizadeh et al. (2015) identify five main domains affecting human subsystems, including social, economic, institutional, physical and natural categories. For example, hydrological hazards may cause injuries, death, and property and infrastructure lost (Liao, 2012), which can be quantified to estimate the approximate cost of disasters (Keating et al., 2015). Apart from this physical aspect, socio-economic condition can also be used to capture the degree of resilience of human systems to hydrological impacts, with economic growth, incomes and livelihoods often used as proxies (Kumar, 2015; Plummer and Armitage, 2007).

Resilience of human systems is usually evaluated from social science perspectives (Lorenz, 2013; Olsson et al., 2015), through concepts such as social capital and network structures, institutions and power relations. Knowledge and discourses have received increased attention (Keck and Sakdapolrak, 2013; Wyborn, 2015). Cutter et al. (2008, 2010) highlight 'community competence' as capacities to understand risks, promote individual physical and emotional health (Norris et al., 2008), and maintain cultural norms such as livelihood practices and social institutions (Crane, 2010). Indeed, recent studies highlight that an alternative approach to engage with challenges posed by resilience is to use a more theoretically pluralist perspective that enhances engagement and utilisation of insights from different angles, alongside insights gained from resilience scholarship (Karpouzoglou et al., 2016a).

Resilience from the perspective of managing human subsystems thus emphasises particular societal norms and goals or normative aspirations in relation to hydrological hazards. However, if social aspects of human subsystems are also considered, more anticipatory targets can be discerned. For example, Cote and Nightingale (2012) argue that the dynamics of social change should be better framed as part of social-ecological resilience research. A similar point is made by MacKinnon and Derickson (2012) in their arguing that resilience as a concept is too conservative in outlook, because it embraces contemporary societal expectations rather than challenging them; they go further by advocating a shift from resilience to resourcefulness as a concept that better matches the aims of emancipatory social sciences.

3.3 Socio-hydrological system and its resilience

While it is possible to examine resilience from the perspective of water or human subsystems, we argue that it can also be considered in relation to coupled socio-hydrological systems within which human and water subsystems are constitutive elements. This move to socio-hydrology as a framing device implies the need to reassess resilience from a co-evolving viewpoint, where water and human systems make and remake each other and are interdependent in time and space (Sivapalan et al., 2012), so implicating water and society in governance arrangements (Sivakumar, 2012). Here it is the state of the coupled system rather than a particular perspective of either water or human systems that is of interest. This third type of coupling foregrounds the states, conditions and interactions of both human and water subsystems to build a more balanced understanding of their process interrelationships.

Resilience of these socio-hydrological systems can be evaluated by a compositional approach (Meerow et al., 2016; Ostadtaghizadeh et al., 2015). Components from both human and water systems are assessed separately and then summed up to obtain a proxy value for the overall coupled system state. For example, community disaster resilience comprises resilience of constitutive ecosystem and human subsystem domains (i.e. social, economic, institutional, and physical) (Ostadtaghizadeh et al., 2015). However, this compositional approach cannot gauge the complex interactions and feedbacks of human-water coupling (Montanari et al., 2013). Instead, measures are needed that model the dynamic interdependencies of continually interacting components. This demands a direct assessment of the coupled system using multi-directional indicators. Examples include human benefits from hydrological systems, water sustainability, and water-supported socioeconomic development. The notion of multidirectional interactions is closely related to the concept of hydrological ecosystem services (Biggs et al., 2012, 2015), which attempt to bridge the two subsystems (Engel and Schaefer, 2013). In effect, the level of ecosystem services provision is the product of conflicting factors from both sides, such as human demand and ecosystem supply, human disturbances and ecosystem regulation and regeneration, and human management and water resources.

The possibility that hydrological ecosystem services offer a good proxy of human-water intersections is also reflected by its normative goals. Thus high ecosystem service provision implicitly requires integration of at least three components. First is healthy biophysical systems. Robust ecosystem structure, processes and functioning are necessary pre-conditions for the sustainable provision of ecosystem services (de Groot et al., 2002). Second is the intrinsic value of biophysical systems to

human society, even if the value does not have a direct use (Pearson, 2016). Third is the range of established routeways in human societies to channel benefits from nature. This implies that using ecosystem services to measure the state of socio-hydrological systems not only reflects the 'naturalness' of the hydrological system, but also human preferences for the resulting coupled system (Dufour and Piégay, 2009). So a continuing supply of ecosystem services does not necessarily

5   mean ecosystems are pristine or close to a 'natural' condition, but instead reflects the preference of the human subsystem to select for particular services (National Research Council, 2013; Zedler, 2000). Ecosystem management thus improves the resilience of ecosystems by deliberate human interventions to achieve a desired level of ecosystem services of a preferred sort.

According to the Millennium Ecosystem Assessment (2005), each water ecosystem provides multiple benefits to human

10   society, including (1) provisioning services such as water, aquatic products and hydropower; (2) regulating services including water purification, flood and climate regulation; and (3) cultural services or nonmaterial benefits obtained from aesthetic or spiritual enrichment, recreation, scientific research and educational activities. Vigerstol and Aukema (2011) identify four processes that produce water-related ecosystem services – water retention, water yield, natural water filtration, and water quality purification. Terrado et al. (2014) specify four hydrological ecosystem services vulnerable to climate

15   extremes – drinking water, hydropower production, nutrient retention and erosion control. Fisheries and products from aquatic ecosystems are essential for human societies but also subject to change, and need to be sustainable and resilient (Barange et al., 2014). Ecosystem services as a framework therefore link the human and water system, while being a viable basis for decision and policymaking (Brauman et al., 2007; Daily et al., 2009). Thus managing socio-hydrological resilience can be understood as regulating and enhancing resilience of ecosystem services that support livelihoods and human needs for

20   natural hazard protection, making it a viable proxy for socio-hydrological systems.

4 Pathways to resilience in the socio-hydrological context

Building on the preceding section, here we conceptualise resilience in the socio-hydrological context as a normative goal that can be achieved by introducing human interventions.

4.1 Absorptive and adaptive capacities, and the 'resilience canvas'

25   Building resilience requires not only improvement of the absorptive capacity to resist existing hydro-hazards, but also enhancing system resilience to cope with future uncertainties. This is where the properties of *adaptive* and *transformative* capacity advanced here enrich the socio-hydrological perspective. By conceptualising resilience this way, represented by

increased *adaptive* and *transformative* capacities, the need for incremental adjustment or radical improvement of systematic states becomes clearer.

An analogy can be drawn with conservation ecology. Gillson et al. (2013) use two axes of concerns (landscape vulnerability and conservation capacity) to design conservation strategy. Based on this approach, here we introduce the 'resilience canvas' by combining absorptive and adaptive capacities as the x- and y-axes (Fig. 3). Four resulting system states are found at the corners of the canvas: most resilient (top-right: high absorptive and high adaptive), vulnerable (bottom-left: low absorptive and low adaptive), susceptible (top-left: low absorptive and high adaptive) and resistant (bottom-right: high absorptive and low adaptive). These four quadrants are not static, and systems can move between them via structured management interventions over time, which we term 'pathways'. A resilient-vulnerable gradient from top-right to bottom-left is shown on the canvas (Fig. 3). The pathways on the resilience canvas represent a series of hypothesised human interventions introduced to effect system change (cf. Haasnoot et al., 2013). Tailored to the initial system conditions, these pathways seek to steer water, human or socio-hydrological systems towards 'most resilient' status, which is commonly regarded as the most valued water management goal. Intensive interventions are necessary for vulnerable systems to prevent further deterioration in system state over time.

4.2 Building pathways to socio-hydrological resilience

The resilience canvas can thus be used as a heuristic tool to design bespoke pathways to resilience for all system types considered here. However, this section focuses on how pathways are planned for susceptible and resistant socio-hydrological systems.

Susceptible socio-hydrological systems can be strengthened by increasing absorptive capacity, and by making hydrological ecosystem services supply more robust and sustainable under current hazard regimes. For example, water pollution may decrease potable water availability, while introducing vegetated buffer zones can protect water quality (Hickey and Doran, 2004; Khamis et al., 2013); aquatic ecosystem degradation may shrink fish populations and food yield from aquatic products, and diversifying abiotic characteristics such as habitat supports the resilience of faunal populations (Bisson et al., 2009; Khamis et al., 2013). Hydrological disasters also deplete human benefits derived from water systems, and setting up early warning systems can increase substantially the capabilities to deal with disasters (Adger et al., 2005).

By contrast, for resistant systems approaches are needed to improve system adaptability and capability to cope with future disturbance. Adaptive capacity can be enhanced in several ways. One approach is to restore the essential ecosystem processes that generate services. For example, hydrological adaptive capacity depends on various intrinsic factors such as biomass, biodiversity and ecological traits of species (Dawson et al., 2011; van Vliet et al., 2013). In an abiotic context, adaptive capacity can also be determined by features such as high river connectivity (Khamis et al., 2013), stable hydrological cycles (Thomas, 2016), and heterogeneous landscape (Czucz et al., 2011). A second approach is to raise social

and institutional capabilities, such as accessibility to information and resources (Milman and Short, 2008), responsiveness to environmental change (Malhotra et al., 2007), enhance institutional structure and governance processes (Folke et al., 2005; da Silveira and Richards, 2013), boost stakeholder participation (Few et al., 2007), and encourage learning and knowledge dissemination and exchange (Pahl-Wostl, 2009).

5 Although pathways can be constructed for the four system states, factors that improve different capacities via different capacity sources (i.e. ecological and social capacity sources) cannot always be distinguished or promoted independently. For example, maintaining diversity and redundancy of system components such as species, landscape types, knowledge systems, actors, cultural groups and institutions, benefits systematic resilience in various ways; so managing connectivity not only facilitates system recovery, but also improves the responsive capability to future uncertainties (Biggs et al., 2012, 2015).
10 These activities are applicable for both social and natural sciences, and cut across the three socio-hydrological resilience capacities.

Scheffer et al. (2015, p.1317) suggest keeping systems within the 'safe operating space' by managing down local stressors (fast variables) to a low value and responding to future climate projections (slow variables). The 'resilience canvas' portrays this management strategy from the perspective of preparedness instead of driving variables. The impact of local stressors as
15 well as climate change can be better mitigated with increasing absorptive and adaptive capacity respectively. It implies that social-hydrological systems should not only be kept within predetermined operating limits but also be the focus of bespoke resilient strategies.

4.3 Development trajectory of global socio-hydrological systems

The resilience canvas can be used at scales from the river basin to the global. By analysing our preparedness to cope with
20 local stressors and change, the resilience canvas illustrates a development trajectory for global socio-hydrological systems (Fig. 4). This section suggests the potential to shift from resistant to resilient water management strategies, and on this basis identifies attendant future research and implementation gaps.

The development phases of global human-water relations are identified and discussed in the literature. Mace (2014) for example argues that we are experiencing a shift in emphasis from 'Nature suffering from People' or 'People benefiting from
25 Nature' to 'People and Nature' as a more interdisciplinary and interactive framing for conservation purposes. Gleick et al. (2009; 2010) also identify three water eras characterised by contrasting water challenges and problems as follows: nature's water resources; intensively manipulating water sources; and massive global crisis, a stage demanding interdisciplinary and integrated approaches for management purposes. Developed from these classifications, three main stages of socio-hydrological systems are summarised and presented on the resilience canvas (Fig. 4).

30 1. *People with Water*. Before intensive modification of environments, human societies mainly relied on natural hydrological cycles for subsistence (e.g. hunter gathering), and to support extensive low productivity agriculture reliant on limited

control of the water subsystem (Gleick, 2009). The ecosystem services provided by water were not optimised, and were often vulnerable to internal or external hazards, such as water-related diseases and adverse hydrological events. However, this did not cause too many problems, because of the small and dispersed population and low demand on hydrological ecosystem services (Gleick, 2009). At this stage, adaptability was provided by the 'naturalness' of ecosystems.

5   2. *Water for People*. As population has grown and socio-economic development risen, ecosystem services obtained by human societies from water systems have no longer proved sufficient. New technologies and approaches were invented to intentionally manipulate water cycles to meet new societal demands (Gleick, 2009). Along with the development of hydraulic engineering, humans have dramatically increased the range of ecosystem services obtained from water subsystems, such as hydropower, water availability, flood regulation and more intensive forms of food production. This
10   development of socio-hydrological systems explicitly emphasised the benefits people received from water, and marks a transition to a 'Water for People' framing (Mace, 2014).

Human modification of hydrological systems is shaped according to prevailing socio-economic and cultural conditions. For example, river canalisation increased the absorptive capacity to flooding, but at the cost of rapid water transfer downstream. Major water transportation projects were built to transfer water as well as ecosystem services from wet to
15   dry areas, in order to increase socioeconomic resilience (Langridge et al., 2006). Absorptive capacity increased through hydraulic engineering at the expense of natural ecosystems, and consequently ecological adaptive capacity fell.

3. *People and Water*. Despite increasing capacities to manage water, societies face water supply crises amid growing realisation that climate and global change are making this ever harder to address. For example, climate change may alter the prevailing hazard regime and put ecosystem services at risk, though it is not straightforward to know what the new
20   regime and risks are. Thus canalised rivers do not have the surplus capacity to absorb more frequent rain events or higher surface runoff, which leads to more severe flooding. The spatial distribution of precipitation regimes may also be shifting under climate change, and this may turn regions from humid to dry, or vice versa (Collins et al., 2010), making water transportation projects redundant. These hard-engineering approaches generally have less flexibility and usually have a lengthier time lag in responding to change. The socio-hydrological system at this stage acts as a valuable heuristic for
25   adaptive water management, offering the most resilient and sustainable hydrological ecosystem services supply. The 'People and Water' framing has shifted from the linear one-way relationship of 'Water for People', to a multi-layered and multi-dimensional relationship between human societies and water systems (Mace, 2014).

We argue that most current water management practice is now seeking to transition from resistant to resilient strategies (Gillson et al., 2013; Khamis et al., 2013) (Fig. 4). From the perspective of a resilient socio-hydrological system, we believe
30   that this strategy is not only needed for water management, but potentially offers a feasible alternative for achieving sustainable hydrological ecosystem service provision. Awareness of change suggests an increase of adaptive capacity, and

implies that the pathway to socio-hydrological resilience will involve 'soft' approaches that are complementary to engineering-based methods (Park et al., 2013). This implies that interventions such as developments in institutional arrangements and management practices, ecosystem restoration, and technological innovations need to be better utilised to address future uncertainties. For example, polycentric water governance and public participation in more centralised forms

5   of decision-making may play important roles in building socio-hydrological resilience (Buytaert et al., 2014, 2016). Ecosystem restorations such as decanalisation, improving river connectivity, and floodplain recovery also suggest enhancing adaptability (Brauman et al., 2007), although in the process absorptive capacity may be compromised (Chen et al., 2016). In addition, technological innovations as well as advances in data collection and prediction models also contribute to improving socio-hydrological resilience, in both absorptive and adaptive ways (Karpouzoglou et al., 2016b). For example, the UK's

10   Environment Agency offers early warning systems that provide forecasting and personalised household information, which builds upon developing technologies and skills to map and measure risk (Environment Agency, 2009).

5 Conclusions

Evaluating resilience in a socio-hydrological context is challenging because of different framings of water-related resilience, including hydrological resilience to anthropogenic disturbances, social resilience to hydrological disasters, and socio-

15   hydrological resilience. Although these reflect different aspects of human-water interactions, they are not easy to distinguish. To better conceptualise the linkage between resilience and socio-hydrology, we have emphasised the need to define the system type prior to discussing their intrinsic resilience, and have argued that resilience be regarded as a set of systematic properties including absorptive, adaptive and transformative capacities. Based on this understanding, we have proposed a conceptual framework of human-water couplings and resilience framings, including a heuristic approach to identify possible

20   pathways to resilience in socio-hydrological contexts.

Focusing on three coupling and framing types, we highlighted the potential of socio-hydrological resilience. If human societies are considered as endogenous components of water cycles, this newly proposed resilience concept is useful to answer how social-hydrological systems respond to and cope with perturbations. On this basis, we have shown the utility and complementarity of resilience with ecosystem services, and argued that the framework of ecosystem services can be a

25   promising tool to describe the resilient dynamics of socio-hydrological systems, since it reflects an essential aspect of the human-water interface.

Different types of resilience may match particular problems with knowledge and research traditions in certain academic fields. For example, hydrological resilience to human hazards may be usefully analysed with biophysical sciences for aquatic

ecosystem conservation, while social resilience to hydrological hazards will require significant inputs from social sciences. It is important to consider the different nature of human and biophysical systems where different resilience approaches are used. For example, the ecologically-oriented concept of resilience has received critiques when applied in human systems, because it oversimplifies the understanding of equilibria and feedbacks, ignores the importance of social conflict and power,

5 and addresses the notion of system function which is not the key focus in social science (Olsson et al., 2015). This does not mean that resilience should be discarded as a concept. However, we should heed calls for pluralism, stimulate dialogue and develop a clearer identity of resilience as applied in the socio-hydrological context (Cote and Nightingale, 2012; Cumming et al., 2005; Olsson et al., 2015).

Resilience is not only a descriptive notion, and usually has normative (goal-setting) objectives. To build pathways to socio-

10 hydrological resilience, we introduced the notion of the 'resilience canvas' to compare absorptive and adaptive capacities. The resilience canvas can be used to design bespoke interventions and strategies for all types of human-water couplings at different scales from single river basin to global level. On this canvas, we showed that the global socio-hydrological system has moved from the stage in 'People with Water', through the 'Water for People' stage, towards the 'People and Water' stage, along with people's growing demand on water and the increasing resilience of hydrological ecosystem services supply.

15 Nonetheless there is still substantial geographic variation globally in the distribution of these socio-hydrological stages.

Our argument provokes a rethinking of using resilience in other human-nature contexts, such as social-ecological systems (Ostrom, 2009), and coupled human and natural systems (Liu et al., 2007). We suggest there is considerable potential to scrutinise the concept of resilience and better refine its identity and capacities in these systems. In a similar manner, different framings such as ecological resilience, social resilience to ecological hazards and social-ecological resilience can also be

20 recognised; and within each framing, resilience as systematic properties can be viewed at the capacity level by using the resilience canvas. Hence we contend this conceptual framework can be used to guide and construct discourses of resilience in the human-nature context, so bringing greater conceptual rigor and clarity to bear on one of the most pressing contemporary public policy challenges of our time.

Author contribution

F. Mao initialised the ideas of the paper with D. Hannah and J. Clark. F. Mao prepared the manuscript with parts written by J. Clark and T. Karpouzoglou, and contributions from all co-authors. Figures were prepared by F. Mao.

Acknowledgements

This paper was developed within the 'Mountain-EVO: Towards a virtual observatory for ecosystem services and poverty alleviation' project, which is supported by the ESPA Project Framework grant (Project code: NE/K010239-1). We thank all the project collaborators from Nepal, Peru, Kyrgyzstan and Ethiopia, for fruitful discussions that facilitated the conception of

ideas discussed herewith.

References

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R. and Rockström, J.: Social-ecological resilience to coastal disasters, Science, 309(5737), 1036–1039, 2005.

Aerts, J. C. J. H., Botzen, W. J. W., Emanuel, K., Lin, N. and Moel, H. De: Evaluating Flood Resilience Strategies for Coastal Megacities, Science, 344(6183), 1–3, 2014.

Anderies, J. M., Janssen, M. A. and Ostrom, E.: A Framework to Analyze the Robustness of Social-Ecological Systems from an Institutional Perspective, Ecol. Soc., 9(1), 1–18, 2004.

Backlund, A.: The definition of system, Kybernetes, 29(4), 444–451, 2000.

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., Allen, J. I., Holt, J. and Jennings, S.: Impacts of climate change on marine ecosystem production in societies dependent on fisheries, Nat. Clim. Chang., 4(3), 211–216, 2014.

Bene, C., Newsham, A., Davies, M., Ulrichs, M. and Godfrey-Wood, R.: Review article: Resilience, poverty and development, J. Int. Dev., 26(5), 598–623, 2014.

Biggs, R., Carpenter, S. R. and Brock, W. a: Turning back from the brink: detecting an impending regime shift in time to avert it., Proc. Natl. Acad. Sci. U. S. A., 106(3), 826–831, 2009.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L. and West, P. C.: Toward Principles for Enhancing the Resilience of Ecosystem Services, Annu. Rev. Environ. Resour., 37(1), 421–448, 2012.

Biggs, R., Schlüter, M. and Schoon, M. L., Eds.: Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems, Cambridge University Press, Cambridge., 2015.

Bisson, P. a., Dunham, J. B. and Reeves, G. H.: Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability, Ecol. Soc., 14(1), 45, 2009.

Botter, G., Basso, S., Rodriguez-Iturbe, I. and Rinaldo, A.: Resilience of river flow regimes, Proc. Natl. Acad. Sci. U. S. A., 110(32), 12925–30, 2013.

Brand, F. S. and Jax, K.: Focusing the Meaning(s) of Resilience : Resilience as a Descriptive Concept and a Boundary Object, Ecol. Soc., 12(1), 2007.

Brauman, K. A., Daily, G. C., Duarte, T. K. and Mooney, H. A.: The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services, Annu. Rev. Environ. Resour., 32(1), 67–98, 2007.

Bunn, S. E., Abal, E. G., Smith, M. J., Choy, S. C., Fellows, C. S., Harch, B. D., Kennard, M. J. and Sheldon, F.: Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation, Freshw. Biol., 55, 223–240, 2010.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Bièvre, B. De, Bhusal, J., Chanie, T., Clark, J., Dewulf, A., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandey, B., Paudel, D., Sharma, K., Steenhuis, T. S., Tilahun, S., Van Hecken, G. and Zhumanova, M.: Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development, Front. Hydrosph., Submitted(October), 1–21, 2014.

Buytaert, W., Dewulf, A., De Bièvre, B., Clark, J. and Hannah, D. M.: Citizen Science for Water Resources Management: Toward Polycentric Monitoring and Governance?, J. Water Resour. Plan. Manag., 142(4), 1816002, 2016.

Carpenter, K. E., Abrar, M., Aeby, G., Aronson, R. B., Banks, S., Bruckner, A., Chiriboga, A., Cortes, J., Delbeek, J. C., DeVantier, L., Edgar, G. J., Edwards, A. J., Fenner, D., Guzman, H. M., Hoeksema, B. W., Hodgson, G., Johan, O., Licuanan, W. Y., Livingstone, S. R., Lovell, E. R., Moore, J. A., Obura, D. O., Ochavillo, D., Polidoro, B. A., Precht, W. F., Quibilan, M. C., Reboton, C., Richards, Z. T., Rogers, A. D., Sanciangco, J., Sheppard, A., Sheppard, C., Smith, J., Stuart, S.,
5 Turak, E., Veron, J. E. N., Wallace, C., Weil, E. and Wood, E.: One-Third of Reef-Building Corals Face Elevated Extinction Risk from Climate Change and Local Impacts, Science, 321(5888), 560–563, 2008.

Carpenter, S., Walker, B., Anderies, J. M. and Abel, N.: From metaphor to measurement: Resilience of what to what?, Ecosystems, 4, 765–781, 2001.

Chen, X., Wang, D., Tian, F. and Sivapalan, M.: From channelization to restoration: Sociohydrologic modeling with
10 changing community preferences in the Kissimmee River Basin, Florida, Water Resour. Res., 51(2), 1–18, 2016.

Collins, M., An, S.-I., Cai, W., Ganachaud, A., Guilyardi, E., Jin, F.-F., Jochum, M., Lengaigne, M., Power, S., Timmermann, A., Vecchi, G. and Wittenberg, A.: The impact of global warming on the tropical Pacific Ocean and El Nino, Nat. Geosci., 3(6), 391–397, 2010.

Cote, M. and Nightingale, A. J.: Resilience thinking meets social theory: Situating social change in socio-ecological systems
15 (SES) research, Prog. Hum. Geogr., 36(4), 475–489, 2012.

Crane, T. A.: Of models and meanings: Cultural resilience in social-ecological systems, Ecol. Soc., 15(4), 2010.

Cumming, G. S., Barnes, G., Perz, S., Schmink, M., Sieving, K. E., Southworth, J., Binford, M., Holt, R. D., Stickler, C. and Van Holt, T.: An exploratory framework for the empirical measurement of resilience, Ecosystems, 8(8), 975–987, 2005.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E. and Webb, J.: A place-based model for understanding
20 community resilience to natural disasters, Glob. Environ. Chang., 18(4), 598–606, 2008.

Cutter, S. L., Burton, C. G. and Emrich, C. T.: Disaster Resilience Indicators for Benchmarking Baseline Conditions, J. Homel. Secur. Emerg. Manag., 7(1), 14, 2010.

Czucz, B., Csecserits, A., Botta-Dukat, Z., Kroel-Dulay, G., Szabo, R., Horvath, F. and Molnar, Z.: An indicator framework for the climatic adaptive capacity of natural ecosystems, J. Veg. Sci., 22(4), 711–725, 2011.

25 Dahm, R.: Flood resilience a must for delta cities, Nature, 2014, 2014.

Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. a, Pejchar, L., Ricketts, T. H., Salzman, J. and Shallenberger, R.: Ecosystem services in decision making: time to deliver, Front. Ecol. Environ., 7(1), 21–28, 2009.

Dawson, T. P., Jackson, S. T., House, J. I., Prentice, I. C. and Mace, G. M.: Beyond predictions: biodiversity conservation in a changing climate, Science, 332(6025), 53–8, 2011.

30 Dent, C. L., Cumming, G. S. and Carpenter, S. R.: Multiple states in river and lake ecosystems, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 357(1421), 635–45, 2002.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., Grebmeier, J. M., Hollowed, A. B., Knowlton, N., Polovina, J., Rabalais, N. N., Sydeman, W. J. and Talley, L. D.: Climate change impacts on marine ecosystems, Ann Rev Mar Sci, 4, 11–37, 2012.

35 Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Leveque, C., Naiman, R. J., Prieur-Richard, A. H., Soto, D., Stiassny, M. L. J. and Sullivan, C. A. D. A.-M. D. O.-10. 1017/s146479310500695.: Freshwater biodiversity: importance, threats, status and conservation challenges, Biol. Rev., 81, 163–182, 2006.

Dufour, S. and Piégay, H.: From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits, River Res. Appl., 25(5), 568–581, 2009.

Engel, S. and Schaefer, M.: Ecosystem services-a useful concept for addressing water challenges?, Curr. Opin. Environ. Sustain., 5(6), 696–707, 2013.

Engle, N. L.: Adaptive capacity and its assessment, Glob. Environ. Chang., 21(2), 647–656, 2011.

Environment Agency: A National Assessment of Flood Risk, Flooding Engl., 36, 2009.

Ernstson, H., Leeuw, S. E. Van Der, Redman, C. L., Meffert, D. J., Davis, G., Alfsen, C. and Elmqvist, T.: Urban transitions: On urban resilience and human-dominated ecosystems, Ambio, 39(8), 531–545, 2010.

Few, R., Brown, K. and Tompkins, E. L.: Public participation and climate change adaptation: avoiding the illusion of inclusion, Clim. Policy, 7(1), 46–59, 2007.

Folke, C., Hahn, T., Olsson, P. and Norberg, J.: Adaptive Governance of Social-Ecological Systems, Annu. Rev. Environ. Resour., 30(1), 441–473, 2005.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J.: Resilience thinking: Integrating resilience, adaptability and transformability, Ecol. Soc., 15(4), 62–68, 2010.

Gallopín, G. C.: Linkages between vulnerability, resilience, and adaptive capacity, Glob. Environ. Chang., 16(3), 293–303, 2006.

Gibbs, M. T.: Resilience: What is it and what does it mean for marine policymakers?, Mar. Policy, 33(2), 322–331, 2009.

Gillson, L., Dawson, T. P., Jack, S. and McGeoch, M. A.: Accommodating climate change contingencies in conservation strategy, Trends Ecol. Evol., 28(3), 135–142, 2013.

Gleick, P. H.: Facing Down the Hydro-Crisis, World Policy J., 26(4), 17, 2009.

Gleick, P. H. and MacDonald, G. M.: Roadmap for sustainable water resources in southwestern North America, Proc. Natl. Acad. Sci. U. S. A., 107(50), 21300–21305, 2010.

Gómez-Baggethun, E., Reyes-García, V., Olsson, P. and Montes, C.: Traditional ecological knowledge and community resilience to environmental extremes: A case study in Doñana, SW Spain, Glob. Environ. Chang., 22(3), 640–650, 2012.

de Groot, R. S., Wilson, M. A. and Boumans, R. M. J.: A typology for the classification, description and valuation of ecosystem functions, goods and services, Ecol. Econ., 41(3), 393–408, 2002.

Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., van den Brink, M., Jong, P., Nooteboom, S. and Bergsma, E.: The Adaptive Capacity Wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society, Environ. Sci. Policy, 13(6), 459–471, 2010.

Haasnoot, M., Kwakkel, J. H., Walker, W. E. and ter Maat, J.: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world, Glob. Environ. Chang., 23(2), 485–498, 2013.

Hallegatte, S., Green, C., Nicholls, R. J. and Corfee-Morlot, J.: Future flood losses in major coastal cities, Nat. Clim. Chang., 3(9), 802–806, 2013.

Harder, P., Pomeroy, J. W. and Westbrook, C. J.: Hydrological resilience of a Canadian Rockies headwaters basin subject to changing climate, extreme weather, and forest management, Hydrol. Process., 29(18), 3905–3924, 2015.

Hickey, M. B. C. and Doran, B.: A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems, Water Qual. Res. J. Canada, 39(3), 311–317, 2004.

Hoegh-Guldberg, O. and Bruno, J. F.: The Impact of Climate Change on the World's Marine Ecosystems, Science, 328(5985), 1523–1528, 2010.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, a. J., S., S. R., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, a. J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, a. and Hatziolos, M. E.: Coral Reefs under Rapic Climate Change and Ocean Acidification, Science, 318(December 2007), 1737–1742, 2008.

Hoffmann, A. and Sgrò, C.: Climate change and evolutionary adaptation, Nature, 470(7335), 479–485, 2011.

Holling, C. S.: Resilience and stability of ecological systems, Annu.Rev.Ecol.Syst., 4, 1–23, 1973.

Josefsson, H. and Baaner, L.: The Water Framework Directive--A Directive for the Twenty-First Century?, J. Environ. Law, 23(3), 463–486, 2011.

Karpouzoglou, T., Dewulf, A. and Clark, J.: Advancing adaptive governance of social-ecological systems through theoretical multiplicity, Environ. Sci. Policy, 57, 1–9, 2016a.

Karpouzoglou, T., Zulkafli, Z., Grainger, S., Dewulf, A., Buytaert, W. and Hannah, D. M.: Environmental Virtual Observatories (EVOs): prospects for knowledge co-creation and resilience in the Information Age, Curr. Opin. Environ. Sustain., 18, 40–48, 2016b.

Keating, K., May, P., Pettit, A. and Pickering, R.: Cost estimation for household flood resitance and resilience measures – summary of evidence, Report - SC080039/R11, , 28, 2015.

Keck, M. and Sakdapolrak, P.: What is social resilience? lessons learned and ways forward, Erdkunde, 67(1), 5–19, 2013.

Kelman, I., Gaillard, J. C. and Mercer, J.: Climate Change's Role in Disaster Risk Reduction's Future: Beyond Vulnerability and Resilience, Int. J. Disaster Risk Sci., 6(1), 21–27, 2015.

Khamis, K., Hannah, D. M. M., Calvis, M. H., Brown, L. E. E., Castella, E., Milner, a. M. M., Clarvis, M. H., Brown, L. E. E., Castella, E. and Milner, a. M. M.: Alpine aquatic ecosystem conservation policy in a changing climate, Environ. Sci. Policy, 43, 39–55, 2013.

Klein, R. J. T., Nicholls, R. J. and Thomalla, F.: Resilience to natural hazards: How useful is this concept?, Environ. Hazards, 5(1–2), 35–45, 2003.

Krimbas, C. B.: On fitness, Biol. Philos., 19, 185:203, 2004.

Kumar, P.: Hydrocomplexity: Addressing water security and emergent environmental risks, Water Resour. Res., 51(7), 5827–5838, 2015.

Kuo, C.-Y., Yuen, Y. S., Meng, P.-J., Ho, P.-H., Wang, J.-T., Liu, P.-J., Chang, Y.-C., Dai, C.-F., Fan, T.-Y., Lin, H.-J., Baird, A. H. and Chen, C. A.: Recurrent Disturbances and the Degradation of Hard Coral Communities in Taiwan, PLoS One, 7(8), e44364, 2012.

Langridge, R., Christian-Smith, J. and Lohse, K. A.: Access and resilience: Analyzing the construction of social resilience to the threat of water scarcity, Ecol. Soc., 11(2), 2006.

Liao, K. H.: A theory on urban resilience to floods - A basis for alternative planning practices, Ecol. Soc., 17(4), 48, 2012.

Limburg, K. E., O'Neill, R. V., Costanza, R. and Farber, S.: Complex systems and valuation, Ecol. Econ., 41(3), 409–420, 2002.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolstr??m, M., Lexer, M. J. and Marchetti, M.: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems, For. Ecol. Manage., 259(4), 698–709, 2010.

Linton, J. and Budds, J.: The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water, Geoforum, 57, 170–180, 2014.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H. and Taylor, W. W.: Complexity of coupled human and natural systems., Science, 317(5844), 1513–6, 2007.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N. and Van Lanen, H. A. J.: Drought in a human-modified world: reframing drought definitions, understanding and analysis approaches, Hydrol. Earth Syst. Sci. Discuss., (1), 1–34, 2016.

Lorenz, D. F.: The diversity of resilience: Contributions from a social science perspective, Nat. Hazards, 67(1), 7–24, 2013.

Mace, G. M.: Whose conservation? Changes in the perception and goals of nature conservation require a solid scientific basis, Science, 245(6204), 1558–1560, 2014.

MacKinnon, D. and Derickson, K. D.: From resilience to resourcefulness: A critique of resilience policy and activism, Prog. Hum. Geogr., 37(2), 253–270, 2012.

Malhotra, S., Kim, T., Zager, J., Bennett, J., Ebright, M., D'Angelica, M. and Fong, Y.: Use of an oncolytic virus secreting GM-CSF as combined oncolytic and immunotherapy for treatment of colorectal and hepatic adenocarcinomas, Surgery, 141(4), 520–529, 2007.

Mao, F. and Richards, K.: Irreversible river water quality and the concept of the reference condition, Area, 44(4), 423–431, 2012.

McGlade, J., McIntosh, B. S. and Jeffrey, P.: Landscape Sensitivity, Resilience and Sustainable Watershed Management, in Coping with Water Deficiency: From Research to Policymaking With Examples from Southern Europe, the Mediterranean and Developing Countries, edited by P. Koundouri, p. 243, Springer Netherlands., 2008.

Meerow, S., Newell, J. P. and Stults, M.: Defining urban resilience : A review, Landsc. Urban Plan., 147, 38–49, 2016.

Millennium Ecosystem Assessment: Ecosystems and human well-being: Synthesis, Island Press, Washington, DC., 2005.

Miller, S. W., Wooster, D. and Li, J.: Resistance and resilience of macroinvertebrates to irrigation water withdrawals, Freshw. Biol., 52(12), 2494–2510, 2007.

Milman, A. and Short, A.: Incorporating resilience into sustainability indicators: An example for the urban water sector, Glob. Environ. Chang., 18(4), 758–767, 2008.

Montanari, a., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, a., Post, D. a., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, a., McMillan, H., Characklis, G., Pang, Z. and Belyaev, V.: "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022, Hydrol. Sci. J., 58(6), 1256–1275, 2013.

National Research Council: Resilience and Ecosystem Services, in An Ecosystem Services Approach to Assessing the Impacts of the Deepwater Horizon Oil Spill in the Gulf of Mexico, National Academies Press., 2013.

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F. and Pfefferbaum, R. L.: Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness, Am. J. Community Psychol., 41(1–2), 127–150, 2008.

O'Reilly, C. M., Alin, S. R., Plisnier, P.-D. D., Cohen, A. S. and McKee, B. a: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa, Nature, 424(6950), 766–768, 2003.

Olsson, L., Jerneck, A., Thoren, H., Persson, J. and O'Byrne, D.: Why resilience is unappealing to social science:

Theoretical and empirical investigations of the scientific use of resilience, Sci. Adv., 1(4), e1400217–e1400217, 2015.

Ostadtaghizadeh, A., Ardalan, A., Paton, D., Jabbari, H. and Khankeh, H. R.: Community Disaster Resilience: a Systematic Review on Assessment Models and Tools, PLoS Curr. Disasters, 1–14, 2015.

Ostrom, E.: A general framework for analyzing sustainability of social-ecological systems., Science, 325(5939), 419–22, 2009.

Ozkan, K., Jeppesen, E., Johansson, L. S. and Beklioglu, M.: The response of periphyton and submerged macrophytes to nitrogen and phosphorus loading in shallow warm lakes: A mesocosm experiment, Freshw. Biol., 55(2), 463–475, 2010.

Pahl-Wostl, C.: A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes, Glob. Environ. Chang., 19(3), 354–365, 2009.

Pahl-Wostl, C., Vorosmarty, C., Bhaduri, A., Bogardi, J., Rockstrom, J. and Alcamo, J.: Towards a sustainable water future: Shaping the next decade of global water research, Curr. Opin. Environ. Sustain., 5(6), 708–714, 2013.

Park, J., Seager, T. P., Rao, P. S. C., Convertino, M. and Linkov, I.: Integrating risk and resilience approaches to catastrophe management in engineering systems, Risk Anal., 33(3), 356–367, 2013.

Pearson, R. G.: Reasons to Conserve Nature, Trends Ecol. Evol., xx(5), 1–6, 2016.

Peterson, T. J., Western, a. W. and Argent, R. M.: Analytical methods for ecosystem resilience: A hydrological investigation, Water Resour. Res., 48(10), 1–16, 2012.

Plummer, R. and Armitage, D.: A resilience-based framework for evaluating adaptive co-management: Linking ecology, economics and society in a complex world, Ecol. Econ., 61(1), 62–74, 2007.

Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., Barron, J., Enfors, E., Gordon, L., Heinke, J., Hoff, H. and Pahl-Wostl, C.: Water resilience for human prosperity, Water Resil. Hum. Prosper., 1784(February), 1–292, 2014.

Sala, O. E., F. Stuart Chapin, I., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M. and Wall, D. H.: Global Biodiversity Scenarios for the Year 2100, Science, 287(5459), 1770–1774, 2000.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B.: Catastrophic shifts in ecosystems, Nature, 413(6856), 591–596, 2001.

Scheffer, M., Barrett, S., Carpenter, S. R., Folke, C., Green, A. J., Holmgren, M., Hughes, T. P., Kosten, S., van de Leemput, I. A., Nepstad, D. C., van Nes, E. H., Peeters, E. T. H. M. and Walker, B.: Creating a safe operating space for iconic ecosystems, Science, 347(6628), 1317–1319, 2015.

da Silveira, A. R. and Richards, K. S.: The Link Between Polycentrism and Adaptive Capacity in River Basin Governance Systems: Insights from the River Rhine and the Zhujiang (Pearl River) Basin, Ann. Assoc. Am. Geogr., 103(2), 319–329, 2013.

Sivakumar, B.: Socio-hydrology: Not a new science, but a recycled and re-worded hydrosociology, Hydrol. Process., 26(24), 3788–3790, 2012.

Sivapalan, M., Savenije, H. H. G. and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol. Process., 26(8), 1270–1276, 2012.

Sivapalan, M., Konar, M. and Srinivasan, V.: Socio-hydrology: Use-inspired water sustainability science for the Anthropocene Earth's Future, Earth's Futur., 2, 225–230, 2014.

Smit, B. and Wandel, J.: Adaptation, adaptive capacity and vulnerability, Glob. Environ. Chang., 16(3), 282–292, 2006.

Strunz, S.: Is conceptual vagueness an asset? Arguments from philosophy of science applied to the concept of resilience, Ecol. Econ., 76, 112–118, 2012.

Sudmeier-Rieux, K. I.: Resilience – an emerging paradigm of danger or of hope?, Disaster Prev. Manag., 23(1), 67–80, 2014.

Terrado, M., Acuña, V., Ennaanay, D., Tallis, H. and Sabater, S.: Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin, Ecol. Indic., 37(PART A), 199–209, 2014.

Thomas, D. S. G., Ed.: The Dictionary of Physical Geography, Fourth Edi., Wiley-Blackwell, Hoboken, NJ., 2016.

Turner, B. L., Kasperson, R. E., Matson, P. a, McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A. and Schiller, A.: A framework for vulnerability analysis in sustainability science, Proc. Natl. Acad. Sci., 100(14), 8074–9, 2003.

Vigerstol, K. L. and Aukema, J. E.: A comparison of tools for modeling freshwater ecosystem services, J. Environ. Manage., 92(10), 2403–2409, 2011.

van Vliet, M. T. H., Ludwig, F. and Kabat, P.: Global streamflow and thermal habitats of freshwater fishes under climate change, Clim. Change, 121(4), 739–754, 2013.

Vorosmarty, C. J., Green, P., Salisbury, J. and Lammers, R. B.: Global Water Resources: Vulnerability from Climate Change and Population Growth, Science, 289(JULY), 284–288, 2000.

Walker, B., Hollin, C. S., Carpenter, S. R., Kinzig, A., Holling, C., Carpenter, S. R. and Kinzig, A.: Resilience, adaptability and transformability in social-ecological systems, Ecol. Soc., 9(2), 2004.

Walker, B. H., Abel, N., Anderies, J. M. and Ryan, P.: Resilience, adaptability, and transformability in the Goulburn-Broken Catchment, Australia, Ecol. Soc., 14(1), 12, 2009.

Walker, B. H., Carpenter, S. R., Rockstrom, J., Crépin, A.-S. and Peterson, G. D.: Drivers, "Slow" Variables, "Fast" Variables, Shocks, and Resilience, Ecol. Soc., 17(3), art30, 2012.

Weichselgartner, J. and Kelman, I.: Geographies of resilience : Challenges and opportunities of a descriptive concept, Prog. Hum. Geogr., 39(3), 249–267, 2015.

Willis, K. J., Bailey, R. M., Bhagwat, S. A. and Birks, H. J. B.: Biodiversity baselines, thresholds and resilience: testing predictions and assumptions using palaeoecological data, Trends Ecol. Evol., 25(10), 583–591, 2010.

Wyborn, C.: Co-productive governance: A relational framework for adaptive governance, Glob. Environ. Chang., 30, 56–67, 2015.

Yan, L. and Xu, X.: Assessing the vulnerability of social-environmental system from the perspective of hazard, sensitivity, and resilience: A case study of Beijing, China, Environ. Earth Sci., 61(6), 1179–1186, 2010.

Zedler, J.: Progress in wetland restoration ecology, Trends Ecol. Evol., 15(10), 402–407, 2000.

Figures and Table
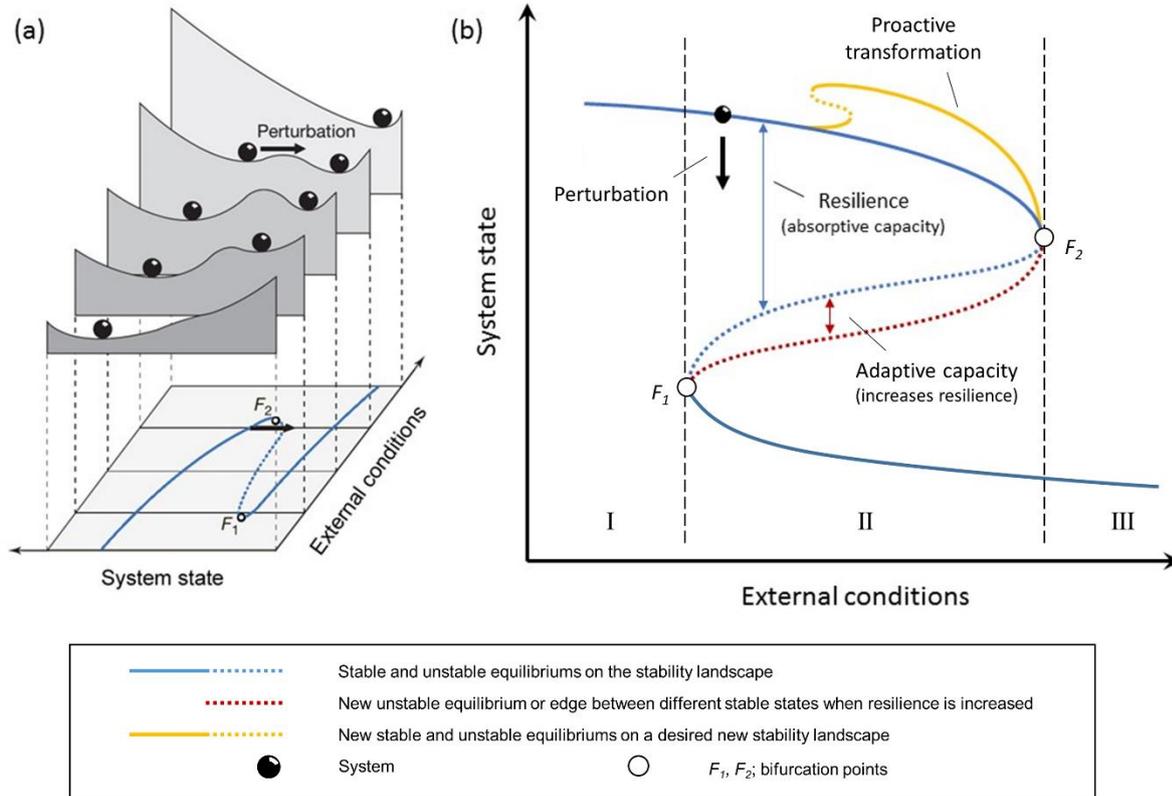
Figure 1. Bifurcation diagrams for socio-hydrological resilience: (a) Stability landscape changes along with external conditions, adapted from Scheffer et al. (2001). (b) Bifurcation diagram illustrating *absorptive, adaptive* **and** *transformative* **capacities. The two dashed lines across F₁ and F₂ divide the bifurcation process into three phases. Phase I and III have only one stable equilibrium, while Phase II has two stable equilibriums. Perturbations in Phase II may drive the system from one stable state to another. Absorptive capacity refers to the original meaning of resilience; adaptive capacity refers to the capability to increase resilience in cope with external change (red line); transformative capacity refers to the capability to proactively navigate the system to a desired new stability landscape (yellow line).**
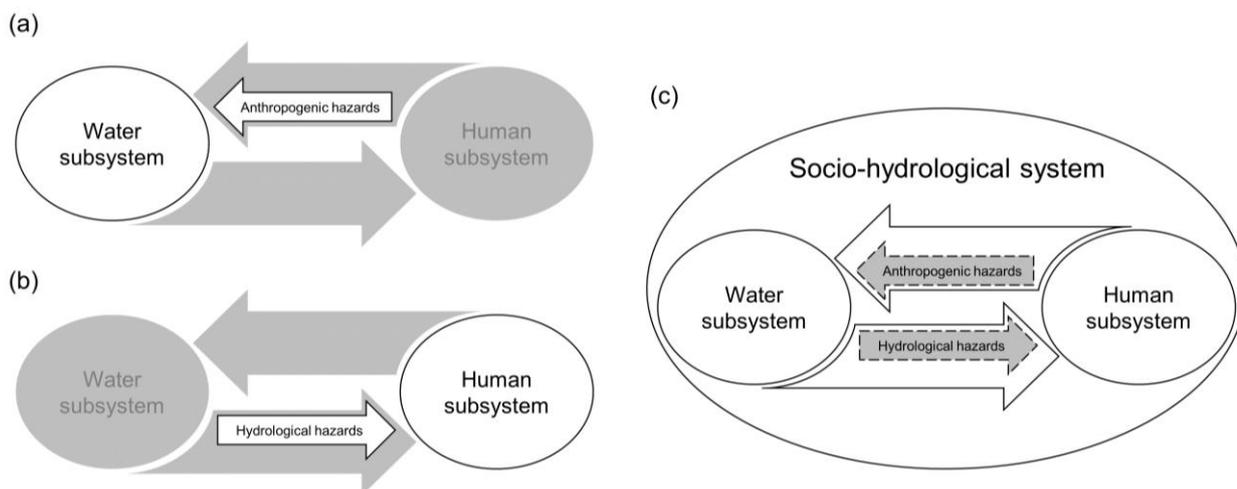
Figure 2. Schematic diagram of three human-water coupling types, each foregrounding different aspects of socio-hydrological system. (a) Water subsystem with anthropogenic hazards, where the human subsystem, water impacts on human subsystem or other forms of human impacts on the water subsystem are not the main focus. (b) Human subsystem with hydrological hazards, where similarly water sub-system, human impacts on water subsystem or other forms of water impact on the water subsystem are not emphasised. (c) Social-hydrological system with water and human subsystems, and anthropogenic and hydrological hazards as two of many forms of human-water interactions.
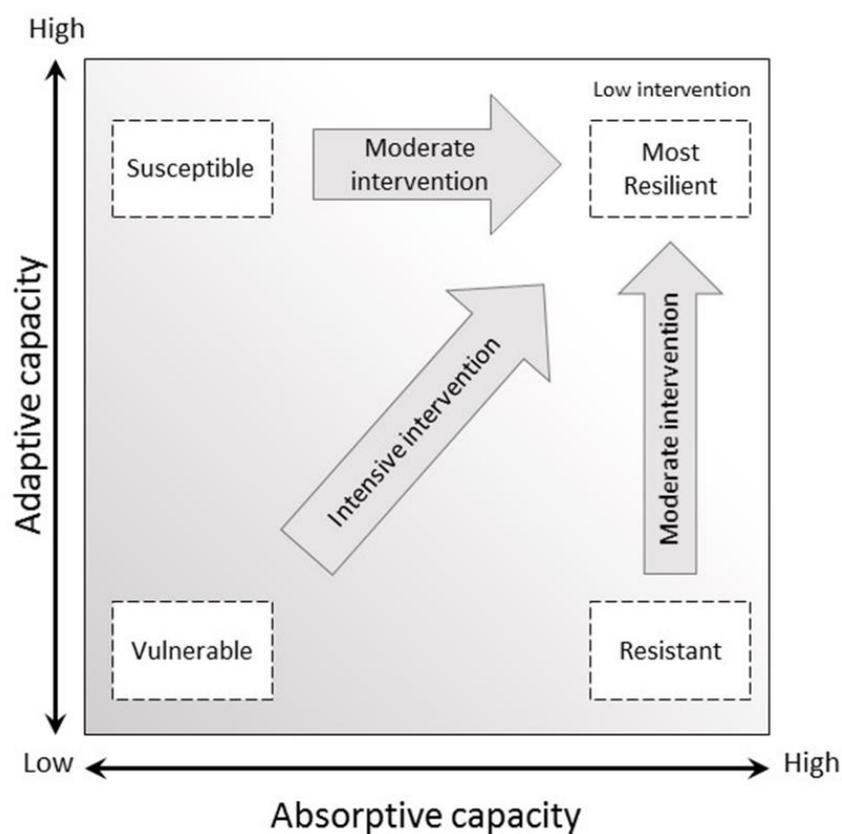
Figure 3. 'Resilience canvas' with absorptive and adaptive capacities as two axes, showing resilient-vulnerable gradient, resilience conditions and pathways to resilience. The four dashed rectangles illustrate resilient, resistant, susceptible and vulnerable system conditions. The grey arrows represent pathways, or a series of concerted interventions designed to drive systems from one condition to another.
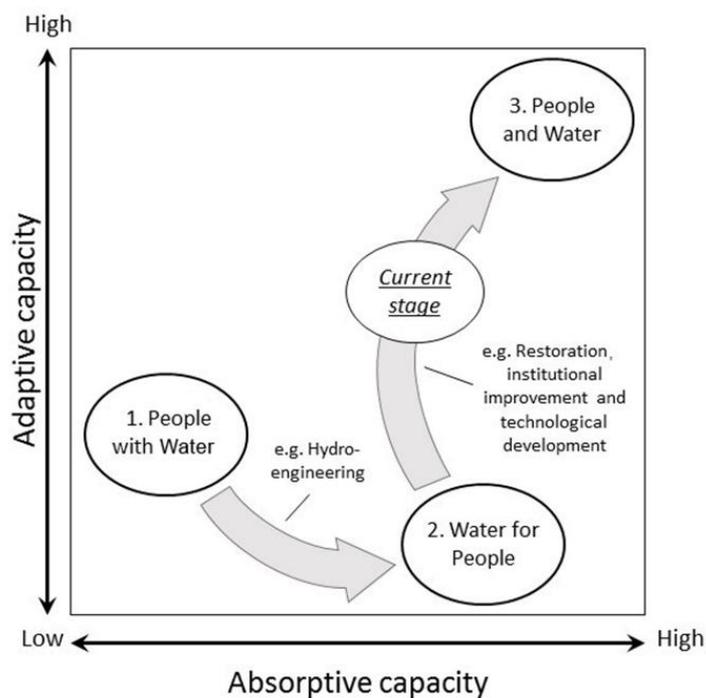
Figure 4. Global development of socio-hydrological systems on the 'Resilience canvas'. Three main developmental stages are (1) People with Water, (2) Water for People and (3) People and Water. The current global socio-hydrological system has been moving from the second to the third stage.

Table 1. A comparison of three types of human-water couplings and resilience framings.

Human-water coupling types	*Water subsystem with anthropogenic hazards*	*Human subsystem with hydrological hazards*	*Socio-hydrological system*
System (resilience of what)	Water subsystem	Human subsystem	Socio-hydrological system
Desired system state (resilience to what)	e.g. High naturalness or historical state	e.g. Social prosperity, development and justice	e.g. System integrity, and healthy human-water relationship
System indicator	Biotic and abiotic indicators, such as aquatic ecological composition, biodiversity and flow regime	e.g. Social, economic, institutional, physical aspects of human societies	e.g. Compositional indicator and human-water relationship
Resilience	e.g. Hydrological resilience and hydro-ecological resilience	e.g. Social resilience	Socio-hydrological resilience
Hazards	Anthropogenic hazards	Hydrological hazards	Internal and external, anthropogenic and hydrological hazards
Application fields	e.g. Water conservation and restoration	e.g. Disaster management	e.g. Water resources and ecosystem services management