

## Authors' response to the reviewer's comments

We thank Dr Wesselink and the anonymous reviewer for their constructive comments on the manuscript. Based on the previous replies to the reviewers, we give a point-by-point response to all comments, and indicate the changes we have made in the revised manuscript. We believe that the changes have well addressed the reviewers' comments, and consequently made significant improvements on the manuscript.

### Response to RC1 (Dr Wesselink)

---

...

#### Reviewer's comment:

My first major problem is that the authors state that (p. 3) 'Resilience can be understood as a set of systemic absorptive, adaptive and transformative capacities (Walker et al., 2004, 2009)'. I do not need to go beyond reading the titles of the two references to know that Walker used the concepts 'resilience, adaptability and transformability'. So instead of resilience as one of three system characteristics (as Walker does), the authors use resilience as overarching concept that includes the other two characteristics, and 'absorptive capacity equates to the original concept of resilience' (p.4). They thereby re-define a very well-known concept. This is never a good idea, and certainly not in an article whose main theme is 'conceptual clarity'. I therefore wonder why the authors redefined resilience to mean 'absorptive, adaptive and transformative capacities', what their relationships are, and how they compose together resilience? Re-definitions lead to confusion rather than clarity. Since I am not an expert on resilience studies, I cannot estimate what this re-definition does in terms of changing what is studied and on what terms. I hope a reviewer with more knowledge in the SES-resilience domain can shed light on this.

#### Authors' response:

*As explained in the preliminary response, we did not 'redefine' the resilience concept as 'absorptive, adaptive and transformative capacities', but followed a popular definition of resilience – 'In popular terms, resilience is having the capacity to persist in the face of change, to continue to develop with ever changing environments' (Folke, 2016, p.2), and 'resilience as the result of absorptive, adaptive and transformative capacities' (Béné et al., 2014, p.601). In fact, we reflect the line of argumentation on resilience in mainstream academic debates, rather than seeking to reconsider or re-evaluate the concept itself.*

*To address this comment, in Section 2 of the revised manuscript, we further explained the resilience concept and the interrelationships of the three capacities.*

#### Reviewer's comment:

I think the treatment of the meaning of resilience in the one way views on human water systems (sections 3.1 and 3.2) is rather brief. I would especially like to see the application of the three elements of resilience that the authors defined, i.e. absorptive, adaptive and transformative capacities. In fact, in 31 the authors themselves the 'old' understanding of resilience when they discuss the water subsystem with anthropogenic hazards when they state that (p.5) 'the implicit goal of maintaining subsystem equilibrium or restoring it to a desired historical state' leads to 'resilience management' –

surely in the authors' definitions this should read 'managing absorptive capacity'? In section 3.2 the same applies, as again in section 4.3.

**Authors' response:**

*We have enriched and expanded Section 3.1 and 3.2, and added one paragraph at the end of each Section to clarify how the three capacities can be applied and improved.*

**Reviewer's comment:**

Related to the above, why does transformative capacity not appear in the 'resilience canvas'? Is this maybe a possibility for coping that is beyond or against the authors' own norms and aspirations? If this is the case, it needs to be made explicit; however, the internal logic of the theoretical argument loses much strength: first resilience is three-part, then only two parts are used to assess resilience (absorptive and adaptive capacity).

**Authors' response:**

*To follow the reviewer's comments, in Section 4.1, we explained why only the first two capacities (i.e. absorptive and adaptive) are compared in the presentation of the 'resilience canvas', and explicitly stated that transformative capacity is beyond the aspirations of this paper. The two main reasons are as follows.*

*(1) There is still an ongoing debate on what exact systematic attributes are needed to support a radical transformation to an entirely new stage (Robinson and Carson, 2015; Wilson et al., 2013).*

*(2) We would like to keep the analysis of resilience capacities in a visually simple way as a 2-dimensional space instead of a 'resilience cube', and thus selected the first two better studied capacities for demonstration purposes.*

*Therefore, transformative capacity is not the main emphasis in the 'resilience canvas' section, but has great potentials to be explored in the future.*

**Reviewer's comment:**

My second major problem is the substitution of 'ecosystem services' for 'resilience' when assessing two-way interactions in human-water systems. In the justification that is presented, ecosystem services are clearly another way to look from the human to the natural system (p.8): 'a continuing supply of ecosystem services does not necessarily mean ecosystems are pristine or close to a 'natural' condition, but instead reflects the preference of the human subsystem to select for particular services'. It turns out that ecosystem services are hardly needed in the rest of the paper, so I suggest to remove it. However, this does leave one of the goals of the paper unfulfilled: to characterise the resilience of the human-water systems. In my view, a major re-think is needed here, or a reduction of the ambitions of the paper. The latter would be perfectly acceptable, since the conceptual content is considerable, as expressed especially in the figures.

**Authors' response:**

*In Section 3.3, we added some sentences in the second paragraph to explain the necessity of having 'ecosystem services' in the discussion which was explained in the previous response:*

*First is that ecosystem services not only provide a means to 'characterise the resilience of the human-water systems', but more importantly offer a novel perspective from which to view resilience in socio-*

*hydrological contexts, and to stimulate new discussion on this under-researched interrelation. In this way, the theoretical contributions from ecosystem services research can we think nourish the comparatively new research field of socio-hydrological resilience, while the policy-relevant nature of ecosystem services may also prove instructive in clarifying resilience-based decision-making in socio-hydrological contexts. Moreover, this novel perspective flags the potential broader connections between resilience and ecosystem services. That is to say, the paper seeks to open up new areas of inquiry based on this novel synthesis of the two literatures as a basis for further research, rather than offering definitive answers.*

*In the paper, we argue that ‘system identities need defining before examination is undertaken of their intrinsic resilience types’, and ‘key indicators of system state need to be established’. For relatively conventional human-water combinations such as ‘Water subsystem with anthropogenic hazards’ and ‘Human subsystem with hydrological hazards’, the system state and its key indicators are straightforward. However, defining the state and indicators of coupled systems (i.e. socio-hydrological systems) is more problematic. The paper addresses this challenge by proposing the use of ecosystem services to describe the dynamics of socio-hydrological systems. Removing reference to ecosystem services would therefore compromise the argument set out in the paper.*

*Furthermore, we use ecosystem services to consider the pathways to resilience in Section 4. So we argue ‘Susceptible socio-hydrological systems can be strengthened [...] by making hydrological ecosystem services supply more robust and sustainable under current hazard regimes’. We argue that managing the supply of ‘hydrological ecosystem services’ is the key to improving susceptible socio-hydrological systems, instead of managing other indicators such as hydrological biodiversity, naturalness, social security, integrity or justice. Without prior discussion of ecosystem services in advance, it would be difficult to describe what needs to be achieved in a resilient socio-hydrological system. Thus, we are clear that introducing ecosystem services and connections to socio-hydrological resilience debates is essential to communicate our key research contributions.*

#### **Reviewer’s comment:**

My final comments relate to the usefulness of the paper/the resilience canvas for policy making. One element of this discussion relates to the (perceived by the authors) need to specify what resilience means. This is commonly known as an activity of framing or structuring, with resilience classified as wicked or unstructured problem (Hisschemoller & Hoppe 1995; Hisschemoller et al 2001; Hoppe 2008). The authors seem to be aware of this (p.13): ‘Resilience is not only a descriptive notion, and usually has normative (goal-setting) objectives’; also in section 3.2 ‘Resilience from the perspective of managing human subsystems thus emphasises particular societal norms and goals or normative aspirations in relation to hydrological hazards’. At the same time, they do not question the notion of ‘desired state’: desired by whom? In the conduct of research, it will be the researchers who decide what is desired (often based on ecological arguments). In other words: targets for the water system would be just as dependent on societal norms and aspirations!

#### **Authors’ response:**

*We agree with the reviewer’s comments that the targets could be ‘dependent on societal norms and aspirations’. However, the ‘desired states’ also depend on what socio-hydrological type they are in. To address this comment, we compared how ‘desired systematic states’ are defined in all three framings throughout Section 3, especially Section 3.3. We argued that ‘desired states of the water sub-system are usually high naturalness or historical conditions measured by biotic and abiotic indicators, while desired states of the human sub-system are more normative societal expectations set by relevant social groups’. In addition, ‘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’.*

**Reviewer’s comment:**

Problem structuring is done when resilience is used within research, but even more so when it is stated as a policy objective, since it can be expected that stakeholders’ values and interests diverge more than researchers’. I therefore question the notion that researchers should prescribe (i.e. pre-structure) how policy processes should engage with boundary or nirvana concepts like resilience – this should be done in the policy process. In fact, the literature on boundary objects (Molle 2008; Walker & Shove 2007) suggests that interpretative flexibility of goals is essential in policy making.

**Authors’ response:**

*We agree with the reviewer that interpretative flexibility of goals is essential for boundary objects in policy making. The classification of three framings is actually supporting this flexibility instead of avoiding it, by clarifying that different people may use one of the three framings in the socio-hydrological context according to their needs. In addition, we highlighted that the expected states for human sub-systems and socio-hydrological systems are set by relevant social groups, and encouraged public participation in the process of determining the goal.*

*In the Introduction Section of the revised manuscript, we elaborated the aim of the paper, which is ‘to propose a conceptual framework for assessing resilience in socio-hydrological contexts, and by which we provide opinions for understanding and managing socio-hydrological resilience. Instead of offering a single prescriptive solution, this framework supports pluralist perspectives and encourages debate on socio-hydrology and its interrelations with resilience.’*

**Reviewer’s comment:**

While I am fascinated by the way in which the authors depict pathways on the resilience canvas, I find the discussion in section 4.2 too general and too obvious. Neither the resilience canvas (or its derivation) nor the concept of socio-hydrology is necessary to make these general statements. Section 4.3 is again interesting [note: this is the only place ecosystems services make a brief appearance, not just as needing to be resilient but also sustainable (p.11 line 25): mentioning this term opens another can of worms at least as large as the resilience confusion!]. However, I do disagree that everywhere the current pathway can be described as ‘people & water’. For example, the EA for England & Wales [NB: not UK!] approach to flood risk management in fact increases individual people’s vulnerability by transferring responsibility to individuals rather than the EA.

**Authors’ response:**

*We have enriched and expanded the discussions in Section 4.2, and provided a new example (comparison of two catchments as well as a new Figure 4) to make it more specific.*

*We have removed the word ‘sustainable’ in the ‘People and Water’ subsection to avoid confusion.*

*As mentioned in the previous reply, we do not describe the current pathway as ‘people and water’. Instead, we introduce the three stages as ‘development phases of global human-water relations’ by reviewing existing research, and state that ‘most current water management practice is now seeking to transition from resistant to resilient strategies’. This should not however be construed as meaning that everywhere in the world at every scale is at exactly the same stage; the picture is of course far more spatially and temporally differentiated.*

*Thanks for pointing out the typo 'the UK's Environment Agency', and we have changed it to 'Environment Agency for England & Wales'.*

*It is debatable whether the EA has transferred ALL responsibility to individuals, or sharing responsibility with individuals. However, it could be understood as an example of increasing individual's resilience by public participation, opening the risk information and using information and communication technologies.*

## **Response to RC2**

---

### **Reviewer's comment:**

1) The authors appear to treat hydro-sociology and socio-hydrology as if these two fields are similar in their demand to understand resilience (or possible instability) in coupled human water systems. The concept proposed by the authors is more formal and requires a post-positivist approach, which seeks regularities and generalizable relationships between human and their water system contingent on disciplines involved. It is not clear where hydro-sociology stands in this context, if it is anti-positivist (i.e. not seeks generalizable relationships) then it will be difficult to interpret outcomes of nonlinear system dynamics such as instability and resilience. Socio-hydrology offers not only a quantitative framework but such a framework that allows for bi-directional feedbacks. I wonder if hydro-sociology is more oriented towards impact assessment and implementation of social objectives or outcomes – and bi-directional feedbacks may be key to understanding resilience of SHS. The authors may want to clarify the positioning and capacity of hydro-sociology in being able to implement the formal concept of resilience that is being presented here.

### **Authors' response:**

*As discussed in the previous response, we agree with the reviewer that the coupled human-water system can be further classified into socio-hydrological systems and hydro-social systems, each of which has different emphasises. We also fully agree that bi-directional feedbacks are the main source of resilience for human-water couplings. However, we think extensive discussion of the differences between the two perspectives on the coupled human-water system (i.e. socio-hydrological system and hydro-sociological system) would go beyond the remit of an opinion paper.*

*In the revision, we emphasised in Section 3 that this paper follows the Sivapalan's interpretation of socio-hydrology which has the focus on the co-evolution and feedbacks of coupled human-water systems to avoid any misunderstandings (Sivapalan et al., 2012).*

### **Reviewer's comment:**

2) Why should we consider the resilience and stability of the hydro and socio subsystems of a SHS if it doesn't affect the bi-directional feedbacks. It runs very contrary to the philosophy of socio-hydrology which emphasizes that endogenization of human agency as its key consideration. Why should we even be bothered to study instabilities isolated to certain sub-systems when it does not spread to the larger system through its coupled dynamics? Why should we study instabilities in hydrological systems when they are of no concern to humans – current or future! If such instabilities are of concern to humans then we are talking about resilience of the entire SHS, not isolated subsystems. I therefore encourage the authors to phrase all 3 types of resilience given in section 2 in context of the larger SHS and to not isolate them.

**Authors' response:**

*As explained in the previous response, we see the logic of this approach to socio-hydrological thinking: indeed, this is part of the reason why this opinion paper builds its connections with the resilience concept.*

*In the revised manuscript, we further explained why three types of resilience framings are classified in the introduction paragraph of Section 3. We argued that 'socio-hydrological resilience should refer to resilience of socio-hydrological systems which is one specific type of resilience in socio-hydrological contexts. 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.' In addition, 'the three types of coupling encapsulate how different fields (e.g. conservation, disaster management and water resources management) deal with human-water couplings, instead of normative expectations of what people should (or should not) do'.*

**Reviewer's comment:**

3) Same as in point 2, the notion that hazard such as pollution (section 3.1) is a short term exogenous perturbation is incorrect in my opinion. It is caused by humans, and humans respond to that through community sensitivity and change their norms. Thus hazard is not an exogenous perturbation but an endogenous one as a result of human agency. It is also not a short term perturbation since its effect through community sensitivity can be over decades, even centuries. See for van Emmerik et al. (2014, HESS) and Kandasamy et al. (2014, HESS). I therefore think isolating the concept of resilience to hydro and socio sub-systems is contrary to socio-hydrology and misguided.

**Authors' response:**

*For the reasons given in the above response to Comment 2, whether pollution is an exogenous or endogenous perturbation depends on how resilience is framed in the socio-hydrological context – pollution is more likely to be an exogenous perturbation for water sub-systems, but an endogenous one for socio-hydrological systems. In addition, we agreed that calling pollution as a 'short term perturbation' is misleading, and changed it into 'occasional, recurrent and continuous perturbations' in the second paragraph of Section 2.*

**Reviewer's comment:**

4) The discussion of absorptive, adaptive and transformative capacity is not clear. I am surprised that the authors decided to discuss such formal concepts in a qualitative manner. To ensure tractability of concepts, I would encourage authors to present a mathematical toy problem and express these concepts more formally.

**Authors' response:**

*In the revised manuscript, we improved the discussion of the three capacities and their relationships.*

*- In Section 2, we further explained where the three capacities come from. We argued in the first paragraph of Section 2 that, in a popular term, 'resilience is "the capacity to persist in the face of change, to continue to develop with ever changing environments" (Folke, 2016 p.2). Thus, this notion is understood as a set of systemic absorptive, adaptive and transformative capacities, which provide a nuanced conceptualisation in three dimensions – persistence for now, response for future contingencies in incremental or radical ways (Béné et al., 2014; Miller et al., 2011).'*

- In Section 3, we provided examples of the three capacities for each type of resilience framing in the last paragraphs of each subsection (Section 3.1, 3.2 and 3.3).

- In the second paragraph of Section 4.1, we explicitly explained why the first two capacities (i.e. absorptive and adaptive capacities) were selected to construct the 'resilience canvas'.

*The discussions of the three capacities reflect the line of argumentation on resilience in mainstream academic debates, and follow some of the most influential papers in the field (see e.g. Béné et al., 2014; Folke, 2016; Walker et al., 2004), which are also in a qualitative manner. We agreed with the reviewer that some mathematical toy problems will be useful to express these concepts more formally. However, providing quantitative expressions of resilience capacities that have seldom appeared in the existing papers might be beyond the scope of this opinion paper. Nevertheless, in the concluding remarks section, we argued that new quantification approaches and mathematical tools are required as future work.*

**Reviewer's comment:**

5) Page 6, Line 27, "...resilience is to use a more theoretically pluralist perspective..": totally agree, and socio-hydrology welcomes such a perspective.

**Authors' response:**

*Thanks for agreeing with this as one of the main purposes of the paper – to encourage pluralist perspectives and debates on the inter-connections between socio-hydrology and resilience.*

**Reviewer's comment:**

6) Section 3.2, line 3, page 7 "... argue that the dynamics of social change should be better framed as part of socio-ecological research.": if you extrapolate it to sociohydrological systems, then this is more about coupling and bi-directional feedbacks between human and their water system, contrary to the idea of the section that resilience should be treated in (social sub-system) isolation with hydrological hazards as (exogenous) boundary conditions.

**Authors' response:**

*We agreed with this comment and have reorganised our summary of Cote and Nightingale's work (2012), changing from '.. argue that the dynamics of social change should be better framed as part of socio-ecological research' to 'argue that there is still far less attention to normative and epistemological questions'.*

**Reviewer's comment:**

7) When I come to section 3, it is not clear where the authors stand in terms of how resilience should be studied (whether in isolation or not). They evoke arguments against the compositional approach but their resilience framing appears to be compositional in nature! The authors should clarify this, I hope in favor of abandoning studying resilience of sub-systems.

**Authors' response:**

*We agreed with the reviewer that the description of the compositional approach in the original version was not clear, and revised Section 3.3. In the revised manuscript, we clarified that the two approaches are to measure the 'state of systems' instead of 'resilience of systems'. It is because defining*

*systematic states helps to explain and clarify the identity of resilience, and answer the classic 'resilience of what' question. Therefore, the differences between the two approaches are now clearer.*

*- A compositional approach is to assess the state of coupled systems by summing up separately assessed 'system components'.*

*- An ecosystem services approach is to directly assess hydrological ecosystem services as one of key human-water interactions. In this method, the 'coupled systems' are not broken down to components to be assessed separately. Although the general hydrological ecosystem services may be comprised of a couple of sub-services (e.g. provisioning, regulating and cultural), the assessment of each sub-service is still a direct evaluation of a certain facet of human-water interactions.*

**Reviewer's comment:**

8) Lines 3-4, page 8: “..human preferences for the resulting coupled system..” It appears that the authors have limited themselves to a normative/prescriptive perspective. This is more common with impact oriented studies such as hydro-economics and hydro-sociology, that operationalize economic and social impact concepts respectively. To broaden it and incorporate the notion of bi-directional feedbacks, I would suggest to replace the word preference by dependence.

**Authors' response:**

*We accepted this suggestion and replaced the word 'preference' by 'dependence' in Section 3.3.*

**Reviewer's comment:**

9) By the time one reached section 4, very little opinion has been offered on how one should go about assessing resilience of socio-hydrological systems. All that has been provided is a literature review. I therefore think that the authors should present a simple mathematical toy model and opine, based on the literature presented, on how the authors would go about assessing its resilience. This will also help better explanation of section 4.

**Authors' response:**

*For the reasons mentioned in the response to Comment 4, we thought mathematical toy models might be beyond the scope of this opinion paper and quantification assessment methods should be developed in the future to transform the 'resilience canvas' from a conceptual tool to a quantifiable one. However, we have enriched the contents of Section 4 and made the opinions more explicit. In summary, the main opinions in Section 4 include:*

*- Pathways to resilience can be designed with help of the newly proposed 'resilience canvas'.*

*- Systems with similar overall resilience evaluation may differ in the composition of their composition of resilience capacities. It implies that bespoke strategies should be developed for each system to make the pathways effective.*

*- The constitutive capacities of resilience do not usually grow equally while the overall resilience is increasing. It means that the pathways are not always in straight lines.*

*- In general, we need to shift from resistant to resilient water management strategies.*

**Reviewer's comment:**

10) The notion of how adaptation exactly increases resilience is not clear, especially because a clear definition of resilience has yet to be provided. The mathematical toy example would be a great asset here. Also, how is adaptation capacity different from absorptive capacity.

**Authors' response:**

*To answer how adaptation increases resilience, as well as how adaptive capacity differs from absorptive capacity, we could refer to the popular definition of resilience introduced in Section 2 - 'resilience is "the capacity to persist in the face of change, to continue to develop with ever changing environments" (Folke, 2016 p.2). Thus, this notion is understood as a set of systemic absorptive, adaptive and transformative capacities, which provide a nuanced conceptualisation in three dimensions – persistence for now, response for future contingencies in incremental or radical ways (Béné et al., 2014; Miller et al., 2011).'*

*We have improved the discussion of the relationship between absorptive (resilience) and adaptive capacities, please refer to the response to Comment 4.*

*For mathematical toy examples, please also refer to the response to Comment 4.*

**Reviewer's comment:**

11) Section 4.3: Please discuss this in context of progress made in socio-hydrological literature. Many socio-hydrology case studies have documented that coupled systems have progress through era of development followed by preservation, e.g. pendulum swing, see Kandasamy et al. (2014, HESS), van Emmerik et al. (2014, HESS) and many more!!

**Authors' response:**

*Thank you for suggesting the case studies for the 'resilience canvas'. Although these studies are about the development of 'socio-hydrological systems', but Section 4.3 is about the development of 'socio-hydrological resilience', significant overlaps between the suggested papers and this one can be found. We used the suggested cases to enrich the contents of Section 4.3. Please refer to the marked-up manuscript for details (especially the second and last paragraph of Section 4.3).*

**Reviewer's comment:**

12) Line 6, page 12: Enhancing adaptability under climate change is a difficult problem to tackle. Just stating that one should adapt is not enough, how one can do so using socio-hydrology is needed in this opinion piece. Again, the paper appears to be a literature review of resilience concepts borrowed from other fields (which is welcome). The authors should try to go to the next level and give us some insights on how one can learn from these ideas of resilience and plan for the Knightian uncertainty ahead (under climate change) using socio-hydrology. What is unique about socio-hydrology that can help us better prepare for the future ahead (e.g. endogenization of human agency implies less dependence on scenarios of e.g. population, land cover etc. that may help us resolve some of the uncertainty)? Overall, the paper appears to be a bit incoherent. It has brought ideas from other disciplines but it still has to provide an opinion based on the literature review. The paper should be made more formal, e.g. by using a mathematical toy model of SHS and all the concepts, including policy implications, should be discussed in its terms.

## **Authors' response:**

*Instead of discussing how 'adaptive capacity' can be practically enhanced under climate change, this opinion paper chose to focus on urgent but easily neglected conceptual questions about 'adaptive capacity' in at least four ways.*

*(1) What is the relationship between adaptive capacity and resilience?*

*We examined the definition of resilience and regarded adaptive capacity as one of the three resilience capacities to cope with future contingencies by incremental improvement and development (Section 2).*

*(2) Where do adaptive capacities come from?*

*We identified three framings of resilience and human-water couplings, and argued that adaptive capacity may come from water sub-system, human sub-system or human-water interactions. For each resilience source, there are specific strategies to enhance adaptive capacity (Section 3, last paragraphs of Section 3.1, 3.2 and 3.3).*

*(3) What is the role of adaptive capacity in water management under change?*

*We advocated a switch of general water management strategies from resistant to resilient building by improving adaptivity. This provides an important conceptual basis to consider adaptive strategies in the resilience context (Section 4).*

*(4) What are the emerging or promising fields that need specially attentions and potentially support the new adaptivity-oriented water management strategy?*

*Three fields have been identified (Section 4.3):*

*- a reemphasis on the ecosystem integrity, which is aligned with the 'pendulum swing' phenomenon (Kandasamy et al., 2014).*

*- polycentric water governance (Buytaert et al., 2014, 2016)*

*- information and communication technologies (Karpouzoglou et al., 2016)*

*Again, as discussed in the above response, in the revised manuscript, we tried to make the opinions more explicit, the structure more coherent, the argument clearer, and discussed future works that can take this conceptual framework forward. We believed these efforts have contributed to the achievement of the purpose, which is to encourage debates on socio-hydrology and its interrelations with resilience.*

## **References**

Béné, 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.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., 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. Earth Sci.*, 2(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.

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

Folke, C.: Resilience ( Republished ), *Ecol. Soc.*, 21(4), 2016.

Kandasamy, J., Sountharajah, D., Sivabalan, P., Chanan, a., Vigneswaran, S. and Sivapalan, M.: Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, 18(3), 1027–1041, 2014.

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, 2016.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., Leeuw, S. van der, Rockström, J., Hinkel, J., Downing, T., Folke, C. and Nelson, D.: Resilience and vulnerability: Complementary or conflicting concepts, *Ecol. Soc.*, 15(3), 11, 2011.

Robinson, G. M. and Carson, D. A.: Resilient communities: Transitions, pathways and resourcefulness, *Geogr. J.*, 2015.

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.

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.

Wilson, S., Pearson, L. J., Kashima, Y., Lusher, D. and Pearson, C.: Separating adaptive maintenance (Resilience) and transformative capacity of social-ecological systems, *Ecol. Soc.*, 18(1), 2013.

# **A conceptual framework for assessing socio-hydrological resilience under change**

Feng Mao<sup>1</sup>, Julian Clark<sup>1</sup>, Timothy Karpouzoglou<sup>2</sup>, Art Dewulf<sup>2</sup>, Wouter Buytaert<sup>3,4</sup>, and David Hannah<sup>1</sup>

5

<sup>1</sup> School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

<sup>2</sup> Public Administration and Policy Group, Wageningen University, Wageningen, Netherlands

<sup>3</sup> Department of Civil and Environmental Engineering, Imperial College London, London, UK

<sup>4</sup> Grantham Institute for Climate Change and the Environment, Imperial College London, London, UK

10

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

## Abstract

5 Despite growing interest in resilience, there is still significant scope for increasing its conceptual clarity and 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 opinion paper, we propose a novel conceptual framework for understanding and assessing resilience in coupled socio-hydrological systems-contexts, and encourage debate on the inter-connections between socio-hydrology and resilience. 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, 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 existing framings of resilience for different types of human-water systems and subsystems, which have been used in different fields: (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 three system types and resiliences afford new insights into the clarification and 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.

25  
**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 assessing~~ resilience in socio-hydrological contexts, and by which we provide opinions for understanding and managing socio-hydrological resilience. Instead of offering a single prescriptive solution, this framework supports pluralist perspectives and encourages debate on socio-hydrology and its interrelations with resilience. 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 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. 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~~focus on this variety, but instead to characterise how resilience is interpreted in order 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)~~is usually defined as the capacity of a system to absorb disturbance without substantially challenging the function and structure (Walker *et al.*, 2004). In a more generalised definition, resilience

is 'the capacity to persist in the face of change, to continue to develop with ever changing environments' (Folke, 2016 p.2). Thus, this notion is understood as a set of systemic *absorptive*, *adaptive* and *transformative* capacities, which provide a nuanced conceptualisation in three dimensions – persistence for now, and response for future contingencies in incremental or in radical ways (Béné et al., 2014; Miller et al., 2011). A clear understanding of the overall *system* is thus an essential precursor to any evaluation of its resilience, since it answers what the identity or subject of resilience is (Carpenter et al., 2001). (Carpenter et al., 2001; Evans and Reid, 2013). 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 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.

Once the system type, or 'the resilience of what in relation to what', identity is defined, it clarifies helps to answer a series of essential questions that sustain the clarity of the resilience concept and application in socio-hydrological contexts. For example, what aspects of systems are being examined-, what key indicators of system state need to be established, and what possible desired state is sought, and ultimately what shapes the resilience process (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. (Carpenter et al., 2001; Mao and Richards, 2012). 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 occasional, recurrent and continuous 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 make which can result in large, abrupt, long-lasting changes to system their 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).

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). (Cumming et al., 2005; Holling, 1973; Walker et al., 2004). It is represented as the size (e.g. width) of the equilibrium region (Walker et al., 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 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 (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, also refers to the human's ability to respond, but in a more radical way. This is a capacity to change the stability landscape or even 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 (Béné 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). For the reasons explained in the previous section, it is critical to clarify the character of resilience in socio-hydrological contexts which in turn is determined by the human-water coupling types. 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). We therefore argue that socio-hydrological resilience should refer to resilience of socio-hydrological systems which is one specific type of resilience in socio-hydrological contexts. 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. Here, it is worth noting that socio-hydrology and hydro-sociology have close connections (Sivakumar, 2012), but different emphasises (Wesselink et al., 2016). Here we adopt Sivapalan's interpretation of socio-hydrology which has as its focus the co-evolution and feedbacks of coupled human-water systems (Sivapalan et al., 2012). Thus these three types of coupling encapsulate how different fields (e.g. conservation, disaster management and water resources management) deal with human-water couplings, rather than normative expectations of what people should (or should not) do. In each type of resilience framing, features such as resilience subjects, desired system states, indicators and application fields will be examined (Table 1).

#### 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~~ecosystems triggered by anthropogenic disturbances (Table 1), such as algal blooms caused by ~~human~~ 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~~ activities or ~~human-induced~~ 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 many~~ water subsystems, such as lakes, rivers, and oceans (e.g. Dudgeon et al., 2006; 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)~~(e.g. Holling, 1973), or through examining other biotic or abiotic components. This coupling model is primarily used in aquatic ecosystem conservation and management, ~~withwhere~~ the ~~implicit goal of maintainingis to maintain~~ subsystem equilibrium or ~~restoringrestore~~ 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 ~~resilieneea need to consider options for resilient water~~ 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).

Absorptive capacity of water subsystems is mainly from essential ecosystem and hydrological processes. Adaptive dimension of hydrological resilience usually comes from diversity of species, habitat or landscape. From a biophysical 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 drives evolution (Krimbas, 2004; Lindner et al., 2010). However, the improvement of hydrological adaptive capacity does not exclude anthropogenic contributions, and can be achieved by restoring the biodiversity and integrity of aquatic ecosystems. Transformative capacity is seldom used in this water-subsystem-centred type, because the idea of creating an entirely new system is inconsistent with the philosophy of conservation, which focuses on maintaining the natural world.

### 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 ~~adverse~~ impacts on human ~~activitieswell-being~~. 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 ~~ehangeaffect~~ 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 ~~lostloss~~ (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~~ Consequently, resilience from the perspective of managing human subsystems ~~thus emphasises~~ tends to emphasise particular societal ~~norms and goals or normative aspirations~~ expectations in relation to how to deal more holistically with hydrological hazards. ~~However, if~~ If social aspects of human subsystems are also considered, more anticipatory targets can be discerned. ~~For example,~~ However, critics of resilience have argued that there is still significant scope for developing a more nuanced understanding of resilience and how it relates to society. Cote and Nightingale (2012) argue that ~~the dynamics of social change should be better framed as part of social-ecological resilience research.~~ there is still far less attention to normative and epistemological questions. For example, the policy use of resilience is often normative in the sense that it implies that resilience is always something ‘good’ to be strived for. However, the tendency to see resilience as being an objectively defined desirable can create challenges for social scientists working with the concept (Olsson et al., 2015). An important point is that questions that relate to power and politics of both how and who gets to define resilience need to be brought into the foreground of resilience research, otherwise resilience runs the risk of becoming a power-blind concept (Davoudi et al., 2012). 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. West et al. have argued that some of the criticisms around resilience can be overcome through identifying better ways for researchers from social and natural science backgrounds to open new dialogues, so establishing common ground while identifying areas of disagreement (West et al., 2014).

In this type of framing, absorptive capacity is the ability to defend from hydrological hazards, while social adaptive capacity is a means to improve this ability and reduce the vulnerability of human subsystems including individuals, communities, groups and institutions in coping with water related shocks and changes (Bennett et al., 2014). Gupta et al. (2010) reviewed the existing literature and summarise six dimensions of adaptive capacity: variety and diversity of problem framing and solving, learning capacity, room for autonomous change, leadership, resources and fair governance. A similar conclusion is made by Bennett et al. (2014) in their four categories of adaptive capacity including flexibility and diversity, capacity to organise, learning and knowledge, and access to assets. Besides incremental improvements, human subsystems can even radically reorganise communities and proactively transform into entirely new settings under global change. An extreme example is climate change-induced migration: here, the subject of resilience under contingent hydrological impacts (populations at-risk) may abandon settlements, migrate to new locations and restructure human subsystems (Methmann and Oels, 2015).

### 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~~ coupled human and water subsystems to build a more balanced

understanding of their process interrelationships, and highlights resilience of socio-hydrological systems to both internal and external hazards.

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). As discussed in the previous section, desired states of the water subsystem are usually high naturalness or historical conditions measured by biotic and abiotic indicators, while desired states of the human subsystem are more normative societal expectations set by relevant social groups. However, it is a challenge to define the current state as well as the desired state of this coupling type of human-water system, which helps to clarify the identity of socio-hydrological resilience and to answer 'resilience of what'. A conventional approach to evaluate coupled systems is to use compositional indicators (Meerow et al., 2016). Components from subsystems are assessed separately and then summed up to obtain a proxy value for the overall coupled system state. For example, disaster resilience index usually regards the overall system as a comprised 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, However, if used in the socio-hydrological context, 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 (Gao et al., 2016). This demands a direct assessment of the coupled system using indicators or measures that depict multi-directional interactions. Examples include human benefits from hydrological systems, water resource use, and water-supported socioeconomic development, governance over water, and societal and behavioural response to hydrological hazards (Carey et al., 2014; Elshafei et al., 2014). Among these we argue that the notion of hydrological ecosystem services, which attempt to bridge the two subsystems, is a promising framework to describe the socio-hydrological state and to be incorporated into the resilience thinking (Biggs et al., 2012, 2015; 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 mean

ecosystems are pristine or close to a ‘natural’ condition, but instead reflects the preference dependence 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 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 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 natural hazard protection, making it a viable proxy for socio-hydrological systems.

Resilience of socio-hydrological system may not only come from its water or human subsystems, but from human-water interactions that are not prominent in the first two types. For example, real-time monitoring of hydrological disasters contributes to absorptive capacity. Adaptive capacity can be underpinned by water governance and institutions, as well as environmental knowledge learning and exchange. Transformative capacity may be rooted in the incentive, ability and innovation in optimisation of water usage model, development of water-dependent socio-economic structure, and reconstruction of human-water relations through resettlement (Arnall, 2015; Barrett and Constanas, 2014; Wilson et al., 2013)

## 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 through human interventions intervention.

### 4.1 Absorptive and adaptive Resilience capacities, and the ‘resilience canvas’

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). two of the constitutive capacities as the x- and y-axes (Fig. 3). This section demonstrates how the ‘resilience canvas’ can be constructed and applied, by emphasising on the first two dimensions of resilience – absorptive capacity for current hazards and adaptive capacity for future contingencies. The transformative capacity is not focused in the discussion because it requires some further exploration compared to the first two capacities – there is still an ongoing debate on what exact systematic attributes are needed to support a radical transformation to an entirely new stage (Robinson and Carson, 2015; Wilson et al., 2013). Here we keep the analysis of resilience capacities in a visually simple way as a 2-dimensional space instead of a ‘resilience cube’, and select the first two capacities for demonstration purposes. 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.

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).

## 4.2 Building pathways to resilience in socio-hydrological resilience contexts

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. The pathways on the resilience canvas represent a series of three hypothesised human intervention scenarios introduced to effect system change (cf. Haasnoot et al., 2013) (See also Fig. 3). These are hypothesised in the sense that in adopting a broad definition of resilience, these pathways could be very different depending on the social actors and hydro-social context of operation. However, for the purposes of illustrating how the pathways approach could be useful in the case of the resilience canvas, pathways help steer socio-hydrological systems towards the 'most resilient' status (i.e. top-right of the canvas). This is regarded for the purposes of this study as the most valued water management goal.

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).

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). These activities are applicable for both social and natural sciences, and cut across the three socio-hydrological resilience capacities.

5 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 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. Khamis et al. (2013) compare the network sensitivity and conservation capacity of two catchments – the Taillon Catchment in French Pyrénées and the Rhone catchment in Swiss Alps – by assessing nine variables. It was found that the Rhone catchment has relatively higher absorptive capacity because of its lower network sensitivity, lower potential for alien species invasion, and higher cryosphere-flow buffering, while the Taillon catchment has higher adaptive capacity due to its larger proportion of conservation area and higher naturalness of river flow. Overall, the two catchments have similar evaluation of resilience for their similar distance to the ‘most resilient’ stage on the ‘resilience canvas’ (Fig. 4). However, customised strategies should be developed for each catchment to achieve the resilient goal.

### 4.3 **Development Resilience** 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 local stressors and change, the resilience canvas illustrates a development trajectory for global socio-hydrological systems (Fig. 4-5). This section suggests that pathways are not always in straight lines, while the constitutive capacities of resilience do not usually grow equally while the overall resilience is increasing. It also shows 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 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). By examining the history of the Murrumbidgee River basin, Australia, Kandasamy et al. (2014) recognise four main development eras of socio-hydrological systems: building irrigation and associated infrastructure; gradual appearance of environmental degradation; awareness of environmental impacts and application of consensus strategies; and switching to a directed government interventionist strategy. There is a lagging societal and governmental response to environmental change during the development – it can take years to aware the side-effect of infrastructure construction, and to test and perform the remedial measures until they have an effect. Kandasamy et al. described this changing attitude in respect of the environment as a ‘pendulum swing’ – the balance point in water allocations is turning around between humans and ecosystems. Along with the development of socio-hydrological systems, their resilience changes and evolves simultaneously. Therefore, based on these classifications, three main stages of socio-hydrological resilience at the global scale are summarised and presented on the resilience canvas (Fig. 5).

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, because of insufficient physical and institutional preparedness. However, the unoptimized ecosystem services~~ did not cause too many problems, because of the small and dispersed population and low demand on hydrological ecosystem services (Gleick, 2009). ~~At~~ Therefore, at this stage, absorptive capacity was low and adaptability was mainly provided by the ‘naturalness’ of ecosystems.

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 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~~ The resilience of socio-hydrological systems is shaped ~~was also altered~~ according to prevailing socio-economic and cultural conditions. ~~For example~~ So, 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 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.~~ Hydraulic engineering was conducted to increase the system’s absorptive capacity to cope with existing and known hazards (e.g. flooding, drought and pollution). For example, damming was once regarded as one of the best solutions to avoid flooding and drought (Endfield, 2012; Ward, 2005). However, this improvement was at the expense of natural ecosystems, and consequently decreased ecological adaptive capacity.

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 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. Fernald et al. (2015) discover that the traditional acequia systems may not be still tenable, when external drivers brought by climate and land cover change push these systems beyond their historical limits. 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 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 are now facing a new challenge of future water contingencies and uncertain water-related hazards, which was transited from the historical challenge of meeting growing needs of hydrological ecosystem services. It implies that a shift of water strategies is urgently required. 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. 4-5). From the perspective of a resilient socio-hydrological system, we believe 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 of decision-making may play important roles in building socio-hydrological resilience (Buytaert et al., 2014, 2016).~~  
5 ~~Ecosystem restorations such as decanalisation, improving river connectivity, and floodplain recovery also suggest enhancing~~This implies that interventions in all the source of resilience, including water and human subsystems and human-water interactions, need to be considered. Some promising example approaches are provided as follows. Ecosystem restorations such as decanalisation, improving river connectivity, and floodplain recovery also suggest enhancing ecological or hydrological adaptability (Brauman et al., 2007), although in the process absorptive capacity may be compromised (Chen et al., 2016). This reemphasis on the ecosystem integrity in response to degrading environmental quality is also aligned with the ‘pendulum swing’ phenomenon discussed by Kandasamy et al. (2014). Polycentric water governance and public participation in more centralised forms of decision-making may play important roles in building socio-hydrological resilience (Buytaert et al., 2014, 2016). Polycentric systems have multiple governance units at multiple scales, which provide the flexibility to deal with the target problems at appropriate scale, and offers institutional back-ups to respond to uncertainties (Andersson and Ostrom, 2008; Garmestani and Benson, 2013).  
10 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~~ Environment Agency for England and Wales 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~~

### 5 Concluding remarks

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-hydrological resilience. Although these reflect different aspects of human-water interactions, they are not easy to distinguish.

25 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 pathways to resilience in socio-hydrological contexts.

30 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 promising tool to describe the resilient dynamics of socio-hydrological systems, since it reflects an essential aspect of the  
35 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.

40 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, 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).

5 Resilience is not only a descriptive notion, and usually has normative (goal-setting) objectives. To build pathways to socio-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  
10 people’s growing demand on water and the increasing resilience of hydrological ecosystem services supply. Nonetheless there is still substantial geographic variation globally in the distribution of these socio-hydrological stages.

~~Our~~Therefore, this new conceptual framework with the ‘resilience canvas’ motivates some future work on resilience. For example, we need to review, compare and classify existing resilience indicators, propose new quantification and assessment methods for different resilience framings, or even develop mathematical tools to quantitatively describe the resilient processes of the capacities (Gao et al., 2016). We also need to conceptualise resilience dynamics and pathways over time with empirical studies, and shift resilience studies from focusing on single cases at particular points in time, to macro-scale comparisons between the past, present and future. In addition, 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  
20 systems. ~~In a similar manner~~Similarly, different framings such as ecological resilience, social resilience to ecological hazards and social-ecological resilience can also be 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~~argue 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

30 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. We thank Dr Kieran Khamis for his advice in selecting examples for the ‘resilience canvas’. There  
35 are no additional data associated with this conceptual paper.

## 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.
- 5 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.
- [Andersson, K. P. and Ostrom, E.: Analyzing decentralized resource regimes from a polycentric perspective. \*Policy Sci.\*, 41\(1\), 71–93, 2008.](#)
- 10 [Arnall, A.: Resilience as transformative capacity: Exploring the quadripartite cycle of structuration in a Mozambican resettlement programme. \*Geoforum\*, 66, 26–36, 2015.](#)
- 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.
- 15 [BeneBarrett, C. B. and Constan, M. A.: Toward a theory of resilience for international development applications., \*Proc. Natl. Acad. Sci. U. S. A.\*, 111\(40\), 14625–30, 2014.](#)
- [Béné, 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.](#)
- 20 [Bennett, N. J., Dearden, P., Murray, G. and Kadfak, A.: The capacity to adapt?: Communities in a changing climate, environment, and economy on the northern Andaman coast of Thailand. \*Ecol. Soc.\*, 19\(2\), 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.
- 25 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.
- 30 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.
- 35 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.
- 40 [Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., BièvreAlemie, T. C., Bastiaensen, J., De BiÃvre, B., De, Bhusal, J., Chanie, T., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., PandeyPandeya, 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., SubmittedEarth Sci.\*, 2\(October\), 1–21, 2014.](#)
- 45 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.
- [Carey, M., Baraer, M., Mark, B. G., French, A., Bury, J., Young, K. R. and McKenzie, J. M.: Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models \(Santa River, Peru\), \*J. Hydrol.\*, 518\(PA\), 60–70, 2014.](#)
- 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., 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 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 Niño, *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 (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 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., Csekerits, 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.
- 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.
- [Davoudi, S., Shaw, K., Haider, L. J., Quinlan, A. E., Peterson, G. D., Wilkinson, C., Fünfgeld, H., McEvoy, D. and Porter, L.: Resilience: A Bridging Concept or a Dead End? “Reframing” Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does it Mean in Planni, \*Plan. Theory Pract.\*, 13\(2\), 299–333, 2012.](#)
- 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.
- 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.
- 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.
- [Elshafei, Y., Sivapalan, M., Tonts, M. and Hipsey, M. R.: A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach, \*Hydrol. Earth Syst. Sci.\*, 18\(6\), 2141–2166, 2014.](#)
- [Endfield, G. H.: The resilience and adaptive capacity of social-environmental systems in colonial Mexico, \*Proc. Natl. Acad. Sci.\*, 109\(10\), 3676–3681, 2012.](#)
- 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.
- [Evans, B. and Reid, J.: Dangerously exposed: the life and death of the resilient subject, \*Resilience\*, 1\(2\), 83–98, 2013.](#)
- 5 [Fernald, A., Guldan, S., Boykin, K., Cibils, A., Gonzales, M., Hurd, B., Lopez, S., Ochoa, C., Ortiz, M., Rivera, J., Rodriguez, S. and Steele, C.: Linked hydrologic and social systems that support resilience of traditional irrigation communities, \*Hydrol. Earth Syst. Sci.\*, 19\(1\), 293–307, 2015.](#)
- 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.
- 10 [Folke, C.: Resilience \( Republished \), \*Ecol. Soc.\*, 21\(4\), 2016.](#)
- [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.
- 15 Gallopín, G. C.: Linkages between vulnerability, resilience, and adaptive capacity, *Glob. Environ. Chang.*, 16(3), 293–303, 2006.
- [Gao, J., Barzel, B. and Barabási, A.-L.: Universal resilience patterns in complex networks, \*Nature\*, 530\(7590\), 307–312, 2016.](#)
- [Garmestani, A. S. and Benson, M. H.: A framework for resilience-based governance of social-ecological systems, \*Ecol. Soc.\*, 18\(1\), 2013.](#)
- 20 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.
- 25 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.
- 30 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.
- 35 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.
- 40 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 Rapid Climate Change and Ocean Acidification, *Science*, 318(December 2007), 1737–1742, 2008.
- 45 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.
- 5 [Kandasamy, J., Sountharajah, D., Sivabalan, P., Chanan, a., Vigneswaran, S. and Sivapalan, M.: Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia, \*Hydrol. Earth Syst. Sci.\*, 18\(3\), 1027–1041, 2014.](#)
- Karpouzoglou, T., Dewulf, A. and Clark, J.: Advancing adaptive governance of social-ecological systems through theoretical multiplicity, *Environ. Sci. Policy*, 57, 1–9, 2016a.
- 10 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 resistance 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.
- 15 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.
- 20 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.
- 25 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.
- 30 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.
- 35 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.
- 40 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., Rangescroft, 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.
- 45 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.
- 5 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.
- 10 [Methmann, C. and Oels, A.: From “fearing” to “empowering” climate refugees: Governing climate-induced migration in the name of resilience, \*Secur. Dialogue\*, 46\(1\), 51–68, 2015.](#)
- Millennium Ecosystem Assessment: Ecosystems and human well-being: Synthesis, Island Press, Washington, DC., 2005.
- Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., Leeuw, S. van der, Rockström, J., Hinkel, J., Downing, T., Folke, C. and Nelson, D.: Resilience and vulnerability: Complementary or conflicting concepts, *Ecol. Soc.*, 15(3), 11, 2011.
- 15 [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.
- 20 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., Schaeffli, 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.
- 25 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.
- 30 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.
- 35 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.
- 40 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.
- 45 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.
- [Robinson, G. M. and Carson, D. A.: Resilient communities: Transitions, pathways and resourcefulness, \*Geogr. J.\*, 2015.](#)

- 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.
- 5 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.
- 10 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.
- 15 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.
- 20 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.
- 25 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.
- 30 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.
- 35 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.
- 40 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.
- [Ward, D. R.: Water Wars: Drought, Flood, Folly and the Politics of Thirst., 2005.](#)
- Weichselgartner, J. and Kelman, I.: Geographies of resilience : Challenges and opportunities of a descriptive concept, *Prog. Hum. Geogr.*, 39(3), 249–267, 2015.
- 45 [Wesseling, A., Kooy, M. and Warner, J.: Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines, Wiley Interdiscip. Rev. Water, \(November\), 2016.](#)
- [West, S., Haider, J., Sinare, H. and Karpouzoglou, T.: Beyond divides: Prospects for synergy between resilience and pathways approaches to sustainability., 2014.](#)
- 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.

[Wilson, S., Pearson, L. J., Kashima, Y., Lusher, D. and Pearson, C.: Separating adaptive maintenance \(Resilience\) and transformative capacity of social-ecological systems, \*Ecol. Soc.\*, 18\(1\), 2013.](#)

5

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.

10

# Figures and Table

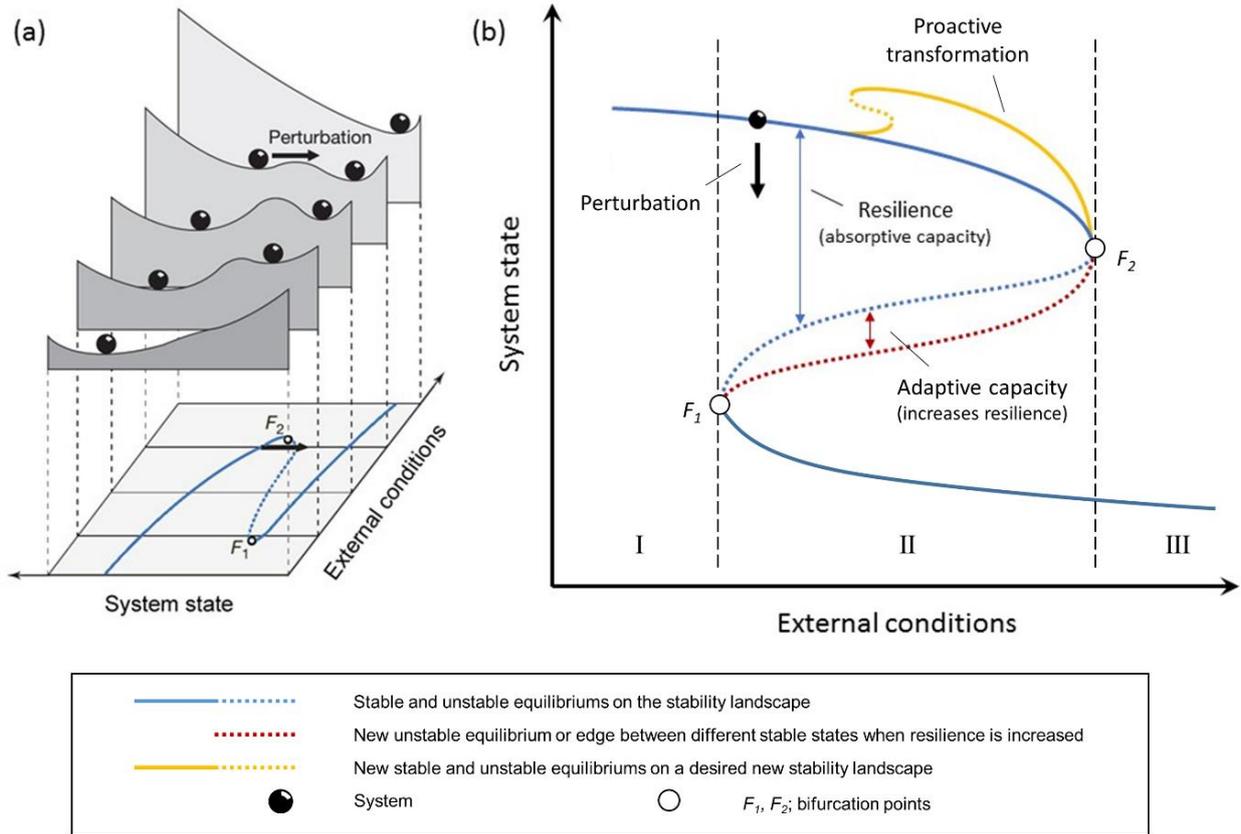
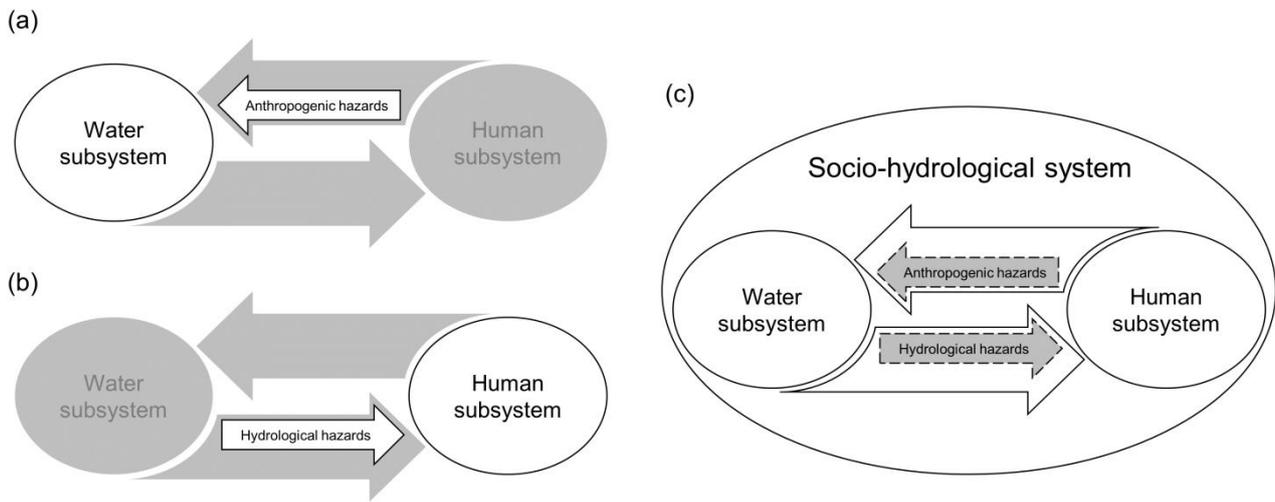
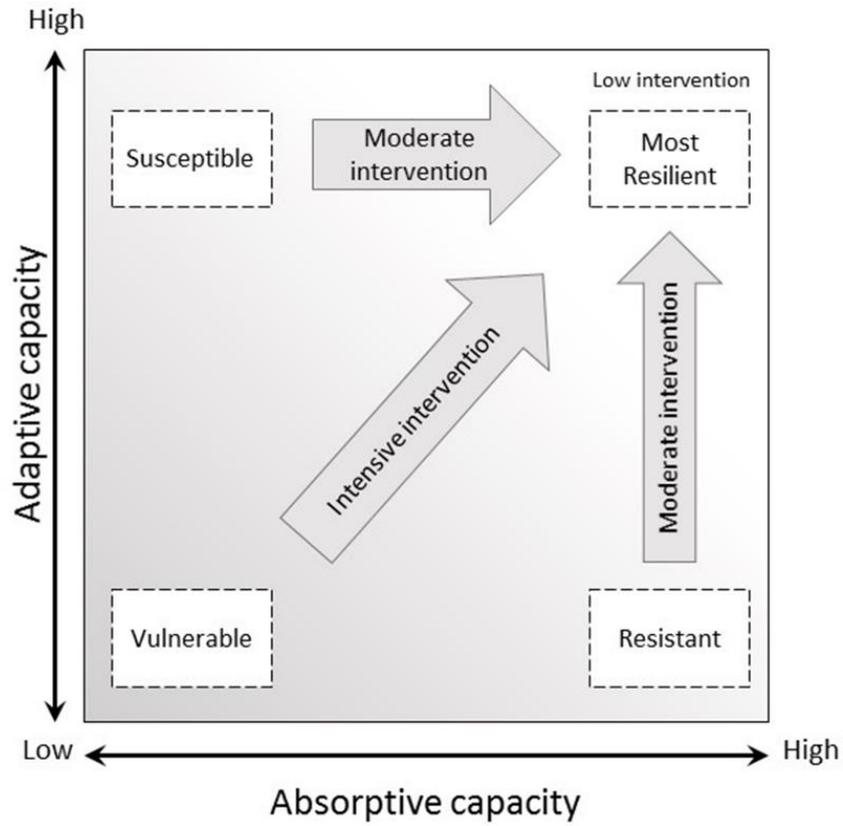


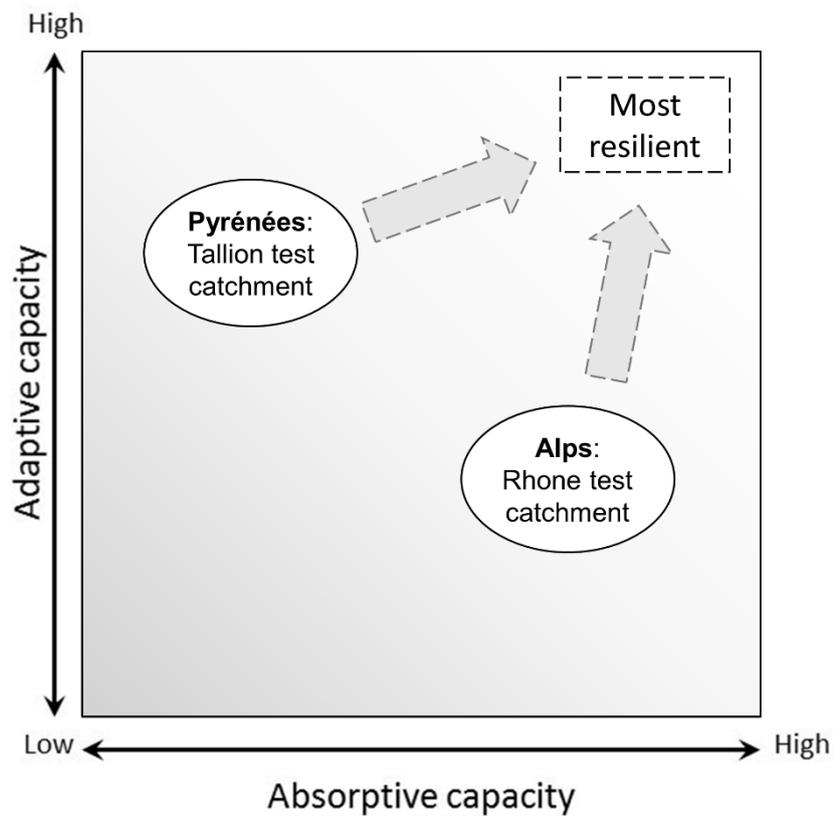
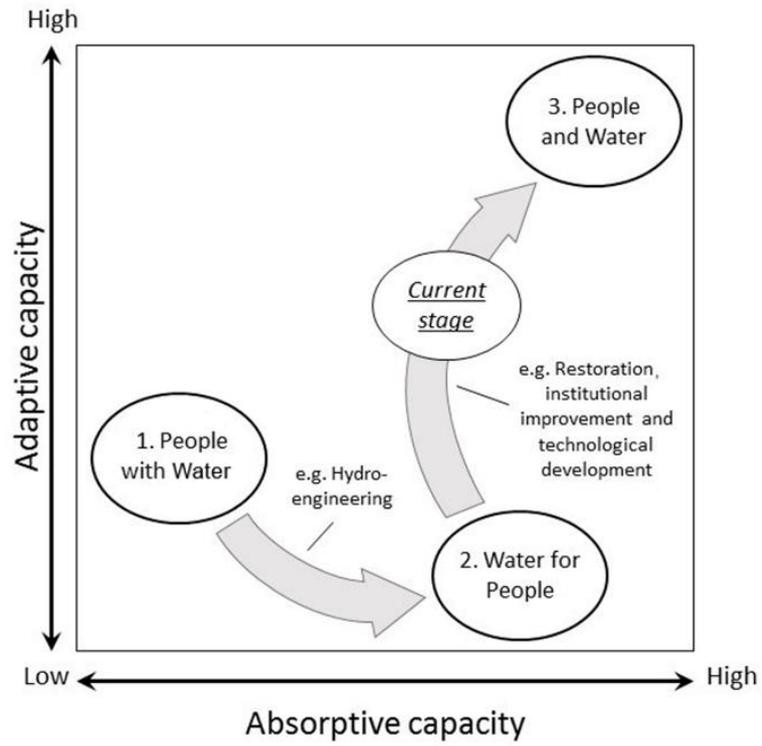
Figure 1. Bifurcation diagrams for socio-hydrological resilience: (a) Stability landscape changes along with external conditions, adapted from Scheffer et al. (2001). (b) Bifurcation diagram illustrating *absorptive*, *adaptive* and *transformative* capacities. The two dashed lines across  $F_1$  and  $F_2$  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 ~~response to~~ external change (red line); transformative capacity refers to the ~~capability to respond more radically, such as~~ proactively ~~navigating~~ navigating the system to a desired new stability landscape (yellow line).



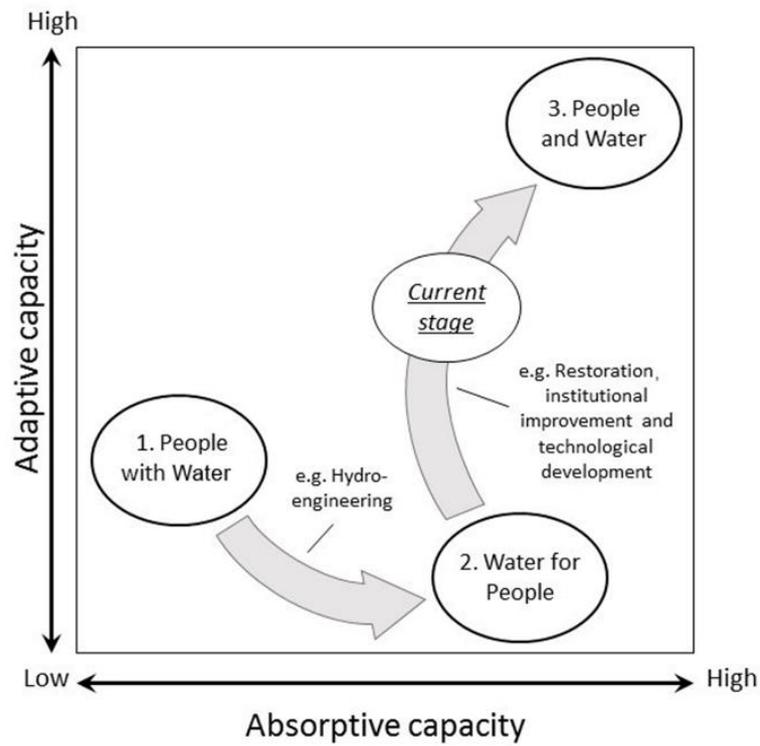
5 **Figure 2. Schematic diagram of three human-water coupling types, each foregrounding different aspects of socio-hydrological system. (a) Water subsystem with anthropogenic hazards, where the human subsystem, water impacts on human subsystem or other forms of human impacts on the water subsystem are not the main focus. (b) Human subsystem with hydrological hazards, where similarly water subsystem, 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.**



5 | 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. Regional comparisons of hydrological resilience. Two test catchments are compared, including Tallion catchment in French Pyrénées and the Rhone catchment in Swiss Alps.**



**Figure 5.** Global development of socio-hydrological systems resilience on the ‘resilience canvas’. Three main developmental stages are (1) people People with water Water, (2) water Water for people People and (3) people People and water 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.**

<i>Human-water coupling types</i>	<i>Water subsystem with anthropogenic hazards</i>	<i>Human subsystem with hydrological hazards</i>	<i>Socio-hydrological system</i>
System	Water subsystem	Human subsystem	Socio-hydrological system
Desired system state	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