Water Security 8 (2019) 100048

Contents lists available at ScienceDirect

Water Security

journal homepage: www.elsevier.com/locate/wasec

Water is a master variable: Solving for resilience in the modern era

Frederick Boltz[a,b], N. LeRoy Poff[c,d], Carl Folke[e,f], Nancy Kete[g], Casey M. Brown[b], Sarah St. George Freeman[b], John H. Matthews[h], Alex Martinez[i], Johan Rockström[e]

[a] *The Resilience Shift, United Kingdom*
[b] *Department of Civil and Environmental Engineering, University of Massachusetts Amherst, United States*
[c] *Department of Biology, Colorado State University, United States*
[d] *Institute for Applied Ecology, University of Canberra, Australia*
[e] *Stockholm Resilience Centre, Stockholm University, Sweden*
[f] *Beijer Institute, Royal Swedish Academy of Sciences, Sweden*
[g] *Kete Consulting, United States*
[h] *Alliance for Global Water Adaptation, United States*
[i] *Stanford University, United States*

ABSTRACT

Resilience is increasingly recognized as an imperative for any prospect of sustainable development, as it relates to our ability to sustain human well-being and progress under the planetary and societal changes that we face now and into the future. Yet, we are ill-prepared to meet this challenge. We neither fully understand nor manage consistently for resilience of the human and natural systems that we must steward through extraordinary change. A unifying approach and common currency would help us to understand and manage for resilience under uncertain futures. Water is an essential, defining element in human and natural systems. Human civilization and water systems have co-evolved as a coupled system, with the majority of natural freshwater systems transformed to meet our demands. Shifting patters of water availability in space and time will define key pathways and tipping points for our resilience, and thus requirements for water system resilience must guide the trajectories and boundaries of human development. Here, we consider the thesis that water offers a key to unlocking the complex challenge of designing and managing for the resilience of coupled human-natural systems. We examine what constitutes a resilient system, what drives freshwater resilience, and how pathways to human resilience may be charted and navigated through the medium of water. Our theoretical treatise frames a portfolio of research that tests this thesis, including modeling and applications to water and water-dependent systems.

1. Introduction

When considering the complex dynamics of natural ecosystems nearly a half century ago, Holling [32] and his contemporaries described "resilience" as the ability of ecosystems to respond to changes in external conditions through internal changes in composition, configuration, and relationships in order to maintain coherent function. Resilience refers to the ability to thrive under change. It has since been broadly adopted to describe the behavior not only of ecological systems, but also of human systems - from built infrastructure and agricultural systems, to economies, cities and our transformed Earth system [20,27,87]. Today, resilience is increasingly recognized as an imperative for any prospect of sustainable development, as it pertains to our ability to sustain human progress in the face of change – whether incremental or abrupt, expected or surprising [19]. Understanding and building the resilience of human and natural systems is an urgent concern, as we face the increasingly immediate and severe effects of Earth system change on our tightly coupled human social-ecological system [60,66,67,34]. The Earth system is currently unstable in many dimensions, portending numerous possible futures, and presenting urgent choices between transforming to a sustainable social organization and stewarding the Earth for continued human progress or failing to preserve a biosphere suitable for our survival and precipitating the collapse of human civilization [14].

It seems an insurmountable challenge to build the resilience of complex human systems to planetary and societal changes of an uncertain pace, variability and magnitude. Complexity wedded with uncertainty is confounding, thus we neither fully understand nor manage consistently for resilience. Rather, our designs respond to those vulnerabilities most evident and acute, which therefore have emerged as priorities for the affected communities. In coastal, low-lying regions, we begin with storms and sea-level rise, whereas in areas suffering chronic wildfires, droughts or disease, or pressured by demographic growth and socio-economic change, we design for the resilience of vulnerable populations and assets to those particular stressors. More commonly, with lesser ambition and an aversion to incur the costs of mitigating risks that seem less immediate, we design for the least cost solution to proximate threats. A coherent approach to understanding and solving for the resilience of human systems remains elusive. While our current designs may not be "wrong", the lack of a consistent, coherent approach to designing for our resilience is a crucial shortcoming. At a minimum, it limits our ability to evaluate alternative resilience design choices. Perhaps more importantly, it undermines our ability to effectively identify and act on key system features crucial to resilience strategies.

https://doi.org/10.1016/j.wasec.2019.100048
Received 24 May 2019; Received in revised form 22 October 2019; Accepted 25 October 2019
Available online 21 November 2019

This likely results in a greater frequency of overlooking issues affecting resilience and thus in deficient designs. Here we suggest that fresh water[1] can serve as a key to solving that puzzle; that water is central to so many dimensions of social-ecological resilience, it may serve as a "master variable" offering a coherent approach to understanding, designing and managing for resilience in the Anthropocene.

Water and climate are common, defining factors of human and natural systems, determining their productivity and function as well as their vulnerability to global change. The warming climate will determine the magnitude of Earth system change and the parameters within which we must operate to solve for our resilient future [66,67]. Climate change impacts will be most immediately and acutely expressed through water, notably through changes in water quantity, quality and distribution relative to human needs [61], and in extreme events, such as flooding and droughts. Along with climate, water dictates the diversity and distribution of the terrestrial biosphere. Water is central to the functioning of the Earth system and is a critical determinant of the quality and quantity of ecosystem services [58,59]. Water of a specific quantity, quality and timing is required to preserve the composition and function of natural ecosystems under localized disturbances and broader environmental change. Under climate change, water availability and variability will define how the terrestrial biosphere adapts, shifting the distribution of species and ecosystems to accommodate new conditions and, thereby, directly affecting established human interactions with previously prevailing environmental norms.

Water's central role in the biosphere has long implied that many of the most important human development challenges are related to water [15] and to freshwater resilience [16]. Water availability has historically defined where humans could settle and produce and has thereby guided the development of societies and economies. Human ingenuity has enabled us to overcome the physical limits imposed by nature – at least temporarily – by damming and diverting water to where we choose to settle, to farm and to prosper. Yet, we have now reached a scale of human demand and water footprint that surpasses conventional solutions [45,76,79,58,16]. Climate change is altering patterns of water availability across the planet, while human demand for water resources grows unabated [16]. The increasing frequency and amplitude of water related shocks and stresses – from more intense droughts and floods to seasonal shifts in precipitation – are a critical resilience concern [71,70]. Human ingenuity is again tested, as we grapple with adapting to a highly uncertain and increasingly volatile future [14].

Here we argue that a coherent approach to understanding and solving for the resilience of human systems under future Earth system and societal change can be found by basing our designs on water. Water is an essential and defining element, a crucial factor or a "master variable" guiding the nature and function of interacting human and natural systems. Shifting patterns of water in space and time will define key pathways and boundaries for their development and resilience. As such, we submit that water provides a consistent and robust basis for navigating the complexity and uncertainty of designing and managing for the resilience of coupled human-natural systems. We draw confidence that water offers a path to our future from the knowledge that water has defined and enabled human progress throughout history [41,83]. Human civilization and water systems have co-evolved as a coupled social-ecological system [65,41,42].

Our work builds upon seminal writings that form the theoretical foundations of social-ecological resilience, [32,21], of engineering resilience in water resources management [18,8,64], and of freshwater ecology [56,74]. We consider what constitutes a resilient system, what influences water system resilience, and how pathways to human resilience may be charted and navigated through the medium of water. Related work compiled in a special issue of Water Security further explores this thesis, including modeling, metrics, and scenario planning work, as well as applications to water systems and to human systems dependent on water [7,10,22,26,36,44,72,75].

2. Conceptual framing: resilient systems

Building upon the work of Homer-Dixon et al. [34], we define a "system" as a set of causally connected entities that are distinguishable as an identifiable whole and that self-organize to persist in characteristic function over an extended period of time. We refer to "natural systems" as ecological systems, with identities formed by their distinct composition of species, structure, and relationships and with characteristic ecological functions and services. We restrict our treatment to ecosystems that are largely influenced by fresh water inputs of precipitation, surface flows and groundwater, i.e., primarily terrestrial but also near-shore marine ecosystems. We consider "human systems" as social-ecological systems – complex, integrated systems in which humans are part of nature [85]. Further, given the particular influence and agency of technology in human development, we recognize that human systems may be more precisely characterized as social-ecological-technological systems [43]. Human systems exist in a dynamic nexus comprising social, ecological and technological aspects that define how the system functions what it produces, and determine its vulnerabilities as well as its resilience [4,24].

Achieving and maintaining a system's preferred functions and services through management intervention is a hallmark of human development. Conventional engineering approaches to resilience solve for the performance and recovery of built systems – infrastructure, water, energy, transport – under shocks and stresses [30,52,64]. Resistance to disturbance and speed of return to equilibrium are used to measure an event response function [29,33]. Robustness describes this ability to maintain performance over a wide range of input uncertainty. Robustness measures inform design options intended to enable systems to persist under varying types and magnitudes of change.

Advances in social-ecological resilience science suggest that resilience is not only measured by a system's ability to remain in its current state or equilibrium, persisting under disturbance, but also by its abilities to adapt to change and to transform – to move from one state into another and function in a changed configuration [20,21,32,81]. Systems are not globally stable but reside in multiple distinct equilibria along an evolutionary trajectory, thus they have a nonzero probability of shifting from current into novel states [32]. From a system management perspective, resilience is about how to navigate the journey among diverse pathways and equilibria, crossing tipping points as the system shifts from one state to another [20].

Here we suggest that resilience is manifested in a system's "identity" – its components, their configuration and interactions – which enables it to maintain coherent "function" under disturbance. A system's function is understood and measured in terms of its generation of characteristic services and outputs: notably, the ecosystem services produced by natural systems and the economic and social capital generated by human systems. Functions are commonly variable due to changes in the relative contribution of different system elements, such as the interannual variation in ecosystem service flows. Following [21], we suggest that three capabilities ("PAT") characterize a resilient system (Fig. 1):

- **Persistence** refers to a human or natural system's ability to maintain coherent function under changing conditions and disruption without altering its identity. The existing components, configuration and interactions of the system enable it to return to its prior function under the exogenous stresses and shocks to which is it exposed.
- **Adaptability** refers to a system's ability to maintain coherent function by modifying its identity to accommodate change.

---

[1] Here, we refer exclusively to fresh water in terrestrial and atmospheric systems, not saline water in marine systems. Throughout, we use the term "water" for simplicity.

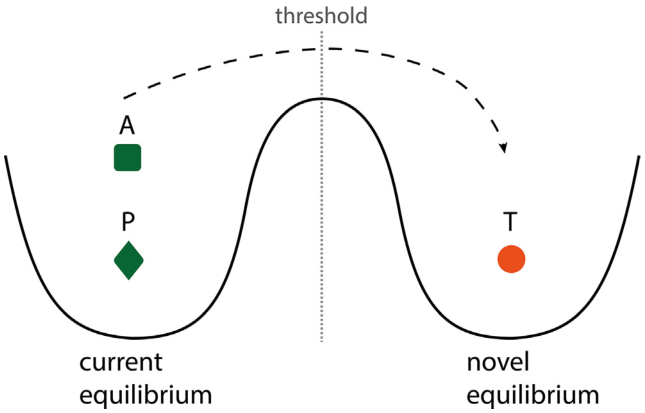

Fig. 1. Three capabilities of a resilient system: Persistence, Adaptability, Transformability (PAT). Shapes represent system identity, which changes in order to adapt and transform. Colors represent system function, which changes as systems shift to new equilibria. (Adapted from Falkenmark et al. [16]).

Adaptability is about continually adjusting responses, innovating, and reorganizing system parts and relationships relative to changing external conditions and internal interactions. Adaptability allows for system development and realignment within its current equilibrium – adjusting to sustain its present function.

- **Transformability** refers to a system's ability to change its identity and to establish a new function in a novel equilibrium when pushed beyond the threshold of its present state. It is the ability to change from one type of system to another with different controlling variables, structure, functions, and feedbacks [48]. Transformation results in a change in both system identity and function. Transformability is the capacity to create a new system when ecological, economic, or social conditions make the existing system untenable [81,21,54].

Transformation is seen by some as a consequence of system failure and collapse, and by others as an essential capability of long-lasting systems [17,14]. Here we suggest that both are plausible outcomes. When complex systems cross tipping points and transform, they are capable of shifting onto numerous alternative pathways [14], some more desirable than others (Fig. 2).

Transformation will distinguish between winners and losers. The new state to which a system might naturally transform may be highly disruptive to existing human and ecological systems and stakeholders. For instance, one may regard the potential regime shift of the Amazon rainforest to savannah as an example of Earth system resilience; but for the humans and biodiversity that must endure that transformation, it will feel like system failure and nothing like thriving! Transformation may be damaging, costly, and irreversible, as with species extinction.

Resilience is not normative; however, it does not imply or attribute specific preferences, choices or values to a system's state or function [1]. Humans attribute value to resilience capabilities, commonly we value the ability of a system to cope with expected stresses and shocks and to continue to perform its expected functions, i.e., to exhibit persistence and adaptability. Likewise, transformability is a system capability which we may choose to value, distinguishing preferable transitions from collapse, success from failure.

Because indiscriminately following a system's natural progression across tipping points to a novel state may lead to massive environmental, economic and social losses, we must strive to transform to more desirable alternative states when tipping points will inevitably be surpassed. A resilient agricultural system faced with changing climatic conditions that threaten crop yields and economic returns shifts to different crops – changing identity to adapt – or transforms to an altogether different land use, as opposed to continuing established practices that will lead to its collapse. Solving for resilience will require that we design and manage human systems for persistence and adaptability to preserve current functions, and that we anticipate and guide transformations onto preferred new development pathways.

Persistence may be achieved by configuring our systems to withstand stresses and shocks, while adaptability may be achieved by adjusting system elements, their configuration, and operation in order to preserve current system function under change. Resilience will also require an improved human capacity to project, plan, and manage for transformation to a preferred new state and trajectory when the current state cannot be maintained (Fig. 2). Novel states, beyond the boundaries of the current equilibrium, may be estimated by modeling and scenario planning, e.g., [7,8,12,28,69]. When faced with the inevitability that a system will cross tipping points, our challenge is to enable system reorganization to desirable new equilibria providing conditions under which we may thrive, and to avert trajectories that may lead to collapse.

The prospect of guiding system transformation to novel states seems a monumental challenge, as our understanding of the space–time interactions of variables that constrain and define the Earth system trajectory and transitions is limited. We argue, however, that while prediction of the full trajectory of change may be infeasible, we can reasonably predict threshold conditions and proximate equilibria to

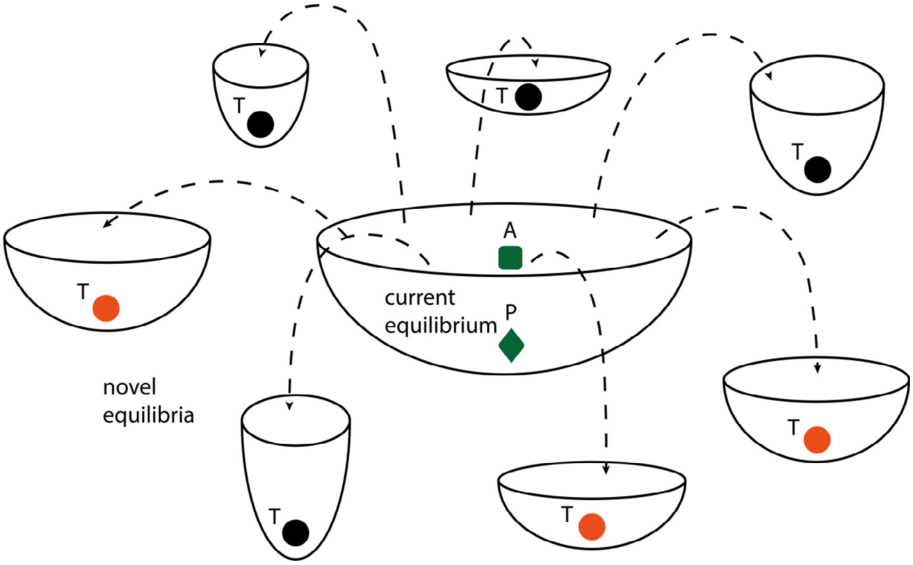

Fig. 2. Beyond the boundary conditions of its present state, within which a system may persist (P) and adapt (A) to maintain its function, the system may transform (T) to a variety of novel equilibria, some of which represent system collapse (black), others shifting to a relatively desirable new state (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which water-dependent systems may shift, as has been done for agricultural systems [23], aquatic ecosystems [13,35,53], river catchments [80] and urban water systems [38]. Accordingly, we can manage for resilience as it relates to all three capabilities: persistence and adaptation within current boundaries and transformation beyond. While this may appear inordinately difficult, such designs are possible with water systems as we have demonstrated throughout history [41,65,83].

Recently, Resilience by Design (RbD) has been developed to help meet this need [7]. RbD is a performance-based optimization approach, which evaluates alternative design options ("identities") relative to their ability to deliver desired functions, and thereby perform system resilience capabilities (PAT) under projected stresses and shocks. RbD evaluates resilient water system design for provisioning, water quality regulation, and waste- and storm-water management services under deep uncertainty. RbD allows examination of both gradual changes in precipitation, as well as extreme events such as flooding or droughts. RbD uses multi-dimensional sensitivity analysis to assess the performance of alternative system identities over a wide range of possible futures, building upon advances in decision making under deep uncertainty [8,68]. RbD solves for the combinations of fixed and adaptive design values that achieve resilience capabilities (PAT), while minimizing the expected cost of design, including the utility of losses when failure occurs.

Following Brown et al. [7], let Z equal the total cost of a given resilience design:

$$z = \sum_i c_i y_i + \sum_j c_j MD_j + \sum_k c_k(\rho_R)(1 - p_D) + \sum_l c_l(\rho_p)p_D + U[L(y_i, \rho_R, \rho_P, p_D, X)] \tag{1}$$

where,

C_i represents the cost of alternative fixed design variables, y_i
C_j is the cost of monitoring and detection MD_j
C_k is the cost of reactive recovery activities, ρ_R
p_D is the probability of detecting problematic performance C_l is the cost of proactive recovery, ρ_p

In addition to the direct costs of system design, the RbD formulation includes losses $L(-)$ that are incurred by a given design due to poor performance under future hazards. Such losses are a function of the fixed design (y_i), recovery (ρ_R, ρ_P), detection (p_D), and the value of a vector of uncertain exogenous factors (X) causing those hazards, such as temperature, precipitation, demand, and extreme events. A utility function, U(L) values these losses relative to stakeholder preferences for their avoidance.

RbD informs benefit-cost analysis related to system design for resilience capabilities (PAT), explicitly considering the benefits and costs implied by decisions to enhance or to limit system designs, simply expressed as follows [7]:

$$\begin{aligned}&[\mathit{Total\ Expected}\ \mathrm{Costs}]\\ &= \underbrace{[\mathit{Fixed\ Design}\ \mathrm{Cost}] + [\mathit{Expected}\ \mathrm{Cost}\ \mathit{of}\ \mathrm{Re}\mathit{active}\ \mathrm{Re}\mathrm{cov}\mathit{ery}]}_{\mathit{Persistance}}\\ &\quad + \underbrace{[\mathit{Expected}\ \mathrm{Cost}\ \mathit{of}\ \mathrm{Pr}\mathit{oactive}\ \mathrm{Re}\mathrm{cov}\mathit{ery}] + [\mathrm{cos}\,\mathit{t\ of\ M\&D}]}_{\mathit{Adaptability}}\\ &\quad + \underbrace{[\mathit{Utility\ of\ Expected}\ \mathrm{Costs}]}_{\mathit{Trigger\ for\ Transformation}}\end{aligned} \tag{2}$$

In RbD applications, for instance, one may choose to limit infrastructure or agricultural systems capabilities to achieve persistence within the boundary conditions defined by historical norms of precipitation, drought and flooding. Such designs would maintain the benefits of water provision and of food production under normal conditions, while minimizing the costs of enabling adaptability and transformability to extreme events. However, these design choices would also result in greater risk of losses due to poor performance or system failure when extremes occur. In an era of increasing uncertainty, we should instead shift to designing for resilience (PAT). RbD enables such calculations and comparisons.

3. The resilience of freshwater ecosystems and human-hydrologic systems

Freshwater ecosystems comprise lakes, rivers, aquifers, marshes and other wetlands. We rely upon freshwater ecosystems for many valuable services including water provisioning and quality regulation, waste- and storm-water management, sustaining productive fisheries, as well as recreation, aesthetics, other cultural services and existence values. These ecosystem services, in turn, depend on the functional integrity of natural freshwater ecosystems and the biodiversity they harbor. Freshwater resilience refers to the ability of natural freshwater ecosystems to persist, adapt and transform to sustain coherent function under change [58,55]. Ecosystem services may be considered the "function" of freshwater ecosystems for the purpose of characterizing their resilience. Freshwater ecosystems exhibit resilience in their ability to maintain their production of ecosystem services under changes in temperature, precipitation and species interactions, as well as under human stresses of pollution, habitat transformation and modified flow regimes. Because human prosperity is dependent on the continued provision of these services [46,73], preserving the attributes necessary for the resilience of freshwater ecosystems must be a central development aim.

Solving for freshwater resilience requires identifying the endogenous and exogenous variables that influence system function, identifying possible threshold effects driven by the interaction of those variables, and considering the possibility of alternate system states. Endogenous attributes comprising freshwater ecosystem "identity" include thermal, light, chemical and nutrient characteristics, sediment and organic matter inputs, native biota, and, perhaps most critically, the hydrologic flow regime [56,3]. Exogenous factors influencing system function and boundary conditions include temperature, precipitation, and human-induced changes. For instance, infrastructure and land use changes commonly disrupt the flow regime and native biota and introduce pollutants and alien species. Managing for variability and maintaining environmental heterogeneity and landscape connectivity are central to freshwater resilience, as they enable broad ecosystem response to changing conditions [31,63,55,74]. Freshwater system function is guided by the interaction of endogenous attributes and exogenous conditions.

When exogenous conditions, such as land use or climate change, force significant alteration of endogenous attributes toward thresholds of persistence and adaptability, freshwater ecosystems become unstable and unpredictable. Once a threshold is transgressed, regime shift may result in a dramatic reorganization to establish a new equilibrium state. Such transformations make it very difficult to restore natural freshwater systems to their previous state and function [62]. Eutrophication and local species extirpation are examples of potentially irreversible impacts of freshwater ecosystem transformation. The potential consequences of transformation are particularly salient to decisions related to freshwater ecosystem management, given their critical importance to human well-being and resilience.

Our transformation of natural freshwater ecosystems to managed hydrological systems has enabled human societies and economies to flourish in places where water resources would otherwise have been insufficient, or insufficiently reliable, to support our development. Over time, the majority of freshwater ecosystems have been modified to meet human demands. At the turn of the last millennium, over half of large river systems had been dammed, with reservoirs intercepting more than 40 per cent of global river discharge [78,77,47,39]. Those transformations have continued and accelerated. A recent global assessment found that only 37 percent of rivers longer than 1000 km remain free-flowing over their entire length and less than a quarter flow uninterrupted to the oceans [25].

Modern water systems are so heavily modified that management for resilience must consider their integrated and interdependent social-ecological-technological makeup and not uniquely their natural attributes. Management of modified freshwater systems or "human-hydrologic systems" (HHS) must account for both natural and anthropogenic variables and their interactions. The development of HHS models with capabilities of simulating both hydrological and human-induced water functions has emerged in response to this need [37,82,84], including some anticipating responses to climate change [7,57].

By design, human-hydrologic systems (HHS) are composed, configured and operated in order to generate desired services to downstream communities [9]. We dam rivers to store and supply water, we connect surface flows to increase water provision, and we open wells to bring groundwater to the surface for our use. The preferred configuration of a HHS is defined to meet human demands for specific functions. Stakeholder demand for ecosystem services and, critically, their tolerance for costs and risk of diminished or lost services [2] reveal preferences for water system function and thus alternative design options. Traditionally, the engineering of water systems has been guided by the imperative of sustaining specific services through the configuration and management of state variables (identity) for persistence under historic hydroclimatic variability.

Water resources management interventions can lead to dramatic changes in HHS identity and function, including unwelcome transformations, such as the drying of Lake Chad and the Aral Sea and the degradation of innumerable river deltas and wetlands [9]. Climate and environmental change will trigger further transformations, pushing natural and human systems beyond thresholds of their current equilibria into novel states. Consequently, we must build and manage water systems for their adaptability and transformability to new configurations and new norms of function, avoiding collapse and mitigating the costs of system failure. Water resources management approaches to supply energy, food and water must be coupled with strategies for building human social-ecological resilience at basin-scale, consistent with natural freshwater ecosystem boundaries. In such efforts, we must strive to maintain critical landscape functions such as moisture feedback from forests, precipitation, soil moisture and stable base flows key to regional and planetary resilience [58,59,36].

We can design and manage water systems (HHS) for resilience through changes in their composition and configuration or system identity. We can moderate consumptive use and reuse, regulate temperature and chemical inputs, manage water releases to maintain or alter environmental flows, and deploy technologies that restore ecosystem services (e.g., pollutant, species and sediment removal). We can also modify natural and hard infrastructure to provide for greater or lesser water capture, storage, and flows [51]. Our decisions and designs will either strengthen or impair freshwater ecosystem resilience, with critical consequences for the provision of services vital to our economic and social welfare. Given the inevitable change that will occur in freshwater and HHS systems, our ability to predict and guide their adaptation and transformation to avoid damaging and costly failures and transitions to undesirable new states is fundamental to solving for our resilience. Our managed adaptations and transformations should aim to preserve as much of the natural freshwater ecosystem identity and function as possible, to sustain their many valuable contributions to human well-being, and to preserve their natural resilience capabilities.

4. Building resilience through water

Considering human systems generally, resilience refers to the capacity to continually adjust and self-organize in the face of change in order maintain the current development path or to actively transform onto a new development trajectory (e.g., [17,80,86]). This applies to simple and to highly complex systems alike – from monoculture farms to diversified economies, cities, and our human-managed Earth system. Designing for the resilience of human systems can be dauntingly complex, as a comprehensive articulation of system identity and function is difficult to achieve, let alone to measure. Instead, we rely upon identifying conditions that can enable or support its emergence [11]. While we have made important progress in describing the characteristics of resilient systems and developing uniform frameworks and assessment processes, e.g., [5,6,40,49,50,81] resilience must be measured not merely by a system's attributes and ”identity”, but fundamentally by its ability to persevere in its function.

Solving for resilience requires that we design and manage human systems for persistence and adaptability to preserve their function under change and for transformability to enable system reorganization towards a preferred state once current functions can no longer be sustained. Technological innovation has been a hallmark of human development and adaptation to social and environmental challenges and will be fundamental to our successful response and future resilience. Social feedback mechanisms can mediate transitions and build resilience – social norms, cultural values, institutions, markets, technology, knowledge, and learning all serve to inform our approach to managing natural and human systems [16,14]. However, protecting and restoring the ecological attributes and functions of natural systems are paramount to preserving the productive capacities of the Earth system and its natural resilience. In our endeavor to build a productive and resilient human future, preserving natural systems and their services is imperative.

The requirements for freshwater system resilience help to define the limits of acceptable human system development and resilience, particularly when such development is predicated upon the certainty of water services. Since human and water systems are coupled and co-evolving, the identity and function of human systems commonly derive from the availability and variability of water services and thus from the conditions necessary for water system resilience. In designing for resilient human systems, water further serves as a "master variable" due to its deep connections across all systems – agricultural, energy, industrial, urban – and virtually all aspects of the human endeavor. As a necessary underpinning of human system resilience, water allows for our estimation of boundary conditions and equilibria to design for persistence, adaptability and transformability (PAT) in discrete and complex systems and across scales. Additionally, as water is a critical factor in natural and human system productivity and resilience from local to planetary scales [16,58,59], it provides a coherent means of understanding and managing vital teleconnections – from atmospheric cycles to surface flows and soil moisture. Sound design and decision-making for resilience require a coherent approach that reveals interdependencies and enables a rigorous evaluation of development options. As, water is a finite resource essential to nearly all discrete human systems (agriculture, energy) and complex systems (cities, economies) alike, it provides a consistent and coherent basis for complex system scenario modeling, planning for PAT, and choices among resilience design and development alternatives. Moreover, because we can diagnose, design, and manage water system "identities" to provide specific functions relative to changing conditions, water system resilience can reveal what is necessary for the resilience of virtually all human systems. From these necessary resilience parameters, we may explore and design for sufficient conditions for human system resilience by considering other stressors, drivers of system function, and threshold conditions.

Water cannot address all system stressors (consider cybersecurity, seismic activity, species extinction). Additionally, some systems are inherently decoupled from water or designed to be so. However, as water is necessary in virtually every system and vital in most, it provides a coherent basis for understanding and navigating complex human system resilience in most instances. The particular opportunity offered by water is that we can manage this vital input to and driver of human system resilience through water system (HHS) design and operation. Deriving the necessary conditions for human system resilience on the basis of what is required for water system resilience provides a coherent means of understanding and navigating our future development. In short, water is a master variable.

5. Conclusions

Throughout history, we have managed and transformed freshwater ecosystems to fuel our development, with little regard for preserving the component species, systems and natural functions vital to their, and to our resilience. As we face prospects of Earth system change and growing threats of water insecurity across the planet, we must no longer heedlessly transform freshwater systems to pursue unsustainable gains in human development. As water systems cross critical tipping points, so will natural and human systems transform and risk collapse. Consequently, our designs for managed adaptations and transformations should aim to preserve natural freshwater ecosystem identity and function, to sustain their many valuable contributions to human well-being, and to preserve their natural resilience capabilities.

Water is life. Humanity's fate is intimately tied to the fate of freshwater systems [16]. Any prospect of human development and resilience to planetary and societal changes that our future holds will depend upon our careful stewardship of water systems. Solving for resilience through the medium of water may guide us through threshold conditions, novel states, and alternative pathways towards resilience. In the face of the complex and urgent challenge of solving for resilience in the modern era, we submit that water may serve as a master variable enabling a coherent approach to defining the conditions and actions necessary to avoid collapse, and revealing pathways for our persistence, adaptation and transformation to preferred futures.

Acknowledgement

We are grateful for the generous support provided by The Resilience Shift for this work.

References

[1] J.M. Anderies, C. Folke, B. Walker, E. Ostrom, Aligning key concepts for global change policy: robustness, resilience, and sustainability, Ecol. Soc. 18 (2) (2013) 8.

[2] D.A. Auerbach, D.B. Deisenroth, R.R. McShane, K.E. McCluney, N.L. Poff, Beyond the concrete: accounting for ecosystem services from free-flowing rivers, Ecosyst. Serv. 10 (2014) 1–5.

[3] J.S. Baron, N.L. Poff, P.L. Angermeier, C.N. Dahm, P.H. Gleick, N.G. Hairston Jr, R.B. Jackson, C.A. Johnston, B.D. Richter, A.D. Steinman, Meeting ecological and societal needs for freshwater, Ecol. Appl. 12 (5) (2002) 1247–1260.

[4] R. Beddoe, R. Costanza, J. Farley, E. Garza, J. Kent, I. Kubiszewski, L. Martinez, T. McCowen, K. Murphy, N. Myers, Z. Ogden, Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies, Proc. Natl. Acad. Sci. 106 (8) (2009) 2483–2489.

[5] F. Berkes, Understanding uncertainty and reducing vulnerability: lessons from resilience thinking, Nat. Hazards 41 (2) (2007) 283–295.

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

[7] C.M. Brown, F. Boltz, S. St. George Freeman, J. Tront, D. Rodriguez, Resilience by design: a deep uncertainty approach for water systems in a changing world, Water Security (2019) In press.

[8] C.M. Brown, Y. Ghile, M. Laverty, K. Li, Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector, Water Resour. Res. 48 (2012).

[9] C.M. Brown, J.R. Lund, X. Cai, P.M. Reed, E.A. Zagona, A. Ostfeld, J. Hall, G.W. Characklis, W. Yu, L. Brekke, The future of water resources systems analysis: toward a scientific framework for sustainable water management, Water Resour. Res. 51 (8) (2015) 6110–6124.

[10] A. Bruce, P. Avello, G. Beane, L. Ellis, M. Fletcher, S. St George Freeman, A. Jimenez, J. Leten, N. Matthews, O. Romano, I. Ruiz-Apilanez, P. Saikia, M. Shouler, P. Simkins, C. Brown, The human dimensions of urban water resilience: perspectives from Cape Town, Mexico City, Miami and Hull, Water Security, In review.

[11] S. Carpenter, K. Arrow, S. Barrett, R. Biggs, W. Brock, A.S. Crépin, G. Engström, C. Folke, T. Hughes, N. Kautsky, C.Z. Li, General resilience to cope with extreme events, Sustainability 4 (12) (2012) 3248–3259.

[12] S. Carpenter, E. Bennett, G. Peterson, Special feature on scenarios for ecosystem services, Ecol. Soc. 11 (2) (2006).

[13] S.R. Carpenter, J.J. Cole, M.L. Pace, R. Batt, W.A. Brock, T. Cline, J. Coloso, J.R. Hodgson, J.F. Kitchell, D.A. Seekell, L. Smith, Early warnings of regime shifts: a whole ecosystem experiment, Science 332 (6033) (2011) 1079–1082.

[14] S. Carpenter, C. Folke, M. Scheffer, F. Westley, Dancing on the volcano: social exploration in times of discontent, Ecol. Soc. 24 (1) (2019).

[15] M. Falkenmark, Global water issues confronting humanity, J. Peace Res. 27 (2) (1990) 177–190.

[16] M. Falkenmark, L. Wang-Erlandsson, J. Rockström, Understanding of water resilience in the anthropocene, J. Hydrol. X 2 (2019) 100009.

[17] G. Feola, Societal transformation in response to global environmental change: a review of emerging concepts, Ambio 44 (5) (2015) 376–390.

[18] M.B. Fiering, C.S. Holling, Management and standards for perturbed ecosystems, Agro-Ecosyst. 1 (1974) 301–321.

[19] C. Folke, Resilience: the emergence of a perspective for social–ecological systems analyses, Global Environ. Change 16 (3) (2006) 253–267.

[20] C. Folke, Resilience (republished), Ecol. Soc. 21 (4) (2016).

[21] C. Folke, S. Carpenter, B. Walker, M. Scheffer, T. Chapin, J. Rockström, Resilience thinking: integrating resilience, adaptability and transformability, Ecol. Soc. 15 (2010) (4).

[22] S. St. George Freeman, C. Brown, H. Cañada, V. Martinez, A. Palma, P. Ray, D. Rodriguez, A. Romo, J. Tracy, E. Vázquez, S. Wi, F. Boltz, Resilience by design in Mexico City: a participatory human-hydrologic systems approach, Water Security (2019) In press.

[23] L.J. Gordon, G.D. Peterson, E.M. Bennett, Agricultural modifications of hydrological flows create ecological surprises, Trends Ecol. Evol. 23 (4) (2008) 211–219.

[24] Z.J. Grabowski, A.M. Matsler, C. Thiel, L. McPhillips, R. Hum, A. Bradshaw, T. Miller, C. Redman, Infrastructures as socio-eco-technical systems: five considerations for interdisciplinary dialogue, J. Infrastruct. Syst. 23 (4) (2017) 2517002.

[25] G. Grill, B. Lehner, M. Thieme, B. Geenen, D. Tickner, F. Antonelli, S. Babu, P. Borrelli, L. Cheng, H. Crochetiere, H.E. Macedo, Mapping the world's free-flowing rivers, Nature 569 (7755) (2019) 215.

[26] J.W. Hall, E. Borgomeo, A. Bruce, M. di Mauro, M. Mortazavi-Naeini, Resilience of water resource systems: lessons from England, Water Security (2019) In press.

[27] P.A. Hall, M. Lamont (Eds.), Social Resilience in the Neoliberal Era, Cambridge University Press, 2013.

[28] S. Hallegatte, A. Shah, R. Lempert, C. Brown, S. Gill, Investment Decision Making Under Deep Uncertainty-application to Climate Change, The World Bank, 2012.

[29] T. Hashimoto, J.R. Stedinger, D.P. Loucks, Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation, Water Resour. Res. 18 (1) (1982) 14–20.

[30] D. Henry, J.E. Ramirez-Marquez, Generic metrics and quantitative approaches for system resilience as a function of time, Reliab. Eng. Syst. Saf. 99 (2012) 114–122.

[31] J.K. Hiers, S.T. Jackson, R.J. Hobbs, E.S. Bernhardt, L.E. Valentine, The precision problem in conservation and restoration, Trends Ecol. Evol. 31 (11) (2016) 820–830.

[32] C.S. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. Syst. 4 (1) (1973) 1–23.

[33] C.S. Holling, Engineering resilience versus ecological resilience, Eng. Ecol. Constr. 31 (1996) (1996) 32.

[34] T. Homer-Dixon, B. Walker, R. Biggs, A.S. Crépin, C. Folke, E.F. Lambin, G. Peterson, J. Rockström, M. Scheffer, W. Steffen, M. Troell, Synchronous failure: the emerging causal architecture of global crisis, 2015.

[35] R.D. Horan, E.P. Fenichel, K.L.S. Drury, D.M. Lodge, Managing ecological thresholds in coupled environmental-human systems, PNAS 108 (2011) 7333–7338.

[36] P.W. Keys, M. Porkka, L. Wang-Erlandsson, I. Fetzer, T. Gleeson, L.J. Gordon, Invisible water security: moisture recycling and water resilience, Water Security (2019).

[37] H.F. Khan, Y.C. Yang, H. Xie, C. Ringler, A coupled modeling framework for sustainable watershed management in transboundary river basins, Hydrol. Earth Syst. Sci. 21 (12) (2017) 6275–6288.

[38] E.H. Krueger, D. Borchardt, J.W. Jawitz, H. Klammler, S. Yang, J. Zischg, P.S.C. Rao, Resilience dynamics of urban water supply security and potential of tipping points, Earth's Future (2019) 1029/2019EF001306.

[39] B. Lehner, C.R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Front. Ecol. Environ. 9 (9) (2011) 494–502.

[40] I. Linkov, D.A. Eisenberg, M.E. Bates, D. Chang, M. Convertino, J.H. Allen, S.E. Flynn, T.P. Seager, Measurable resilience for actionable policy, Environ. Sci. Technol. (2013) 2013471810108 10110.

[41] J. Linton, J. Budds, The hydrosocial cycle: defining and mobilizing a relational-dialectical approach to water, Geoforum 57 (2014) 170–180.

[42] F. Mao, J. Clark, T. Karpouzoglou, A. Dewulf, W. Buytaert, D. Hannah, HESS opinions: a conceptual framework for assessing socio-hydrological resilience under change, Hydrol. Earth Syst. Sci. 21 (7) (2017) 3655–3670.

[43] S.A. Markolf, M.V. Chester, D.A. Eisenberg, D.M. Iwaniec, C.I. Davidson, R. Zimmerman, T.R. Miller, B.L. Ruddell, H. Chang, Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience, Earth's Future 6 (12) (2018) 1638–1659.

[44] T. Grantham, J.H. Matthews, B.P. Bledsoe, Shifting currents: Managing freshwater systems for ecological resilience in a changing climate, Water Security (2019) In press.

[45] M. Meybeck, Global analysis of river systems: from Earth system controls to Anthropocene syndromes, Philos. Trans. R. Soc. London Ser. B: Biol. Sci. 358 (2003) 1935–1955.

[46] Millennium Ecosystem Assessment, M.E.A., 2005. Ecosystems and human well-being. Synthesis.

[47] C. Nilsson, C.A. Reidy, M. Dynesius, C. Revenga, Fragmentation and flow regulation of the world's large river systems, Science 308 (5720) (2005) 405–408.

[48] D. O'Connell, B. Walker, N. Abel, N. Grigg, The resilience, adaptation and transformation assessment framework: from theory to application, GEN (2015).

[49] P. Olsson, L. Gunderson, S. Carpenter, P. Ryan, L. Lebel, C. Folke, C.S. Holling, Shooting the rapids: navigating transitions to adaptive governance of social-ecological systems, Ecol. Soc. (1) (2006) 11.

[50] E. Ostrom, A general framework for analyzing sustainability of social-ecological systems, Science 325 (5939) (2009) 419–422.

[51] M.A. Palmer, J. Liu, J.H. Matthews, M. Mumba, P. D'Odorico, Manage water in a green way, Science 349 (6248) (2015) 584–585.

[52] R. Pant, K. Barker, J.E. Ramirez-Marquez, C.M. Rocco, Stochastic measures of resilience and their application to container terminals, Comput. Ind. Eng. 70 (2014) 183–194.

[53] J. Park, P.S.C. Rao, Regime shifts under forcing of non-stationary attractors: conceptual model and case studies in hydrologic systems, J. Contam. Hydrol. 169 (2014) 112–122.

[54] S.E. Park, N.A. Marshall, E. Jakku, A.M. Dowd, S.M. Howden, E. Mendham, A. Fleming, Informing adaptation responses to climate change through theories of transformation, Global Environ. Change 22 (1) (2012) 115–126.

[55] N.L. Poff, Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world, Freshw. Biol. 63 (8) (2018) 1011–1021.

[56] N.L. Poff, J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, J.C. Stromberg, The natural flow regime, Bioscience 47 (11) (1997) 769–784.

[57] N.L. Poff, C.M. Brown, T.E. Grantham, J.H. Matthews, M.A. Palmer, C.M. Spence, R.L. Wilby, M. Haasnoot, G.F. Mendoza, K.C. Dominique, A. Baeza, Sustainable water management under future uncertainty with eco-engineering decision scaling, Nat. Clim. Change 6 (1) (2016) 25.

[58] J. Rockström, M. Falkenmark, T. Allan, C. Folke, L. Gordon, A. Jägerskog, M. Kummu, M. Lannerstad, M. Meybeck, D. Molden, S. Postel, The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability, Ecohydrology 7 (5) (2014) 1249–1261.

[59] J. Rockström, M. Falkenmark, C. Folke, M. Lannerstad, J. Barron, E. Enfors, L. Gordon, J. Heinke, H. Hoff, C. Pahl-Wostl, Water Resilience for Human Prosperity, Cambridge University Press, 2014.

[60] J. Rockström, W. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, A safe operating space for humanity, Nature 461 (7263) (2009) 472.

[61] C.W. Sadoff, M. Muller, Better water resources management: greater resilience today. More effective adaptation tomorrow, GWP TEC Perspectives Paper. Global Water Partnership, Stockholm, (2009).

[62] M. Scheffer, S.H. Hosper, M.L. Meijer, B. Moss, E. Jeppesen, Alternative equilibria in shallow lakes, Trends Ecol. Evol. 8 (8) (1993) 275–279.

[63] D.E. Schindler, R. Hilborn, Prediction, precaution, and policy under global change, Science 347 (6225) (2015) 953–954.

[64] S.P. Simonovic, R. Arunkumar, Comparison of static and dynamic resilience for a multipurpose reservoir operation, Water Resour. Res. 52 (11) (2016) 8630–8649.

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

[66] W. Steffen, K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. De Vries, C.A. De Wit, C. Folke, Planetary boundaries: guiding human development on a changing planet, Science 347 (6223) (2015) 1259855.

[67] W. Steffen, J. Rockström, K. Richardson, T.M. Lenton, C. Folke, D. Liverman, C.P. Summerhayes, A.D. Barnosky, S.E. Cornell, M. Crucifix, J.F. Donges, Trajectories of the earth system in the anthropocene, Proc. Natl. Acad. Sci. 115 (33) (2018) 8252–8259.

[68] S. Steinschneider, R. McCrary, L.O. Mearns, C.M. Brown, The effects of climate model similarity on probabilistic climate projections and the implications for local, risk-based adaptation planning, Geophys. Res. Lett. 42 (12) (2015) 5014–5044.

[69] R.J. Swart, P. Raskin, J. Robinson, The problem of the future: sustainability science and scenario analysis, Global Environ. Change 14 (2) (2004) 137–146.

[70] K.E. Trenberth, Changes in precipitation with climate change, Climate Res. 47 (1–2) (2011) 123–138.

[71] K.E. Trenberth, P.D. Jones, P. Ambenje, R.D. Bojariu, A. Easterling, P. Zhai, Observations: surface and atmospheric climate change, in: S. Solomon, D. Qin, M. Manning, Z. Chen (Eds.), Climate Change 2007. The Physical Science Basis. Intergovernmental Panel on Climate Change 4th Assessment Report, Cambridge University Press, Cambridge, 2007, pp. 235–336.

[72] J. Tront, A. Lohani, A. Tanabe, W. Rex, Cooperation for climate resilience in Africa, Water Security, In review.

[73] United Nations, Transforming our world: The 2030 agenda for sustainable development. Resolution adopted by the General Assembly, 2015.

[74] K. Van Looy, J.D. Tonkin, M. Floury, C. Leigh, J. Soininen, S. Larsen, J. Heino, N.L. Poff, M. Delong, S.C. Jähnig, T. Datry, N. Bonada, J. Rosebery, A. Jamoneau, S.J. Ormerod, K. Collier, C. Wolter, The three Rs of river resilience: resources, recruitment and refugia, River Res. Appl. 35 (2019) 107–120.

[75] N. Voisin, V. Tidwell, M. Kintner-Meyer, F. Boltz, Planning for sustained water-electricity resilience over the US: persistence of current water-electricity operations and long-term transformative plans, Water Security 7 (2019) 100035.

[76] C.J. Vörösmarty, D. Lettenmaier, C. Leveque, M. Meybeck, C. Pahl-Wostl, J. Alcamo, W. Cosgrove, H. Grassl, H. Hoff, P. Kabat, F. Lansigan, R. Lawford, R. Naiman, Humans transforming the global water system, Eos 85 (48) (2004) 509–520.

[77] C.J. Vörösmarty, P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, P.M. Davies, Global threats to human water security and river biodiversity, Nature 467 (7315) (2010) 555.

[78] C.J. Vörösmarty, M. Meybeck, B. Fekete, K. Sharma, P. Green, J.P. Syvitski, Anthropogenic sediment retention: major global impact from registered river impoundments, Global Planet. Change 39 (1–2) (2003) 169–190.

[79] Y. Wada, L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens, Global depletion of groundwater resources, Geophys. Res. Lett. 37 (2010) 1–5.

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

[81] B. Walker, C.S. Holling, S. Carpenter, A. Kinzig, Resilience, adaptability and transformability in social–ecological systems, Ecol. Soc. 9 (2) (2004).

[82] W.D. Welsh, J. Vaze, D. Dutta, D. Rassam, J.M. Rahman, I.D. Jolly, P. Wallbrink, G.M. Podger, M. Bethune, M.J. Hardy, J. Teng, An integrated modelling framework for regulated river systems, Environ. Modell. Software 39 (2013) 81–102.

[83] D. Worster, Rivers of Empire: Water, Aridity, and the Growth of the American West, Oxford University Press, USA, 1992.

[84] G. Zhao, H. Gao, B.S. Naz, S.C. Kao, N. Voisin, Integrating a reservoir regulation scheme into a spatially distributed hydrological model, Adv. Water Resour. 98 (2016) 16–31.

[85] F. Berkes, C. Folke (Eds.), Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience, Cambridge University Press, 1998.

[86] N.A. Marshall, S.E. Park, W.N. Adger, K. Brown, S.M. Howden, Transformational capacity and the influence of place and identity, Environ. Res. Lett. 7 (3) (2012) 34022.

[87] S. Levin, T. Xepapadeas, A.-S. Crépin, J. Norberg, A. de Zeeuw, C. Folke, T.P. Hughes, K. Arrow, S. Barrett, G. Daily, P. Ehrlich, N. Kautsky, K.-G. Mäler, S. Polasky, M. Troell, J. Vincent, B.H. Walker, Social-ecological systems as complex adaptive systems: modeling and policy implications, Environ. Dev. Econ. 18 (2013) 111–132.