Conceptualizing Cascading Effects of Resilience in Human–Water Systems

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Introduction

Resilience was introduced to ecological research by C. S. Holling in the 1970s (Holling, 1973). Originally, the concept of resilience described the properties of an ecological system and its ability to withstand or recover from severe disturbance. This concept has had a substantial impact within ecology while also experiencing exponential growth in academic fields ranging from psychology and engineering to social sciences and interdisciplinary domains (Xu, Marinova, & Guo, 2015a). Resilience theory opens up new ways of thinking about how a system shifts from one stable state to another by investigating dynamics between thresholds of variables (how much stress they can tolerate before they must change) and external disturbances. Despite this, measuring resilience is challenging due to the complex system dynamics characterized by multiple interactions of system components both within and across scales over time and space (Quinlan, Berbés-Blázquez, Haider, & Peterson, 2016). Systemic interactions are even more complicated when social dimensions are involved in natural processes, exemplified by domains of social-ecological and socio-hydrological systems. An investigation of resilience thus requires a systematic perspective looking at not only resilience of the system of interest, but also its potential to affect the resilience of interconnected systems, which is referred to as "systemic resilience" (Ungar, 2018).

A number of questions become important when systemic thinking about resilience is applied to interconnected systems, such as cascading effects of resilience across systems. Cascading effects can be defined as the effects on one system that are generated by initial

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events or factors and that propagate to other systems due to the existence of interdependencies and cause-effect relationships between systems and their components (Pescaroli & Alexander, 2016). Several early studies in ecology have demonstrated clearly the existence of cascading effects in many ecological systems (see Schmitz, Hambäck, & Beckerman, 2000), and such cascading mechanisms can also occur in the connected ecological and socioeconomic systems because of threshold interactions (Kinzig et al., 2006). In systems, cascading effects could exist among thresholds, meaning that the tendency of crossing thresholds to induce the crossing of other thresholds, which could lead to changes in system states (Kinzig et al., 2006). Based on their previous syntheses, Rocha, Peterson, Bodin, and Levin (2018), for example, identified 30 types of regime shifts in social-ecological systems and found the importance of cross-scale interactions in determininig different regimes of systems. They suggested that the key for the sustainable management of future environmental change be better understanding of connections between human and natural systems.

Human actions exert pressures on water systems, while also being influenced by the changes of hydrological regimes. In examining such human and water coupled systems, there is a need to discover whether and how cascading effects occur in social and hydrological systems (i.e., how do shifts in one system's regime result in regime shifts in another?). Exploring answers to this question can help to identify ways to avoid undesirable regime shifts of systems and to reduce what may be called "systemic risks." Systemic risk describes an adverse risk to a component of a system, with the potential of spreading throughout the connected and coupled socio-hydrological system (Renn, 2016). In an extreme case, this could lead to the breakdown of the whole socio-hydrological system. In this chapter, we explore the mechanisms that explain cascading effects in coupled socio-hydrological systems and what they mean for interactions between people and water. In doing so, we propose a conceptual framework to explain how changes in resilience of any ecological system may generate cascading effects on its interconnected systems, both human and ecological. We use a case study of an agricultural drainage basin in the Canadian Prairies where extensive wetland drainage has occurred to exemplify resilience in socio-hydrological systems that are challenged by human activity and resulting climate change.

Human–Water Coupled System

While water systems are broader in definition, the hydrological system is critical for water systems as it provides essential functions to support water systems and the associated ecosystem services. In this chapter, we examine human–water relations by emphasizing the interaction between social and hydrological systems. Human and water systems are interconnected in the whole hydrological cycle (Figure 1a). The interplay between the two systems represents as two-way feedback loops that integrate both social and hydrological components and processes (Figure 1b). However, the conventional way hydrology treats humans as exogenous factors, or drivers to hydrological dynamics, overlooks contributions from the social sciences that focus on social processes and the hydrological variations that occur when water systems are exposed to exogenous constraints. The traditional research hypotheses are no longer appropriate for understanding the water cycle, in that water systems confront a myriad of threats, changes, and uncertainties brought about by anthropogenic disturbances (Wada et al., 2017). When examining water problems, Sivapalan, Savenije, and Blöschl (2012) have called for research to focus on the interface between water and social systems at the same time.

Increasing evidence has pointed to regime shifts of diverse water systems due to processes at various scales, from microscopic natural forces to macroscopic socioeconomic processes. For example, global changes in patterns of water availability, due to anthropogenic climate change and other human activities such as groundwater pumping (Rodell, Velicogna, & Famiglietti, 2009; Thomas & Famiglietti, 2019); hypoxia environments in coastal water systems, caused by excessive nutrient inputs from fertilizers or untreated sewage (Conley et al., 2009); river channel position, modified by land clearance and artificial channel widening (Knox, 2006); and the shift in freshwater lakes from clean water state to murky water state, as a result of long-term eutrophication (Carpenter, Ludwig, & Brock, 1999).

In turn, changes in hydrologic conditions (either in quantity, quality, or both) of water systems have had significant impacts on society at a number of scales. Globally, the overexploitation of groundwater has decreased the resilience of depleted regions in the face of drought events (Rodell et al., 2018). Regionally, increased water extraction has become a major force leading to changed flow regimes and groundwater levels, and therefore the increased risk of seawater intrusion and water insecurity. These patterns have been well-studied, notably in coastal regions of Australia. While data are sparse due to difficulty in monitoring, a national assessment of coastal aquifers has estimated that 47% of coastal areas in Australia had high vulnerability to seawater intrusion, and this figure is expected to increase to 57% in the future (Commonwealth of Australia, 2011). In Canada, land-use change and agricultural drainage of surface depressional storage on the Prairies have led to the dramatic loss of wetlands and increased flood risk downstream in many basins (Pomeroy et al., 2014). It is thus essential to understand how humans affect, and are affected by, water in a co-evolutionary systematic perspective (Sivapalan et al., 2012; Wada et al., 2017) with wide interdisciplinary collaboration needed to investigate more synthetic topics such as sustainability and resilience (Xu, Gober, Wheater, & Kajikawa, 2018).

Defining Resilience in the Coupled Human–Water Context

The concept of resilience is abstract, which makes it challenging to define and measure when it is fused to human–water systems because of ambiguous system boundaries. While interpretations of resilience can be diverse in different research fields (see Meerow, Newell, & Stults, 2016; Xu et al., 2015a; also see chapters in this volume), most of these definitions share principles and features that can be integrated for a clearer application to different contexts (Biggs, Schlüter, & Schoon, 2015; Brown, 2016; Ungar, 2018; Xu & Kajikawa, 2018). For example, definitions of resilience are always related to the capacity of a system to retain specific functions in the face of disturbance and change.

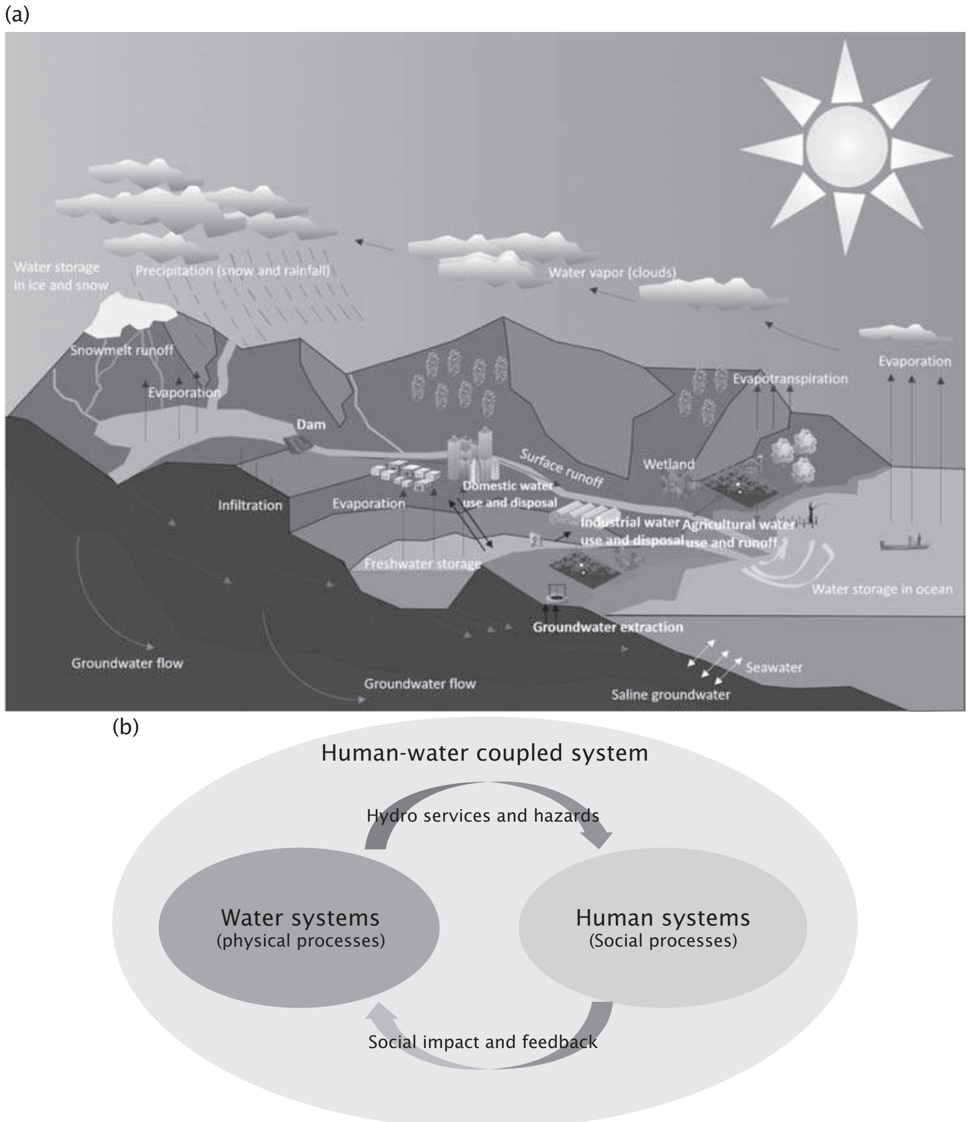

FIGURE 38.1 (a) Social and hydrologic processes in the hydrological cycle. (b) The interplay between human and water systems. *Notes*: Authors' own drawings. The Figure 38.1a was modified from the base diagram in Wikimedia for Water Cycle (https://commons.wikimedia.org/wiki/File:Water_cycle_blank.svg) under the GNU Free Documentation License. It illustrates the hydrological cycle in which some human activities are included and marked in red color.

The flexible interpretation of resilience has made the concept widely applicable to the study of the feedback between human and natural systems (e.g., social-ecological systems; Walker, Holling, Carpenter, & Kinzig, 2004). In a similar vein, resilience in socio-hydrological systems has been linked to stochastic hydrological events such as drought and flood and the ability of communities, either on their own or collectively, to adapt to and recover from these events (Ciullo, Viglione, Castellarin, Crisci, & Di Baldassarre, 2017; Yu, Sangwan, Sung, Chen, & Merwade, 2017). From a social science point of view, resilience in socio-hydrological systems is defined as the capacity of social systems—including broad social processes such as governance, institutions and policy-making—to convert public perceptions into collective action in adapting to flood and other water-related events (Gober & Wheater, 2015). This definition highlights the role of public awareness and its translation into social behaviors to improve human adaptations to environmental changes. It is inclusive of broader management structures and practices to explain even more complex social decision-making processes and their feedback to water systems when modeling socio-hydrological processes that contribute to resilience (Konar, Garcia, Sanderson, Yu, & Sivapalan, 2019; Xu et al., 2018). To understand and demonstrate the cascading effect of resilience in the coupled human–water context, in this chapter we describe three framings of resilience in socio-hydrological couplings, following the systematic perspective proposed in Mao et al. (2017) as (a) social resilience to hydrological change; (b) hydrological resilience to social (human) perturbations; and (c) socio-hydrological resilience dealing with bidirectional feedback between human and water systems in the face of disturbance and adversity.

Social Resilience to Hydrological Change

Social resilience to hydrological change is defined as the ability of individuals and communities to adapt to changed hydrological conditions or to deal with social, political, and cultural changes resulting from the alteration of hydrologic regimes, such as flow rates, volume, and the level and quality of water in rivers and lakes. Social resilience is an important feature that determines the ability of society to live with hydrological change, in particular for those communities and groups whose activities are highly reliant on water resources. Hence, social resilience to hydrological change depends on the structure and other characteristics of social institutions that govern society, including social memory, learning ability, networks, and social rules and norms.

To illustrate, people residing in flood-prone areas with flood protection infrastructure may be resilient to nonextreme flood events but may have less resilience to heavy precipitation events than those without levee protection. In some cases, communities exposed to occasional flood events could exhibit more resilience for a longer time period because they share a collective memory from previous flood events and have more experiences in adapting to flooding than those who have been protected from such events (Yu et al., 2017).

Hydrological Resilience to Social Perturbations

Hydrological resilience to social perturbations refers to the capacity of hydrological systems to absorb disturbances from human activities without losing their functions in both quantity and quality to safeguard the needs for attendant ecosystem services and human well-being. The hydrological system is a system of interconnected components involved in the natural processes of precipitation, transpiration, infiltration and flows, and infrastructure that support the management of the system. Human-created systems such as levees, dams, river canals, and irrigation ditches have significantly affected hydrologic processes and the storage of freshwater due to the reallocation of water resources in time and space. These human activities substantially disturb hydrological functions and have the potential to push water systems toward a tipping point that leads to fundamental shifts in system feedback (Dumanski, Pomeroy, & Westbrook, 2015; Falkenmark, Wang-Erlandsson, & Rockström, 2019; Famiglietti et al., 2011; Harder, Pomeroy, & Westbrook, 2015; Rocha et al., 2018; Rodell et al., 2018). As a result, losing resilience in hydrological systems will affect hydrological functions for ecosystems services that are critical to human welfare, which further result in the loss of resilience in joint social and economic systems.

Socio-Hydrological Resilience

Fusing resilience into a coupled human–water context is challenging but has become especially urgent in the era of the Anthropocene where human and water systems need to cope with disturbances from each other (Falkenmark et al., 2019). There is growing evidence that the bidirectional feedback between human and water systems worldwide results in interrelated regime shifts in social-ecological systems related to water (Rocha et al., 2018). However, when and how changes in resilience of either human or water systems react positively or negatively to another is not straightforward.

As an attempt, Mao et al. (2017) developed a conceptual framework to explain socio-hydrological resilience and argued that resilience of socio-hydrological systems could be derived from human and water interactions. Building upon their proposal, we define socio-hydrological resilience as the ability of socio-hydrological systems to maintain the feedback that keeps both human and water systems in a desired state during socio-hydrological (people and water) interactions. In such a coupled system, resilience refers to the system's ability to deal with not only external hazards resulting from environmental change but also the internal perturbations caused by the interactions of human and hydrological systems, such as competing demands for water. For instance, maintaining the complete hydrological function of a river may require a dramatic decrease in water uses in the whole basin, but it would be a significant sacrifice for many water sectors. Therefore, one critical mission to achieve a resilient socio-hydrological system is to deal with conflicts and trade-offs among individuals whose interests and preferences vary. Water governance and policy could play an important role in solving these challenges as they help to integrate management of water resources and safeguard provisions of water services at multiple levels of society to direct the resource toward a desirable state (Pahl-Wostl, 2015). However, what state can be desirable for different societal parties requires negotiation and needs to rely on wider interdisciplinary and transdisciplinary approaches engaging various stakeholders at different levels.

Systematic Understanding of Socio-Hydrological Resilience

Resilience theory offers a systematic thinking of the bifurcation of systems' stable states controlled by a critical threshold (tipping point) at which a system's state can be easily shifted to a new stability domain or a contrasting regime, or even collapse, through its self-reinforcing mechanisms or by external shocks (Scheffer et al., 2009). One example of system collapse is when high nutrient loads to freshwater lakes lead to algal blooms. The enhanced nutrient status of lakes makes them vulnerable to eutrophication, particularly in combination with warm weather, resulting in algal blooms and their concurrent social and economic problems, with implications for drinking water and human and environmental health. Understanding why and when such regime shifts occur is not straightforward because the causal mechanisms can be varied and occur at different scales. They are also sometimes hidden as most systems do not exist alone but intimately connect and interact with others (Rocha et al., 2018). This requires exploring the dynamic mechanisms that affect resilience of a system and its synergistic effects on the resilience of interrelated systems.

Systemic Resilience

Loss of resilience in a system has the potential to erode the resilience of related systems, which would increase the likelihood of regime shifts of systems and the risk of system collapse. However, this is not always the case for all systems. Even perceived positive aspects of resilience of one system may have a negative impact on the resilience of interconnected systems in different temporal and spatial scales, especially those systems that are inherently nonlinear in nature, such as ecosystems and coupled human-natural systems. This is due to the fact that the interactions between system components are complicated by a hysteresis effect on system states (Levin et al., 2013). There exist trade-offs between systems' resilience, such as resilience in the short term versus resilience in the long term, and resilience in one place versus resilience in another.

The "levee effect" phenomenon is a good example of this pattern (Di Baldassarre et al., 2013). Floodplain areas have many benefits to human well-being, such as the fertilized soil condition for farming. However, the population and development plans for these areas have to remain a safe distance from rivers where there is high flood risk. Since the construction of levees, the "safe" distance is shortened. Although engineering has increased the resilience of hydrological systems to flood events, the increasing disturbances of slow variables including human-induced interference in water processes and climate-related hydrological change could decrease social resilience in the long-term in the face of catastrophic events such as extreme flooding and bank breach. In another situation, the increase in the height of a levee on one side of a river can enhance resilience of local population but might jeopardize resilience of communities on the other bank. Accordingly, exploring the patterns of resilience across systems and scales becomes a necessary part of any study of socio-hydrological systems.

Changing Patterns of Socio-Hydrological Resilience

Resilience is a dynamic process, rather than a static trait of a system. These processes account for a system's changing behaviors (i.e., adaptation, recovery, resistance, persistence, transformation, and absorption) in response to disturbances. Previous studies have defined three system behaviors that can critically determine the resilience of a system: absorbability, adaptability and transformability (Béné, Wood, Newsham, & Davies, 2012; Organisation for Economic Co-operation and Development, 2014; Mao et al., 2017). In other words, a resilient system must be embodied with these three capacities. Other studies demonstrated that these system behaviors and capacities are affected by the performance of common characteristics represented as redundancy, diversity, connectivity, flexibility, and participation in system's components and elements (Ungar, 2018; Xu & Kajikawa, 2018). This is because these system characteristics can be attributed to the system's ability to resist and persist in the presence of a disturbance, its capacity to recover to its predisturbed state, and the ability to adjust and transition to a new desirable state after the disturbance.

More specifically, absorbability requires the system be persistent in a relatively stable state when disturbance or shock happens. Adaptability means the system should be flexible in structure and be redundant and diverse in function, which allows the system to adjust in the face of changes. Transformability enables the system to create a fundamentally new system by introducing new components and features, which means that the system is flexible when required to change (Walker et al. 2004). Social (human) and hydrological (water) systems are evolving simultaneously in dynamic ways through time and space; their resilience results from interactions between social and hydrological systems, which is described as a resilience "canvas" or "cube" in Mao et al. (2017) and Karpouzoglou and Mao (2018) (Figure 38.2a).

In Figure 38.2b, the resilience of human–water systems is defined by social resilience, hydrological resilience, as well as the integrated socio-hydrological resilience. In state A, both social and hydrological resilience are undesirably low. In this state, due to the differences in environmental conditions such as stream morphology and heterogeneous climate, the hydrological system is susceptible to anthropogenic disturbances. Meanwhile, concurrent social systems have difficulty dealing with changes in hydrological conditions because of a lack of resources. For instance, the Three Gorges Dam in China has caused the instability of flow regimes along the Yangtze River and the intensification of wet and dry conditions in its adjacent lakes and downstream ecosystem services (Fu et al., 2010). The altered flow regimes have made communities at the inlet and outlet regions of the lakes less resilient to both excessively wet and dry conditions (Xu, Marinova, & Guo, 2015b). When a system is locked in this state, management interventions are usually taken to achieve state C where both hydrological and social systems are highly resilient. However, mismanagement (e.g., management that only aims to improve either hydrological or social capacities) may lead the system to state B where there is high resilience in societal systems but low resilience in hydrological systems (B_1) or high hydrological resilience but low social resilience (B_2). In other words, improving hydrological resilience may be achieved at the expense of social resilience, or the other way around. Typically, this pattern is known as upstream–downstream trade-offs at the catchment scale (Savenije, Hoekstra, & van der Zaag, 2014). For example, the development of hydropower and irrigation systems upstream may increase the resilience of upstream regions to impacts of droughts but affects water allocation in the entire basin reducing the resilience of downstream farming systems.

We are now beginning to observe some of the emerging trends in water systems and the evidence of feedback loops between water and human systems that are important for planetary health and human well-being. Understanding what drivers trigger these changes and the interactions between drivers and variables that control a system's state is one of the most important challenges for building multisystemic resilience and ways to manage it. In this chapter, we propose that cascading analysis and ecosystem services can be the critical lens to link human and water systems and serve as the vehicle for investigating synergistic impacts

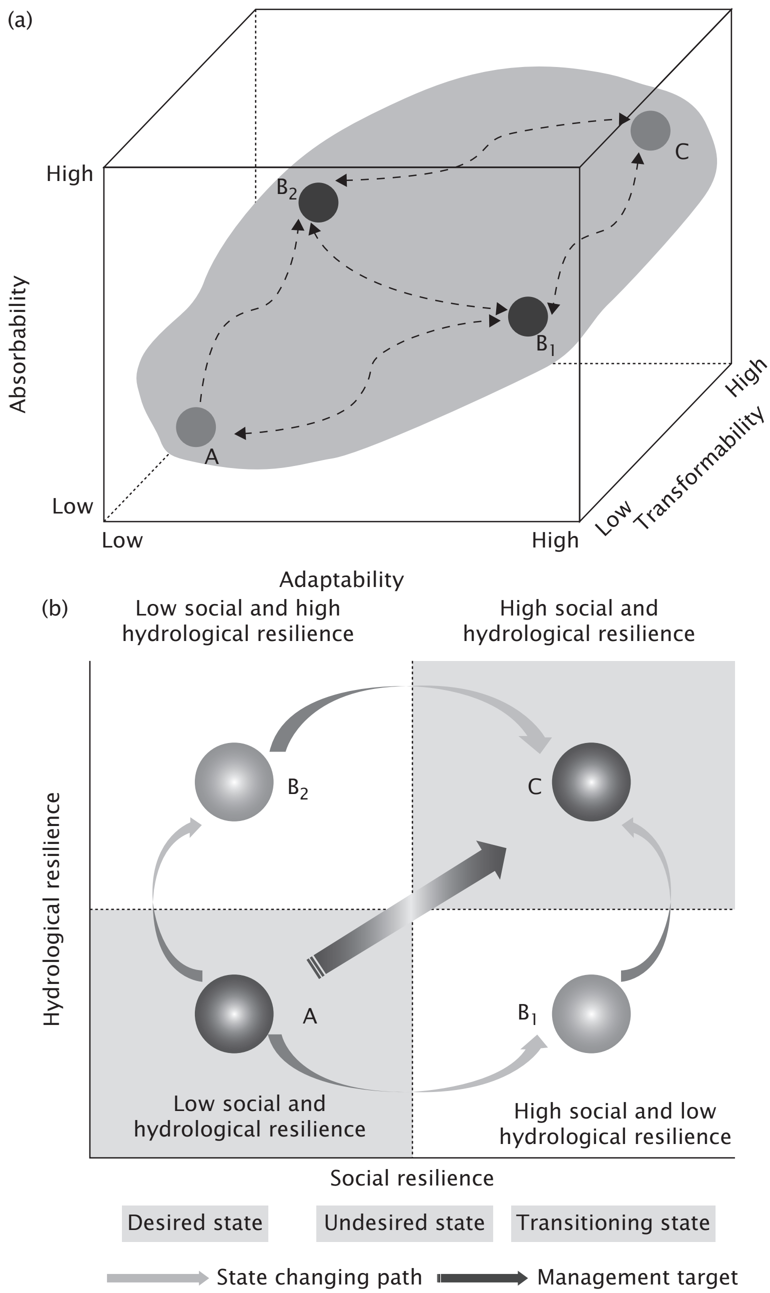

FIGURE 38.2 (a) Resilience in socio-hydrological systems and its transition between different states. (b) Resilience in human–water systems and its transition between different states. *Notes*: Authors' own figures. Figure 38.2a was modified from Karpouzoglou and Mao (2018).

of resilience across systemic levels. In the next section, we propose a conceptual framework to guide our understanding of the internal and interactive dynamics of human–water systems and the cascading effects of resilience across different system levels.

Cascading Effects in Socio-Hydrological Resilience

Cascading effects can take place once an impact on the system exceeds the system's boundary (a threshold) causing spillover effects on regimes of other interdependent systems. Likewise, changes in features of resilience of one system can increase the risk of crossing such a threshold, which can cause regime shifts of the system under shock and then alter the resilience of connected systems and their regime shifts at other spatial or temporal scales. In this chapter, we reveal that cascading effects in human–water systems could happen in three contexts. First, *cascading within the system*, meaning the synergistic impacts between components or features within the system that leads to changes in resilience itself, and then to the changes in the resilience of another through interacting dynamics of system components. Second, *cascading across systems*, meaning the effects from hydrological systems to social systems, or from social systems to hydrological systems. Third, *cascading across scales*, meaning that effects can spill over or propagate from one system to another at different temporal and spatial scales.

Cascading Effects Within the System

A system can be composed of several core subsystems (Ostrom, 2009). Each subsystem demonstrates resilience if its components help the system to deal with disturbances. The cascading effects within a system means that changes in the features of one of the subsystem's components would affect features of other components within the same system, which further affect the resilience of each interdependent subsystem. In this way, the resilience of a system is determined by the system's capacity of absorption, adaptation, and transformation, which are affected by the combined features of the diversity, redundancy, flexibility, connectivity, and openness of the system's component parts. The system is in the safe operation space if its structure and function are maintained by the combination of these features at a certain level. In turn, if the system is resilient with absorbability, adaptability, and transformability, it can nurture the features of system components to withstand disturbances. However, if this level is surpassed because of an external disturbance and internal dynamics, then the system loses its resilience making critical transition of the system state (Figure 38.3).

Water systems can be generally classified into three subsystems: surface/near-surface water, groundwater, and atmospheric water. Water moves among these subsystems through the workings of the hydrological cycle. Human systems, meanwhile, include three subsystems—production, community, and governance—which are related to water utilization. Within each subsystem, resilience is embodied with features and capacities that allow the system to avoid regime shifts. Prior to crossing the threshold, a system's state changes because of synergistic impacts between a system's features and capacities. Yet, the incremental perturbations

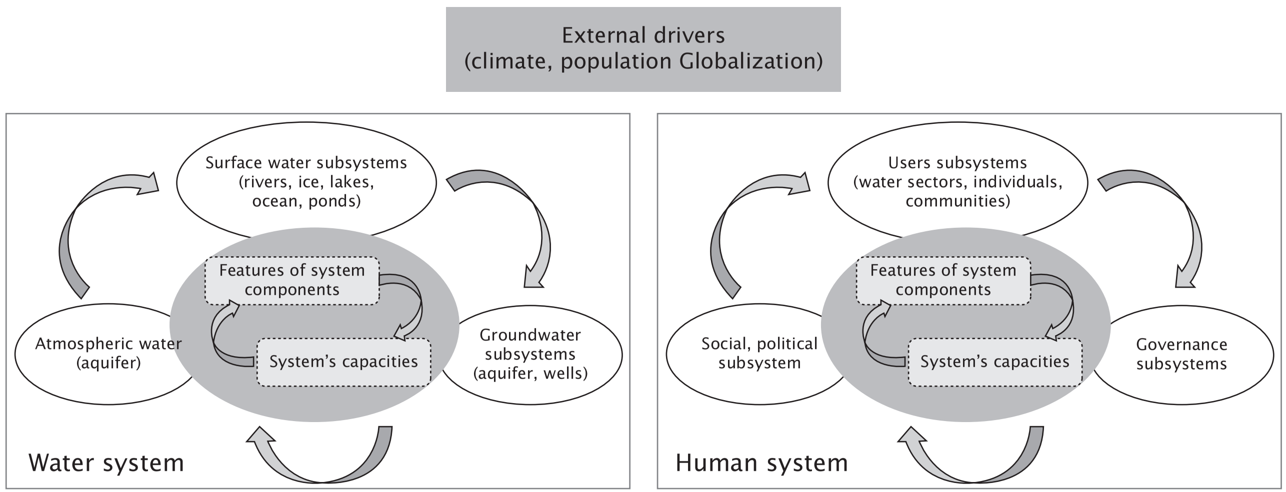

FIGURE 38.3 Cascading effects within the system. *Notes*: Authors' own figure.

(slow variables) to the subsystems can change the features of system components, affecting their capacities to withstand shocks (fast variables). Prior to a threshold being surpassed, there is strong positive feedback that maintains the system in a stable state. During the process, slow variables affect the absorptive capacity of systems while fast variables change the state of the system. Both types of variables have different impacts on a system's resilience. For example, a resilient river basin with sufficient flows of surface water can contribute to more resilient groundwater systems as it provides sufficient groundwater recharge to compensate for the impacts of climate variability (Grönwall & Oduro-Kwarteng, 2017).

Cascading Effects Across Systems

Cascading effects of resilience also occur across both human and water systems. Such effects of the two systems are usually nonlinear due to hysteresis effect determined by underlying variables and their synergies with other variables, that is, the feedback between tipping elements and between tipping and nontipping elements (Scheffer et al., 2009). In the feedback process, water can be the source of resilience, the carrier of disturbances, and the driver of change to social-ecological systems, all at the same time (Falkenmark et al., 2019). This is due to the fact that water provides benefits for ecological and social systems through multiple hydrological functions and processes. However, water can also threaten the state of social-ecological systems because of hydrological variations and crises (Figure 38.4). Defined by different attributes of quantity and quality, location, and timing of base and peak flows, water systems provides numerous hydrological ecosystem services, including a water supply for nature and different socioeconomic sectors, water damage mitigation for social-ecological systems (e.g., the reduction of flood damage, dryland salinization, saltwater intrusion, and

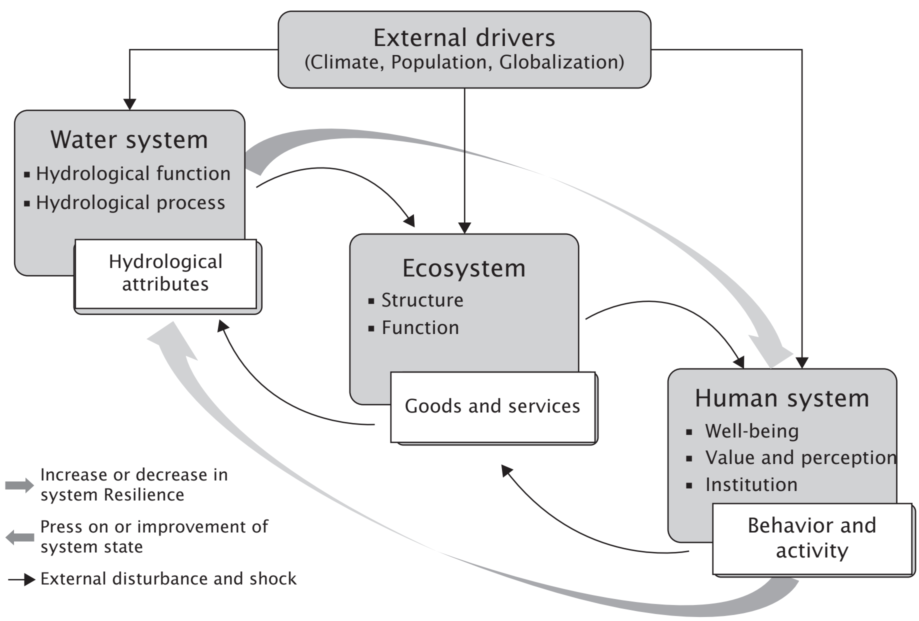

FIGURE 38.4 Cascading effects across systems. *Notes*: Authors' own figure.

sedimentation), support services for terrestrial ecosystems, and spiritual and aesthetic services for human well-being (Brauman, Daily, Duarte, & Mooney, 2007).

In a cascading way, external drivers have impacts on the water system interrupting hydrological attributes, functions, and processes. The altered hydrological systems produce effects on the structure and function of the ecosystem and its services, and changes in these services affect social well-being, people's value and perception on environmental changes, and the institutions that form human behaviors and activities. As feedbacks, social systems are resilient facing the hydrological hazards and variations, in that the society obtains experience and knowledge from the past events, which increase individuals' risk perceptions. Once effective social learning and social networks are embedded in communities, social norms and behavioral preferences in harmonizing with water can be formed, which further increases the resilience of hydrological systems.

Hydrological resilience emphasizes hydrological functions of water to safeguard ecosystem services and human utilization in the presence of human disturbances and climate variations. The failure of hydrological adaptation can jeopardize social resilience to climatic events, whereas the collapse of a water system can be a trigger for social and civilization collapse. This is because water crisis can lead to the loss of hydrological functions and services and, further, the collapse of biophysical systems on which most human civilizations rely (Falkenmark et al., 2019; Kuil, Carr, Viglione, Prskawetz, & Blöschl, 2016). However, this does not mean that the more that water is available, the more resilient a hydrological system is. On the contrary, too much water can increase the flood risks and reduce resilience of hydrological systems, particularly in engineering and social infrastructure, which may be unable to withstand heavy precipitation events. Predictability of the water supply is also crucial for the design of successful adaptations and management systems. In water supply systems, this requires not only an adequate quantity of water, but also an acceptable quality of water. The deterioration of water quality has been known to accelerate conflicts between regions, with notable examples being the Arab Spring and the Syrian War (Gleick, 2014). Furthermore, hydrological functions can affect social-ecological systems by indirect means of changing the integrity of an ecosystem and its attendant services to society. Hence, too little water can lead to the decline of social-ecological resilience. For instance, the depopulation in Tikal city and collapse of the Mayan civilization are most likely the consequences of the limited social accessibility to water, and the hydrologic vulnerability to drought (Kuil et al., 2016). Yet, the thresholds for how much water is too much or too little remain to be identified. Many tradeoffs need to be balanced when looking at the cascading effects of multisystemic resilience to avoid lock-in and path dependence of unstainable socio-hydrological interactions.

Cascading Effects Across Scales

Cross-scale interactions refer to the processes and changes occurring at one scale that cause changes at another scale (Peters et al., 2004). In coupled human–water systems, cross-scale interactions represent the dynamics between processes of social, ecological, and hydrological changes over time and space (Figure 38.5). At the global scale, over decades or centuries, human-induced impacts on the planet are driving changes in climatic conditions, resulting in calls for global adaptations and mitigations. At intermediate scales, in addition

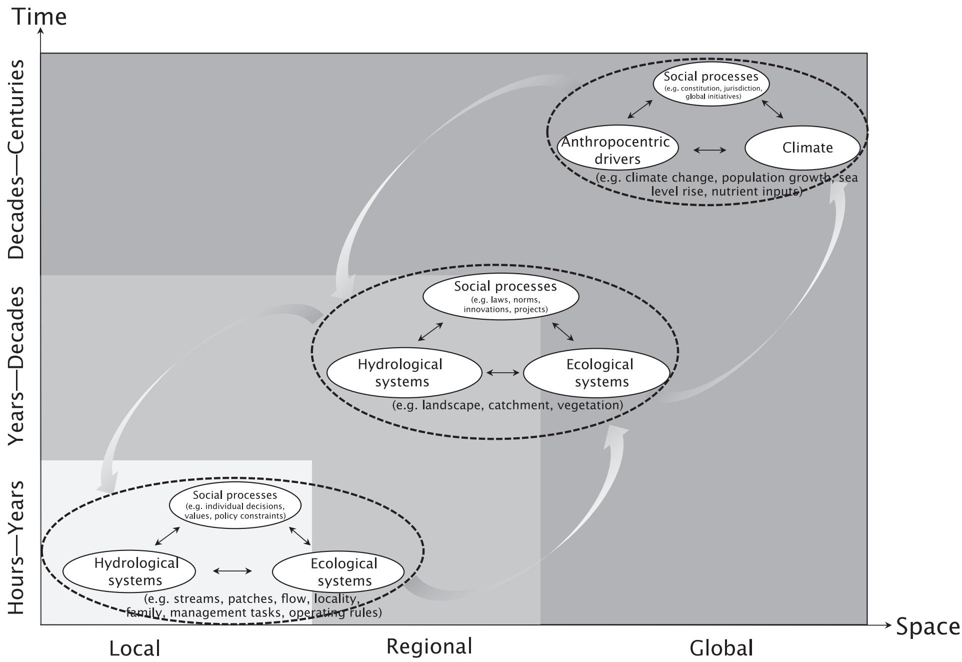

FIGURE 38.5 Cascading effects across different temporal and spatial scales. *Notes*: Authors' own figure.

to human impacts on the landscape because of land-use decisions, global changes have altered ecohydrological processes and the supply of ecosystem services (Isbell et al., 2017). These human impacts can either be immediate (such as land-use conversions from one type to another) or hysteretic over decades or even longer (e.g., land clearance for agriculture and extinctions of species; Tilman, May, Lehman, & Nowak, 1994). Small-scale hydrological processes usually happen in local streams and rivers, which affect ecosystem functions and structures in the form of patches (relatively homogeneous areas that differ from their surroundings) and are constrained to decisions of local people and policymakers. Local patchiness can lead to emergent dynamics at regional scales, and the clusters of patches can form the specific landscape at larger scales (Levin, 1992).

The observed cross-scale phenomena raise other trade-offs of systemic resilience: resilience in the short term versus resilience in the long term and resilience in one place versus resilience in another place. Resilience of a system evolves due to the interactions with other systems across different scales which have been well studied with the advantages of the analyzing approach of Gunderson and Holling's (2001) *Panarchy: Understanding Transformations in Human and Natural Systems*. The cross-scale interactions have been found to be the critical dynamics that determine the state of human and environmental systems, although the mechanism is different for each type (Rocha et al., 2018). On the one hand, given the hysteresis phenomenon, regime shifts of one system could have cascading effects on the regime shift of another system on a different time scale, sometimes from decades to centuries. For instance, the increase in global drought and land use changes may give rise to a long-term trend in landscape shifts and local changes of production due to individual risk-aversion and self-interest. The increasing water stress and other climate-induced environmental disasters may lead to substantial population displacement and migration in years or decades to come (Wrathall, Hoek, Walters, & Devenish, 2018). Furthermore, pumping wells can provide accessible source of freshwater for farmers in the short term (i.e., months to years), increasing the resilience of social systems to adapt to drought events, but threatening the resilience of groundwater systems in the longer term (decades to centuries) because of declining aquifer storage manifesting as dropping water tables. North India and California are good examples of this phenomenon (Famiglietti, 2014; Famiglietti et al., 2011; Richey et al., 2015; Rodell et al., 2009).

On the other hand, disasters at the most local levels are usually the consequences of global changes. To illustrate, resilience at the local level (e.g., community resilience) is affected by the response time of natural processes and moderated by absorptive capacity embodied as endogenous factors in the local community. The local absorptive capacity is the ability of a local community to successfully respond to hazard events with coping strategies learned from past events (Cutter et al., 2008). If a hazard event at the local scale is so large that the absorptive capacity of the local system fails to resist, such as flash flooding caused by tornados, then a certain threshold may be exceeded which will result in catastrophic damages and losses at a larger scale. Sometimes these local effects may be extended to the global level. For example, the 2010 Russian heat wave harmed wheat production and raised global food prices (Welton, 2011). Similarly, rainforest–savanna system shifts can result from local deforestation, which can cause modifications to the regional climate in the Amazon rainforest (Staal, Dekker, Hirota, & van Nes, 2015).

The previously proposed framework is, admittedly, highly conceptual in nature. It describes how cascading effects would occur in the context of multisystemic resilience. To be useful, it should be testable and scalable to different areas and across relevant temporal and spatial domains. In the next section, we make use of a basin in the Canadian Prairie as an example that demonstrates the local application of this framework for the study of cascading effects across social and hydrological systems.

Cascading Effects in Resilience of Human-Water Systems: A Case in Canadian Prairie

The Canadian Prairie is a semi-arid region characterized by a mosaic landscape formed mainly by the mixture of cropland, grassland, pastureland, and wetland. A characteristic element of the prairie landscape is the extensive occurrence of shallow depressions that lack surface water connections. These depressions were formed during the Pleistocene deglaciation of the region, and they are generally hydrologically disconnected from the stream and river networks. Wetlands and ponds have been formed in many depressions, but storage is highly varied due to the variable climate of the region (Fang et al., 2010). Agriculture is important in shaping the landscape and hydrology of the Canadian Prairies and is a major component of the economy. The region has a long history of intensive agricultural drainage, which has led to widespread loss of these depressions and associated wetlands. While research on Prairie

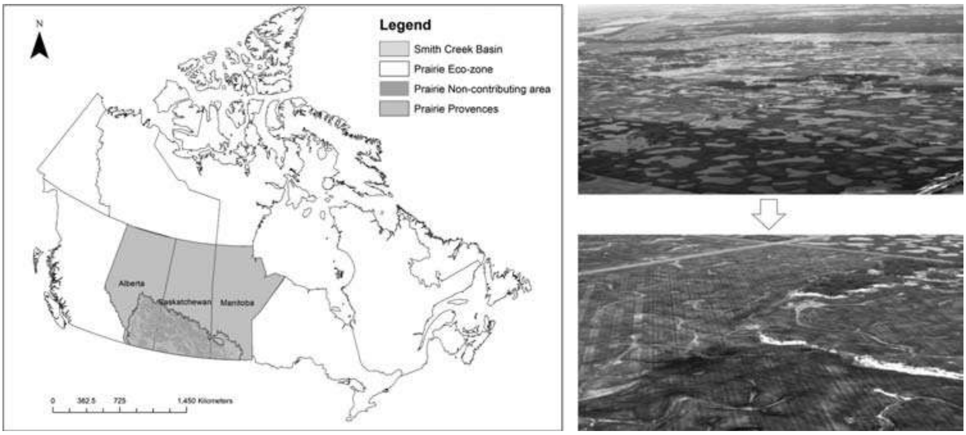

FIGURE 38.6 Human-induced alterations to landscape and water systems in the Smith Creek Basin, Canada. The right two aerial photos show two sections of land in the SCB during rapid snowmelt in April 2011. The section on the top has no artificial drainage, allowing water to pool in small and shallow natural depressions. The section on the bottom shows the impact of an artificial drainage network, which clears the land of water, increases basin connectivity and increases the flow volume downstream. *Photo credit:* Ducks Unlimited Canada.

hydrology and ecology started decades ago (Gray, 1964; LaBaugh, Winter, & Rosenberry, 1998; Pomeroy, Gray, & Landine, 1993; van der Kamp, Hayashi, & Gallén, 2003; Woo & Rowsell, 1993), the social dimensions and their coupling with water systems are relatively new (Pattison-Williams, Pomeroy, Badiou, & Gabor, 2018). In particular, the resilience of socio-hydrological systems needs to be explored given the increasing disturbances and uncertainties observed.

The Smith Creek Basin (SCB), located in southeastern Saskatchewan, Canada, is a typical prairie area which has undergone substantial drainage of depressions in recent years (Figure 38.6, left). In many parts of the basin the landscape has shifted due to the drainage activity of farmers (Figure 38.6, right). The acreage devoted to wetlands declined from 96 square kilometers (24% of the basin area) to 43 square kilometers (11% of the basin area in 2013; Dumanski et al., 2015). Benefits to farmers are offset by the social costs of agricultural drainage that include the loss of wetlands for migratory birds, increased flooding in the river basin as a whole, and reduced water quality downstream as nutrients from agricultural production are flushed downstream rather than processed in adjacent wetlands.

Changes in Hydrological Regimes and Resilience

The SCB is vulnerable to climate drivers such as floods and droughts. Millions of ponds in prairie basins absorb surges of rain, snow, and floodwaters, thus reducing the risk and severity of downstream flooding. These ponds supply water for depression-focused recharge of groundwater (Pavlovskii, Hayashi, & Cey, 2019) and provide a hedge against drought as more surface water is available to support wildlife during dry years (Wheater & Gober, 2013). These capacities maintain the hydrological resilience of the basin to climate variability. The SCB is also remarkably sensitive to the wetland drainage activity of local farmers, because

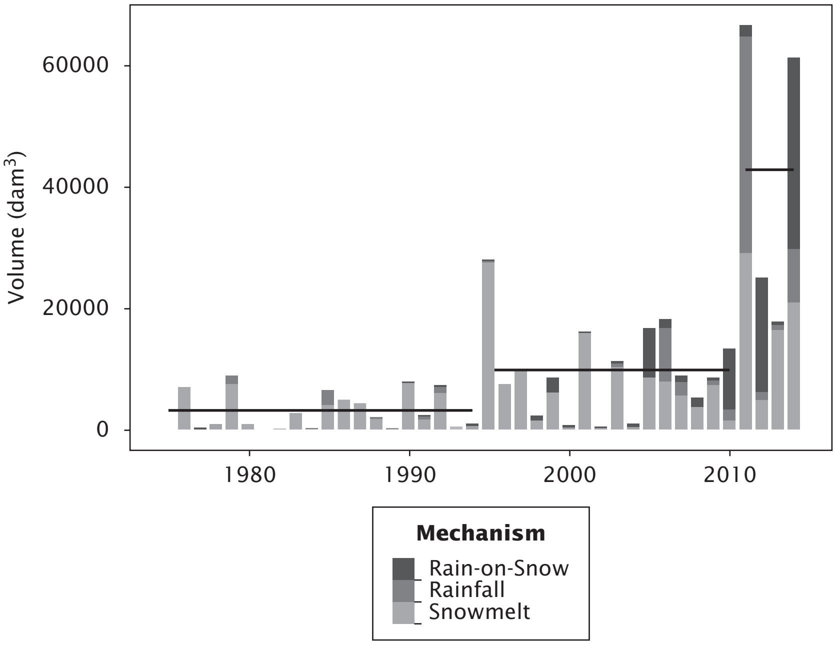

FIGURE 38.7 Changes in hydrological regimes and resilience in SCB. Figure reproduced with permission from Dumanski et al. (2015).

the drainage changes hydrological flows and self-organization capacities of the basin in dealing with floods and droughts. Specifically, drainage infrastructure opens links between noncontributing areas to the network of local streams and eventually to the Assiniboine River and Lake Winnipeg Basin. Observation and simulations show that the hydrological regime during the spring in SCB has shifted from snowmelt dominated streamflow to rainfall-runoff domination. The annual streamflow volume tripled between 1995 and 2010, a period that included a significant drought episode between 1999 and 2005 (Pomeroy et al., 2014); springtime peak flows increased causing significant flooding in 2011; and a second summer peak occurred in recent years when the creek is normally dry (Dumanski et al., 2015). Annual flow volumes from Smith Creek have increase 14-fold from the 1970s to the 2010s without a concomitant increase in precipitation (Figure 38.7). This is one of the largest increases in runoff efficiency ever measured in the world.

The drainage of depressions can increase the connectivity of surface water, but reduces the numbers of ponds on lands and the resilience of downstream areas to flooding (Figure 38.8). Hydrological modeling and observations also link farmers' drainage to the increase in flood problems and raise the potential for even more severe impacts under climate change scenarios. The complete drainage of existing wetlands would have increased the peak of a disastrous 2011 flood by 78%, and the yearly volume of stream flow, by 32% (Pomeroy et al., 2014). The combined changes in hydrological regimes and the loss of wetlands have decreased hydrological resilience in the face of climate change.

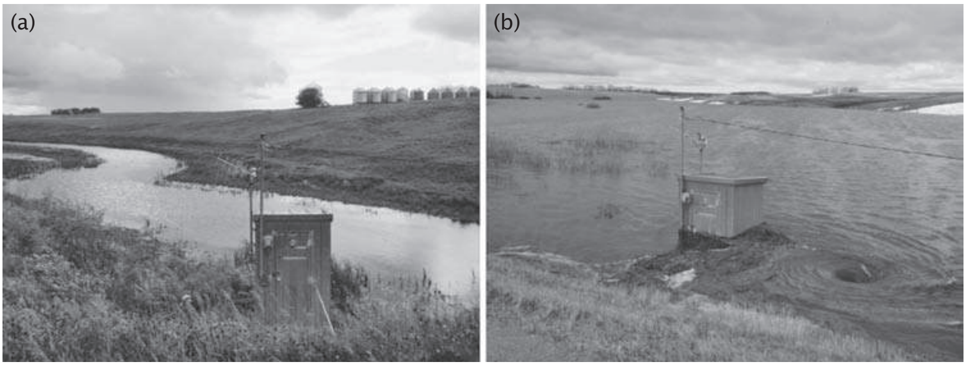

FIGURE 38.8 Less resilient hydrological system in the face of climate variations. These two photos were taken in 2011 in the same area where one of the hydrological gauges is located in the SCB: (a) shows how the stream channel appears in summer when there is no heavy rainfall—the stream flows through a culvert to the right of the station housing; (b) shows the inundation due to backwatering in the area when snow starts to melt in addition to a heavy rainfall event in late spring—the whirlpool is the streamflow entering the now inundated culvert. *Photo credit*: Nicole Seitz, Centre for Hydrology, University of Saskatchewan.

Changes in Ecosystem Services and Social Resilience

Losing hydrological resilience leads to cascading effects and a decrease in social resilience when adapting to changing hydrological regimes. Draining wetlands causes the loss of ecosystem services and social resilience to climate variability and hydrological hazards. In this case, resilience can be treated as a capital asset for both social and ecological systems (Walker et al., 2010). Changes in wetlands water storage via drainage activity will change socio-hydrological resilience because of the alteration to hydrological regimes and the reduction of regulating services that wetlands provide to human and water systems such as flood control and nutrient absorption. In short, the reduction of wetland storage decreases absorptive and adaptive capacities of social-ecological systems in the face of floods and droughts (Figure 38.9). Reducing per unit of wetland stock can increase the likelihood of flood damage, and continuous loss of wetlands causes the system to become vulnerable to heavy run-off events.

Furthermore, landscape modification allowed little to no residual local storage on farmlands, and unregulated drainage ditches transported water from one local depression to another, causing flood damage to adjacent croplands and communities surrounding the terminal depression. The wet hydrological conditions caused damage to croplands because of the wet soil moisture. Local communities are able to adapt to a changed environment based on their memory and experience, but their adaptation fails when extreme hydrological events occur, such as the July 2014 flooding caused by rain in SCB. This produced the highest peak streamflow of all time at a time of year when the creek is normally dry and from rainfall run-off processes that produced only 15% of streamflow 30 years ago. Local farmers are not prepared to deal with such unexpected events. When this happens and people are negatively affected, scientific and public discussion about land and water management can contribute to improved social resilience.

FIGURE 38.9 Failure of social-ecological systems to adapt to flood events These three photos were taken in May of 2011 in the same area in SCB: (a) and (b) show how farmers protected their lands by using simple wood boards to block the water drained from their neighboring lands. However, as the water coming from upstream increased, the adaptation failed causing overtopping across the roads as shown in (c). *Photo credit:* Nicole Seitz, Centre for Hydrology, University of Saskatchewan.

Conclusion

Human influences have become a major force for change in water system dynamics. While the emerging field of socio-hydrology has made efforts to incorporate human dimensions as endogenous factors into hydrological models to simulate humans' role in the whole hydrologic cycle, the interactions and feedback between human and environmental elements of water systems have the potential to push coupled systems past critical thresholds and cause regime shifts. Hence, one key to managing human–water coupled systems is to avoid critical transitions in rapidly changing and highly uncertain environments. Resilience can be a powerful systemic way of thinking for coping with that. It emphasizes nonlinear dynamics of systems, the existence of thresholds, uncertainties, and feedback loops between human and natural systems across temporal and spatial scales (Folke, 2006). However, the integration of resilience to socio-hydrological research is still new.

When introducing resilience to socio-hydrological research, some urgent issues must be accommodated given the changes happening to river hydrology. Examples of such issues include whether or not there will be alternative regimes for farming systems if changed hydrological conditions lead to changes in farm production patterns, or even the resettlement of farmers, and whether tipping points (critical thresholds) exist between them; whether ecology should be treated as the boundary condition when it comes to socio-hydrological resilience and its modeling; whether and how different policy settings change behaviors of people, which could further affect hydrologic systems and avoid systems crossing tipping points; and how to detect early warning signs of undesirable regime shifts, which may be caused by the changing hydrology.

In addition, smart decision-making under deep uncertainty is needed, which can benefit from interdisciplinary and transdisciplinary research as well as the implementation of adaptive water governance. Managing water involves managing people and their attitudes, needs, values, and beliefs about how hydrological systems function. Continuing to foster interdisciplinary and transdisciplinary research is one possible way to adapt to this uncertainty and change. Interdisciplinary water research that brings together different disciplines will help people to understand complex human–water problems and identify uncertainties. Transdisciplinary studies that engage various stakeholders to share values and knowledge will improve people's knowledge about what the current water situation is, what the future might be, and inform science and policy-makings about the real need to live better with changing circumstances. Furthermore, adaptive water governance and management should be improved through learning processes (or cycles) and take into account different kinds of uncertainties (Pahl-Wostl et al., 2007). For example, flexible management and governance should be built to allow learning and address uncertainties in decision-making processes. This means that the governance and management systems must be flexible and adaptive to respond to new information (e.g., from experience or from prediction; Pahl-Wostl et al., 2007). The uncertainties that need to be considered stem not only from the environment, but also from economic, societal, and political changes.

To help understand these patterns and cope with uncertainties, we have introduced in this chapter the concept of socio-hydrology to investigate cascading effects of resilience in coupled human–water systems. We first defined socio-hydrological resilience and then proposed a conceptual framework to explore how changes in the resilience of either hydrological systems or human systems could impact each other. In the framework, we argued that cascading effects of multisystemic resilience could take place under three conditions: cascading effects within a system, across systems, and through cross-scale interactions. In each circumstance, we suggested that ecosystem services be the critical lens to understand how changes to the resilience of water systems can have synergistic effects on the resilience of social systems, and the other way around. We used the example of a basin on the Canadian Prairies to illustrate how hydrological resilience can be changed because of human perturbations that affect agricultural drainage and how changes in hydrological resilience can affect social resilience by altering the conditions of ecosystem services. We recommend that socio-hydrological models, such as stylized models, be built based on this framework to better describe the dynamic cascading mechanisms of human and water coupled systems and the resilience of the systems involved.

Key Messages

1. Human (social) and water systems need to be understood in a coupled context.
2. Resilience of human systems require the resilience of hydrological systems.
3. A resilient hydrological system should be capable of absorbing social disturbances.
4. Resilience of human-water systems requires investigating bidirectional feedback between social and hydrological systems.

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