Synthesis

Socio-hydrology: Insights into the Interplay of Engineering Design and Self-organization in a Multi-level World.

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ABSTRACT

The emerging field of socio-hydrology is a special case of social-ecological systems research that focuses on coupled human-water systems, exploring how the hydrologic cycle and human cultural traits co-evolve and how such co-evolutions lead to phenomena of relevance to water security and sustainability. As such, most problems tackled by socio-hydrology involve some aspects of engineering design, such as large-scale water infrastructure, and self-organization in a broad context, such as cultural change at the population level and the hydrologic shift at the river basin or aquifer level. However, within the field of socio-hydrology, it has been difficult to find general theories that assist our understanding of the dynamics emerging from the interplay between design and self-organization, hindering generalization of phenomena between cases. This paper addresses this gap by developing insights on how the theoretical frameworks of robustness-fragility tradeoff and cultural multi-level selection can inform our understanding in this regard. We apply the two theories to two cases in the Ganges Brahmaputra Delta in Bangladesh and the Kissimmee River Basin in Florida, illustrating how the two theories may provide general insights into causal mechanisms shaping the socio-hydrological phenomena observed in the two cases. Specifically, we use the two theories to address (1) the transference of system fragility across different domains due to design choices and (2) the multi-level social processes in the nested organizational hierarchy that lead to the formation or collapse of shared cultural traits. We show that these two theories, separately or taken together, can provide richer theoretical grounding for understanding socio-hydrological phenomena.

Key words: socio-hydrology; coupled human-water system; robustness-fragility tradeoffs; cultural

multi-level selection; robustness; cultural evolution; the levee effect

1. Introduction

The continued surge of interdisciplinary systems approaches to studying environmental and sustainability problems, notably the resilience of social-ecological systems, has highlighted the importance of viewing nature and society as interdependent systems and the tight feedback that connects them (Folke 2016). A similar systems approach, socio-hydrology or coupled human-water systems, has only recently emerged within the discipline of hydrology and water resources, driven by a growing appreciation that many of the serious, recurring problems in water resources use originate from the lack of consideration of the two-way feedback between hydrologic and social systems (Sivapalan et al. 2012). Socio-hydrology is a rapidly growing research area, with a potential to push the field of hydrology beyond its traditional boundaries of focusing solely on hydrologic systems and processes (Konar et al. 2019). A core question in socio-hydrology is whether common phenomena can be identified in disparate cases and how they may be explained by the two-way feedback, thus creating general insights that transcend specific instances (Troy et al. 2015, Di Baldassarre et al. 2019). Several studies explored such phenomena, including tradeoffs between short- and long-term flood vulnerabilities (Di Baldassarre et al. 2013, Merz et al. 2015), the shifting of societal preference about water allocation from economic production to environmental conservation (Van Emmerik et al. 2014, Chen et al. 2016), unintended consequences of improving irrigation efficiency (Scott 2011, Grafton et al. 2018), urban water supply issues in less developed regions (Srinivasan 2015), and unintended consequences from the expansion of and over-reliance on water reservoirs (Di Baldassarre et al. 2018).

While building on social-ecology, socio-hydrology studies tend to be differentiated by three distinct features. First, the spatial and time scales of analysis are often at the levels where changes in the hydrologic cycle can be observed and examined. For example, regional spatial extents such as watersheds, river basins, aquifers, and citywide water supply networks are analyzed over a relatively long time scale to track changes in the hydrologic cycle (Zhang et al. 2014, Gunderson et al. 2017). Second, on par with emphasis on the evolution of hydrologic cycle, the field is interested in the evolution of human cultural traits (e.g., social norms, practices, etc.) concerning water and the mechanisms and conditioning factors behind it (Sanderson et al. 2017, Roobavannan et al. 2017). Third, the role of built infrastructure is often explicitly recognized and included in analysis, especially the effects of infrastructure design on the trajectories of human-water interactions(Di Baldassarre et al. 2013, Yu et al. 2015, 2017). Given these features, a systems approach to studying socio-hydrology requires a consideration of how the interplay between design (infrastructure or policy design) and self-organization (hydrological shifts or social change) and generates emergent dynamics. Further, coupled human-water systems tend to contain multiple social units embedded in a nested hierarchy (Gunderson et al. 2017). For example, smallholder households are embedded within irrigation communities, which are embedded within the jurisdictional hierarchies of local, regional, and federal level organizations. Given this multi-level nature, socio-hydrology also requires understanding of how multi-level dynamics in social organizations shape outcomes. It is, therefore, useful to think of coupled human-water systems are part designed and part self-organized systems. In other words, infrastructure or policy designs may be imposed to achieve particular goals, but actual outcomes depend on how the hydrologic cycle shifts or how social processes within and between levels in a nested hierarchy evolve in response to such designs, often in unexpected ways.

However, general insights into the causal mechanisms affecting the interplay between design and self-organization and the multi-level nature of social change have been elusive in the field of socio-hydrology. Such insights are critical for improving understanding of how and why coupled human-water systems co-evolve along certain trajectories and why they can be sustainable in certain cases and not others. This paper, therefore, aims to examine how co-evolutionary patterns of socio-hydrology can be examined and linked by applying an overarching theoretical framework. Specifically, we draw on the theories of robustness-fragility tradeoff (RFTO) and cultural multi-level selection (CMLS), two independent approaches that are, together, useful for understanding a wide range of dynamics exhibited by part designed and part self-organized systems. The theory of RFTO presents generalizable insights about how system design altered to enhance robustness in one domain may lead to amplified fragilities in other ways (Csete and Doyle 2002, Anderies 2015). The theory of CMLS, in contrast, explains the cultural change of human societies by identifying cultural transmission and selection processes operating at different levels of organizational hierarchy, and the consequences of these multi-level selection pressures on cultural trait emergence and persistence (Boyd and Richerson 1985, Waring et al. 2015). To illustrate the utility of these two theoretical lenses, we apply them to socio-hydrological phenomena observed in two case areas: community-managed flood protection systems (polders) in southwest Bangladesh and the Kissimmee River Basin, Florida.

We examine how the theoretical lenses of RFTO and CMLS can facilitate generalization by applying them to the phenomena of "levee effect" (Montz and Tobin 2008) and "pendulum swing" (Kandasamy et al. 2014), two iconic patterns of socio-hydrology. The levee effect has been the subject of multiple socio-hydrology studies (Di Baldassarre et al. 2013, Viglione et al. 2014, Yu et al. 2017, Sung et al. 2018). According to the levee effect, building higher levees ultimately increases vulnerability to flooding in long run, rather than decreasing it, because short-term stability created by building levees can lead to expansion of practices that increase the costs and risks of rarer long-term disasters. The opposite of the levee effect is referred to as the adaptation effect, which means that allowing moderate exposure to flood events can lead to enhanced social capacity to cope with rare flood disasters in long run (Di Baldassarre et al. 2015). In summary, both effects involve tradeoffs in system fragility between two levels of time scale (frequent vs. rare) and that these tradeoffs arise because of the effects of design choices (infrastructure or policy designs) on the self-organization of flood memory, human settlement pattern, or flood hydrology.

The phenomenon of "pendulum swing" has been also studied by multiple socio-hydrology studies (Elshafei et al. 2014, Van Emmerik et al. 2014, Mostert 2017). This phenomenon pertains to the shifting of people's collective preference for allocation of water resources from economic development to environmental health. The current socio-hydrology literature provides only a mechanistic description of the phenomenon at the population level. For example, it relies on metaphors such as collective memory and community sensitivity, which identify a society's shared memory, attitude, or preference toward certain hydrological or environmental conditions. The basic idea is that the state of collective memory or community sensitivity is affected by hydrological events (e.g., flooding), which in turn feeds back to affect hydrology via a social response (e.g., construction of more levees), leading to altered hydrological processes in the future. Although simple and straightforward, these composite concepts abstract away much of the underlying causal mechanisms of social change. In other words, there is a need to account for how a cultural trait may spread and become widely shared in a society despite diverse traits that may have initially existed at the level of individuals and how such shared norms may become stabilized or collapse and be overtaken by another cultural trait.

Producing general insights about multiple socio-hydrological phenomena would thereby require theories that address (1) tradeoffs in system fragility that arise as a result of design choices and the self-organized response of social or hydrological components, and (2) multi-level analysis covering both individual-level cultural variation and selection and population-level cultural dynamics. RFTO and CMLS, two theoretical approaches that are increasingly being used in sustainability studies (Reyes-García et al. 2016, Ishtiaque et al. 2017, Brooks et al. 2018a, Ellis et al. 2018, Tellman et al. 2018), can meet these respective requirements, suggesting the benefits of these theories for addressing socio-hydrological phenomena. Both separately and taken together, we argue that these two theories provide richer theoretical grounding to socio-hydrology.

The rest of this paper is organized as follows. In the following two sections, we provide brief introductions to the theories of RFTO and CMLS. In section 4, we discuss the case of a community-managed flood protection system (polder) in southwest Bangladesh. A case-driven model of a polder is then used to illustrate RFTOs and their connections to the levee and adaptation effects.

We also use a cultural evolutionary perspective to analyze the emergence and evolution of cooperation in the case. In section 5, we discuss the case of channelization and restoration of the Kissimmee River Basin in Florida over the last 50 years. We use this case to illustrate RFTOs and CMLS, and then discuss how these two theories individually help us understand the co-evolution of human and water systems observed in the basin. In the last two sections, we provide discussion and conclusions on how the two theories complement each other and how their combined use may provide an effective way to interpret socio-hydrological phenomena in general.

2 Robustness-Fragility Tradeoff

According to RFTO, structural modification or fine-tuning of control of complex feedback systems to increase its robustness to one set of disturbances necessarily leads to increased fragilities to disturbances outside that set (Anderies 2015). Such tradeoffs in robustness, or conversely, fragility, is a fundamental property of feedback systems (Bode 1945), and has been labelled the "conservation of fragility" elsewhere (Csete and Doyle 2002). The basic insight is that efforts to enhance robustness often serve merely to move fragilities around to different domains, rather than eliminating them. Such tradeoffs are dangerous because people tend to develop a false sense of security, as emergent fragilities from altering system design are often hidden, and revealed only through catastrophic failures (Anderies 2015).

RFTOs have been illustrated in a wide range of controlled systems, from linear feedback systems to complex engineered systems and social-ecological systems. Within the social-ecological systems literature, RFTO theory has been applied primarily to understand how human efforts to cope with environmental variability through the use of built infrastructures, policy actions, or both lead to the shifting of fragility across different scales or levels within a scale (e.g., Ishtiaque et al. 2017, Tellman et al. 2018). RFTO theory has also been discussed in a socio-hydrology context in a recent study (Yu et al. 2017). This study characterized the levee effect as an example of RFTO-induced phenomena by exposing hidden social problems that emerge because of building more flood infrastructure.

A typology of RFTO (Figure 1) has been proposed to help conceptualize how such tradeoffs occur in a social-ecological system context (Anderies 2015). Four basic types of RFTOs can exist according to this typology: structural RFTO, network RFTO, feedback RFTO, and feedback and structural RFTO. Structural RFTO represents a direct modification to the system structure, e.g., converting a natural floodplain to a semi-engineered environment by the construction of levees (Figure 1A). Such modifications help to suppress short-term environmental variability (e.g., daily tidal inundation), but also tend to be associated with increased fragilities at a different level of the time scale, such as catastrophic outcomes when a 500-year flood occurs, or on altogether different scale, such as free-riding behaviors of people regarding infrastructure maintenance. By contrast, network RFTO represents an insertion of an exchange network among multiple "source" systems, whose outputs or benefit flows respond differently (or do not co-vary in time) to a disturbance, and a "sink" system that taps into these benefit flows. Such an exchange network helps to reduce the effects of short-term fluctuations in the source side on the sink side because of an insurance effect, i.e., even if one of source systems cannot withstand a disturbance and fails to perform, other source systems that have the same function may withstand it and still allow the sink system to receive benefit flows (Figure 1B). However, the connection to the larger network and the resultant interdependencies (where outputs of one node becomes inputs to another node) may exacerbate the risk of cascading failures triggered by a node failure in the network.

Feedback RFTO represents an introduction of feedback "control" response to variations in a system state to achieve stability (Figure 1C). Such feedback controls are often dictated by some existing management policy or regulatory protocols. For example, dam or reservoir operations can be guided by pre-existing operation rules that have been based on historical streamflow trends. However, when the streamflow pattern deviates significantly from the historical trend, conforming to these existing operation rules might worsen outcomes. Finally, structural and feedback RFTO occurs when both infrastructure modification (e.g., altering the design of flood protection infrastructure) and feedback control (e.g., dynamically adjusting reservoir water levels) occur to achieve stability (Figure 1D). This form of system control is extremely powerful, and the system appears to be highly robust because of the combined effects of engineering design and feedback-driven regulatory control. However, it is also the most problematic because fragilities are hidden by the very power of structural changes and feedback controls and are revealed only because of rare catastrophic failures. Self-organization is behind the manifestation of most of these fragilities: from development of a false sense of security among people and the resulting shifts in their collective memory and land use patterns, to gradual shifts in natural system states and processes.

Figure 1 about here

3 Cultural Evolution and Cultural Multi-Level Selection

Social change, or shifts in the frequencies of cultural traits within populations, is an integral part of socio-hydrology, and is regarded as endogenous to coupled human-water systems dynamics (Sivapalan et al. 2012, Montanari et al. 2013). The question of how to theorize and model social change, and its two-way connection with hydrological processes, has garnered much interest and debate recently among hydrologists and water resources researchers (Gober and Wheater 2015, Loucks 2015, Yu et al. 2017, Roobavannan et al. 2017). We argue that the broader theory of cultural evolution and cultural multi-level selection (Boyd and Richerson 1985, Brooks et al. 2018b) already provides excellent conceptual tools for understanding social change in this regard.

According to the dual-inheritance theory of cultural evolution (Richerson and Boyd 2005), individuals inherit traits culturally, through social learning, in addition to genetically, through reproduction. This cultural form of inheritance then gives rises to a distinct, non-genetic process of Darwinian selection (cultural selection), which can be modeled according to the same principles that biologists use to track relative frequencies among genetic traits over time. In this approach, cultural traits are defined as information, values, skills or practices that individuals acquire specifically through social learning. And just as functional complexity accumulates over time among genetically inherited traits, so too does it accumulate in cultural traits, as we see in the accumulation of knowledge in science and technology, and in the complexity of social rules, norms, and practices involved in the management and use of natural resources (e.g., Ostrom 1990). Understanding the dynamics of cultural evolution is important to socio-hydrology because cultural traits strongly shape human interactions both with one another and with the environment and thus outcomes of human-water interactions in long run. One way or another, any theory capable of tracking and explaining social change will have to address underlying cultural processes that give rise to regularities in cultural traits among individuals.

Cultural selection, the cultural equivalent of Darwinian natural selection, occurs when a particular cultural trait is transmitted in a population at the expense of others because of its effect on individuals who use it in a given context (Mesoudi et al. 2006). For example, an individually-costly water conservation practice, like converting a lawn to a xeriscape, may be selected and persist in a society either because of formal incentives and regulations, or because of informal sanctions of peer pressure, reputation and social comparison, or because individuals have personally internalized norms of conservation. But whatever the nature of the particular cultural selection pressures involved, they will depend on the particular cultural context, or the contingent history of shared beliefs and values that either promote or discourage the uptake of various practices. Thus, for example, when pre-existing rules and norms in a city favor structural measures of flood protection, an alternative norm for non-structural forms of flood protection cannot easily invade and spread.

As these examples suggest, cultural traits can be transmitted vertically across generations, as children inherit the culture of their genetic parents, as well as horizontally, among peers of the same age or generation (Figure 2A). In cases of horizontal transmission, learning strategies include conformist learning biases, in which individuals disproportionately copy the majority behavior, and success-biased learning, in which individuals preferentially copy other successful individuals. A shared cultural trait is formed when such learning strategies used by numerous individuals give rise to regularities in social rules, beliefs, values, or practices in a social group. Once established, a cultural trait can be further reinforced and stabilized through social effects such as peer pressure and group selection (Figure 2C) (Chudek et al. 2013). Alternatively, perturbations such as innovations, or cultural mutations, may disrupt an existing equilibrium (Figure 2B). The theory of cultural evolution, therefore, provides a powerful set of ideas explaining both the emergence and stability of cultural traits over time, including those that influence the use and management of water resources.

Figure 2 about here

It is critical to note that cultural selection can occur at multiple levels of the social organization (Richerson et al. 2014). Just as cultural traits can spread among individuals via social learning, so can they spread among groups of individuals, if the dominant level of selection is at the group level. This process of cultural selection at multiple levels is termed cultural multilevel selection (CMLS) (Wilson and Kniffin 1997, Wilson et al. 2013). Waring et al. (2015) recently applied CMLS to social-ecological systems in the context of collective action problems in order to study the evolution of cooperative cultural traits within social groups. The force of cultural selection on a focal cultural trait can vary across different levels of social organization (individual vs. group) (Richerson et al. 2014). For example, a water conservation norm might replace a wasteful norm to achieve the common goal of water sustainability, if groups who adopt water conservation are more successful than those that do not. Whether or not this occurs, however, likely depends on the level of the social organization scale at which cultural selection is the strongest (Figure 3). When water is abundant, and thus enforcement is weak, cultural selection would be dominant at the level of individuals and collective action for voluntary water conservation would likely fail. However, when water is scarce, water rates are high, and the government provides financial incentives to groups that achieve higher water conservation, cultural selection would be dominant at the group level (i.e., group selection). In this scenario, a group-benefiting cultural trait would proliferate through mechanisms such as peer pressure and group competition. In reality, selection pressures occur at multiple levels in several connected social groups: an individualistic trait may prevail in some groups due to their unique physical or social context, while individuals in other groups may be driven more by peer pressure and group competition and adopt a group-benefiting trait.

Figure 3 about here

4 Polders in Southwest Bangladesh

Hydrological variability and associated events such as riverine flooding adversely impact human livelihood. Thus, in many human-flood systems, build infrastructures such as levees and upstream dams are constructed to contain and smooth out hydrological variability. The frequency of flooding is dramatically reduced, and hydrological dynamics are largely unnoticed as a result. However, each flood that is contained is a loss of opportunity for social learning, and the absence of people's earlier exposure to such actual flooding experiences and learning opportunities may lead to a serious reduction, or loss, of local flood response capacity to be able to cope effectively with rarer disasters (Liao 2012). This phenomenon, referred to as the levee effect (Montz and Tobin 2008), is increasingly being observed worldwide (Di Baldassarre et al. 2015). Here, we use the case of polders in Southwest Bangladesh to illustrate how RFTO and CMLS can be used to interpret the levee and adaptation effects.

4.1 Background

The coastal region of southwest Bangladesh is characterized by deltaic floodplains of the Ganges and Brahmaputra Rivers. This region is regularly exposed to flood-related natural hazards (Brammer 2010, Auerbach et al. 2015). Before the British colonization in the 18th century, much of the region was a forested with little human intervention. People depended on forest resources, inshore fishing, and small-scale agriculture for living. Extensive agriculture was impossible because the area's low-lying lands were exposed to seawater inundation twice a day. With the British colonization, however, major changes to land-use and livelihood took place (Ishtiaque et al. 2017). Landlords cleared large tracts of forest lands and leased them for farming. Population size increased and farmers constructed pockets of small earthen levees with the support of landlords. Although the earthen levees provided some protection against saline water intrusion, the region and the communities within it were still exposed to rare floods caused by major weather events, such as tropical cyclones. There was little or no sign of major collective action for flood protection during this period, for instance via voluntary contributions to support large-scale infrastructure.

In the 1960s and 1970s, however, the Bangladesh government initiated the Coastal Embankment Project to suppress flood risk and to increase agricultural productivity in the region. Multi-lateral agencies supported the project. This project led to the construction of 37 polders in the country's southwest region, encompassing 1556 km of levees (or embankments) designed to protect low-lying lands from riverine flooding and storm surge (Dewan et al. 2015). A polder is an engineered hydrological unit that surrounds a tract of floodplain enclosed by embankments and sluice gates (Figure 4A). Embankments protect the area inside from flooding. Sluice gates are used to exchange water with surrounding bodies of water. Two major changes took place because of the project. First, with the enhanced flood protection, extensive agriculture and aquaculture became widespread (Swapan and Gavin 2011, Amoako Johnson et al. 2016). This led to increased population and increased land use for economic production. Second, the presence of shared polder infrastructure required involvement or collective action of local communities to maintain the infrastructure (Sultana and Thompson 2010, 2017). Because insufficient or delayed support from the central government is common in this region, the local residents have no choice but to initiate effort to engage in such maintenance activities. Collective action tends to occur in two forms: in normal situations, people need to work together periodically to counter the natural erosion of embankments, while in emergency, people must work together to address breakdowns of embankments that randomly occur when storm surges hit the coasts. Indeed, local communities tend to have strong social norms, which effectively suppress free riding, for collective maintenance of the polders (Afroz et al. 2016).

The construction of the polders has led to improved protection against more regular floods. However, as indicated by the great losses suffered from the Great Bhola Cyclone of 1970, which included the deaths of more than 250,000 people, the region is still vulnerable to rare but acute floods (Hossain et al. 2008). In fact, due to increased population size and economic activity in the polders, combined with the deteriorating quality of polder infrastructure, the region probably has developed increased fragility to rare floods.

4.2 RFTO analysis

We use the stylized model of collective management of a polder in southwest Bangladesh developed by Yu et al. (2017) to illustrate how RFTO can be used to interpret the levee and adaptation effects. The model was developed to understand critical general features that affect the long-term resilience of coastal communities in the region. Two model elements are key drivers of human-flood interaction in the model system: polder infrastructure and collective action for polder maintenance. Polder infrastructure protects residents from flooding. The level of flood protection provided by embankment height, however, can decline over time through natural erosion or breaches caused by storm surges. The model assumes that the residents share a collective goal to maintain a pre-determined level of flood protection through regular maintenance. Individuals can choose from two behavioral strategies about this social goal: contribute to community-organized maintenance work (cooperators) and free-ride without contribution (defectors). In each time step, an individual chooses the strategy that gives a higher expected payoff. Strategy payoff is comprised of monetary and non-monetary portions. Monetary payoff is determined by flood damage, agricultural yield, and the cost of polder maintenance. Non-monetary payoff is determined by the penalty accruing to defectors in the form of social ostracism and the cost of sanctioning borne by cooperators.

Two model processes are especially important here. First, more flood protection is associated with more costly infrastructure maintenance and reduced flood exposure. Second, a lack of exposure to flooding can lead to reduced ostracism of defectors because there is less awareness of flood risk. The conceptual model used in this study captures these social and hydrological processes and shows how outcomes such as agricultural yield and level of collective action (percentage of cooperators) change over time. The model results suggest that allowing some hydrological variability to enter into the polder can increase the community resilience through the preservation of social norm for collective action. More detailed description of the model can be found in the work of Yu et al. (2017).

A set of model outputs illustrates the levee effect in our model simulations. Greater flood protection reduces the occurrence of flooding (which happens when water level is higher than the embankment level) in the early stages of the simulations (Figure 3D). This signifies enhanced robustness to frequent, regular floods. This success, however, leads to an increase in fragility to the collective action problem of infrastructure maintenance because the defector strategy can more easily spread due to a lack of flood exposure and a higher cost of maintenance (Figures 4E). As such, when a rarer flood that calls for greater collective action occurs, the model system collapses. In short, there is a tradeoff in robustness or conservation of fragility between frequent floods and rarer floods, which is mediated by the collective action problem of maintaining the infrastructure. The case thus fits the conditions described by RFTO theory. More specifically, based on the RFTO typology shown in Figure 1, the levee effect can be interpreted as a case of structural and feedback RFTO (Figure 1D), because of the presence of structural modification (embankments) and the associated feedback-driven social actions to maintain the embankment level to a pre-determined level. It is worth mentioning that the levee effect is also concordant with a concept in resilience thinking referred to as "specified resilience," which is akin to RFTO. Specified resilience is about "resilience of what to what and for whom" (Carpenter et al. 2001, Lebel et al. 2006). Just as tradeoffs in robustness are predicted by RFTO theory, resilience theorists have suggested that enhancing specified resilience to one kind of disturbance regime may often come at the expense of reducing specified resilience to other disturbance regimes (Folke 2016).

RFTO also provides a theoretical grounding for the adaptation effect. A moderate level of flood protection, which occasionally allows flooding, appears to be less robust to flood events and more sensitive to agricultural yields in the early stage of simulations (Figure 4B). This deliberate allowance of flooding, however, helps to preserve the shared awareness of flood risk and the social norm for collective action within the model community, leading to an increase in robustness to rarer flooding (Figures 4C). Thus, the notion of the conservation of fragility also applies to this pattern. Since frequent, regular flooding is not overly suppressed in this case, the total amount of fragility is conserved by not amplifying fragility to another disturbance regime (i.e., rarer flooding). In summary, RFTO provides a generalized viewpoint to understanding the levee and adaptation effects, regardless of where they occur or what specific forms of fragility are involved.

Figure 4 about here

4.3 CMLS analysis

CMLS theory provides another lens with which to understand human-flood interactions in southwest Bangladesh. In this region, the hierarchy of social organization is generally divided into three levels: individual, community (polder), and the government. Prior to the Coastal Embankment Project, there was no significant group-level organization at all with regard to practices of flood prevention, so selection among the relevant cultural traits could only have occurred at the level of individuals. At that time, the dominant level of selection was probably the individuals (the 1st column in Figure 5). Farmers who did a better job maintaining small-scale levees for their own farmlands would have been more successful, and effective individual-level coping strategies to floods might have spread among farmers via cultural evolution, for example, if farmers imitated other successful farmers. This is an instance of the adaptation effect occurring at the individual level. Even after British colonization, the dominant level of selection remained the same because landlords and farmers still had to manage and build small-scale levees for their own farmlands. Group-beneficial or collective behaviors did not immediately follow colonization. However, continuous floods were a significant problem for landlords and farmers as they looked to cultivate crops on a larger scale. Flood coping activities at the level of individuals were not nearly enough to support large-scale, extensive agriculture in the low-lying floodplains.

To encourage productivity on a larger scale, and increase cultural fitness of nation as a whole, the Bangladesh government implemented the Coastal Embankment Project, which constructed embankments (polders) around low-lying lands on floodplains (the 2nd column in Figure 5). However, a lack of government support for polder maintenance led to selection occurring at the community level (the 3rd column in Figure 5). In the absence of top-down incentives or enforcement from the government, residents confronted a collective action problem regarding the maintenance of the polders. Individuals who could have spent their time farming, or engaging in other activities that would have been more profitable to them, began to act instead for the group's interest by participating in polder maintenance. As in other cases in which cultural selection is shifted from competition among traits of individuals to traits of groups, culturally learned norms imposed reputation-based costs that countered the benefits of selfish actions (the 4th column in Figure 5). This enabled residents along the Bangladesh coast to cooperate with their neighbors for the benefit of the community, in spite of the temptation to act for their own individual benefit instead. Simultaneously, effective norms of polder maintenance most likely spread among communities through knowledge transfer, in a form of group-level, success-biased social learning. Both mechanisms provide a plausible pathway through which culturally inherited traits that contribute to flood protection came to be what they are. This is an instance of the adaptation effect occurring at the group level because community adaptive capacity is reinforced through frequent exposure to the collective action problem of polder maintenance, which, if unresolved, threatens people's livelihoods.

Without effective government incentives or enforcement, which restrain the behavioral choices of individuals, social learning and polder maintenance cost per household probably became critical features that enable community sustainability and extensive agriculture. Further, the region is and will be increasingly exposed to flood risks from human-induced sinking of delta lands and extreme weather events. Thus, the coupled human-water systems in the region are at the crossroads of pursuing more techno-centric solutions versus learning to live with floods. The techno-centric approach of continuous levee heightening can lead to a greater decay of flood memory (due to lack of people's exposure to regular floods and lost opportunities for social learning) and an increase in per household cost for polder maintenance. In such cases, the dominant level of selection will likely shift from community to individuals and make collective action difficult. This hypothetical scenario is an instance of the levee effect, i.e., over-dependence on the polder infrastructure leading to an erosion of community adaptive capacity.

Figure 5 about here

5 Channelization and Restoration in the Kissimmee River Basin, Florida

In socio-hydrology, the metaphor of a swinging pendulum has been used to conceptualize shifts in a society's preferences for water allocation between emphasizing development and economic gain, on one hand, and environmental protection and restoration, on the other. A key construct used to model such swings is that of "community sensitivity" to environmental health (Elshafei et al. 2015, Mostert 2017). The state of community sensitivity is assumed to be affected by some hydrological event (e.g., flood damages), which in turn feeds back to affect behavioral responses (e.g., building higher levees). Community sensitivity to environmental concerns is decreased when flooding occurs, and sensitivity becomes progressively lower, a society prefers more development and control of water resources for stability and economic gain. In contrast, when environmental degradation occurs, because of the development and control of water resources, community sensitivity to environmental health is increased. Here, we use the case of channelization and restoration in the Kissimmee River basin to illustrate how RFTO and CMLS can aid our interpretation of such swings in social preference.

5.1 Background

The Kissimmee River basin lies in central Florida, extending from the south side of Orlando to Lake

Okeechobee. This river basin was channelized in the 1960s, as the pendulum swung in the direction of economic development, but the channelization was later reversed in 1990s, as the pendulum swung in the other direction. Here, the upstream and downstream regions are characterized by different social and natural environments. Urban communities are found in the upstream region, and since most urban residents live far away from the river corridor, floods are not a primary issue. In contrast, most of the downstream residents depend on agriculture for their livelihood, and since most of their farmlands are located on floodplains, their livelihoods are sensitive to flooding. Over the past several decades, the population in the upstream region has increased substantially, while the downstream population has increased only slightly (Chen et al. 2016). Hurricanes have periodically caused more agricultural damage in the downstream region. For example, the two consecutive hurricane events of 1947 destroyed much of the agriculture in the downstream area (Koebel 1995). Indeed, this agricultural vulnerability provided the initial impetus for residents to petition the government for hydrological intervention (Chen et al. 2016).

In response to the residents' request, the US government commissioned the U.S. Army Corps of Engineers to initiate the Kissimmee River Channelization Project, which was implemented between 1962 and 1971. This project transformed the natural winding river to a man-made straightened canal that is 90 km in length. As intended, the channelization effectively reduced flooding in the downstream region by suppressing runoff fluctuations. This success, however, created a new problem-wetland loss in the downstream areas (Toth et al. 1995). The wetlands in the region gradually dried out because water runoff was cut short by the channelized river. The region's wetlands shrunk in size by approximately 120 km^2, which equates to about 70 percent of the original wetland area. This consequently resulted in a serious loss of biodiversity in the region (Koebel and Bousquin 2014). This destruction of the wetland ecosystem greatly concerned urban residents in the upstream region, who had greater population size, and thus greater political influence than downstream residents. Upstream residents actively voiced their concerns to the government, and sought to reverse the loss of the wetlands, ultimately resulting in the authorization of the Kissimmee River Restoration Act by the federal and state government (Chen et al. 2016).

The restoration project began in 1999 and is expected to be completed by 2019. To minimize the loss flood control provided by the channels, only the midstream section of channels was removed and returned to its past natural conditions. Simultaneously, lands near the river were bought out by the government and restored to floodplains to provide "room for river". As the floodplains store a great amount of water, this kind of green infrastructure provides a buffer against flood waters, while also restoring the wetland ecosystem. In the final analysis, the restoration project has increased the risk of downstream floods, but this increased risk is estimated to be acceptable for agricultural purposes (Bousquin et al. 2009).

5.2 RFTO analysis

We can use an RFTO lens to identify shifts in system fragility as the region's coupled human-water system went from channelization to restoration of the Kissimmee River Basin. Chen et al. (2016) designed a stylized model of the case to capture the shifts in built infrastructure and their impacts, noting that the channelization project and the restoration project targeted different domains of disturbance. According to RFTO, the coupled system cannot be perfectly robust to all disturbances at different domains. The channelization was done mainly to increase the robustness of agriculture to floods, whereas the restoration project primarily aimed to reduce the vulnerability of biodiversity and wetland ecosystem health to altered hydrological regime. Both structural changes, mainly driven by the conflicting cultural concerns of upstream and downstream residents, can be interpreted as a case of structural RFTI (Figure 1A). But the resulting changes of hydrological and natural systems are fed back to influence cultural concerns of the residents, resulting in feedback running in both directions between human systems and water systems.

Channelization, the goal of which was to enhance robustness to floods, initially performed well. Reduced flood intensity and variance limited damage to crops of downstream farmers. However, this improvement to hard infrastructure did not eliminate fragility but actually moved it to a different domain (from flooding to loss of biodiversity). Despite robust protection against floods, wetland health problems arose, creating a new threat to the sustainability of the coupled human-water system in the region. The channelization was an adequate solution with regards to flood protection but had an adverse impact with regards to wetland biodiversity. The government and society perceived this emergent vulnerability only after the degradation of the wetlands and thus started a restoration project in the Kissimmee River Basin to recover already diminished wetlands. The restoration project, while still ongoing, has recovered substantial wetland habitat that was destroyed by the channelization. In the course of restoration, however, the government considered both flood protection and the area's ecological health. While some amount of flood risk is inevitable now in the downstream region, it is limited to an acceptable level. The wetlands, meanwhile, have improved substantially, recovering almost back to the original level. In summary, application of RFTO to the case helps an analyst to think about potential fragility tradeoffs across entirely different domains or scales (floods vs. biodiversity), as opposed to across different levels of a scale (frequent vs. rare floods), that arise as a result of structural changes.

5.3 CMLS analysis

Cultural evolution and the CMLS theory help us interpret the multi-level social changes that likely have occurred in the Kissimmee River Basin, which are primarily due to the regional conflict in cultural values between downstream residents, who are less concerned with protecting the environmental, and upstream residents, who are more concerned. Chen et al. (2016) captured these changing norms over time using the composite variable of community sensitivity, but CMLS allows us to understand the detailed dynamics driving community sensitivity at multiple levels of social organization, including the individual, community (upstream and downstream), and federal levels.

Downstream residents have historically attempted to protect their farmlands from intensive floods because their crop yields are a direct function of flood damage. Floods thus serve as a powerful source of selection acting on farmers' preferences regarding flood protection. When destructive hurricanes in 1947 devastated crops, concerns about flooding spread rapidly through the population of downstream residents. These regional floods effectively shifted selection to the group level, as individual downstream residents were unable to protect themselves from floods without organizing collective action and making their voice heard to bringing about government intervention (the 2nd column in Figure 6). Yet at a higher level of organization, the group of downstream residents also had to compete with the group of upstream residents, who were not overly concerned about floods. Initially, downstream residents won this competition, because preferences for wetland conservation had not yet evolved. The overall frequency of preferences in the combined population thus favored increased flood protection, and at the federal level, the group acted to channelize the river (the 3rd column in Figure 6).

The channelization successfully protected farmlands by decreasing the intensity and variance of floods, but the resulting decline in wetlands resulted in the emergence of a new set of preferences among upstream residents, in virtue of a cultural norm favoring environmental protection. Among upstream communities, this norm-based preference was not constrained by the realities of agricultural flood protection. Downstream farmers, meanwhile, were still worried about flood damage to their farmlands. Due to the rapid population growth in the upstream region, however, preferences for wetland protection among upstream residents became more dominant in the general population overall than preferences for flood protection (the 4th column in Figure 6). As a result, the downstream group now lost the competition with the upstream group, the pendulum swung back in the direction of community sensitivity to the environment, and the government intervened to reverse the previous channelization project (the 5th column in Figure 6).

In summary, cultural evolution and CMLS theory help an analyst to account for the changing cultural norms over time in the Kissimmee River basin by illuminating multi-level processes that underlie community sensitivity. Instead of relying on the concept of community sensitivity itself to describe an important social change (e.g., Chen et al. 2016)., and thereby abstracting away from processes about why and how the relevant frequencies of individual preferences changed as they did, an analysis based on CMLS is capable of providing causal pathways through which these frequency changes, in terms of fundamental principles of cultural selection acting on different types of preferences within groups arising at different levels of social organization. Figure 5 illustrates our analysis, again employing the organizational levels of individual, community (upstream vs. downstream) and federal.

Figure 6 about here

6 Discussion: Complementarity of RFTO and CMLS

Socio-hydrology, or the study of coupled human-water system, is a research field still in its infancy, with much to be clarified. As such, the field still leaves room for further improvement from more perspectives that are theoretical. In particular, we argue that coupled human-water systems are part designed and part self-organized in nature and, thus, are in need of theoretical perspectives that assist our understanding of how the interplay between design and self-organization shapes emergent dynamics. A lack of unifying theoretical frameworks hinders the generalization of results between cases, as has been lamented in the related field of sustainability science (Levin and Clark 2010).

We have shown that theoretical cross-fertilization can overcome the generalizability problem in the coupled human-water systems of southwest Bangladesh and Kissimmee River Basin, Florida. Specifically, we have shown that the theories of RFTO and CMLS already provide excellent conceptual tools for linking and understanding the phenomena of the levee effect and pendulum swing in these two case areas. This generalization exercise has yielded some interesting comparisons. Both areas display significant built infrastructure developments: mega-scale embankments in coastal Bangladesh and the Kissimmee River channelization. Both regions also display a latter change in which built infrastructure is removed (Kissimmee River Basin) or is faced with maintenance problem (coastal Bangladesh). Moreover, both regions display changes in the level of social decision-making over time.

More importantly, RFTO and CMLS are complementary, rather than competing, in assisting our understanding of the phenomena. RFTO theory explains how over-all system changes, including structural modifications such as the construction of embankments or channels, can generate hidden endogenous risks. Built infrastructure is especially prominent in human-water relationships (Di Baldassarre et al. 2015), and thus important in socio-hydrology. This theory exposes an illusion of robustness from hard infrastructure improvement and can help identify potential dangers for system sustainability. The CMLS theory, meanwhile, concerns how human cultural dynamics can act as an endogenous driver of system change (Waring et al. 2015), a major challenge in theories of sustainability (Caldas et al. 2015). This perspective can strengthen our understanding of how human water management systems evolve. The key predictive mechanism of CMLS theory is that within a hierarchically organized society, the level of social organization at which environmental adaptations will emerge is the level that experiences the strongest evolutionary pressures for environmental management. Because modern societies have a nested structure of social organizations (Gowdy and Krall 2015), this insight is globally applicable. In addition, these two theory sets have one other important commonality; both CMLS and RFTO propose endogenous factors to help explain coupled human-water system dynamics. CMLS explains endogenous cultural adaptation to the environment as a result of social and environmental pressures and RFTO explains endogenous systemic weaknesses that arise as a result of fine-tuning of system designs. We believe that this endogeneity gives each theory extra value in understanding the socio-hydrological phenomena.

Applying two theories has gained us a few key benefits. From an RFTO perspective, structural modifications that seem to enhance the robustness of the present coupled human-water system may also generate concealed fragilities in other domains. When these fragilities are exposed to people, they abruptly bring failures of systems. Linking infrastructure alteration with human-water interactions in an RFTO concept, the theory assist our interpretation of the levee and adaptation effects. On the other hand, CMLS theory provided a way to identify the social factors that drive changes in system management by focusing on forces that enable individuals to act in individual or in the collective interest. For example, when the dominant level of cultural selection changes, we observed that major infrastructure projects were either undertaken or abandoned. Based upon this comparative exercise, we suggest that combining theories to suit a given case study may be an effective way to study and interpret coupled human-water systems. In the case of Bangladesh, for example, the RFTO theory does not sufficiently account for multi-level social processes that shaped infrastructure design choices, but CMLS theory clarify how social processes (e.g. collective action and social learning) influenced the engineering design choices and system stability after the design implementations. In the case of the Kissimmee River Basin, CMLS provides a more satisfying account of the shifting of people's collective preference for water resources allocation and accompanying social decision-making on engineering design by describing how social processes within and between levels in a nested hierarchy evolve in response to changing circumstances. However, CMLS does not clearly delineate how these multi-level social processes might transfer fragilities to other scales or levels within a scale, an aspect that is well addressed by RFTO

7 Conclusions

Socio-hydrology is a special case of social-ecological systems research with an explicit focus on water and coupled human-water system dynamics. Although coupled human-water systems tend to contain both designed and self-organized components, theoretical frameworks that assist our understanding of the interplay between design and self-organization have been elusive. We argue that this is particularly the case for emergent tradeoffs in system fragility that arise because of design choices and how social processes within and between the levels of organizational hierarchy influence and are influenced by such design choices. Thus, our goal here has been to contribute to addressing this gap by applying and developing insights on how the theoretical frameworks of robustness-fragility tradeoff (RFTO) and cultural multi-level selection (CMLS) can be effective in this regard. We have done so by showing how RFTO and CMLS can be applied to the levee effect and the pendulum swing cases in southwest Bangladesh and central Florida, respectively.

A single theory is limited in its demonstration of the complex nature of coupled human-water systems, but combined, theories such as RFTO and CMLS can complement each other, connecting discontinuous stories and enriching the field of socio-hydrology with generalized interpretations. In this way, we will be able to better identify and analyze causal relationships of historical events involved with water issues. This is not to say that place-based studies are less important. By reflecting the unique contexts of a place and its water history, place-based studies of coupled human-water systems can be valuable for generating rich context-specific understanding. However, from a long-term, systems thinking perspective, we argue that such place-based studies often exhibit recurring features that call for generalization. Combining general theories that address the part designed and part self-organized nature of coupled human-water systems can be effective in illuminating such common aspects across different place-based studies. Furthermore, generalized information from combined theories will not only broaden our insight into human-water co-evolution of the past but also help us cope with water sustainability crises in the future. Generalization from theories in combination can facilitate a more comprehensive analysis with long-term systems perspectives for the future water management. That is, it will be possible for policy makers to grasp complex interrelations among human behavior, water resources, governance arrangements, and built infrastructure, guided by synergistic insights from combined theories. This will help them implement policies and engineering designs that contribute towards water security and sustainability in long run.

LITERATURE CITED

Afroz, S., R. Cramb, and C. Grunbuhel. 2016. Collective Management of Water Resources in Coastal Bangladesh: Formal and Substantive Approaches. *Human Ecology* 44(1):17-31.

Amoako Johnson, F., C. W. Hutton, D. Hornby, A. N. Lázár, and A. Mukhopadhyay. 2016. Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges-Brahmaputra-Meghna Delta of Bangladesh. *Sustainability Science* 11(3):423-439.

Anderies, J. M. 2015. Managing variance: Key policy challenges for the Anthropocene. *Proceedings of* the National Academy of Sciences 112(47):14402-14403.

Auerbach, L. W., S. L. Goodbred Jr, D. R. Mondal, C. a. Wilson, K. R. Ahmed, K. Roy, M. S. Steckler, C. Small, J. M. Gilligan, and B. a. Ackerly. 2015. Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change* 5(2):153-157.

Di Baldassarre, G., M. Sivapalan, M. Rusca, C. Cudennec, M. Garcia, H. Kreibich, M. Konar, E. Mondino, J. Mård, S. Pande, M. R. Sanderson, F. Tian, A. Viglione, J. Wei, Y. Wei, D. J. Yu, V. Srinivasan, and G. Blöschl. 2019. Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. *Water Resources Research* 55:2018WR023901.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J. L. Salinas, and G. Blöschl. 2013. Socio-hydrology: Conceptualising human-flood interactions. *Hydrology and Earth System Sciences* 17(8):3295-3303.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, K. Yan, L. Brandimarte, and G. Blöschl. 2015. Debates-Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resources Research* 51(6):4770-4781.

Di Baldassarre, G., N. Wanders, A. AghaKouchak, L. Kuil, S. Rangecroft, T. I. E. Veldkamp, M. Garcia, P. R. van Oel, K. Breinl, and A. F. Van Loon. 2018. Water shortages worsened by reservoir effects. *Nature Sustainability* 1(11):617-622.

Bode, H. W. 1945. Network analysis and feedback amplifier design.

Bousquin, S. G., D. H. Anderson, M. D. Cheek, D. J. Colangelo, L. Dirk, J. L. Glen, B. L. Jones, J. W. Koebel Jr., J. A. Mossa, and J. Valdes. 2009. *Chapter 11: Kissimmee Basin. In South Florida* Environmental Report 2009, Volume I.

Boyd, R., and P. J. Richerson. 1985. *Culture and the evolutionary process*. University of Chicago Press, Chicago, IL.

Brammer, H. 2010. After the Bangladesh Flood Action Plan: Looking to the future. *Environmental* Hazards 9(May 2014):118-130.

Brooks, J. S., T. M. Waring, M. Borgerhoff, and M. Peter. 2018a. Applying cultural evolution to sustainability challenges : an introduction to the special issue. *Sustainability Science*

13(1):1-8.

Brooks, J. S., T. M. Waring, M. Borgerhoff Mulder, and P. J. Richerson. 2018b. Applying cultural evolution to sustainability challenges: an introduction to the special issue. *Sustainability Science* 13(1):1-8.

Caldas, M. M., M. R. Sanderson, M. Mather, M. D. Daniels, J. S. Bergtold, J. Aistrup, J. L. Heier Stamm, D. Haukos, K. Douglas-Mankin, A. Y. Sheshukov, and D. Lopez-Carr. 2015. Opinion: Endogenizing culture in sustainability science research and policy: Fig. 1. *Proceedings of the National Academy* of Sciences 112(27):8157-8159.

Carpenter, S., B. Walker, J. M. Anderies, and N. Abel. 2001. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* 4(8):765-781.

Chen, X., D. Wang, F. Tian, and M. Sivapalan. 2016. From channelization to restoration: Sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida. *Water Resources Research* 51(2):n/a-n/a.

Chudek, M., W. Zhao, and J. Henrich. 2013. Culture-gene coevolution, large-scale cooperation, and the shaping of human social psychology. Pages 425-257 *Cooperation and its evolution*.

Csete, M. E., and J. C. Doyle. 2002. Reverse engineering of biological complexity. *Science (New* York, N.Y.) 295(5560):1664-9.

Dewan, C., A. Mukherji, and M.-C. Buisson. 2015. Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders. *Water* International 40(3):401-416.

Ellis, E. C., N. R. Magliocca, C. J. Stevens, and D. Q. Fuller. 2018. Evolving the Anthropocene: linking multi-level selection with long-term social-ecological change. *Sustainability Science* 13(1):119-128.

Elshafei, Y., J. Z. Coletti, M. Sivapalan, and M. R. Hipsey. 2015. A model of the socio-hydrologic dynamics in a semiarid catchment: Isolating feedbacks in the coupled human-hydrology system. *Water* Resources Research 51(8):6442-6471.

Elshafei, Y., M. Sivapalan, M. Tonts, and M. R. Hipsey. 2014. A prototype framework for models of socio-hydrology: Identification of key feedback loops and parameterisation approach. *Hydrology and* Earth System Sciences 18(6):2141-2166.

Van Emmerik, T. H. M., Z. Li, M. Sivapalan, S. Pande, J. Kandasamy, H. H. G. Savenije, A. Chanan, and S. Vigneswaran. 2014. Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* 18(10):4239-4259.

Folke, C. 2016. Resilience (Republished). *Ecology and Society* 21(4):art44.

Gober, P., and H. S. Wheater. 2015. Debates - Perspectives on socio-hydrology: Modeling flood risk as a public policy problem. *Water Resources Research* 51(6):4782-4788.

Gowdy, J., and L. Krall. 2015. The economic origins of ultrasociality. *The Behavioral and brain* sciences Unpublishe(JUNE):1-63.

Grafton, R. Q., J. Williams, C. J. Perry, F. Molle, C. Ringler, P. Steduto, B. Udall, S. A. Wheeler, Y. Wang, D. Garrick, and R. G. Allen. 2018. The paradox of irrigation efficiency. *Science* 361(6404):748-750.

Gunderson, L., B. A. Cosens, B. C. Chaffin, C. A. T. Arnold, A. K. Fremier, A. S. Garmestani, R. K. Craig, H. Gosnell, H. E. Birge, C. R. Allen, M. H. Benson, R. R. Morrison, M. C. Stone, J. A. Hamm, K. Nemec, E. Schlager, and D. Llewellyn. 2017. Regime shifts and panarchies in regional scale social-ecological water systems. *Ecology and Society* 22(1).

Hossain, M. Z., M. T. Islam, T. Sakai, and M. Ishida. 2008. Impact of tropical cyclones on rural infrastructures in Bangladesh. *Agricultural Engineering International: CIGR Journal* X(2):1-13.

Ishtiaque, A., N. Sangwan, and D. J. Yu. 2017. Robust-yet-fragile nature of partly engineered social-ecological systems : a case study of coastal Bangladesh. *Ecology And Society* 22(3).

Kandasamy, J., D. Sounthararajah, P. Sivabalan, A. Chanan, S. Vigneswaran, and M. Sivapalan. 2014. Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: A case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* 18(3):1027-1041.

Koebel, J. W. 1995. An Historical Perspective on the Kissimmee River Restoration Project.

Koebel, J. W., and S. G. Bousquin. 2014. The Kissimmee River Restoration Project and Evaluation Program, Florida, USA. *Restoration Ecology* 22(3):345-352.

Konar, M., M. Garcia, M. R. Sanderson, D. J. Yu, and M. Sivapalan. 2019. Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems. *Water Resources* Research 55(2):874-887.

Lebel, L., J. M. Anderies, B. Campbell, C. Folke, S. Hatfield-Dodds, T. P. Hughes, and J. Wilson.

2006. Governance and the capacity to manage resilience in regional social-ecological systems. *Ecology and Society* 11(1).

Levin, S. A., and W. C. Clark. 2010. Toward a Science of Sustainability: Report from Toward a Science of Sustainability Conference. Page *Toward a Science of Sustainability*. Warrenton, Virginia.

Liao, K. H. 2012. A theory on urban resilience to floods-A basis for alternative planning practices. *Ecology and Society* 17(4).

Loucks, D. P. 2015. Debates-Perspectives on socio-hydrology: Simulating hydrologic-human interactions. *Water Resources Research* 51(6):4789-4794.

Merz, B., S. Vorogushyn, U. Lall, A. Viglione, and G. Blöschl. 2015. Charting unknown waters-On the role of surprise in flood risk assessment and management. *Water Resources Research* 51(8):6399-6416.

Mesoudi, A., A. Whiten, and K. N. N. Laland. 2006. Towards a unified science of cultural evolution. *Behavioral and Brain Sciences* 29(4):329-347.

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

Montz, B. E., and G. a. Tobin. 2008. Livin' Large with Levees: Lessons Learned and Lost. *Natural* Hazards Review 9(3):150-157.

Mostert, E. 2017. An alternative approach for socio-hydrology: case study research. *Hydrology and* Earth System Sciences Discussions:1-14.

Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press, Cambridge, UK.

Reyes-García, V., A. L. Balbo, E. Gómez-Baggethun, M. Gueze, A. Mesoudi, P. J. Richerson, X. Rubio-Campillo, I. Ruiz-Mallén, and S. Shennan. 2016. Multilevel processes and cultural adaptation: Examples from past and present small-scale societies. *Ecology and Society* 21(4).

Richerson, P., R. Baldini, A. Bell, K. Demps, K. Frost, V. Hillis, S. Mathew, E. Newton, N. Narr, L.

Newson, C. Ross, P. Smaldino, T. Waring, and M. Zefferman. 2014. Cultural Group Selection Plays an Essential Role in Explaining Human Cooperation: A Sketch of the Evidence. *The Behavioral and brain* sciences:1-71.

Richerson, P. J., and R. Boyd. 2005. *Not by Genes Alone: How Culture Transformed Human Evolution*. Page *A Brand New Bird: How Two Amateur Scientists …*.

Roobavannan, M., T. H. M. van Emmerik, Y. Elshafei, J. Kandasamy, M. Sanderson, S. Vigneswaran, S. Pande, and M. Sivapalan. 2017. Norms and values in socio-hydrological models. *Hydrology and Earth* System Sciences Discussions(July):1-27.

Sanderson, M. R., J. S. Bergtold, J. L. Heier Stamm, M. M. Caldas, and S. M. Ramsey. 2017. Bringing the "social" into sociohydrology: Conservation policy support in the Central Great Plains of Kansas, USA. *Water Resources Research* 53(8):6725-6743.

Scott, C. A. 2011. The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico. *Water Resources Research* 47(6).

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

Srinivasan, V. 2015. Reimagining the past - Use of counterfactual trajectories in socio-hydrological modelling: The case of Chennai, India. *Hydrology and Earth System Sciences* 19(2):785-801.

Sultana, P., and P. M. Thompson. 2010. Local institutions for floodplain management in Bangladesh and the influence of the Flood Action Plan. *Environmental Hazards* 7891(January 2015):26-42.

Sultana, P., and P. M. Thompson. 2017. Adaptation or conflict? Responses to climate change in water management in Bangladesh. *Environmental Science and Policy* 78(October):149-156.

Sung, K., H. Jeong, N. Sangwan, and D. J. Yu. 2018. Effects of Flood Control Strategies on Flood Resilience Under Sociohydrological Disturbances. *Water Resources Research* 54(4):2661-2680.

Swapan, M. S. H., and M. Gavin. 2011. A desert in the delta: Participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. *Ocean & Coastal* Management 54(1):45-54.

Tellman, B., J. C. Bausch, H. Eakin, J. M. Anderies, M. Mazari-hiriart, and D. Manuel-navarrete. 2018. Adaptive pathways and coupled infrastructure : seven centuries of adaptation to water risk and the production of vulnerability in Mexico City 23(1).

Toth, L., A. Arrington, M. Brady, and D. Muszick. 1995. Conceptual Evaluation of Factors Potentially

Affecting Restoration of Habitat Structure within the Channelized Kissimmee River Ecosystem. *Restoration Ecology* 3(3):160-180.

Troy, T. J., M. Konar, V. Srinivasan, and S. Thompson. 2015. Moving sociohydrology forward: A synthesis across studies. *Hydrology and Earth System Sciences* 19(8):3667-3679.

Viglione, A., G. Di Baldassarre, L. Brandimarte, L. Kuil, G. Carr, J. L. Salinas, A. Scolobig, and G. Blöschl. 2014. Insights from socio-hydrology modelling on dealing with flood risk - Roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology* 518:71-82.

Waring, T. M., M. A. Kline, J. S. Brooks, S. H. Goff, J. Gowdy, M. a Janssen, P. E. Smaldino, and J. Jacquet. 2015. A multilevel evolutionary framework for sustainability analysis. *Ecology and Society* 20(2):art34.

Wilson, D. S., and K. M. Kniffin. 1997. MULTILEVEL SELECTION A N D THE SOCIAL TRANSMISSION OF BEHAVIOR 10(3):291-310.

Wilson, D. S., E. Ostrom, and M. E. Cox. 2013. Generalizing the core design principles for the efficacy of groups. *Journal of Economic Behavior and Organization* 90:S21-S32.

Yu, D. J., M. R. Qubbaj, R. Muneepeerakul, J. M. Anderies, and R. M. Aggarwal. 2015. Effect of infrastructure design on commons dilemmas in social−ecological system dynamics. *Proceedings of* the National Academy of Sciences 112(43):13207-13212.

Yu, D. J., N. Sangwan, K. Sung, X. Chen, and V. Merwade. 2017. Incorporating institutions and collective action into a sociohydrological model of flood resilience. *Water Resources Research* 53(2):1336-1353.

Zhang, Z., H. Hu, F. Tian, X. Yao, and M. Sivapalan. 2014. Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim River basin of western China. *Hydrology and Earth System Sciences* 18(10):3951-3967.

Fig. 1. Figure 1. A typology of robustness-fragility tradeoff (RFTO). (A) Structural RFTO represents a direct modification to a resource system structure (e.g., the construction of levees, dams, or irrigation canals) to reduce variability in a system output (e.g., water availability, flood risk, etc.). (B) Network RFTO. Two “source” resource systems whose outputs or benefit flows do not co-vary under a disturbance and a “sink” consumer system are connected through an exchange network. This exchange network reduces variability in the combined benefit flows to the sink system. (C). Feedback RFTO represents an insertion of feedback responses (e.g., control actions guided by pre-existing policies) to variations in a system state to achieve stability. (D) Structural and feedback RFTO combines structural RFTO and feedback RFTO, i.e., system structure is modified, and feedback responses are generated simultaneously. Adapted from Anderies (2015).

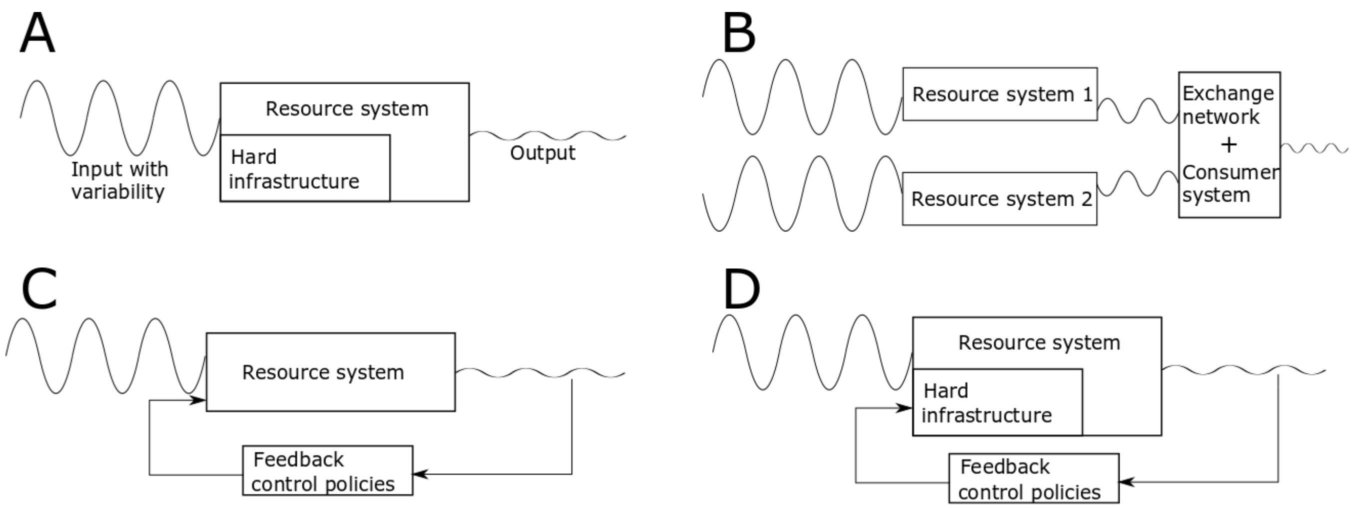

Fig. 2. Figure 2. traits through cultural selection. (b) A cultural trait (norm C) is unstable, being overrun by a mutant trait (norm A). (c) A cultural trait (norm C) is stable, resisting invasion by a horizontally transmitted mutant (norm A).

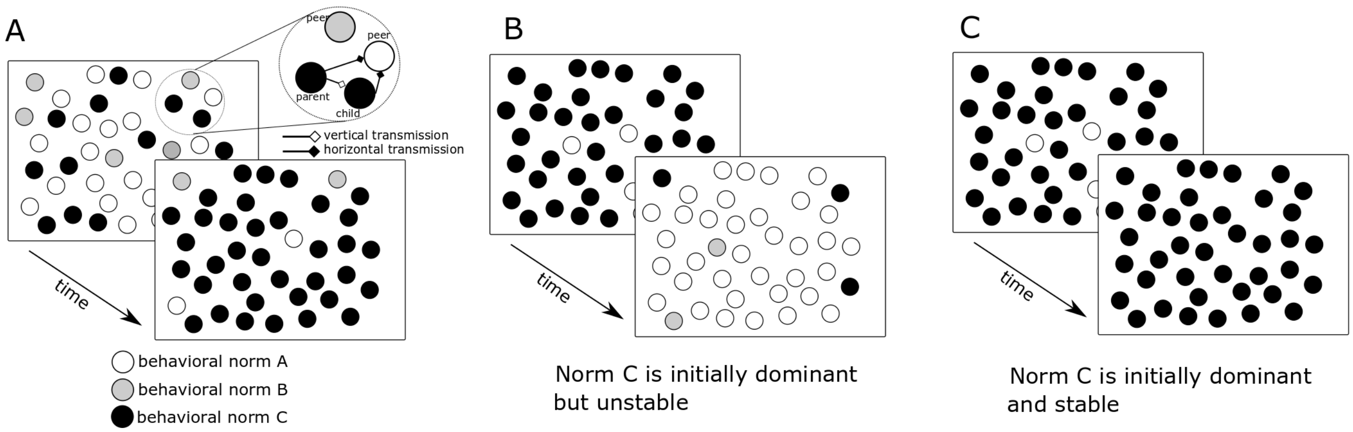

Fig. 3. An illustration of the cultural multi-level selection (CMLS) framework. Cultural selection can occur at multiple levels (individual, group, or both). When cultural selection is stronger at the group level, a group-benefiting cultural trait proliferates. When selection is stronger at the individual level, an individualistic trait is favored and spreads. Adapted from Waring et al. (2015).

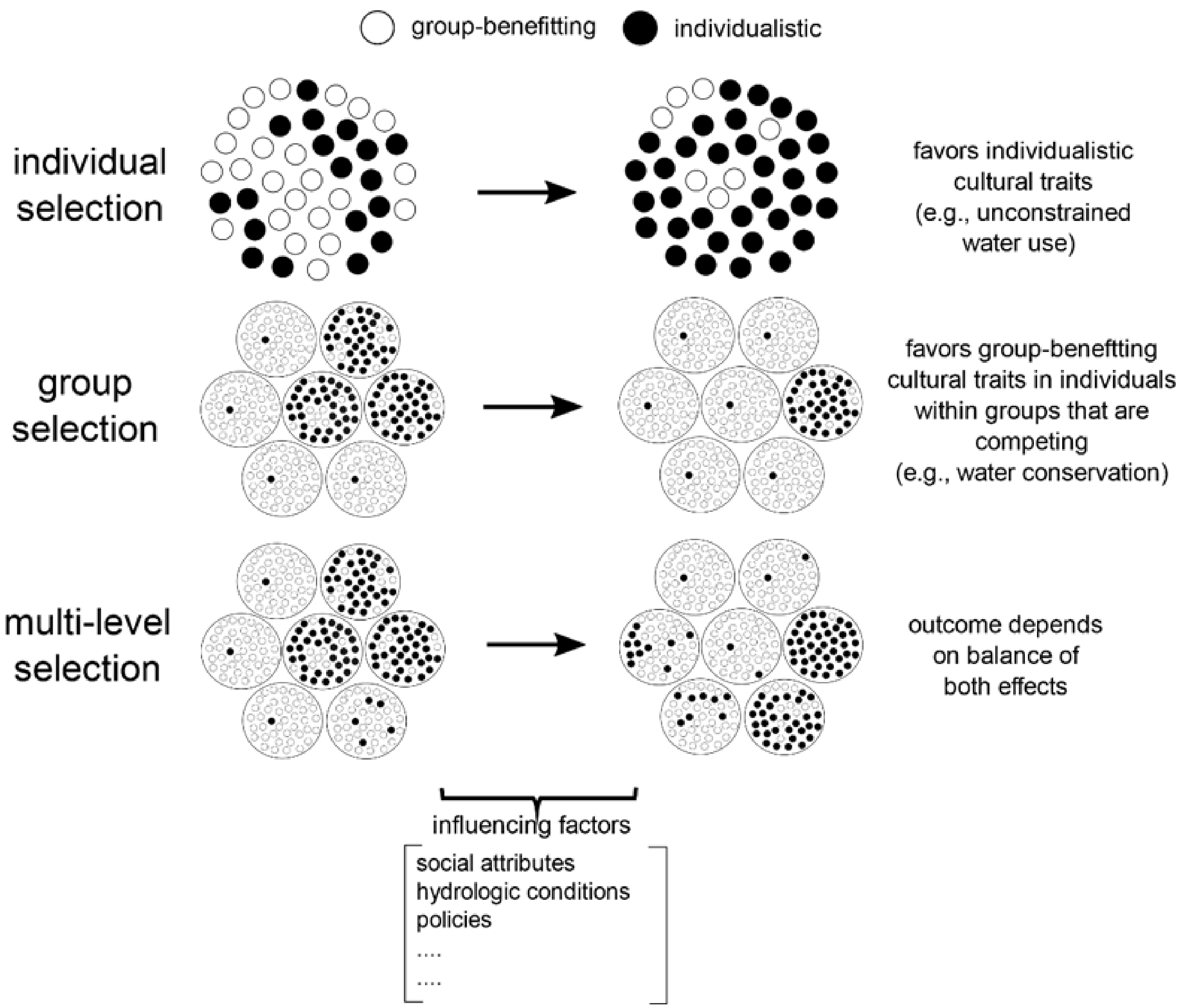

Fig. 4. (a) A conceptual cross-section view of polders. (b-c) A scenario of moderate flood protection level. The dynamics of three variables are traced over time under this scenario: peak water surge level (W), embankment height (K), and percentage of cooperator (X). This scenario shows that allowing moderate exposure to flooding can help maintain the community norm for collective action. (d-e) A scenario of high flood protection level. The dynamics of W, K, and X under this scenario show that the suppression of hydrological variability and the lost opportunities for social learning can cause the community norm to decay and eventually collapse. Adapted from Yu et al. (2017).

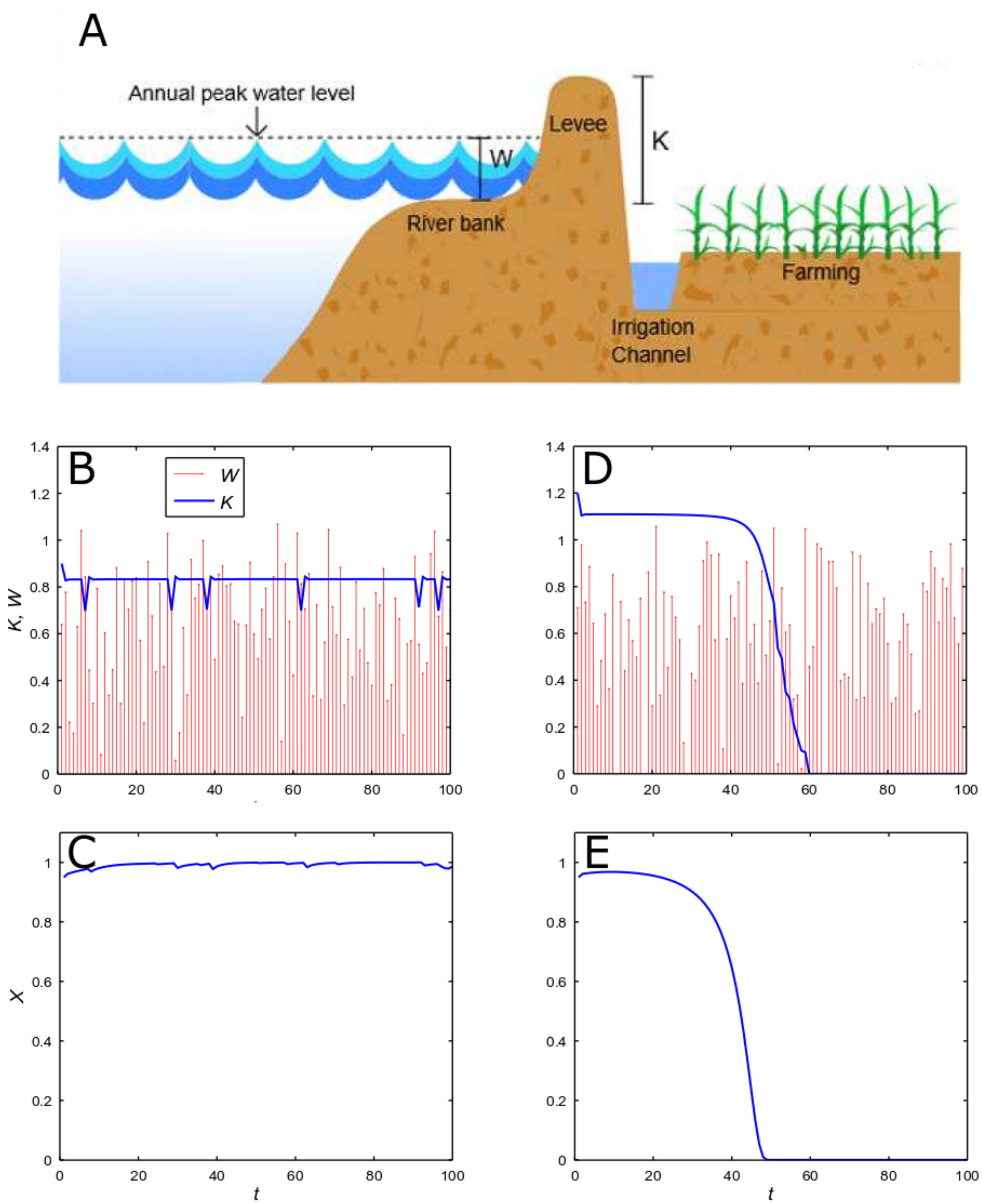

Fig. 5. A CMLS-style diagram of the levee and adaptation effects in the Bangladesh coast. Shaded boxes indicate the dominant level of selection. (+) signifies much improved prospect for extensive agriculture because of some actions taken at a particular level of organizational hierarchy; (-) signifies insignificant or negative effects on the prospect of extensive agriculture because of some actions taken at a particular level of organizational hierarchy; (↑) signifies collective action; and (↓) signifies positive effects of group norm on individuals' participation in collective action. In the second column, farmers only protected their farmlands, which made large-scale extensive agriculture difficult. In the third column, group level selection occurred, in the form of intervention by national government, which produced a large-scale flood protection infrastructure that enabled extensive agriculture. In the fourth column, however, the government failed to provide ongoing maintenance of this hard infrastructure, causing group-level selection to act at the community level, through informal norms, rather than through formal laws and policies. Finally, in the fifth column, these informal group norms continue to motivate and reinforce individuals' participation in the collective maintenance of the polder infrastructure in the face of ageing infrastructure and land sinking problems.

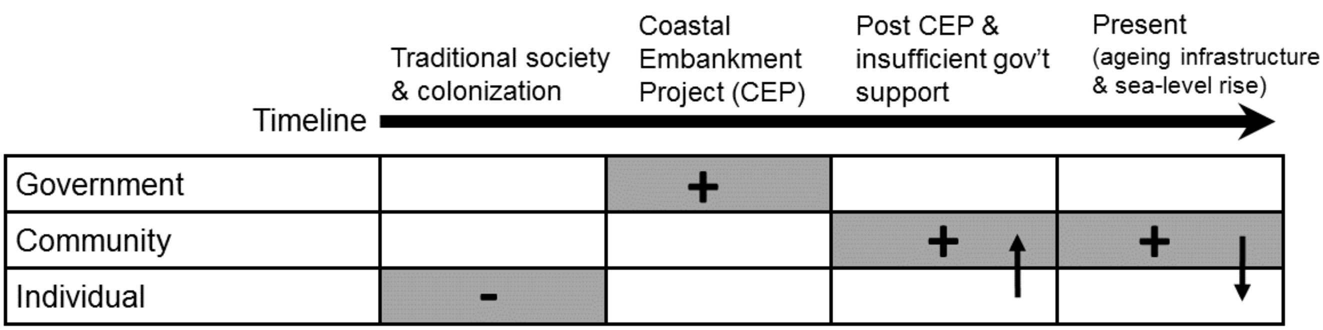

Fig. 6. A CMLS-style diagram, adapted from Waring et al. (2015), of cultural selection in the Kissimmee River Basin. (+) signifies positive outcomes or events; (-) signifies negative outcomes or events. The shaded cell represents the dominant level of selection or action. In the first column, the negative outcome of flood damage to farmland shifts selection from individual-level hydrological practices (e.g., nothing) to group-level collective action, and a collective preference for channelizing the river emerges in the downstream community. In the second column, selection favors the downstream community's preference over the upstream community's preference, and the overall preference, at the federal level, results in channelizing the river. In the third column, wetland degradation, along with norms of environmental conservation, create selection pressures within the upstream community favoring a preference for environmental protection over flood protection. Here, competition clearly occurs between two groups at the community level. In the fourth column, the competition is won by the upstream community; at the federal level, the collective preference is for reversing channelization.