EFFECTS OF FLOOD CONTROL STRATEGIES ON LONG-TERM FLOOD RESILIENCE UNDER SOCIO-HYDROLOGICAL DISTURBANCES

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ABSTRACT

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Human societies typically depend on hard engineering infrastructure such as dams and levees to protect themselves from floods. However, in this era of global change, this conventional approach is being increasingly challenged for its lack of adaptiveness. A growing number of studies suggest that an alternative strategy of flood control is needed to build long-term flood resilience. This study tackles this challenge by developing a conceptual model of the interplay between flood control strategies and long-term human-flood interaction. Our model development is motivated by a case of community-based flood protection system in coastal Bangladesh. We used the model to examine the effects of several archetypal flood control strategies (adaptive and non-adaptive ones) on the model community’s capacity to cope with hydrological variability, particularly the dynamics of this capacity under the external disturbances of sea level rise, tidal water level, and outside economic opportunities. The model results reveal vulnerabilities of conventional flood control strategies to the disturbances, and some of the ways how such vulnerabilities may emerge. The results also underscore the importance of adaptive strategies that dynamically mediate the feedback between social and hydrologic processes. These findings suggest that resilience-based, adaptive strategies can help build flood resilience under global change.
CHAPTER 1. INTRODUCTION

1.1 Problem Statement

Conventional flood control approach has focused on reducing the frequency of human exposure to flood events by relying on structural and technology-oriented measures such as river engineering, constructing embankments, or better forecasting of flood hazards [Vis et al., 2003]. However, this conventional approach, which is based on the principle of resistance or robustness to flooding, is being increasingly criticized for its lack of adaptiveness and because of empirical observation that nonoccurrence of small or “nuisance” flooding is associated with increased vulnerability to rarer flooding [Vis et al., 2003; Adger et al., 2005; Di Baldassarre et al., 2015]. These studies suggest that preventing small floods by hard infrastructures attracts new development in the floodplain, and induces catastrophic losses when the infrastructures fail. In addition, flood damage can be exacerbated by rigid, top-down approaches and increased uncertainty of flood events associated with climate change [Liao, 2014; Vojinovic et al., 2016]. Although heavy dependence on flood protection infrastructure is less desirable in the perspective of resilience thinking, it is necessary or the only option for some societies. Deliberate allowance of small floods to “live with floods” can be an alternative principle in designing flood protection infrastructure to build resilient capacity in general for the unknown and unknowable flood shocks [Liao, 2014; Vojinovic et al., 2014, 2016]. Thus, flood management should focus on not only building flood defense structures based on holistic and future-oriented assessments but also implementing and operating these structures by actively responding to changes in social and hydrological processes based on resilience thinking [Goytia et al., 2016; Barendrecht et al., 2017].
In this sense, dynamic adaptive controls, which rely on monitoring and adapting the management plan rather than implementing a fixed policy can be an alternative way of flood management to include provisions for being prepared for changes [Pahl-Wostl, 2006; Zevenbergen et al., 2013; Walker et al., 2015]. In addition, a school of thoughts now advocates a capacity of the society to cope with flood hazards which emerges from the interplay between hydrological and social processes [Di Baldassarre et al., 2013; Viglione et al., 2014]. The feedbacks between the water cycle and human society have come to the foreground, and this co-evolved system is called socio-hydrological system [Sivapalan et al., 2012; Gober et al., 2014; Blair and Buytaert, 2015; Loucks, 2015]. This socio-hydrological study focuses on investigating the dynamics emerged by those interplays in coupled human-water resources. The shape of the interplay between human and flood, in turn, usually determined by a flood control strategy which is continuously applied by a society. Broadly, flood control strategies can be categorized into two contrasting types: the traditional approach (command-and-control) for resisting floods and suppressing hydrological variability and the resilience-based approach of embracing uncertainty and learning to live with floods.

A growing number of scholars has emphasized the alternative way of flood control strategy to adapt to future flood risks. For example, Brown and Damery, [2002] suggested an institutional framework for managing floods focusing reinforcing physical and social resilience in U.K. Also, Stefanidis and Stathis, [2013] emphasized both natural and anthropogenic factors in analyzing flood hazard. Koks et al., [2014] studied that flood risk is reduced depending on the social vulnerability, i.e., the capacity of households to adapt and respond to floods. Based on this finding, the authors suggested the flood risk management should be tailored to a local level considering socio-economic characteristics of households and neighborhoods. Fuchs et al., [2017] emphasized
the public perception and information about floods in developing risk management plans. However, those existing studies are still lack of understanding feedback dynamics between social and hydrological system. Although socio-hydrological studies aim to capture those feedback dynamics, but these studies still underscore the importance of incorporating the adaptive control strategies for operationalizing flood resilience.

As mentioned, little research has been on done how different aspect of flood control strategies affects interplay between social and hydrological processes in the long run. Specifically, the socio-hydrologic modeling to explore how different control characteristics affect the long-term flood resilience is currently very limited. For example, the socio-hydrologic model by Di Baldassarre et al. [2013] analyzed only two opposing ends of a continuum of flood control strategies: the “green society” (no direct control) and the “technological society” (rigid control, e.g., the continuous heightening of levees). Similarly, the socio-hydrologic modeling study by Yu et al., [2017] generated their results in the context of only one control strategy which the control plan never changes during a simulation period. Although these studies made interesting forays into exploring the effects of basic control strategies, examined strategies are by no means the only ones that can be adopted by a society. Thus, further work is needed on how different characterizations of adaptive forms of flood control shape the long-term trajectories of human-flood interactions.

In addition, human-flood systems are experiencing accelerated changes worldwide in this era of global environmental change. The rate of change in some hydrological conditions is getting so fast that these conditions can no longer be treated as static or slow-varying variables in the time-scale of social systems change [Gunderson, 2010]. The rising land-sea level difference is one of the
most accelerated changes observed in the coastal areas of the world [Syvitski et al., 2009; Giosan et al., 2014a]. The relative sea level (RSL) change is driven by both sea level rise and land sinking downward from natural and anthropogenic causes and exacerbates flood risk and pose major challenges to flood management [Adger et al., 2005; FitzGerald et al., 2008; Tessler et al., 2015]. These low-lying deltaic environments are highly influenced by water discharge and vulnerable to impacts of climate change [Balica et al., 2012]. In addition, this directional change in land-sea level differences is further complicated by the increasing trend and variance of large seasonal water level fluctuation in many coastal areas of the world. [Auerbach, 2013; Pethick and Orford, 2013]. Although the two-way feedbacks between human actions and sea level rise or between human actions and floods have been highlighted, there is little research embracing all these three processes. Also, special flood control strategies considering characteristics of coastal system is required to reinforce adaptive capacity and resilience in coastal area [Sterr, 2008; Aerts et al., 2014; Rosati et al., 2015]. To bridge this research gap, this research includes the relative sea level(RSL) dynamics interplay with the human-flood system to focus on the coastal floodplain where is experiencing relative sea level rise.

In addition, temporary societies also live in the era of globalization. Populations residing in rural coastal areas are increasingly exposed to economic incentives that draw them away from traditional means of livelihood and community-organized activities that are labor-intensive [Di Baldassarre et al., 2014]. For example, widespread adoption of non-farm labor work (which tends to be less sensitive to the impact of flooding) can be an additional challenge to the farming oriented community because people’s participation in community collective action such as maintaining flood protection structure, which is often critical to community resilience, can be reduced.
1.2 Thesis Objectives

Based on the background mentioned above, this thesis aims to explore 1) impacts of different flood control strategies on long-term human-flood interactions 2) impacts of external disturbances (the pressures of rising land-sea level differences, seasonal water level fluctuations, and economic incentives that undermine voluntary actions) on the performances of the strategies. To achieve this goal, I conduct the conceptual socio-hydrologic modeling based on the case of community-managed flood protection system (polder) in southwest Bangladesh as an exemplary case in which flood control strategy and collective action for infrastructure maintenance are the key drivers of human-flood interactions.

To approach the goal, this study extends an existing socio-hydrologic model [Yu et al., 2017] that incorporated community-organized maintenance of a polder levees and informal institutions, or social norms, of people toward this collective action. The current research adds two new features to the model: feedback-driven flood control strategy dynamics and relative land-sea level difference dynamics. These two features will be integrated with existing model features (collective action dynamics, water level fluctuations, and economic incentives for non-farm work) to understand their combined effects on human-flood interactions. Specifically, this study borrows from the concept of feedback controls in the socio-ecological system (SES) to study the adaptive flood control strategies. As such, the socio-hydrological study can learn from SESs and coupled human and natural systems (CHANS) which have many similarities involving: feedbacks, adaptation, resilience, vulnerability [Blair and Buytaert, 2015]. So, this study applied adaptive feedback controls to a socio-hydrological system based on the study of Anderies [2014] in which viewed the SES as a part of self-organizing regulatory feedback networks. The stable feedback
system is closely related to sustainability of SES system. The logic of feedback control, which captures the self-regulating dynamics of a wide range of different classes of complex systems, provides a powerful set of ideas that facilitate characterization of flood control strategies.

Several qualitatively different strategies of flood control can exist: little or no control (e.g., allowing natural occurrences of floods), fixed control (e.g., trying to maintain a fixed set point in flood protection level regardless of changing conditions), rigid control (e.g., heightening levees every time flood damages occur), and more adaptive forms of control in which a set point for flood protection level is dynamically adjusted by a society through monitoring and learning. Further, within the adaptive forms of control, different characterizations are possible: being highly reactionary (i.e., decision is based on the most recent flood damage level), being mindful of the past flooding trend (i.e., decision is based on the past few years’ cumulative flood damage level), and being sensitive to the impacts of repeated flooding (i.e., decision is based on the rate of change in the recent flood damage levels).

In addition, the dynamics of relative seal level difference are formulated by incorporating hydrological processes and anthropogenic effect (e.g., reduced sediment aggradation from levees and land compaction). The relative sea level difference in agriculture-based, embanked deltaic areas are heavily influenced by these processes. Taken together, these model extensions provide an opportunity to understand the effects of flood control strategies under the presence of multiple pressures, and to search for general insights on how to enhance flood resilience.
This thesis proceeds as follows. In the following Chapter 2.1, the basic logic of adaptive feedback controls that applied for flood control strategies is explained. PID controller is explained as a basic structure of adaptive control. In Chapter 2.2, the study area in southwest Bangladesh is illustrated in socio-hydrological context. I explain the model framework in terms of flood control strategies, RSL change, and the base model of Yu et al.,[2017] and two flood disturbance scenarios: one with hydrologic disturbance and the other with combined hydrologic and economic (increased non-farm wage rates) disturbances are explained in chapter 3. Then, the simulation results regarding dynamics of social-hydrological system under various control strategies are illustrated in chapter 4. In Chapter 5, I presented the testing results regarding the performances of various flood control strategies under the two scenarios. In chapter 6, I discuss lessons learned regarding adaptive flood control strategies as a means to achieving flood resilience and briefly mention the possible further study.
CHAPTER 2. BACKGROUND

2.1 Adaptive Feedback Controls

This study examines several qualitatively different types of flood control strategies beyond the ones used by earlier socio-hydrologic modeling studies. The approach of this study is motivated by feedback controls in the social-ecological system (SES) that are part of self-organizing regulatory feedback networks. The stable feedback system is closely related to sustainability of SES system [Anderies, 2014]. The structure of feedback control systems is extensively studied in control systems engineering [Doyle et al., 1990]. Feedback controls are a fundamental building block of many engineered (e.g., cruise control) and biological (e.g., temperature regulation in human body) systems. Sustained functioning of these systems depends on their self-regulating processes for minimizing the error value between a set point and an actual value in some critical performance level. For example, human body tries to minimize the gap between 37 °C (a set point) and the current body temperature regardless of the external environment through self-regulating control processes such as sweating and shivering. Likewise, cruise control function of automobile vehicles also operates by the essentially same logic. A car senses its current speed, computes the error value between the target speed set by driver and its current speed, and then adjusts its speed (accelerate or decelerate) to reduce the error. In fact, all systems that sense internal and external states and regulate themselves to converge on a set point in a key performance level in the face of external variability can be thought of as a feedback control system. In this sense, adaptive forms of flood control strategy employed by human societies to maintain a certain flood protection level can be interpreted as a feedback control.
2.1.1 PID Control

The flood control strategies examined in this study are derived from a well-known feedback-control scheme referred to as Proportional-Integral-Derivative (PID) controller in control systems engineering [Doyle et al., 1990]. The PID controller operates via three fundamental processes: gather information from monitoring system conditions, make control decision based on the processing of collected information, and give corresponding feedbacks into the system to steer it [Anderies et al., 2013]. The logic of PID is as follows. Proportional (P) part of the controller tries to minimize the performance error by issuing control actions the strength of which is proportional to the size of the present error. In terms of flood control, this means that the larger the flood damage is, the stronger the ensuing flood prevention efforts are (i.e., being highly reactionary). Integral (I) part of the controller generates control actions based on the sum or integral of error values over a time period. This corresponds to a scenario in which flood control decisions are made based on past historical trends (e.g., the past few years’ cumulative flood damage level). Derivative (D) part of the controller generates control signals that are sensitive to the rate of change in, or derivative of, recent error values. This corresponds to a scenario in which flood control decisions are actuated only when repeated flooding damages with differing severity occur. The flood control strategies examined in this study will be formalized in terms of P, I, D, or some combinations of them.

Feedback controls can also operate at multiple levels: inner-loop and outer-loop (Figure 1) [Yu et al., 2016]. Inner-loop control involves continuous updating of control actions to better meet an existing set point. This kind of feedback control focuses on the question: Are we achieving the set goals? Outer-loop control involves updating of a desired set point itself. This type of feedback control concerns the question: Are we setting right goals? Thus, another way to characterize flood
control strategy is in terms of the levels of loop control. In the case of inner-loop flood control, actions are taken to adjust flood protection level to better meet a target level, while in the case of outer-loop flood control, actions are taken to update the target flood protection level itself. In this sense, the “green society” in the conceptual model of Di Baldassarre et al. [2013] can be thought of as the absence of P, I, D, and loop controls. The same model’s “technological society” scenario can be interpreted as a system with an outer-loop control based on rigid control (i.e., always increases target levee height whenever a high-water level exceeds previous target level) and an inner-loop control based on P that reduces the error to zero whenever there are enough financial resources.

Of course, in real-world human-flood systems, flood control involves much more complicated social and physical processes than what has been described above. However, the aim of the thesis is not to create the most realistic flood control scenario. Rather, I am aiming to understand the effects of several qualitatively different schemes of flood controls on the long-term dynamics of human-flood systems in a generalized way. Characterizing flood controls in terms of P, I, D, and levels of loop control facilitate the approach of this study toward this goal.
This study is motivated by the polders in southwest Bangladesh. Polder is a tract of floodplain enclosed by levees (or embankments) that are engineered to protect the area inside from flooding and storm surges. Southwest Bangladesh is also home to the Ganges-Brahmaputra river delta. Because much of the study area is about few meters above mean sea level and is below high tides level, the region is very vulnerable to climatic hazards such as floods, tidal surges or cyclones. Before the construction of polders, the study area was naturally inundated twice a day by low and high tides. This has made agriculture difficult in the area. To solve the problem, the Bangladesh government initiated a large-scale coastal embankment project that led to the construction of 37 polders comprised of 1556 km of levees in the region in the 1960s and 70s. Although this massive investment reduced flood risk, other problems began to appear as a result of the project, such as

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Figure 1. Block diagram explaining two loop-levels of adaptive flood control. The symbol $d_i$ represent internal disturbances (e.g., collective action problems) and the symbol $d_o$ represent external disturbances (e.g., extreme weather events). The circle C represents comparison between the current system state (current flood protection level) and desired set point (target flood protection level) for computing the error value. Inner-loop process involves control activities that are done to minimize the error. Outer-loop process involves updating of the desired set point itself.

2.2 Study Area: Ganges-Brahmaputra River Delta, Bangladesh

This study is motivated by the polders in southwest Bangladesh. Polder is a tract of floodplain enclosed by levees (or embankments) that are engineered to protect the area inside from flooding and storm surges. Southwest Bangladesh is also home to the Ganges-Brahmaputra river delta. Because much of the study area is about few meters above mean sea level and is below high tides level, the region is very vulnerable to climatic hazards such as floods, tidal surges or cyclones. Before the construction of polders, the study area was naturally inundated twice a day by low and high tides. This has made agriculture difficult in the area. To solve the problem, the Bangladesh government initiated a large-scale coastal embankment project that led to the construction of 37 polders comprised of 1556 km of levees in the region in the 1960s and 70s. Although this massive investment reduced flood risk, other problems began to appear as a result of the project, such as
waterlogging, rising land-sea level difference, and infrastructure maintenance issues [Tutu, 2005; Sarwar and Khan, 2007; Bakuluzzaman, 2012; Giosan et al., 2014].

![Figure 2](http://news.vanderbilt.edu/2015/01/flood-control-efforts-in-bangladesh-exacerbate-flooding-threaten-millions)

2.2.1 Sea Level Rise

Sea level rise is one of the most pressing problems in the study area. The RSL, which is the combined movement of both water and land levels, has been increasing at a rate of about 2.8 - 8.8 mm per year (note however that high water level has been increasing at a greater rate, with the average of 15.9 mm per year and the maximum of 17.2 mm per year). A World Bank report [2001] estimated that the sea level rise will reach about 1.0 m by the year 2100 and cause the inundation
of 17.5% of the total land mass in Bangladesh. Among diverse factors that are known to exacerbate the RSL problem, the presence of polder levees is thought to be the leading cause of the issue in this region [Sarwar and Khan, 2007]. Levees reduce frictional damping and constrict waterways, thereby causing an increase in tidal range as well as average sea level. Also, levees hinder the process of land subsidence recovery by impeding sediment accretion. Sedimentation through flooded water mitigates the land sea level difference. A study reports that the levee construction has significantly reduced the amount of sediments delivered into the polders in the region. [Goodbred and Kuehl, 1998; Auerbach et al., 2015].

Anthropogenic activities on deltaic lands intended for flood risk mitigation and agriculture have ironically exacerbated the issue of sea level rise in the study area [Pethick and Orford, 2013]. As reported by Auerbach et al. [2015], when a portion of the levees in polder 32 was breached in 2010, the area inside was covered by an average depth of 0.1 m of water during every high tide for 9.8 hours per day. However, adjacent mangrove forests (called the Sundarbans) was covered by a mean depth of 0.02 m of water during high tides. This difference in inundation level indicates the sediment starvation of the man-made polder lands. The land subsidence issue causes severe water logging problem in the polder. Another important problem caused by the land subsidence is the increase in saline water intrusion. The RSL issue causes both water and soil salinity to increase at a faster rate. The saline water intrusion induces fresh water shortage and soil degradation, which greatly reduces agriculture productivity. For every 0.3 m of sea level rise and the associated increase in soil salinity, there would be loss of 0.5 million metric tons of rice production [World bank, 2001].
2.2.2 Community Based Management

The communities in the study area also face the collective action problem of maintaining the polders. Due to the lack of governmental support, most of the polders have undergone serious deterioration in the condition in the last couple decades [Bhuiyan and Dutta, 2012]. For example, Bakuluzzaman [2012] describes that although polders were severely damaged by Hurricane Aila in 2009, the government provided little support to the repair work due to the lack of economic resources. Because insufficient and delayed governmental support is quite common, local communities in the polder have had to take on a greater role in maintaining the polder [Tutu, 2005; Afroz et al., 2016]. Community collective action is, therefore, critical for infrastructure maintenance, i.e., although some compensation is provided to the workers, most of the repair work is done on voluntary basis. People are willing to participate in the collective repair work because their livelihoods are at stake. Further, there is a strong social norm within the communities that motivate people to participate in the repair work [Bakuluzzaman, 2012]. Since the communities in the region are small in population and people interact with each other on a face-to-face basis, villagers can easily identify who are participating (or free-riding) in the repair work. Peer pressure and the possibility of social sanctions to free-riding behavior provide a powerful incentive for everyone to conform to the collective maintenance effort [Afroz et al., 2016]. However, as discussed by Yu et al., [2017], increased economic incentives for wage labor (e.g., increased wage rates for non-farm work) can weaken the level of voluntary participation.
The communities in the region take charge in decision-making for matters related to polder maintenance. Although there are formal government offices with the responsibility of managing flood infrastructure, few actual work-site operations are carried out by them. Instead, local communities organize village-level council meetings and meet regularly to decide which repair works are to be done. Items discussed include levee repair, operation of sluice gates, and management of funding and labor for the work. Diverse issues are discussed in these meetings, including whether parts of the levees need to be intentionally cut open to allow increased sediment inflow [Tutu, 2005] and which sections of the levees are particular more vulnerable to overflow and thus need to be fortified with extra effort [Lewis et al., 2008].
CHAPTER 3. CONCEPTUAL MODELING FOR THE SOCIO-HYDROLOGICAL SYSTEM

This model is based on the work of Yu et al. [2017], which was motivated by the experience of community-managed flood protection system (polder) in southwest Bangladesh. The aim of the modeling is to explore the effects of different characterizations of adaptive flood control strategies on long-term human-flood interactions under various disturbance scenarios. In this section, I describe the flood control strategies tested in this study, hydrologic and socioeconomic disturbance scenarios to which the model system is subjected to, and the base model structure. Before proceeding further, I would like to highlight that the purpose of this conceptual model is to better understand the generalized dynamics and underlying key drivers of human-flood interactions in rural coastal areas in a developing country context, not to generate accurate results for future prediction.

3.1 Flood Control Strategies

Several flood control strategies are tested: five adaptive forms of control and two non-adaptive ones. Adaptive control strategies are formalized by combining the P, I and D terms in various ways: P, PI_S (where I_S means integrating a performance error over a short time period), PI_L (where I_L means integrating a performance error over a long-time period), PD and PID. These adaptive controls are based on monitoring of two variables, social memory, and flood damage to determine the target level of flood protection. Flood damage occurs when water surge exceeds flood protection level, and the embankment breach can be occurred by structure erosion or extreme high tide water. Social memory is defined as a community’s inherited awareness level of flood risk based on past flooding events [Di Baldassarre et al, 2013; Viglione et al, 2014a]. The different
combinations are made depending on what types of information of variables are used for decision-making.

The P control only considers the present situation (e.g., if the current social memory is dropped below a certain level, the community reduces the flood protection goal). The PI strategies are created to explore the characteristics of the control methods that determine the flood protection goal by analyzing the cumulated past experiences with the current status. PI strategies are created in two different ways, depending on the time periods that influence to decide the target level of flood protection. The PI_{S} strategy uses the short-term period (5 years) and the PI_{L} strategy uses the long-term experiences over the last 20 years. The PD control monitors the current events and trends of the variables over the last 5 years (e.g., increasing or decreasing tendencies). The trend of variable change is related to a prediction of future errors. For example, if the flood damage has been increased recently, the community expects that the future flood damage will be increased. The PID control considers all three factors, including the current error, the integrated errors and the trend of the errors over the last 5 years. Detail process to estimate target protection level is explained in section 2.5.

In addition, fixed and rigid controls are used to represent a non-adaptive control. First, a fixed control does not modify the target flood protection level, regardless of the conditions in the community. This method is used in Yu et al., [2017], and I applied as a baseline strategy to compare to other strategies. Second, the rigid control does not consider a social memory but only uses the flood damage to decide a flood protection plan. Thereby, this method renews the protection goal in one direction that reinforces the levee height. This was created to describe the many engineered
societies in the real world, where the infrastructure keeps being intensified to solve the flood related problems.

3.2 Hydrologic and Economic Disturbances Scenarios

The possible impacts of climate change on coastal Bangladesh include an increase in the frequency of unexpected large floods and an increase in the average water level. Many researchers have proven that the water tidal level in Bangladesh has increased [World Bank, 2001]. Hence, unexpectedly large floods frequently occur, due to cyclones or a sea level rise [Sarwar and Khan, 2007; Syvitski, 2008; Auerbach et al., 2015]. However, only a few studies have predicted the water level or the flood frequency in the future [Karim and Mimura, 2008]. In addition, those results have limited accuracy due to lots of variance in seasonal tide and future environmental change [Brammer, 2014]. Considering this uncertainty, I created two simple scenarios of hydrologic change: 1) an average annual water tidal level change, and 2) a variance of water level change, through changing parameters of the water level distribution (Figure 2).

To create the scenarios, I analyzed annual peak tidal level data from 1977 to 2011 year at the Mongla tidal gauge, where is close to the polder 32. The water level data has a mean of 0.35 m and a standard deviation of 0.38 m, above the river bank. First, the Generalized Extreme Value (GEV) distribution was selected as the best-fitted water level distribution function. I then compared the characteristics of water level before (1977 - 1990) and after 1990 (1991 - 2011), since a significant increase in water level was observed around year 1990. To better understand the water level characteristics, the scale and location parameters of the GEV function of each data sets were calculated. The scale parameter is closely related to the variance of data sets, and the
location parameter determines the average of data sets. I found that the scale parameter changed from 0.07 to 0.31 after 1990, which indicates that the chances of occurring high return periods flow significantly increased. In addition, the location parameter is increased from -0.06 to 0.55 implying that the annual peak water tidal level has rapidly increased. Motivated by these results, the input water tidal level scenarios are created changing variance and average of the water level based on the data sets from 1991 to 2011. The variance of water level is simulated by changing scale parameters to a range between 0.1 and 1.0 (Figure 2a). Also, the shift of average annual peak water level was simulated by decreasing and increasing the location parameter of the GEV distribution from 0.35 to 1.05 m (Figure 2b). These scenarios reflect the recent trends and possible future changes of the annual peak water tidal level impacted by climate change.

In terms of the economic disturbance, I investigated the impacts of the rapid development of an urban area near the polder in Bangladesh. An economic development outside of the polder provides community members more chances to work outside of the polder instead of farming. The increase in the non-farming population may cause changes in the shape of the human-flood interactions. This concept is included in the model by increasing the outside wage rate from 0.03 to 0.05 in the middle of the simulation periods (time step 45 to 55 year).

3.3 Evaluating Performance of management strategies

The performance of flood management strategies is evaluated by means of the probability to maintain a social norm for collective action for the flood maintenance work. Maintaining collective action can be interpreted that cooperators who voluntarily work for the polder repairing are highly dominant in the community during entire simulation periods. The probability to maintain a high
rate of cooperators (PHC) is computed by 1) simulating 100 times with the randomly generated water tidal level based on the GEV distribution based on the data observed after 1990, and 2) counting the number of simulations where the rate of cooperators has not collapsed during the simulation period. In this study, the adaptive capacity to external disturbance can be interpreted as maintaining a high PHC. It is because the cooperation contributes the most to maintaining flood infrastructure, the ability to protect flood is greater with the high number of PHC. Thus, the flood control strategy with a high PHC is more likely to be adapted to the long-term socio-hydrological changes. In addition, the simulation is conducted in various hydrologic and economic disturbance scenarios. By doing this, this study explored how the climate change and increased livelihood options challenge the flood management strategies in terms of infrastructure maintenance.
3.4 Relative Sea Level Change Modeling

The RSL change is included in the model as a hydrological disturbance in addition to the annual peak water tidal level. The RSL is defined as a vertical change in the delta surfaces, relative to the local mean sea level. The dynamics of RSL change are estimated as a part of a socio-hydrological system that is closely related to flood risk and anthropogenic activities. The annual rate of the RSL is defined as: \( \Delta RSL \ (m/year) = A - \Delta E - C_N - C_A \pm M \) [Syvitski et al., 2009], where \( A \) is an aggradation rate, \( \Delta E \) is a eustatic sea level change, \( C_N \) is a natural land compaction, \( C_A \) represents an accelerated compaction and \( M \) is the natural subsidence movement. A positive RSL means the land surface is located above the mean sea level. Conversely, if the RSL value is below 0, the delta is below sea level.
The delta’s aggradation rate \((A)\) is determined by the volume of sediment delivered to and retained on the delta surface. The aggradation is the predominant source for recovering or increasing the RSL difference. The Ganges–Brahmaputra region creates a considerable amount of sediment accretion through overbank flooding or levee breach. This plays an important role in recovering the eroded land surface elevation \([\text{Auerbach}, 2013]\). However, flood-control structures along the waterways in the polder area inhibit sediment inflow contained in the flooded waters \([\text{Goodbred and Kuehl}, 2000]\). That is, as the community builds the levee higher, the volume of the overflow in the polder decreases, hence, causes reduced sediment accumulation. The annual sediment volume flow rate \((Q_d)\) through overtopped water \((Q_w)\) in polder 32 was estimated as:

\[
Q_d = \frac{C_s Q_w}{D_s} \quad (1)
\]

where: \(C_s\) represents the sediment concentration and \(D_s\) is the average soil density, which are 0.590 kg/m\(^3\) and 1600 kg/m\(^3\), respectively \([\text{Rice, 2007}]\). These values are assumed to be constant over time. In order to calculate the volume of the flooded water over the levee \((Q_w)\), a conventional equation is applied for rectangular and sharp-crested weir as below Equation (2) \([\text{Bagheri and Heidarpour, 2009}]\):

\[
Q_w = C_e \frac{2}{3} \sqrt{2gh_e W_b (h_e)^{3/2}} \quad (2)
\]

where: \(C_e\) is an effective discharge coefficient, \(g\) is an acceleration of gravity, \(W_b\) is the effective weir length, and \(h_e\) is the effective head overtopping the levee. The \(C_e\) is 0.601 determined based on the Kindsvater and Carter tests. The effective weir length and head are assumed to be levee length and levee height, respectively.
Then, I estimated the increased height of the polder ground by dividing the total sediment volume by the total study area. The annual sediment aggradation rate contained in the overflow was estimated using following Equation (3).

\[ dA = \sigma_A \frac{Q_d}{Area} \]  

(3)

Where: \( \sigma_A \) is a rate coefficient to account for the sediment loss. This coefficient is applied to consider the amount of sediment that did not contribute to recovering the polder ground.

The compaction rate is divided into the natural compaction (\( C_N \)) and the anthropogenic compaction (\( C_A \)). The natural compaction rate is the natural changes in the void space in the subsurface. It is normally about 3 mm/year [Syvitski, 2008]. The anthropogenic contribution to the subsurface volume change can occur by water, gas or oil extraction. Since irrigated agriculture is the predominant consumer of groundwater resources in the study area, the anthropogenic compaction (\( C_A \)) is assumed to be mostly affected by agriculture activity. Hence, the anthropogenic compaction increases exponentially as farming yield (\( Y \)) grows (Equation (4)). Both \( C_a \) and \( C_b \) are coefficients to convert crop yield into a compaction rate. These values are determined by regressing the historical data of the crop yield and compaction rate.

\[ C_A = C_a Y^{C_b} \]  

(4)

The rate of eustatic sea level change (\( \Delta E \)) represents the global volume change in the water over time. The variation in this volume depends on the storage change of water or geometric change of the basins that hold the water. \( \Delta E \) is estimated to 2 mm/year [Pethick and Orford, 2013]. Also, the subsidence (\( M \)) is the vertical movement of the land surface due to the tectonic activity or the crustal deformation. Goodbred and Kuehl [2000] estimated the actual subsidence in this region to be 2 - 4 mm/year. Hence, this study assumed that the subsidence rate of the polder was 3 mm/year.
Combining the mentioned variables, RSL is estimated annually as an external disturbance. The calculated RSL is generally about 1m - 2m after a hundred years and this value is similar to prediction of other study [Syvitski et al., 2009].

Figure 5.(a) Social and hydrological context of a community-managed polder in the study area. This region is experiencing water level rise and land level sinking. Social goal is to maintain the flood protection goal to a certain target level (K*). Broadly, community members adopt two behavioral strategies toward this social goal. Cooperators volunteer to reduce the gap between current protection level (K) and K*. Defectors do not contribute toward this goal. Flood damages occur when high water level (W) exceeds K. (b) Block diagram of feedbacks among social and hydrological variables (rounded rectangles) under the impact of external disturbances (sharp edged rectangles), where full arrows indicate positive correlation, dashed arrows indicate negative correlation and dotted line indicates that the relation can be either positive or negative. The outer-loop decides K* based on the current flood damage (F), dam breach (H) and social memory (M) (all marked in grey shaded rectangles) of the polder.
3.5 Modeling Human-Flood Interactions

Here I explain the base model structure describing the human – flood interactions. Figure 3a shows the essential social - hydrological features of the study area that are captured by model of this study. The community suffers from frequent floods due to high tide level, sea level rise and the land subsidence. To protect themselves from floods, community sets up the target protection level ($K^*$) using flood control strategies. The community members have two options regarding flood maintenance work, to be either a cooperator ($C$) or defector ($D$). Cooperators ($C_s$) make a cooperation to maintain the flood protection system. On the other hand, the defectors ($D_s$) do not participate in the levee repairing work but exit from the polder and take other sources of income when agriculture is impossible due to flooding.

The detail model framework inter-related with the mentioned socio-hydrological feature are presented in Figure 3b. The interactions between subsystems in the study area shed light on both the outer loop and inner loop of the feedback process of Figure 1. The outer loop in Figure 3b determines the intensified height of the target flood protection level ($K^*$) depending on flood control strategies. The system compares the $K^*$ with the current protection level ($K$), and the gap between $K^*$ and $K$ determines the amount of labor work for the flood protection system. Since only cooperators participate in levee repairing work, demanding levee repair reduces the benefit of cooperators ($\pi_c$) and increases benefits of defectors ($\pi_d$), which has a negative influence to maintain the number of cooperators ($X$).

The actual flood protection level ($K$) is determined by the inner loop process. The hydrological disturbances and actual flood protection level affect the intensity of flood damage and embankment
breach damage, and these damages cause salt water intrusion to the polder. The salt water damages crop yield which threatens the livelihood of the community members. Conversely, the flood/breach damage help to recover land sea level difference as well as maintaining social memory in the community. To protect themselves from flooding, each household can choose their behavior either to be a cooperator (C) or defector (D) of which provide the household to higher benefits ($\pi$). The complex interactions determine the adaptive capacity to flood in the polder. Details of each variable are outlined (Figure 3) in the rest of the section. The parameters used in the model are summarized in Table 1.

3.5.1 Flood damage from overtopped water and the levee breach

The flood damage ($F$) equation was modeled as shown in Equation (5). In this equation, flood damage occurs when the water level is higher than the embankment height. The existing equation suggested by *Di Baldassarre et al.* [2013] was tailored to the coastal region where the RSL increase contributes to exacerbating flood damage. When land sinks downwards, storms of a given magnitude reach higher elevations and inundate more extensive areas [FitzGerald et al., 2008]. Hence, the intensity of flood damage is affected by RSL as Equation (5).

$$F = \begin{cases} 1 - \exp(-\sigma_F W - \omega_F RSL), & W > K_0, \\ 0, & Otherwise \end{cases} \quad (5)$$

Here, $K_0$ is an embankment height right before the current flood, $W$ is annual peak tidal of water level. Also, $\sigma_F$ and $\omega_F$ represents a sensitivity coefficient converts the tidal water level and RSL to the flood damage, respectively.

Besides the flood damage by overtopped water tides, the breach of a flood protection infrastructure induces even greater flood risk. Most commonly, levees fail from structure erosion or overtopping
during storm events or high tides. Also, the sea-level rise and land subsidence destabilize levees, which increases the probability of levee failure [Suddeth et al., 2010]. Reflecting on the mentioned causes, a levee breach risk was modeled by modifying the work of Di Baldassarre et al. [2013] as shown in Equation (6).

\[
V = \begin{cases} 
1 - \exp(-\sigma_v(W - K) - \omega_v RSL), & W > K_- \\
0, & Otherwise 
\end{cases}
\]  

(6)

The levee breach occurs when the water tidal level \( W \) is higher than the current levee height \( K_- \). The model of this study captures that the breach risk depends on the flood level above the levee \( (W - K) \) and the RSL. The sensitivity factor of overtopped water \( (\sigma_v) \) and that of RSL \( (\omega_v) \) are determined by the levee conditions (e.g., material or erosion status). In the case that the embankment breaches, the breach damage \( (H) \) is denoted by \( H = \zeta W \), where \( \zeta \) is the breach coefficient that converts \( W \) to the level of breach damage. This study hypothesized that the RSL change increases the breach risk, and the damage intensity of embankment breach mainly depends on the water tide level.
Table 1. Parameters used in the socio-hydrological model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_e$</td>
<td>Effective discharge coefficient</td>
<td>RSL</td>
<td>-</td>
<td>0.601</td>
</tr>
<tr>
<td>$D_s$</td>
<td>Average soil density</td>
<td>RSL</td>
<td>kg/m$^3$</td>
<td>1600</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Average sediment concentration</td>
<td>RSL</td>
<td>[kg/m$^3$]</td>
<td>0.590</td>
</tr>
<tr>
<td>$C_a$</td>
<td>Compaction coefficient 1</td>
<td>RSL</td>
<td>m/kg</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$C_b$</td>
<td>Compaction coefficient 2</td>
<td>RSL</td>
<td>-</td>
<td>0.57</td>
</tr>
<tr>
<td>$\sigma_A$</td>
<td>Sediment loss rate</td>
<td>RSL</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\sigma_F$</td>
<td>Flood damage sensitivity to high water level</td>
<td>Flood damage</td>
<td>[m$^{-1}$]</td>
<td>1</td>
</tr>
<tr>
<td>$\omega_F$</td>
<td>Damage sensitivity to land-sea level difference</td>
<td>Flood damage</td>
<td>[m$^{-1}$]</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_V$</td>
<td>Breach risk sensitivity to overtopped water level</td>
<td>Breach risk</td>
<td>[m$^{-1}$]</td>
<td>5</td>
</tr>
<tr>
<td>$\omega_V$</td>
<td>Breach risk sensitivity to land-sea level difference</td>
<td>Breach risk</td>
<td>[m$^{-1}$]</td>
<td>1.5</td>
</tr>
<tr>
<td>$\delta_K$</td>
<td>Annual erosion rate of infrastructure</td>
<td>Flood protection structure</td>
<td>[yr$^{-1}$]</td>
<td>0.08</td>
</tr>
<tr>
<td>$\mu_M$</td>
<td>Rate of gain in social memory caused by $F$</td>
<td>Social memory</td>
<td>[m$^{-1}$]</td>
<td>1</td>
</tr>
<tr>
<td>$\delta_M$</td>
<td>Annual decay rate of social memory</td>
<td>Social memory</td>
<td>[yr$^{-1}$]</td>
<td>0.05</td>
</tr>
<tr>
<td>$\mu_S$</td>
<td>Rate of gain in soil salinity caused by $F$</td>
<td>Soil salinity</td>
<td>[dS/m/yr]</td>
<td>12.5</td>
</tr>
<tr>
<td>$\delta_S$</td>
<td>Leaching efficiency coefficient</td>
<td>Soil salinity</td>
<td>[yr$^{-1}$]</td>
<td>0.4</td>
</tr>
<tr>
<td>$P$</td>
<td>Price per unit crop output</td>
<td>Payoffs</td>
<td>[BDT/kg]</td>
<td>0.00017</td>
</tr>
<tr>
<td>$A$</td>
<td>Output elasticity of farming labor</td>
<td>Payoffs</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>$Z$</td>
<td>Wage rate for the outside employment work</td>
<td>Payoffs</td>
<td>[BDT/h-mos]</td>
<td>varied</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Default penalty for free riding</td>
<td>Payoffs</td>
<td>[BDT/yr]</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Default cost sanctioning</td>
<td>Payoffs</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>Cost of sanctioning for one unit of increase in the fraction of defectors</td>
<td>Payoffs</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>$\xi_M$</td>
<td>Multiplicative coefficients for additional penalty induced by social memory</td>
<td>Payoffs</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>$\Xi_x$</td>
<td>Multiplicative coefficients for additional penalty induced by cooperators</td>
<td>Payoffs</td>
<td>-</td>
<td>1.6</td>
</tr>
</tbody>
</table>
3.5.2 Soil salinity

Soil salinity ($S$) is one of the key factors that influences the crop yield. The high soil salinity due to floods damages agriculture output of the polder. The salinity dynamic is represented by Equation (7).

$$\frac{dS}{dt} = qF - \gamma S \tag{7}$$

Where: $q$ is the gain rate of salinity in the soil, and $\gamma$ is a leaching efficiency coefficient. The salinity in the soil increases as the flooded water filtrates into the ground; $qF$ reflects the process. In addition, the salinity can be reduced when the rainfall infiltrates the soil and the $\gamma S$ term explains the dilution process of the soil salinity.

3.5.3 Flood protection structure

The flood protection level ($K$) is represented by the embankment height above the riverbank. The dynamics of $K$ are illustrated as:

$$\frac{dK}{dt} = R - \delta K - H \tag{8}$$

In Equation (8), $R$ represents a newly repaired levee/embankment height every year through the collective action, $\delta$ is the annual erosion rate, and $H$ is the decayed height that occurred from the levee breach. $H$ is over 0 only when the dam breach occurs.

Regarding the management of the flood protection infrastructure ($K$), society has shared goals about flood protection levels ($K^*$) e.g. how much the embankment should be reinforced or released. The community members make cooperation in order to achieve $K$ to the same level of $K^*$. The
required amount of cooperation to close gap between $K^*$ and $K$ is called maintenance labor ($l_m$) and is related to the dynamics of social systems in the polder.

3.5.4 Target flood protection level

The target flood protection level ($K^*$) is determined by social memory ($M$) and flood ($F$) or levee breach damage ($H$). The size of levee adjustment ($u(t)$) is calculated using the PID equation (Equation (9)). The equation is applied separately to both social memory ($u_m(t)$) and flood damage ($u_f(t)$). Using these variables, $K^*$ is calculated as follows: $K^* = K^*_- + u_m(t) + u_f(t)$, in which $K^*_-\) is the current target flood protection level.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$ (9)

Here, $e(t)$ represents an error value, the difference between the desired value and the actual value at the time step $t$. Thus, the $e(t)$ for flood damage ($e_f(t)$) and social memory ($e_m(t)$) are shown below.

$$e_f(t) = 0 - \max(F,H)$$ (10)

$$e_m(t) = 1 - M$$ (11)

$K_p$, $K_i$ and $K_d$ are coefficients of error values of P, I and D controls, and are decided by manual tuning in a way to minimizing the error($e(t)$) over time [Astrom and Hagglund, 1995]. In this study, the coefficient sets are tuned to show the highest PHCs based on the input water level using original parameters. Those coefficient sets are determined differently for each strategy. Table 2 summarizes the types and rules of the flood management strategies developed in this study.
Table 2. Types and rules of flood control strategies. (Error represents a desired value of monitored variable – a current state of monitored variable)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Monitoring variable</th>
<th>Used information of monitored variables for planning flood protection level ($K^*$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (Little change)</td>
<td>Flood damage</td>
<td>Current error</td>
</tr>
<tr>
<td></td>
<td>Social memory</td>
<td></td>
</tr>
<tr>
<td>PIₜ (Short-term based PI)</td>
<td>Flood damage</td>
<td>Current error</td>
</tr>
<tr>
<td></td>
<td>Social memory</td>
<td>Cumulated errors for 5 years</td>
</tr>
<tr>
<td>PIₙ (Long-term based PI)</td>
<td>Flood damage</td>
<td>Current error</td>
</tr>
<tr>
<td></td>
<td>Social memory</td>
<td>Cumulated errors for 20 years</td>
</tr>
<tr>
<td>PD</td>
<td>Flood damage</td>
<td>Current errors</td>
</tr>
<tr>
<td></td>
<td>Social memory</td>
<td>Trend of errors for previous 5 years</td>
</tr>
<tr>
<td>PID</td>
<td>Flood damage</td>
<td>Current error</td>
</tr>
<tr>
<td></td>
<td>Social memory</td>
<td>Cumulated errors for 5 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trend of errors for 5 years</td>
</tr>
<tr>
<td>Fixed</td>
<td>-</td>
<td>Flood protection level is constant for the simulation period</td>
</tr>
<tr>
<td>Rigid</td>
<td>Flood damage</td>
<td>Flood protection level only increases</td>
</tr>
</tbody>
</table>

3.5.5 Dynamics of the collective action of cooperators

The social system is modeled based on the anecdotal records about the polder in Bangladesh. This model assumes that people mostly maintain their livelihood through agriculture that each household has the same farming yield with the same amount of labor. Each household can engage in three activities: farming ($l_f$), flood infrastructure maintenance ($l_m$), and employment outside of the polder ($l_e$). Each household decides how much labor is put into the different activities each year. This decision is made by their own judgment and the influence of their surroundings.
Especially, considering cooperation for the flood infrastructure maintenance \((l_m)\), each household can choose to be either a cooperator \((C)\) or defector \((D)\). Cooperators have a commitment to maintain a flood protection system, and allocate the rest of their labor to farming and outside employment. On the other hand, the defectors do not contribute to repairing the flood protection infrastructure. They only obtain the benefits of living inside the polder. The payoffs of the cooperators \((C)\) and the defectors \((D)\) are described in Equation (12) and (13):

\[
\pi^C = p(1 - F)b(l_{f}^C)^a(\alpha)^{1-a} + z(l_e^C) - \lambda[1 - \varepsilon(1 - X)]
\]  
(12)

\[
\pi^D = p(1 - F)b(l_{f}^D)(\alpha)^{1-a} + z(l_e^D) - \frac{L_f}{L_f - L_m} \gamma(1 + \xi X)(1 + \xi_M M)
\]  
(13)

Here, \(L\) is the aggregate labor of all households (i.e., \(L_f = \sum_{i=1}^{n} l_f, L_m = \sum_{i=1}^{n} l_m, L_e = \sum_{i=1}^{n} L_e\)). \(X\) and \(1 - X\) represent the rate of the cooperators and defectors, respectively. Each year, people choose a strategy that gives them higher benefits between \(C\) or \(D\). This strategy is imitated by the people around them. An expected rate of cooperators \((X)\) is described by a standard replicator equation [Nowak, 2006]. Equation (14) shows the replicator equation for estimating the dynamic of the \(X\) rate used in this study.

\[
\frac{dX}{dt} = X[\eta(\pi^C - \bar{\pi})]
\]  
(14)

\(\bar{\pi}\) is an average payoff, and is calculated as \(\pi^C X + \pi^d (1 - X)\). The equation illustrates that the rate of \(X\) increases as the payoff of \(C\) is large and the current rate of cooperators is large. In other words, if the number of \(C\)s is larger than \(D\)s, more people in the community take a collective action for polder repairing work as \(C\)s.
3.5.6 Social memory

The social memory of the flood experience is an important driver for the awareness of flood risk and taking action [Adger et al, 2005; Liao, 2012; Viglione et al, 2014b; Lazrus et al, 2016]. Collective memory can be modeled as follows [Di Baldassarre et al., 2009]:

\[
\frac{dM}{dt} = \mu_M F - \delta_M M
\]  

(15)

\( \mu_M F \) is explained as the magnitude of awareness or shock that was gained immediately after the current flood event; it is proportional to the flood damage. The parameter \( \delta_M \) is the annual decay rate of social memory. When society doesn’t experience a flood, the social memory decays until another shock occurs.
CHAPTER 4. FEEDBACK DYNAMICS OF HUMAN-FLOOD INTERACTION

I now present the modeling result investigating 1) how socio-hydrological system is shaped by various flood control strategies, and 2) the performance of flood control strategies is changed under external disturbance scenarios. In Chapter 4.1, performances of the flood control strategies are compared under various tidal level scenarios. Then, I show how the target and the actual protection level change under various flood control strategies during the simulation period. Here, the actual levee height represents the flood protection level of the community, the maintenance of which requires community collective action. Also, I also explore the effects of various control strategies on flood resilience when the model system faces RSL changes in addition to water level disturbances. Lastly, I examine the combined effects of the three disturbance scenarios (i.e., changes in water tidal level and RSL change and an increase in wage rate). I observes the number of times the community is maintaining a high rate of cooperators among 100 simulations to compare the performance of the strategies.

4.1 Dynamics of Infrastructure Level

Figure 6 illustrates an example of how the target flood protection goal ($K^*$) is updated by various flood control strategies as well as how the $K^*$ affects to the actual protection level ($K$). In the simulated example, the PD, PI, and PID controls (Figure 6d, 6e, and 6g, respectively) enable the model community to successfully cope with high water levels and maintain the polder throughout the simulation period. These successful strategies have two important characteristics. One is alertness or responsiveness in reinforcement of levee height based on continuous monitoring of the flood and levee break damages. Opportune levee reinforcement helps the community to protect
themselves from severe repeated floods and saline water intrusion. Another characteristic of the successful strategies is the easement of the target flood protection goal ($K^*$) based on monitored information of social memory. As can be seen in PD control (Figure 6d), $K^*$ continues to decrease after around 90th time-step because flood damages have been decreased or not occurred for many time-steps. $K^*$ of PIs and PID strategies (Figures 6e and 6g) are notably alleviated around 90th time-step because the target level is determined to be overly protective. This opportune easement of $K^*$ allows a moderate level of community exposure to floods, which helps to maintain social memory of flood risk and community social norm for collective maintenance of the polder. Further, allowing some degree of decay or easement of levee helps to alleviate the burden of levee repair work on cooperator strategy. This makes cooperators more competitive and thus, leads to improved flood resilience.
On the contrary, opposite stories occur in the fixed, rigid, P and PI strategies (Figures 6a-6c and 6f). Since the fixed strategy (Figure 6a) always tries to maintain an initial $K^*$ regardless of changing conditions, the model community gradually becomes exposed to floods or levee breach too often as the average water level and RSL increase. From the modeling context, frequent exposure to flooding is associated with continuous saline water intrusions, agricultural failures, and emergency...
repair works, causing a downward spiral to system collapse. The rigid strategy (Figure 6b) only focuses on reinforcing the levees; it does not monitor social memory and allow an opportune easement of levee height. Social memory of flood risk and social norms for collective action decline as a result. This strategy is allows robustness to floods in the short run through heavy reliance on built structures. However, the side-effect is that it becomes progressively costly or burdensome to organize and maintain the collective maintenance of the levees in the long-run. In the P control (Figure 6c), $K^*$ is updated through monitoring, but in a manner, that is not enough to effectively manage the flood infrastructure. Figure 6c shows the model community does not reinforce the flood protection goal high enough to protect severe floods in the early stages of the simulation. In the case of PI$_L$ (Figure 6f), updating of $K^*$ is driven by the summing up or integrating past experiences of flood damage over a longer period (20 years). Thus, if the external disturbances rapidly increase over time, this strategy may not adequately reflect the severity of the rapidly changing conditions on $K^*$. Further, as Figure 6f shows, memories of severe floods last for a longer duration under PI$_L$, so that $K^*$ might be unnecessarily maintained at a higher level even though $K$ could be sufficient for current conditions (see around 60$^{th}$ and 90$^{th}$ time-steps). This can burden cooperators and undermine sustained collective action. As such, the PI$_L$ control has the disadvantage of not being able to quickly respond to the rapidly changing conditions.
4.2 Dynamics of Soil Salinity and Social Memory

Figure 7 and 8 shows dynamics of social memory, soil salinity and rate of cooperators that feedback with given water and flood protection level in Figure 6. Under adaptive flood control (PD, PIₜ, PIₖ and PID), the polder infrastructure is maintained near the target level which is determined by the community. In this condition, agriculture is possible because soil salinity is low, also the social memory of flood risk is maintained (Figures 7d-7g). Having stable livelihood and awareness of floods induce more community members to participate in laboring for flood

![Figure 7](image_url)

Figure 7. Dynamics of social memory (M) and soil salinity (S) under various flood control strategies. The social memory is marked in blue line and the soil salinity is marked in red line. The simulation is conducted under the condition when sea level rise occurs but outside wage shock does not occur. Generated water level is shown in Figure 6. The flood control strategies include (a) Fixed (b) Rigid (c) P (d) PD (e) PIₜ (f) PIₖ (g) PID.
protection infrastructure (Figure 8d-8g). Hence, both the physical (embankments and soil salinity) and social (social norm for collective action and social memory) factors for reinforcing flood resilience are kept high.

As mentioned in previous section, the adaptive strategies design infrastructure allows some degree of hydrological variability. Thus, the residents face moderate flood damage about every 10 years. These external shocks undermine crop outputs and soil quality and negatively affect payoffs of cooperators through emergency repair duties, but keep the certain level of social memory. The combined effect of existing social norm for collective actions and the resulting social memory affects the level of social ostracism experienced by Defectors. These interactions determine the rate of cooperators (Figure 8) and finally reinforce flood resilience by adapting to social and hydrological situations of the polder.

In cases of non-adaptive management, in contrast, soil salinity increases because low rate of cooperators induces collapse of infrastructure (Figure 7a-7c). Thus, agriculture becomes impossible because of high soil salinity. Repeated crop loss induced by frequent flooding and high soil salinity, and excessive emergency repair work make the system unable to recover sufficiently before another flooding occurs. Thus, having alternative livelihood outside of the polder and defecting maintenance duty become more rewarding. The social norm for collective action eventually disappears as a result (Figure 8a-8c). High rate of defectors allows them to more easily spread in the community because the relative benefit of free riding increases and the social ostracism decreased. Once a sufficient number of defectors is spread, the system transitions to the trap of disaster-poverty cycle because the flood protection infrastructure has deteriorated.
significantly. The declined social ostracism, decayed infrastructure, and increasing maintenance costs causes the system to collapse.

Figure 8. Dynamics of social memory (M) and soil salinity (S) under various flood control strategies. The social memory is marked in blue line and the soil salinity is marked in red line. The simulation is conducted under the condition when sea level rise occurs but outside wage shock does not occur. Generated water level is shown in Figure 6. The flood control strategies include (a) Fixed (b) Rigid (c) P (d) PD (e) PIS (f) PIL (g) PID.
CHAPTER 5. PERFORMANCE OF FLOOD CONTROL STRATEGIES

5.1 Performances of flood control strategies under different water level scenarios

I subjected the model system to the input annual peak tidal levels shown in Figure 4. The variability of the water tidal level increases with the scale parameter of the fitted GEV distribution, i.e., larger uncertainties in water level and a possibility of unexpected large floods. A smaller value of the same parameter is associated with less uncertainties in annual peak tidal level and less variances in water level. The water level distribution is shifted to the right (i.e., water levels become higher in general) as the location parameter is increased.

As Figure 9 shows, the performance of the flood control strategies in terms of PHCs is sensitive to the disturbance scenarios generated by varying the scale and location parameters. PHCs generally decline when both parameters are increased. Under higher water levels, frequent and severe floods reduce agricultural productivity in the model polder. People abandon farming as a result, causing the community social norm for collective action to weaken. To make matters worse, frequent flood damages lead to more repair work to be done by the community members. Under these conditions, defectors thrive and eventually overtake the community, leading to a low or zero PHC. Meanwhile, all strategies show high PHCs when the parameter values are set to values around the current condition (vicinity of the vertical dashed lines in pink in Figures 4a and 4b). This happens because the initial flood protection level of the model is set to a moderate level that filters most of the floods and is less burdensome to maintain, i.e., the flood protection goal does not need to be modified significantly during the simulation periods. Under stable flood protection
goals with moderate external disturbances, the model polder can be maintained quite effectively with high levels of PHC.

Figure 9. The probability that the collective action for repairing flood protection structure remains resilient (PHC) under annual peak tidal level scenarios. The scenarios are created by changing (a) the scale parameter and (b) the location parameter of input water level distribution. Pink dotted line represents the parameter from the original data sets. The simulation is conducted 100 times for each scale and location parameter.

Note that the performances of two non-adaptive controls (the fixed and rigid controls) decline even when the variance and average tidal level are less than the original values, meaning that the model system fails under the favorable condition of more predictable and less uncertain conditions. Under this situation, the fixed control sticks to the initial protection level ($K^* = 0.9$) and the rigid control maintains the initial or even a higher protection level. This reduces the community exposure to moderate floods, and hence cause a rapid decay of social memory and weaken social norms for collective action. As a result, defectors thrive again and eventually overrun the model community population. In contrast, adaptive strategies allow the community to adjust to the changing disturbance regimes by monitoring the polder conditions and updating the target level of flood protection. No significant differences exist in the PHCs among the adaptive strategies.
Nevertheless, the PID control has a slight edge in the performance in both cases compared to others.

5.2 Performance of Flood Control Strategies Under RSL Change

Figure 10 compares the performances of the flood control strategies when RSL change occurs in addition to the variability in the input annual peak tidal levels. As expected, the PHC is less compared to the case when RSL change is absent. This happens because with the RSL difference (i.e., the combined dynamics of a land level sink and sea level rise), a larger damage will likely occur from a flooding event [FitzGerald et al., 2008], which makes it costlier for the community to maintain the polder and its agriculture-based livelihood. The impact of RSL change on PHC is more significant under the fixed and rigid control, while PHCs of adaptive controls are less impacted. Note that the performance of the PI_L strategy is significantly reduced with RSL. As discussed in Chapter 5.1, updating of $K^*$ based on overly long past data can hinder prompt reflection of rapidly changing conditions on $K^*$. The large performance gap between the PI_L and PI_S controls suggests the importance of getting the past data right (i.e., not too long in time period) for successful adaptive management of floods.
The model results also suggest the importance of considering the rate of change in recent conditions (the D part of the controls) to determine $K^*$. Figure 10 shows that, as the RSL and average water level increase (Figure 10b), the PID control has much higher PHC values than other control strategies. Similarly, the PD control is less affected by the RSL change compared to other strategies. These show two important things to consider in the long-term management of a community-managed flood protection system: 1) reflect the short-term social memory and the flood experiences and 2) reflect the expected future changes in social memory and flood damage, especially when the external disturbances change rapidly, by considering the rate of change in recent conditions.

![Figure 10](image)

Figure 10. PHCs under annual peak tidal level scenarios when RSL change occurs. The scenarios are created by changing (a) the scale parameter and (b) the location parameter of input water level distribution. Pink dotted line represents the parameter from the original data sets. The simulation is conducted 100 times for each scale and location parameter.
5.3 Effects of flood control strategies under hydrological disturbances and economic disturbances

The author now analyzes how the model human-flood interactions play out when they are subjected to both hydrologic disturbances and economic change. Figure 9 shows the PHCs of various water level scenarios, when wage rates for outside employment is increased. The modeling analysis is based on the following two cases: 1) the RSL change does not occur (Figures 9a and 9b) and 2) the RSL change occurs (Figures 7c and 7d). As can be seen in Figure 7, increased wage rates, or increased opportunity cost of maintaining agriculture-based livelihoods in the polder, clearly reduce the performances of the control strategies in all scenarios. This occurs because an increase in outside wage rates attracts more people to depend on non-farm livelihoods. Since non-farm wage labor opportunities are less sensitive to flood damage compared to farming, these people are less motivated to participate in the levee repair work, i.e., reduced social norms for collective action. Hence, defectors can more easily invade and spread in the population.

Figures 11a and 11b show that the sensitivity to PHC to increases in the variance and average tidal level is higher compared to that shown in Figure 4. Variations, however, exist in the performance levels of the control strategies under the hydrologic disturbances. The PID, PI_{S} and PI_{L} controls tend to enable the model community to perform better. The Fixed, Rigid and P controls, in contrast, are associated with lower performances. Figures 11c and 11d show that the flood resilience is significantly reduced when the community is exposed to both hydrologic disturbances and economic change. In this case, an increase in average water tide level (Figure 11d) has a larger impact on PHC than variance of water tide level (Figure 11c). Comparing the performances of all control strategies, this study finds that the PID control generally shows the best performance except
some specific cases (e.g., the location parameter is between 0.6 - 0.7 and the scale parameter is less than 0.4). Also, consistent with the previous sub-section, the performance of the PI_L control notably decreases as the RSL change occurs.

Figure 11. PHCs under annual peak tidal level scenarios when economic opportunities outside of the polder increase. (a) The scale parameter of tidal level and RSL change (b) The location parameter of tidal level and RSL change (c) Only scale parameters of tidal level change (RSL change does not occur) (d) Only location parameters of tidal level change (RSL change does not occur). Pink dotted line represents the parameter from the original data sets. The simulation is conducted 100 times for each scale and location parameter.
CHAPTER 6. DISCUSSION AND CONCLUSION

Flood management aiming to reinforce long-term resilience has received a considerable scholarly attention in the recent years. Scholars suggest that the conventional approach depending on robust infrastructure such as building levee can not always be an ideal solution because of emerging effects from feedbacks between the social and hydrological system [Barendrecht et al., 2017]. Rather, allowing some degree of flood exposure could be an alternative way to achieve flood resilience. Given that the flood resilience (the capacity of a society to cope with flood hazards) emerges from the feedbacks between hydrological and social processes, it is imperative to understand how this interplay is shaped by the flood control strategy adopted by a society. In this study, I used a term flood control strategy as a general protocol that characterizes how a society sets its desired flood protection level and based on what information and how the society attempts to achieve this desired target. To date, relatively little research has been carried out on the details of how different aspects of flood control strategies influence the interplay between hydrological and social processes and ultimately flood resilience in the long-run. Through this study, I filled this research gap by conceptual mathematical modeling and found out this modeling study can contribute to understanding impacts of broader concept of flood management on the long-term flood resilience under the wider range of possible futures, including unexpected disturbances.

To model the adaptive control strategies, this study borrowed the basic structure of feedback control loop from PID controller which is commonly used in control systems engineering. Then, I extended an existing conceptual socio-hydrologic model to describe feedbacks between human and flood based on the context of community-managed flood protection system in southwest Bangladesh. Through the modeling, the effects of these control strategies on long-term human-
flood interactions are analyzed especially under the pressures of rising land-sea level differences, seasonal water level fluctuations, and economic incentives that undermine the collective action in the community.

Results of study provide important messages to consider in managing floods. First, an increase in the water tidal level, rising RSL and economic change weakens the model community’s capacity to maintain its polder system regardless of the flood control strategies adopted by the community. However, flood control strategies determine degree of vulnerability. For example, the rigid control, which represents the general flood control used in many engineered societies in real world, seems to be robust in the short run under moderate external disturbances. However, it is potentially vulnerable to deviations from these moderate conditions. This vulnerability emerges from aggravated flood damage, soil salinity and the reduced benefit of cooperation. In contrast, adaptive flood control shows better performance in exacerbated disturbances.

Thus, the adaptive control strategy needs to be explored as an alternative to flood control to reinforce adaptive capacity to floods as the social – hydrological disturbances are exacerbating in the real world [Liao, 2014]. In that sense, the performance of PID control provides good insights to design future flood management. Properties of PID control tells the importance of comprehensive monitoring including the current, short-term past and expected polder condition. Note that the system monitoring should not only focus on hydrologic condition, but consider social conditions such as awareness of floods or the social norm for cooperation for repairing flood protection system.
An existed study of Gain et al., [2017] who evaluated the current river management system of Bangladesh also supported the idea. The authors emphasized the importance of transdisciplinary approach in managing river that integrates needs of hydrologists, local community and stakeholder, as well as the routine monitoring of key hydro and environmental indicators to evaluate the current management system.

In addition, this study shows that allowing moderate floods in the community ultimately helps the community to reinforce adaptive capacity by maintaining proper degree of social memory. As many studies have already highlighted, the flood experience could reveal the flood risk to the public and lead to better understanding of flood protection [Carpenter et al., 2015; Liao et al., 2016].

Third, this finding is in line with the concept of “rigidity trap” and “adaptive range,” which are general characteristic or status of a system that affect decision-making and adaptive capacity [Carpenter and Brock 2008]. Adaptive range is the social status in which the community is able to inspects system regularly and has enough resources to put their decision into practice. Rigidity trap is defined as the centralized and inflexible system that adhere to their current system. Where a system belongs (whether in an adaptive range or caught in the rigidity trap) influences the community adaptive capacity to deal with disturbances. Applying this concept to the current study, a system belonging in an adaptive range can be interpreted as a community that uses an adaptive form of flood control. The community keeps monitoring social and hydrological situations of the polder, and takes actions to achieve their target flood protection level. In contrast, the fixed or rigid control is related to the rigidity in this study, in the sense that the community adheres to the
conventional method of flood protection without considering changing environment. The rigidity trap represents societies that heavily rely on built structures to deal with flood-related hazards from rising RSL and variability in high water levels. These societies tend to not sufficiently consider social conditions such as the collective action or social memory. They prefer a command-and-control approach to subdue the variability of natural systems. This study presents an alternative view to this conventional thinking. Adaptive forms of flood control and embracing uncertainty through deliberate allowance of floods can help to improve flood resilience.

Lastly, this study shows that being exposed by both economic and hydrologic changes makes the collective maintenance of the model polder to be difficult. This supports the theory of double exposure [Brien and Leichenko, 2000; Akter and Basher, 2014], which suggests that climate change and economic globalization can potentially create synergies. The combined effects of climate and economic changes can significantly undermine the long-term resilience of a society to flood-related hazards [Brien and Leichenko, 2000]. Since many rural areas in developing countries, including Bangladesh, have experienced an increase in wage rates or labor mobility due to the economic globalization [Akter and Basher, 2014; Brammer, 2014], it is imperative to understand the impacts of double exposure on the rural societies and the design of effective flood control strategies to deal with the issue.

Taken together, this study suggests some directions for future studies. This research focused on the place-based modeling in a small-scale flood protection system maintained by the voluntary work of community members. As such, the effects of external centralized interventions (e.g., support of governments or NGOs) were not sufficiently considered. It will be interesting to explore
how incorporating the role of the external agencies can change the results obtained in the current study. In addition, the model can be modified to reflect the context of urban areas where the flood protection system is controlled by the centralized government and human-water interplays are more complex. Understanding centralized socio-hydrological system under expected land use, extreme events scenarios using spatial planning techniques will be meaningful to grow insights about flood resilience.
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