ADAPTATION TO GLOBAL CHANGE IN FARMER-MANAGED IRRIGATION SYSTEMS OF THE GANDAKI BASIN IN NEPAL

by

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DEDICATION

To my mother, father, and Sri Sathya Sai Baba

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The food security and livelihood of millions of marginal farmers depend on the productivity of smallholder farms that account for 50 percent of global farmland production. However, these farms are increasingly under stress from global change, including climate change, market integration, and international out-migration. In addition, there is limited information on how farmers and local irrigation institutions cope with and adapt to these multilevel changes. Using the case of 379 farmers located in 12 farmer-managed irrigation systems (FMIS) in the Gandaki Basin of Central and Western Nepal, this study explores how FMIS and farmers cope with and adapt to water stress. Drawing on empirical evidence of these FMIS, I build on the understanding of adaptive capacity -- a central aspect of institutional adaptation -- based on five capitals (human, social, physical, natural and financial) and two governance attributes. The institutional adaptation of FMIS can be broadly categorized into structural (e.g. canal lining, temporary dams) and operational measures (e.g. water allocation rules). Some of the factors that facilitate effective adaptation include collective action, leadership, and good governance as well as physical attributes including the presence of an economically feasible alternative water source. At the farmers' level, I studied crop choice, which emerged as one of the common adaptation strategies to global change, by incorporating multilevel drivers at household, institution, and regional level. The household attributes included farmer's demographic and socioeconomic characteristics, institutional information focused on irrigation system attributes, and regional variables included precipitation and temperature variables. The study showed that crop choice is driven by biophysical system, (measured by the size of the river that feeds the irrigation system),

market integration, and farmer's age. Climate change and variability act as a threat multiplier because they compound the existing impacts the system faces from social, economic and biophysical changes. Overall, the dissertation helps us better understand the institutional adaptive capacity that incorporates both the assets and governance-based dimensions, expands the typology of irrigated agriculture to include both the structural and operational measures. Further, the multilevel modeling adds as a quantitative tool to assess the effects of global change. The dissertation, therefore, makes theoretical, empirical, and methodological contributions to the literature on adaptation and resilience.

1. INTRODUCTION

Globally, smallholder farming, which is mostly done by single families on very small plots of land (0.2-0.5 hectares), contributes significantly to global food production and to the livelihood of millions of marginal farmers. It accounts for 50 percent of the global farmland and produces more than half of the world's food (Samberg, Gerber, Ramankutty, Herrero, & West, 2016). In Nepal alone, 2.1 million smallholder farms, each with less than 0.5 hectares of land, grow up to 70 percent of the country's total food (Rapsomanikis, 2015; Roka, 2017).

Many smallholder farms in developing countries rely on small and medium-scale irrigation systems, often well managed by local communities. In Nepal, 67 percent of the total agricultural land irrigated by surface water sources is managed by communities via farmer-managed irrigation systems (FMIS) (DOI, 2007). FMIS are autonomous institutions whose community members are responsible for overall irrigation management including water appropriation, distribution, canal maintenance, and conflict management through collective action. In Nepal, they are characterized by use of low-cost technology appropriate for heterogeneous local conditions, autonomous decision making suited to local sociopolitical contexts, and collective action for operation and maintenance of infrastructure (Lam, 2015; Ostrom, Lam, Pradhan, & Shivakoti, 2011; Thapa, Scott, Wester, & Varady, 2016). In the context of Nepal, FMIS have generally performed better than agency-managed irrigation systems that are managed by government agencies, because of FMIS' collective action and incentives for farmers to work together (Lam, 1996a).

Over recent decades, the irrigated agriculture in Nepal and many parts of the world is facing multiple drivers of change, including climate variability and change, urbanization, and market integration, collectively known as global change (Bastakoti, Shivakoti, & Lebel, 2010; Döll, 2002; Pokharel, 2015). Global change is changes in both the biophysical and human systems at different spatial scales that alter the dynamics of the Earth system (Rotmans et al., 1994). Climate variability and change have partly contributed to greater variability in the timing and intensity of precipitation, leading to increased frequency of drought and flood events (Douglas, 2009). In 2005/2006, the delay in the onset of the monsoon in the Eastern Terai region of Nepal reduced the national crop production by around 12.5 percent (Miller, Immerzeel, & Rees, 2012). Besides experiencing climatic changes, Nepal has also witnessed rapid urbanization and international out-migration -- both affecting the agricultural practices in unique ways. A study of land cover change in Pokhara, one of the major cities in the Gandaki Basin, between 1977 and 2010 found an expansion in urban area by 51 percent and reduction in the cultivated land by 30 percent (Rimal, 2012). The increasing trend of international out-migration has created shortages in the labor force, particularly of young agricultural workers, in some parts of Nepal (Bhandari, 2004).

However, many farmers have managed to continue their agricultural practices while coping with and adapting to these changes in at least two ways. At an individual level, farmers modify their agronomic practices, such as alteration of crop choices, seed varieties and planting dates (Chhetri, Chaudhary, Tiwari, & Yadaw, 2012). At an irrigation system level, farmers collectively alter water distribution rules and rehabilitate the irrigation system to meet the agricultural water demand (Yoder, 1994).

Though three decades of intellectual inquiry provide rich insight into multiple facets of FMIS in Nepal and other regions, limited studies have focused on climate change and FMIS. The early literature of the 1980's documented the organizational fperformance in irrigation systems in the hills and plains and demonstrated how the systems effectively function using local resources and collective action (Martin & Yoder, 1988; Pradhan, 1989b). Studies in the 1990's and 2000's explored the role of technological investments in collective action and design principles of long enduring irrigation institutions (Bastakoti & Shivakoti, 2012; Lam, 1996a; Lam & Ostrom, 2010). In the last decade, there has been increasing attention to the ability of FMIS to cope with and adapt to external disturbances including climate shocks (Bastakoti, Ale, & Shivakoti, 2015; Cifdaloz, Regmi, Anderies, & Rodriguez, 2010). While these literature provide useful insights on institutional adaptation strategies, they are either based on a single case study or have paid limited attention to adaptation against water stress. Similarly, very few studies have explored the household-level production heterogeneity within the irrigation system (Upadhyaya et al., 1993).

In light of these research gaps, this dissertation focuses on coping and adaptation strategies of households and institutions to two aspects of global change – market integration and water stress. I define water stress as the supply of water relative to the farmers' perceptions of the irrigation demand for the crop at a given time period (Yoder, 1994). Water stress is generally a result of biophysical and climatic changes, infrastructure conditions, water management rules, and socioeconomic conditions of the farmers. A rigorous understanding of the existing coping and adaptation strategies at household and institutional level can provide valuable insights into adaptation to present and future global change.

1.1. Research questions

The main objective of this research is to understand how farmers and FMIS are coping and adapting to water stress in the Gandaki Basin of Central and Western Nepal. In particular, I inquire:

i. What are the main components of adaptive capacity of FMIS?

ii. How do FMIS cope with and adapt to water stress? What are the effects of different institutional strategies on the agricultural performance of the irrigation system?

iii. What are the key determinants of crop choice among the farmers located in the FMIS during the monsoon season?

Each question is separately addressed in the appendices. Appendix A addresses the first question and identifies the main components of adaptive capacity of FMIS in the context of Nepal. I utilize the definition of adaptive capacity as proposed by Bettini, Brown, & de Haan (2015) where it is defined as "the ability to mobilize and combine different capacities within a system, to anticipate or respond to economic, environmental, and social stressors, in order to initiate structural or functional change to a system and thereby achieve resilient or transformative adaptation." It is a synthesis paper based on a review of the literature. Appendix B is an empirical paper based on field surveys where I identify different strategies adopted by the FMIS to cope with and adapt to water stress in the Gandaki River Basin. It also analyzes the implications of these adaptation strategies for the agricultural productivity of the irrigation systems. In Appendix C, I study the key determinants of farmers' crop choice, particularly the choice of rice over other crops, during the monsoon season with a focus on water stress. Since rice is a water-intensive crop, I analyze if water stress has driven the farmers to choose alternative crops. The study is based on the household survey of farmers located in the FMIS.

1.2. Explanation of the dissertation format

The dissertation consists of three appended papers that address each research question separately. The introductory section, which just begun, summarizes the overall research motivation that binds together the three papers. Following this is the literature review that gives an overview of the literature on FMIS and related theoretical framework and concepts that I draw upon from geography and other disciplines. This is followed by the study design and data collection. The results and conclusion in the introductory section highlight the main findings from the three appended papers.

2. LITERATURE REVIEW

In this section, I provide an overview of FMIS and the impacts of climate variability and change. This is followed by the literature on social-ecological systems, adaptation to climate change, human dimensions of global change, and adaptation typology and assessment of adaptive capacity. Since this dissertation is based on interdisciplinary research, I also review the literature on common-pool resources (CPR) which is situated in the economic governance and institution literature. My research builds on the intellectual legacy of these research domains. I conclude the chapter outlining the main contributions this dissertation makes to the existing literature.

2.1. Overview of farmer-managed irrigation systems

Nepal has a distinct history of irrigation systems managed by communities. Over the last two centuries, Nepalese farmers have constructed irrigation systems deliberately to intensify their agricultural production. This tradition gave birth to FMIS that are scattered all over the country (Pradhan, 1989). FMIS are local autonomous institutions in which community members assume the responsibility of governing water resources, including water acquisition, water allocation and distribution, and overall management of the system on an ongoing basis.

It was not until the Government of Nepal started to actively promote irrigation development in the 1980's that it recognized FMIS as an institutional entity (Pradhan, 1989). Currently, irrigation systems in Nepal are managed either as FMIS or as Agency-managed irrigation systems (AIMS). Under AIMS, government personnel is responsible for managing the system with varying levels of farmer participation (Pradhan, 1989). In contrast, in FMIS overall irrigation management is performed by the farmers themselves with minimal interference from outside agencies. FMIS only receive occasional financial and technical support from government agencies for infrastructure rehabilitation and institutional strengthening (Pradhan, 1989b). FMIS in Nepal are characterized by their use of low-cost technology appropriate for heterogeneous local conditions, autonomous decision making suited to local contexts, and collective action for the maintenance and operation of irrigation systems.

Despite the primitive infrastructure developed and employed by many FMIS, they are still important for food security and livelihood of Nepalese people. In Nepal, 960,000 hectares of the total agricultural land is irrigated by surface waters sources of which 67 percent are managed as FMIS (DOI, 2007). About 40 percent of the country's food requirements comes from these irrigation systems (Pradhan, 2012). As Nepal's population is expected to double by 2050, the country will face a significant challenge in meeting the domestic food security. The irrigated agriculture not only increases crop yield but also creates local employment opportunities (Smith, 2004). Irrigated agriculture thus contributes to both food and livelihood securities.

However, FMIS are facing multiple challenges. One of the main challenges in irrigated agriculture is the out-migration of male farmers from hills and Terai, which has at least two implications – it leads to labor shortage in agriculture thereby forcing people to bring the hired labor and technology, and there is less collective action for irrigation system maintenance (Bastakoti et al., 2015; FAO, 2016; Sugden et al., 2014). There is also an increase in competing water demand for other purposes such as drinking water and hydropower that reduces the water available for irrigation particularly during the dry season when the river discharge is low whereas water demand is high for both electricity and agriculture production (Parajuli, 2017; Scott, Crootof, Thapa, & Shrestha, 2016). Other challenges include an increase in urbanization that reduces the agricultural land for irrigation, and gradual deterioration of FMIS due to switch to non-farm livelihood sources (Khanal, 2018; Parajuli, 2017). Despite these challenges, many irrigation systems are functional with mixed performance. A longitudinal study of 233 FMIS in Nepal found that only 13 percent of the total canals were dysfunctional compared to earlier surveys in 1980's and 1990's; however, the functional FMIS had a heterogeneous performance characteristic (Pokharel, 2016).

2.2. Climate conditions, their variability and change and potential effects on farmer-managed irrigation systems

The diverse geography of Nepal gives rise to distinct climate conditions. Though Nepal is geologically divided into five zones - Terai and Bhabar zone, Siwaliks and intermontane zone, Lesser Himalaya, Higher Himalaya, and Tethys Himalaya (Dhital, 2015), for administrative purposes, the country is divided into three agro-ecological zones – Terai, which includes Terai, Bhabar, Siwaliks and intermontane zone; hills that mainly consists of Lesser Himalaya; and the mountains that includes Higher and Tethys Himalayas. The Terai and hills have the sub-tropical and warm-temperate climate, respectively, whereas the mountain region has cool temperate, alpine and arctic climate. The geography and regional circulation patterns of wind create three seasons in Nepal – wet monsoon between June and September, cold winter between October and February, and dry summer between March and May (Gyawali, 2003).

The two major regional circulations influence the summer and winter precipitation. During summer, the warm and moist air from the Indian Ocean moves towards the low-pressure Asian continent developing clouds and precipitation called the southwesterly monsoon of South Asia (Rohli & Vega, 2015). The monsoon typically reaches the eastern Himalaya by mid-June and deflects westwards by early July while losing intensity as it moves from east to west (Gyawali, 2003). As rain pours most of the precipitation on the windward side of the Himalaya, a rain-shadow region is created on the leeward side of the Himalaya, including Mustang, which is one of our study sites. Nepal receives up to 80 % of its total precipitation during the summer monsoon period. The winter precipitation is the result of relatively cold continental air from eastern

Europe and western Asia that breaks on to the Asian mainland from the west. In Nepal, though the winter rainfall accounts for only 13 percent of total annual rainfall, western Nepal receives relatively more winter rainfall than the eastern region (Gyawali, 2003).

Nepal has witnessed increasing climatic variability and change over the past few decades. While climate variability measures the variation in the mean state and other statistics of the climate over the long term, measuring the deviations from the long-term mean values are typically called anomalies. Climate change, on the other hand, measures variation in either the mean state of climate or in its variability, persisting for an extended period, typically decades or longer (WMO, 2018). The nationwide study of extreme precipitation trends in Nepal from 1966-2015 showed that there is no definitive country-wide decadal trend in 1-day extreme precipitation peak; however, there is an increase in extreme precipitation events in western mountainous regions and a mixed pattern in other regions including the Gandaki Basin (Talchabhadel, Karki, Thapa, Maharjan, & Parajuli, 2018). In addition, 32 percent of the total stations in Nepal have crossed the 1-day precipitation threshold estimated to trigger landslides (Figure 1). The study of seasonal precipitation change in the Gandaki River Basin showed a decrease in winter and pre-monsoon precipitation in the hills and a decrease in post-monsoon rainfall in the Trans-Himalaya region (Panthi et al., 2015). Similarly, the study of temperature trends from 1977 to 1994 showed that Nepal is warming at an average annual rate of about 0.06 ^{o}C per year (Shrestha & Aryal, 2011). More alarming is the fact that warming is more pronounced at higher altitudes, which has resulted in the retreat of major glaciers at the rate of 12-20 meter over the 10 to 15 year period. At the basin scale, precipitation rather than snowmelt has the dominant effect on river discharge in all the basins of Nepal

(Alford & Armstrong, 2010). However, the relationship between monsoon and streamflow is variable, which is partly attributed to complex topography and groundwater contributions (Hannah, Kansakar, Gerrard, & Rees, 2005). The instrumental study of river discharge showed an increasing trend for the Narayani River and decreasing trends for the Kali Gandaki, Sapta Koshi, and Koshi basins (Shrestha & Aryal, 2011).

Climatic variability and change can affect irrigated agriculture in several ways. The extreme rainfall events can trigger landslides and flood risks that can damage irrigation diversions, canals and agricultural land (Ostrom et al., 2011). The variability in precipitation events including onset and retreat of the monsoon season can directly influence crop choice decisions and alter crop productivity. For example, rice plantation requires significant water during the pre-monsoon and early monsoon season for land preparation. In Girwari FMIS located near the Narayani River within the Gandaki Basin, farmers perceive that September rainfall, which is critical for flowering and grain formation of rice cultivation, is decreasing; however, the unusual wet September in 2016 caused flood damage rather than alleviating water shortages for crops (Parajuli, 2017). In addition, many irrigation systems use the small seasonal tributaries that are dependent on rainfall for the discharge; however, many of them are drying up and farmers perceive climate change as the main driver (Parajuli, 2017; Poudel & Duex, 2017).

2.3. Farmer-managed irrigation systems as social-ecological systems

This dissertation adopts a broader social-ecological system (SES) framework as proposed by Ostrom (2011). Based on the Ostrom framework, the SES is composed of multiple subsystems, divided into four main categories – resource system (watershed), resource unit (water), users (farmers), and governance system (FMIS) (Figure 2). Each subsystem consists of different variables, with the SES framework allowing identification and analysis of the relationships among these variables at temporal and spatial scales (Ostrom, 2011).

Though there are variations in the definition of SES in different disciplines, they share some common characteristics. In ecology, SES is defined as the "nested, multilevel systems that provide essential services to society such as the supply of food, fiber, energy, and drinking water" (Berkes, Colding, & Folke, 2003). In CPR setting, SES are complex systems composed of multiple subsystems and internal variables within these systems at multiple levels, analogous to organisms composed of organs, organs composed of tissues, and tissues composed of cells (Ostrom, 2011). From an institutional perspective, Anderies, Janssen, & Ostrom (2004) define SES as an ecological system intricately linked with and affected by one or more social systems. Despite the variations in SES definition, the common characteristics of SES such as: *integrated and linked, nested and multilevel, complex, adaptive, and with mutual feedbacks.* The basic premise of the SES is that social and ecological systems are linked and any delineation between the two is artificial and arbitrary (Berkes et al., 2003). *Nested and multilevel systems* refer to larger systems containing the smaller subsystems. For example, at the biophysical level, multiple FMIS are located within a watershed. Similarly, the governance mechanisms including water appropriation and provisioning, irrigation monitoring and conflict resolution – as organized in multiple layers of nested enterprise, like smaller groups of farmers, Water User Associations (WUA), and local government and national agencies (Anderies et al., 2004) . *Integrated systems* are considered a complex system because they possess unique attributes of nonlinearity, uncertainty, emergence, scale, and self-organization that are not found in linear systems (Berkes et al., 2003). The interconnectedness of the biophysical system components, mainly the surface and subsurface flow, land use and cover, the groundwater and soil conditions, and larger scale hydro-meteorological factors exert considerable uncertainty and non-linearity in the system. *Adaptiveness* is the capacity to respond in a flexible way (Holling & Gunderson 2002). Since the systems are inter-linked in a nested framework, the SES can be characterized as having the capacity to exchange information, learning, and resources across scalar and temporal dimensions through *mutual feedback*.

In the case of irrigation systems, the FMIS consist of human agents (mainly the farmers), physical infrastructure (e.g. conveyance system, storage tanks), social infrastructure (e.g. trust, reciprocity, structured relationship), and institutional infrastructure (e.g. water allocation rules, and governance arrangements) (Anderies, Janssen, & Schlager, 2016; Cifdaloz et al., 2010). The ecological system on other hand consists of abiotic components, mainly the surface and sub-surface water, watershed, soil and other environmental resources supporting the FMIS. These are highly integrated and interactive across temporal and spatial scales through the nested and multilevel interactions.

I have adopted the SES framework to identify and understand the relationships among hydroclimatic, socio-economic, biophysical, and irrigation institutional variables in the context of FMIS. In particular, I focus on climatic, biophysical, socioeconomic, and institutional variables that are situated at different levels.

2.4. Climate change adaptation

While adaptation has its roots in cultural and human ecology and anthropology, geographers' study of climate change adaptation can be traced back to natural hazards research. In the book *The Environment as Hazard*, co-authored by Ian Burton, Robert Kates, and Gilbert White, adaptation is defined as an adjustment to reduce or minimize the risk from the natural hazard (Burton, Kates, & White, 1978). The main purpose of adaptation is to pursue preventive adjustment and reduce the damage through technological solutions, such as early warning systems, flood embankments, and drought-tolerant crop varieties. Adaptation is built on the premise that individuals choose from a range of possible options based on economic calculation and subjective evaluation (Bassett & Fogelman, 2013; Smit & Skinner, 2002).

The political ecology and political economy lenses have been used to study the social and causal factors driving vulnerability. Scholars have studied the role of social contracts in adaptation (Adger, Quinn, Lorenzoni, Murphy, & Sweeney, 2012); land tenure and economic drivers of vulnerability among farmers in Mexico (Liverman, 1990); impact of marginalization on social vulnerability (Ribot, 2010); and relationship between entitlement, poverty and famine in Nigeria (Swift, 1989). Political economists critique the natural hazards approach because it undermines social processes that are the causal factors exposing people to a wide range of social and biophysical stressors (Ribot, 2010). Watts (1983) studied the structural causes of famine in northern Nigeria and found that the time-tested agro-ecological practices that helped farmers to build their adaptive capacity against drought were slowly eroded by the European colonialism and new social relations of capitalist production. Based on Amartya Sen's capability approach (Sen,

2000) which focuses on strengthening the individual's opportunity to generate valuable outcomes such as freedom to choose the quality of life and well-being, scholars have also identified entitlements-based drivers of vulnerabilities such as social status and gender (Bohle, Downing, & Watts, 1994; Swift, 1989).

My research on adaptation is situated in the middle ground between these two views. Pelling (2011) and Ribot (2010) discuss an integrative framework where adaptation and vulnerability are studied by incorporating both biophysical and social factors. Many scholars have used the integrative approach to study climate change adaptation and vulnerability. Turner et al. (2003) proposed a system framework to assess vulnerability by incorporating biophysical and social factors in the assessment. Scott et al. (2013) used the societal-ecosystem-hydroclimatic interactions approach to study the interactions, dynamics, and uncertainties associated with water security and adaptive management in the arid Americas.

From an institutional perspective, Agrawal (2008) argues that local institution influence adaptation and climate vulnerability in at least three ways – they structure vulnerability, mediate between individual and collective response, and act as a means to deliver external resources to individuals. Wang et al. found that local institutions facilitate livelihood adaptation strategies among herders in Mongolia (Wang, Brown, & Agrawal, 2013). Similarly, Chhetri and Easterling (2010) revealed that multilevel coordination among stakeholders drives adaptive innovation in rice farming in Nepal.

2.5. Human dimensions of global change

My research also draws upon the literature on human dimensions of global change (HDGC) because they incorporate drivers of change at multiple spatial scales. HDGC scholars study problems at multiple scales usually from a systems' perspective. Butzer (1980) proposed multilevel and long-range planning to tackle global environmental changes such as atmospheric pollution. Liverman (1990) studied the factors driving vulnerability of farmers to drought and famine in Mexico to social relations, environmental conditions, health and demography and technology. Eakin (2005) conducted a multi-scalar and multi-stress assessment of rural vulnerability in Central Mexico and found that market integration alone may not mitigate the agricultural risks against drought. O'Brien and Leichenko (2000) proposed a double exposure framework where subjects are exposed to global environmental change and globalization resulting in some winners and losers. I expand upon the double exposure framework to incorporate changes at multiple scales at local to global levels. My study considers climate variability and change and local and regional market integration as potential drivers of global change. However, instead of focusing on winners and losers of these multilevel changes, I assess the impact of these drivers on farmer's agricultural productivity and FMIS performance.

2.6. Adaptation typology and assessment of adaptive capacity

Appendices A and B focus on characterization of adaptive capacity and formulation of adaptation typology respectively. There has been considerable work on developing the typology of adaptation. Spearman & McGray (2011) classified adaptive capacity into the generic and specific capacities. Generic Adaptive Capacity (GAC) addresses the structural deficits that are critical for the sustainability of a system (Lemos et al., 2013; Lemos, Lo, Nelson, Eakin, & Bedran-martins, 2016). It comprises of endowments that enable flexible responses to a spectrum of climatic and non-climatic stressors (Eakin, Lemos, & Nelson, 2014). Specific Adaptive Capacity (SAC) refers to strategies to manage the risk of climate hazards or other global-change drivers. SAC helps individuals by furnishing tools and knowledge required to anticipate and effectively respond to specific climate threats (Eakin et al., 2014). I use the existing typology of adaptation in agricultural and water sector to develop an adaptation typology for FMIS.

Assessment of adaptive capacity generally takes one of the two approaches. An asset-based approach emphasizes the five livelihood capitals (human, financial, natural, social, physical), usually applied at the household and institutional levels (Huai, 2016; Lemos et al., 2016; Shivakoti & Shrestha, 2005). On the other hand, a process-based approach emphasizes decision making processes including multi-stakeholder collaboration, flexibility, and learning (Dutra et al., 2015; Fernández-Giménez, Batkhishig, Batbuyan, & Ulambayar, 2015; Pahl-Wostl, Lebel, Knieper, & Nikitina, 2012). Nonetheless, the multi-dimensionality and latency of adaptive capacity, which makes it invisible until external (climate or other) event occurs, complicate the measurement of adaptive capacity(Berman, Quinn, & Paavola, 2012). My study attempts to incorporate both the asset- and process-based dimensions to define and operationalize adaptive capacity.

2.7. Common-pool resources and institutional adaptation

I also draw upon the literature on common-pool resources (CPR). Hardin (1968) argued that a shared resource system that is freely available to everyone will ultimately degrade and collapse because individuals will try to maximize the personal benefit motivated by self-interest. In contradiction, Olson (1965) argued that individuals also work on common interest through voluntary mechanisms. The topic of collective action in natural resources management grew into the literature of common-pool resources (CPR), which focuses on community-managed natural resources such as irrigation system, forestry, and fishery. A significant body of literature emerged in 1980's and 1990's on self-organization of CPR, seeking to better explain collective action, adaptive decision making and social and institutional learning (Bardhan, 2000; Benjamin, Lam, Ostrom, & Shivakoti, 1994; Lam, 1996; Lam & Ostrom, 2010; Ostrom & Benjamin, 1993; Pradhan, 1989; Scott & Silva-Ochoa, 2010).

Agrarian systems in the hills of Southeast Asia have also been analyzed from critical anthropology and political ecology perspectives. Scott (2009) argues that hill societies are "stateless spaces" where people are less governed by states and instead focus more on egalitarian, mobile and informal exchanges (gifts, labor, and other assets). People prefer the separation of the hills to avoid the rule of states authorities.

FMIS have also been explored through an interdisciplinary lens by incorporating socio-political, institutional, technical, and organizational perspectives, generally based on hydrosocial and materialist institutionalism theories (Roth & Vincent, 2012). Focusing on in-depth study of water sources, technologies, and institutions, Vincent and colleagues argue that hydrological, political and agricultural boundaries often also determine the adoption and evolution of FMIS technology and governance preferences.

A large database was developed in the 1990's on Nepal's irrigation system, also called Nepal Irrigation Institutions and Systems (NIIS) database. It was used in multiple studies including the institutional performance assessment between farmer- and government-management institutions (Bastakoti & Shivakoti, 2012; Lam, 1996a; Lam &

Ostrom, 2010). The database has been revisited to explore the relationship between irrigation performance and perceived fairness (Pokharel, 2016).

In the last decade, there has been increasing attention to the topic of FMIS capacity to respond to external and internal disturbances including climate shocks. Cifdaloz et al. (2010) highlight the trade-offs between robustness and efficiency in FMIS, i.e., as FMIS become robust to cope with specific climate shock, they may generate greater vulnerability to the novel, unforeseen shocks. Institutional attributes such as autonomy in decision making, flexibility in rulemaking, trusted local leaders, and strong social capital are crucial for irrigation systems to respond to market pressures and policy changes (Bastakoti et al., 2010). Adaptation strategies are not only affected by institutional characteristics but also by institutional nesting, i.e., multiple tiers of overlapped organizations operating at different spatial scales (Lam & Chiu, 2016). Systems that are tightly nested or institutions that have to follow higher-scale authorities for irrigation planning have a limited role in rule crafting and thus are vulnerable to the risks posed by external stressors (Lam & Chiu, 2016). Ostrom (2014) identified the evolution of rules to suit new contexts as another important attribute of institutional adaptation. Given shortcomings in the characterization of dynamic and interactive social and ecological processes, the Institutional Analysis and Development (IAD) framework has also been reconceptualized and refined to address the robustness of SES (Anderies et al., 2004) and coupled infrastructure system (Anderies, Janssen, & Schlager, 2016).

2.8. Contribution of the present study

The dissertation and specific results presented in the articles in Appendices A-C contribute and advance the literature in several ways. Taken as a whole, my work assesses the combined institutional and household adaptation to water stress in FMIS, which very few studies in the published literature have explored. Appendix A contributes to the CPR literature on institutional adaptive capacity. It adds to the literature on assessment of CPR and assessment of institutional adaptive capacity. Similarly, there is limited research on ground-based evidence of climate change adaptation (Cutter & Finch, 2008). Appendix B contributes to the literature by offering empirical evidence of adaptation actions in FMIS. Also, many scholars have pointed towards the difficulty of integrated assessment of adaptation by incorporating political, economic, biophysical and household factors (Eakin & Luers, 2006; O'Brien, Eriksen, Nygaard, & Schjolden, 2007; Smit & Wandel, 2006). Appendix C offers a methodological contribution to the assessment of adaptation to global change. The econometric modeling disaggregates the impacts of the multilevel variables.

3. STUDY AREA, SAMPLE DESIGN AND DATA COLLECTION

The study was conducted in the Gandaki River Basin (GRB) of Central and Western Nepal (Figure 3). Originating in the mountain region of Central Nepal and Tibet, the GRB has a total catchment area of 46,300 km^2. It is a major river system providing water for agriculture, households, and energy for one-third of Nepal's 28 million people. The transboundary GRB consists of the Trishuli River that originates from the autonomous region of Tibet and the Kali Gandaki River that originates in Tibet and meets the Trishuli downstream in the lowland areas of Narayani district.

The study was conducted in five administrative districts of Central and Western Nepal. Mustang and Rasuwa are located in the Trans-Himalayan and Himalayan region respectively whereas Nuwakot and Dhading districts are located in Mahabharat range in the hills (Dhital, 2015). Chitwan district is located in Terai, which is the relatively flat lowlands in the southern parts of the country.

3.1. Sample design

The research used a stratified sampling of FMIS. An appraisal survey was conducted for 25 randomly selected FMIS in mountain, hills, and Terai regions (Appendix E). Basic information was collected on governance, agricultural practices, and water sources. From the list of 25 FMIS, 12 FMIS were selected for in-depth study based on two parameters –geography and size of the river (Table 1).

Geographically, I clustered FMIS based on their locations in mountains, hills, and Terai. The type of biophysical risks and adaptive responses differ according to the geography that has distinct elevation, cultural, socioeconomic, and institutional configuration. For example, mountains and hills face the risk of flash floods and debris flow whereas meandering of the rivers is common in flat Terai region.

The second parameter of segregation was river category. Since the study focuses on adaptation to water stress, I selected FMIS based on the water source of the irrigation canal; in all cases, these were rivers and springs. I assumed that water stress is strongly correlated with the size of the river – irrigation systems from large and perennial rivers have relatively more water available for irrigation compared to the systems by fed by small- and medium- size rivers.

A household survey was also conducted in these 12 FMIS using stratified sampling. Around 30-45 household were randomly selected in each FMIS. The samples were around equally distributed in the head, middle, and tail sections of the irrigation system. The stratification was done based on the location of the farmers in the canal because farmers who are located at the tail section of the canal are generally more water stressed than those located at the head and middle sections.

3.2. Data collection

I collected data through household surveys, focus group discussions (FGD), and transect walk. The household survey covered information on household demography, agricultural practices, climate change perception and perceived institutional performance. At least one FGD was conducted in each FMIS to collect information on irrigation governance. I also did transect walks in each irrigation system, where I surveyed the canal from the tail to head section and inspected the condition of the canal, photographed major biophysical risks, estimated intake river category, and the calculated discharge of the river diversion where feasible.

4. RESULTS

The results are presented here, summarizing the appended sections.

In Appendix A, I review the existing literature and synthesize the dimensions and indicators of adaptive capacity of FMIS. The main findings of the paper are that a refined understanding of adaptive capacity must include: i) the combination of both assets and governance dimensions; ii) generic as well as specific place-based features; iii) complex interconnections, synergies and tradeoffs between different adaptive capacity dimensions; and iv) spatial and temporal dimensions of adaptive capacities. I elaborate on each of these specific observations below.

Adaptive capacity of the FMIS is characterized by seven dimensions—the *five capital assets, governance, and learning*. The five capitals include human, social, physical, natural, and financial capitals based on the livelihood framework (Scoones, 1998). Around 20 categories of variables have been identified to assess these seven dimensions of adaptive capacity.

To understand cross-scale and multi-dimensional linkages, adaptive capacity is further classified into *generic and specific capacities*. The generic adaptive capacity fosters broader development goals (e.g. educational attainment to measure human capital) while the specific adaptive capacity strengthens the capacities to address climate-related risks (e.g. drought management training and strategies, alternative water source).

From the perspective of policy and practice, it is important not only to identify various dimensions of adaptive capacity but to understand their *interconnections including synergies and trade-offs*. For example, strong water governance rules can supplement or offset poor physical infrastructure of the irrigation system. On the other hand, the erosion of social capital, through less collective action in irrigated agriculture, can be detrimental to the effective functioning of irrigation systems with good infrastructure.

An understanding of *the spatial and temporal dimensions* of institutional adaptive capacity is very important for their long-term sustainability. For instance, while flexibility is considered an appropriate indicator of adaptive capacity in a shortterm, an un-coordinated flexible action may be counter-productive in the long term. I demonstrate this case with an example. Groundwater extraction by farmers may increase their flexibility to secure water during water stress period; however, if it is not coordinated at the watershed level, the water table can decline, thus decreasing the overall productivity.

Appendix B focuses on understanding how local irrigation institutions cope with and adapt to water stress and what the effects of different institutional strategies are on the system's agricultural productivity. The paper highlights the following findings: (i) typologies of institutional adaptation in FMIS, (ii) effect of adaptation measures on agricultural performance, (iii) institutional factors contributing to effective adaptation, and (iv) role of climate change and technology in adaptation.

There are *four broad categories* of institutional approaches implemented by FMIS to address water stress: (i) expansion of water source by bringing in additional water, (ii) improvement of system efficiency through infrastructure rehabilitation and management changes, (iii) enforcement of equitable water distribution, and (iv) water sharing both within and between the irrigation systems. These four categories can be broadly divided into *structural* and *non-structural measures*. Structural measures include infrastructure related activities such as dam construction and infrastructure rehabilitation works, and operational measures include soft-path activities such as management and rule changes.

The effect of these adaptation measures on *agricultural performance* varies by the institutions implementing these strategies. Institutions that implement structural measures to bring in additional water have higher crop intensity than the systems that only implement operational measures. In systems that are water scarce, operational measures do not yield significant water savings to boost the crop intensity.

I also study the *institutional factors* that contribute to the effective governance of FMIS in the context of global change. These factors include institutional variables such as *collective action among farmers*, *community leadership, good governance* and *biophysical variables such as economically feasible alternative water source*. From the perspective of climate change adaptation, the ability to secure funding from government and non-governmental agencies for infrastructure works, which is one of the attributes of leadership, is an important enabling factor for their maintenance. In the context of Nepal, natural hazards frequently damage the irrigation infrastructure that can be very expensive to rehabilitate. Traditionally, FMIS leaders have focused on collective action within the community. However, in the last few decades, government and non-government agencies have promoted infrastructure rehabilitation policies. A well-networked leader can play an important role in securing additional funding for improving the irrigation infrastructure.

I also find that *climate variability and change* act as a *risk multiplier* in irrigation systems. Farmers in FMIS fed by small rivers are more likely to choose alternate crop than those fed by large rivers. Furthermore, small rivers are more sensitive to climatic variability and change than the large ones, thus exerting extra stress on smaller systems. However, the increase in flood and landslide risks due to increasing climate variability and change will impact the irrigation system infrastructure of all types.

In Appendix C, I study the determinants of crop choice of smallholder farmers in FMIS with a focus on the choice of rice over other crops during monsoon season. I incorporate the determinants at multiple levels ranging from the household (e.g. household income and other characteristics), institutional (e.g. irrigation system characteristics), national (e.g. market integration) and regional (e.g. climate variability and change). Specifically, I inquire: What are the key determinants of crop choice among the farmers in FMIS during the monsoon season? The paper finds that while many farmers are planting rice, a considerable number of farmers are choosing cash crop such as vegetables during the monsoon season.

The determinants of crop choice are situated at various levels. At the *household level*, I find that *age* is a significant determinant of crop choice. The younger farmers are more likely to choose alternate crops than the older farmers because generally, they are more willing to take risks than older farmers. The irrigation systems fed by *large rivers* have more rice growers than those that are fed by small rivers. The large rivers provide adequate water for most of the farmers, which in turn encourage them to plant rice over other crops. Similarly, *market integration* is one of the key determinants for crop choice at regional and national level. The farmers who are more integrated into markets are choosing alternative cash crops, which show that financial incentive is an influential determinant of crop choice. At the *regional and global level*, I find that climatic drivers - the *long-term precipitation* and *temperature trends* - also affect the farmers' crop choice. I find that 35 years of monsoon precipitation trend were positive and statistically significant. Farmers are more likely to choose rice under the conditions of the wet monsoon precipitation trend. However, I was unable to test the effect of changes in the onset of monsoon period because the trend was not statistically significant.

Overall, farmers are affected by multilevel drivers of change located at different scales. Climate variability and change is only one of the factors affecting the crop choice. Other factors include market integration and the age of the farmer. The climate variability will make smaller irrigation systems more vulnerable to change.

5. CONCLUSION

This dissertation explores adaptation to global change among farmers and community managed irrigation institutions, also called FMIS, in Central and Western Nepal. In particular, I focus on two aspects of global change, i.e., farmers' perceived water stress and their integration to regional and national market. The dissertation centers on three research questions on the characterization of adaptive capacity, exploration of institutional adaptation of FMIS, and econometric modeling of household adaptation to global change. The study is based on 379 household surveys conducted in 12 FMIS during the post-monsoon season of 2016.

In relation to the first research question of this dissertation on the characterization of adaptive capacity of FMIS, I find that both the five capital assets (human, physical, natural, financial and social) and governance attributes (learning, leadership, transparency, multi-functionality, and equity) are important components. While previous work on assessment of adaptive capacity is mostly based on sustainable livelihood indicators (Huai, 2016; Lemos et al., 2016; Shivakoti & Shrestha, 2005) or governance indicators (Berman et al., 2012; Pahl-Wostl, 2009), I evaluate the adaptive capacity by incorporating both the livelihood and governance variables. One of the benefits of this integrated approach is that it allows us to explore interconnections, synergies, and trade-offs between different variables. For example, strong governance and social capital can help to maintain some level of productivity despite the poor physical infrastructure (e.g. concrete canal). The subtle interconnections like this can shed light on mechanisms to strengthen the adaptive capacity of institutions. Because literature was not found that delineates between specific and generic adaptive capacities in the context of irrigation systems, I clustered the variables based on my own judgment. However, the categorization could be further improved through stakeholder feedback.

The appended paper based on the first research question has a few policy implications. There are multiple cases where development interventions have been labeled as adaptation projects (Vij et al., 2017). The difference between generic and specific adaptive capacity can help policymakers and practitioners to distinguish climate-specific interventions from broader development interventions. I also argue that generic adaptive capacity is the foundational base to facilitate specific adaptive capacity. Therefore, both capacities have to be strengthened in order for outcomes to be sustainable. For example, an early warning system, which is a specific capacity, can only perform well in a context where there is good governance, which is a generic capacity.

The second research question addressed in Appendix B provides ground-based evidence on adaptation to water stress by FMIS. For any adaptation action, the first step is to identify the different forms and types of adaptation actions (Smit & Skinner, 2002). This paper makes a couple of contributions to the adaptation literature. It offers empirical evidence of adaptation in irrigated agriculture. Previous studies on irrigation systems have focused on limited aspects of adaptation. For example, Cifdaloz et al. (2010) only explore the role of rule changes to manage climate shocks in FMIS in Nepal, while Bastakoti et al. (2010) highlights the institutional dimensions of FMIS to mediate global change risks in a comparative study of Thailand and Nepal. I expand the typology of adaptation by incorporating both the structural and operational measures in the context of irrigation systems. Structural measures include hard infrastructure works such as lift irrigation, reservoir, and canal rehabilitation, whereas operational measures include soft measures through enactment and enforcement of water allocation rules, and water sharing mechanisms both within and between FMIS. I also argue that both are equally important and interdependent for sustainable adaptation. Hard measures such as alternative water source or concrete canals can improve the water availability to the farmers, whereas the soft measures such as collective action, leadership, and good governance can provide institutional mechanism to deliver water resources to the farmers in a timely, adequate and equitable manner. Another contribution of this paper is the emphasis on the temporal aspect of adaptation. I argue that temporal dimension of adaptation, captured by critical water stress period, can offer valuable insight on adaptation as it serves as a "policy windows" to encourage major changes (Kates, Travis, & Wilbanks, 2012). Critical water stress period is a time window when farmers are severely water deficient and actively engaged in coping and adaptation mechanisms. For example, a few FMIS in Mustang and Nuwakot have developed water allocation rules applicable only during the critical stress period. Such rules are prevalent in many FMIS of Nepal (Pradhan, 1989a). A FMIS in Chitwan borrows the water from neighboring FMIS only during the pre-monsoon season when the water demand is very high. Hence, the temporal focus on critical period allows us better identify and assess the adaptation strategies.

The final research question addressed in Appendix C assesses the multilevel determinants of crop choice by farmers located in FMIS during the monsoon season. I consider four levels of determinants: households, irrigation institutions, local and regional market systems, and climatic regions. As a result, this paper offers methodological contributions to the assessment of multilevel drivers of change. Previous scholars have identified multilevel drivers and nested vulnerability affecting livelihood (Adger et al., 2005; Eakin et al., 2009; Liverman, 1999; McCord, Waldman, Baldwin, Dell'Angelo, & Evans, 2018; O'Brien & Leichenko, 2000). However, many of these studies use qualitative and descriptive methods using causal diagrams and descriptive statistics, with exceptions (Liverman, 1990; McCord et al., 2018). I expand upon the analytical toolset to study global change by using multilevel econometric modeling. One of the benefits of multilevel econometric modeling is that it helps us to understand the relative importance of multilevel variables on adaptation decision. While other statistical tools such as correlation study can quantify the degree to which two variables are related, the multilevel regression analysis quantifies the change in dependent variable with the change in multilevel independent variables. It also helps in predicting the outcomes.

Another methodological contribution of the 3rd paper is that it broadens the number of determinants by incorporating biophysical, social, institutional and household variables. Such a comprehensive approach allows us to see the role of different variables in adaptation decision making. For example, I incorporate the river category which is a biophysical attribute that very few studies have incorporated. And indeed, I find this to be a significant driver. Farmers living in the irrigation systems that are fed by small and medium-size rivers are more likely to choose less water-demanding crops than those fed by large rivers.

Taken together, this dissertation helps us understand the household and institutional adaptation to global change, particularly focusing on water stress and market integration. I apply the broader SES framework to understand diverse and multilevel drivers of change in the context of irrigated agriculture, contributing to the works by other scholars (Anderies et al., 2016; Bastakoti et al., 2015; Cárdenas et al., 2017; Cox et al., 2016; Hinkel, Cox, Schlüter, Binder, & Falk, 2015; Lam & Chiu, 2016; Ostrom, 2011; Shivakoti, 2015). I contribute to better understanding and assessment of multi-faceted adaptive capacity and institutional adaptation in the context of agriculture and food security, as expanded by other scholars (Bedran-Martins et al., 2017; Charli-Joseph et al., 2018; Chhetri et al., 2012; Delaney et al., 2018; Eakin et al., 2016; Holland et al., 2017; Lockwood, Raymond, Oczkowski, & Morrison, 2015; McCord, Dell'angelo, Gower, Caylor, & Evans, 2017; Rodima-Taylor, Olwig, & Chhetri, 2012). This dissertation offers several new insights to the literature on adaptation and resilience that is situated within the sub-fields of natural hazards, political economy, and human dimensions of global change. For a better understanding of institutional adaptive capacity, I incorporate both the asset and governance dimensions. The typology of institutional adaptation that encompasses both the structural and operational measures can guide us in effective adaptation planning. The multilevel modeling allows us to understand the spatial interconnectedness of different variables. Overall, this dissertation makes theoretical, empirical, and methodological contributions to the literature on adaptation and resilience.

5.1. Broader implications

Climate change adaptation will continue to be a dominant body of research in the present and coming decades. Questions such as how can different sectors adapt to present and future global change and how to build a climate resilient society are critical questions of academic and policy relevance. This study contributes to the better understanding of adaptation and adaptive capacity in the context of irrigated agriculture. This study has multiple implications within and beyond the study area.

Adaptive capacity is a multidimensional concept that can be difficult to operationalize. One of the approaches to measuring institutional adaptive capacity is by incorporating the five capitals and governance attributes. While we can make a long list of variables to measure adaptive capacity, it's equally important to understand the synergies and trade-off between these components and their temporal and spatial interconnections. Failure to do so may result in mal-adaptation, which is an action that may promote adaptation in the short-term but may hinder it in the long-term. For example, while flexibility is considered to build an adaptive capacity, an unregulated flexibility by the farmers to pump groundwater can become a mal-adaptation because it hinders adaptation to future multi-year drought events. This calls for an integrated understanding of adaptation and adaptive capacity by incorporating the biophysical, social, economic and institutional dimensions across spatial and temporal scales. While synergies and trade-offs are often inevitable, the goal of adaptation is to harness the synergies while minimizing the trade-off.

The effective adaptation needs to emphasize on both the hard and soft interventions. In the case of irrigation systems, the institutional adaptation strategies can be categorized into structural and operational measures. While structural measures are important to improve water availability, the soft measures such as collective action, leadership, and good governance are necessary for the effective functioning of these infrastructures.

An effective adaptation also has to ensure that the indigenous approaches are not eroded while promoting technological adaptation intervention. For example, lift irrigation, which can provide an alternative water source during drought, can hinder the collective action that's critical for sustainable management of FMIS. One approach to promoting sustainable adaptation is by encouraging collective action in the context of lift irrigation through collective cleaning of canals and collective decision making. While the impacts of technological changes on collective action are inevitable, however, policies can encourage sustainable behaviors.

Lastly, any coping and adaptation decisions do not happen in isolation in response to one parameter, such as climate change. Rather, multiple drivers at different levels are simultaneously affecting the individual's decision. Furthermore, climate variability and change is just one of the drivers. However, climate variability and change generally acts as a threat multiplier because it compounds the existing threats the system faces from social, economic and biophysical changes. Hence, there is a value in understanding adaptation by incorporating multiple drivers of change including biophysical, social, economic, and demographic characteristics.

5.2. Future work

During the research, besides the above-mentioned findings, I have also identified three major research topics that are important from the perspectives of climate change adaptation, particularly in the CPR research.

In CPR research, it is less clear how the *market integration* affects the collective action. While my research finds that market integration can incentivize farmers to pursue a collective action, Cárdenas et al. (2017) in their multi-country experimental study of farmers in irrigation systems has shown that increased integration of the communities with the broader economic system can lower the investments in public goods. Studies of the conditions and attributes that make institutions resilient to global change is an important research area of regional and global relevance.

Similarly, the *role of technology*, such as lift irrigation and household hand-ups, on collective action is another area that requires further investigation. Historically, FMIS have mostly relied on local resources. However, with access to modern technologies, such as hand pumps and lift irrigation, it is not clear how these technologies alter collective action, which is vital for the long-term sustainability of irrigated agriculture in Nepal and many developing countries.

The role of *migration* on collective action is another promising area. Nepal has witnessed significant international migration that can have both positive and negative effects on FMIS. While migration changes the agricultural labor dynamics in the region, it also brings in-flow of financial capital and technical know-how. Very few research studies have looked at the role of migration on the sustainability of irrigated agriculture, which is important in the context of increasing labor mobility in the region.

While all of these questions are very important for agricultural sustainability, I find that the role of migration and technology in irrigated agriculture to be perhaps the most urgent issue particularly because of its important policy implications. With a high rate of out-migration in Nepal, innovative policies and technological intervention can ease the burden of women in the agricultural labor force. International donor agencies have been promoting technologies such as plastic ponds to address labor and water shortages in the hills of Nepal (Sugden et al., 2014). Such use-inspired research can produce innovative solutions that suit the local context.

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FIGURES

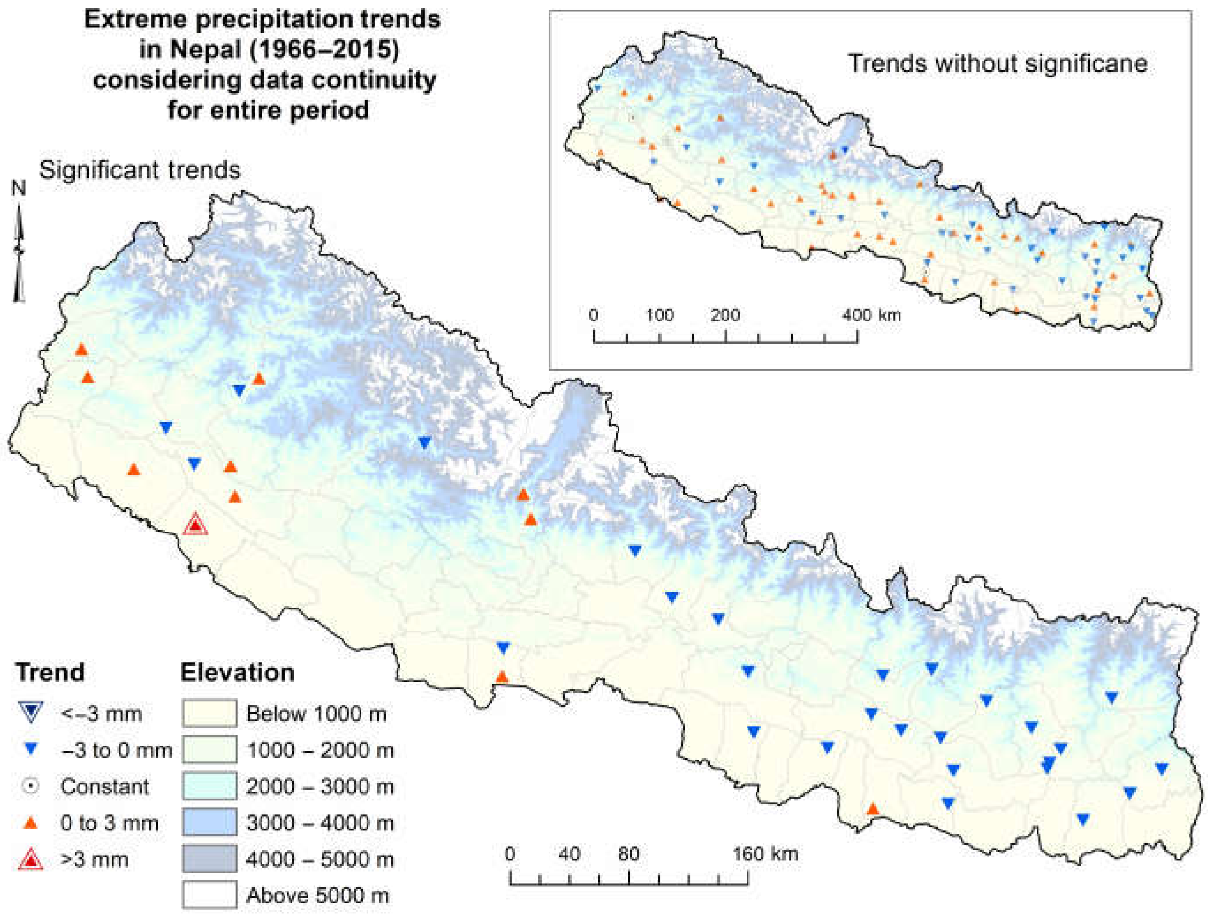

Figure 1: Station-wise trend (1966-2015) of 1-day extreme precipitation (Source: Talchabhadel et al., 2018)

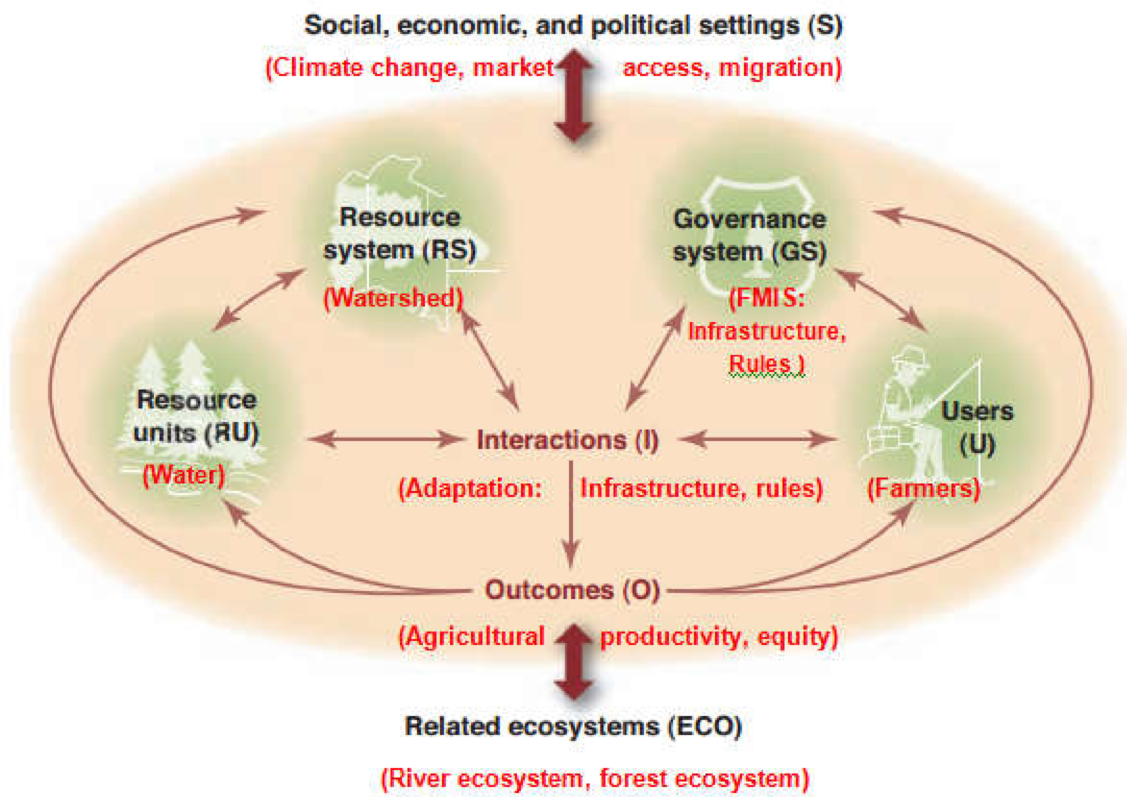

Figure 2: The sub-systems of a social-ecological system for farmer-managed irrigation systems (Source: Adopted from Ostrom, 2011)

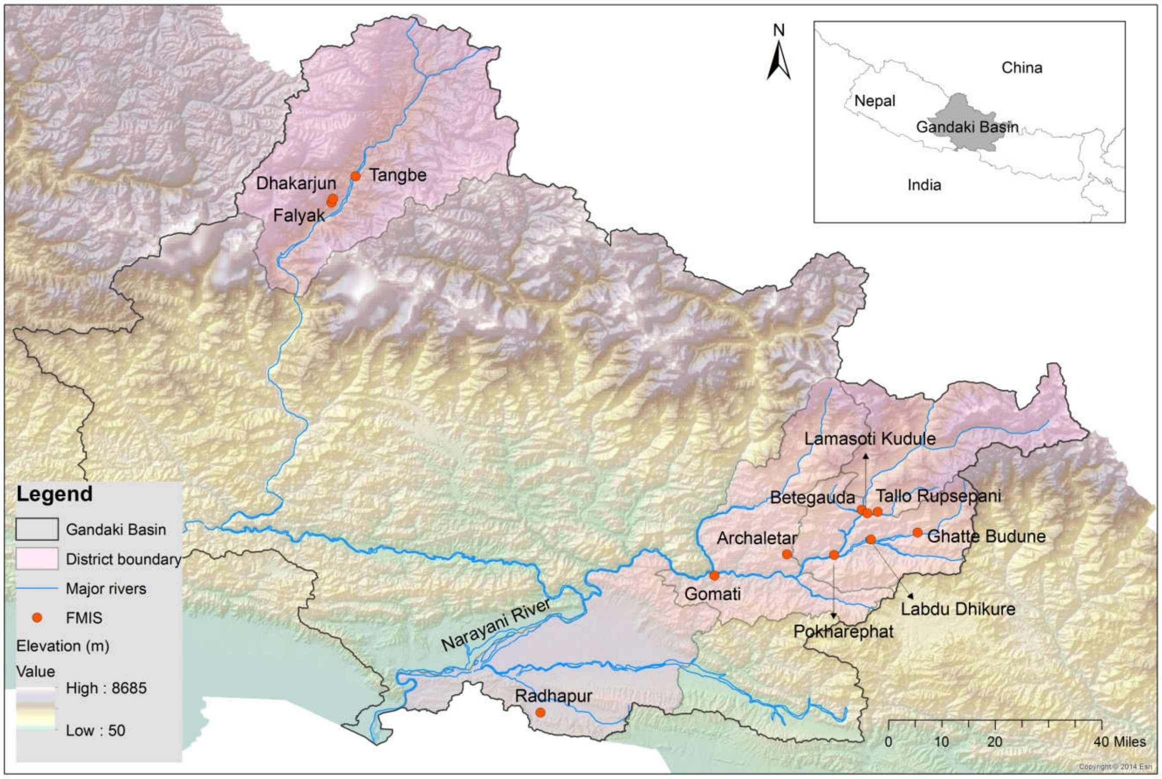

Figure 3: Study sites in the Gandaki River Basin of Nepal (Source: Author)

TABLES

Table 1: Sampling of farmer-managed irrigation systems and households

River category	Mountains		Hills		Terai		Total	
	FMIS	HH	FMIS	HH	FMIS	HH	FMIS	HH
Small	3	59	2	55	0	0	5	114
Medium	0	0	2	63	1	38	3	101
Large	0	0	4	164	0	0	4	164
Total							12	379

Note: HH: Household; River category: small-size river (lean flow <1,000 liters per seconds), medium-size river (lean flow 1,000 - 10,000 liter per seconds), and large-size rivers (lean flow>10,000 liters per seconds)

APPENDIX A: Towards characterizing the adaptive capacity of farmer-managed irrigation systems: learnings from Nepal[1]

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ABSTRACT

Small-scale irrigation systems managed by farmers are facing multiple challenges including competing water demand, climatic variability and change, and socioeconomic transformation. Though the relevant institutions for irrigation management have developed coping and adaptation mechanisms, the intensity and frequency of the changes have weakened their institutional adaptive capacity. Using case examples mostly from Nepal, this paper studies the interconnections between seven key dimensions of adaptive capacity: the five capitals (human, financial, natural, social, and physical), governance, and learning. Long-term adaptation requires harnessing the synergies and tradeoffs between generic adaptive capacity that fosters broader development goals and specific adaptive capacity that strengthens climate-risk management. Measuring and addressing the interrelations among the seven adaptive-capacity dimensions aids in strengthening the long-term sustainability of farmer-managed irrigation systems.

Keywords: FMIS, mountain, adaptation, irrigated agriculture, Asia, resilience, institution

1. INTRODUCTION

Local institutions across the globe to varying degrees are coping with and adapting to changing climate and rapidly evolving socioeconomic conditions like migration, urbanization, and income diversification [1,2]. Farmer-managed irrigation systems (FMIS) in Nepal and other Asian countries (e.g., Philippines, Thailand, and Cambodia), are among the prevalent local resource-governance institutions that have survived decades and even centuries of social, ecological, and cultural changes [1,3,4]. FMIS are autonomous institutions whose community members are responsible for overall irrigation management including water appropriation, distribution, canal maintenance, and conflict management through collective action [3,5]. In Nepal, they are characterized by the use of low-cost technology appropriate for heterogeneous local conditions such as diverse geographic terrain, autonomous decision making suited to local sociopolitical contexts, and collective action for maintenance and operation of infrastructure [6–8]. FMIS are adaptive to changing hydroclimatic and socioeconomic conditions partly attributed to the high autonomy in farmers' decisionmaking; flexible rules that suit users' needs; and high social capital in the form of trust, mutual cooperation, and collective action [9].

While many FMIS remain functional, dramatically changing hydroclimatic conditions, accelerated biophysical risk, and rapidly evolving socioeconomic change—together understood as global change [10]—have weakened their capacity to cope with and adapt to these changes. Climatic change and variability have contributed to delays in the onset of monsoon and winter rainfall, which means more intense and unpredictable precipitation causing flash floods and drought [11]. Higher evapotranspiration and temperature causes shifts in irrigation-water demand and crop choice [12]. The situation is further compounded by socioeconomic changes including a palpable rise in the responsibility of women in FMIS governance due to male out-migration; and erosion of interest in collective action due to decreased productivity and profitability of irrigated agriculture [1,13,14]. Understanding and strengthening the key elements of adaptive capacity is crucial for the long-term sustainability of FMIS. This paper reviews the main components of adaptive capacity of FMIS, with case examples mostly from Nepal, and identifies potential indicators to measure them.

Since very few articles are published on adaptive capacity and FMIS, we first reviewed the literature on adaptive capacity in general. The seven dimensions and indicators of adaptive capacity were short-listed (Table 1) based on their relevance to FMIS (see the additional notes for a description of the methodology).

2. CHARACTERISTICS OF ADAPTIVE CAPACITY

Institutional adaptive capacity has been defined focusing on various aspects like climate risk management [15], multi-level learning process [16], and diversity of functions [17]. This paper uses the definition proposed by Bettini *et al.*, "the ability to mobilize and combine different capacities within a system, to anticipate or respond to economic, environmental, and social stressors, in order to initiate structural or functional change to a system and thereby achieve resilient or transformative adaptation [18]." This definition is particularly useful in our case because it incorporates multiple stressors and emphasizes the role of human agency in responding to stresses through governance. Here, human agency refers to an individual or collective ability to mobilize, respond, anticipate, initiate, and achieve adaptive changes within a sociocultural context [18].

The literature that assesses adaptive capacity has grown in the last decade [18,19]. These assessments generally take one of two approaches. An asset-based approach emphasises on the five livelihood capitals (human, financial, natural, social, physical), usually applied at household and individual levels [20–22], while a process-based approach emphasizes decisionmaking including multi-stakeholder collaboration, flexibility in decision making, and learning through refinement in rules, procedures and routines of organizational activities [23–26]. Nonetheless, the multi-dimensionality and latency of adaptive capacity, which makes it invisible until external (climate or other) event occurs, complicate the measurement of adaptive capacity [27].

While there has been some progress in characterizing adaptive capacity, very few studies have explored that for FMIS. Most of the literature on assessment of FMIS has concentrated on self-governance and institutional performance [26,28,29]. Some studies have explored the robustness of institutional arrangements to external drivers of change—including climate change—but none has elaborated the adaptive-capacity dimensions [3,30]. This paper contributes to the literature by applying and extending institutional adaptation analyses to FMIS facing global change. Capturing the dynamic nature of adaptive capacity, the paper addresses both the assets and process dimensions.

2.1. Generic and specific adaptive capacities

In order to understand the inter-linkages, adaptive capacity is classified into two broad categories- generic and specific. Generic Adaptive Capacity (GAC) addresses the structural deficits that must be addressed for the sustainability of a system or an institution [22,31]. These capacities are clustered into the seven dimensions that consist of five capital assets, plus governance and learning. GAC comprises the endowments that enable flexible responses to a spectrum of climatic and non-climatic stressors [32]. Specific Adaptive Capacity (SAC), by contrast, refers to strategies to manage the risk of climate hazards (or other global-change drivers; for the sake of brevity, we refer here primarily to climate-induced water shortages and hazards). SAC helps users by furnishing tools and knowledge required to anticipate and effectively respond to specific climate threats [32]. Examples of SAC include climate-related knowledge and skills, access to external finance, alternate water sources to buffer shortages, and formal and informal rules to address climate risks. SAC can be considered part of a broader continuum of GAC because, while SAC focuses solely on climate risks, GAC incorporates all types of risks (Figure 1).

Based on the literature review, the key components of adaptive capacity are as follows:

The five capitals: The five capitals—human, physical, natural, social, and financial—are critical assets for the long-term sustainability of an effective institution. We further classify a type of capital as generic or specific in terms of the adaptive capacity it confers to FMIS facing global change and climate-induced water scarcity, in particular. Human capital in SAC terms refers to farmers' local knowledge of climate risk (e.g., drought severity and duration), as well as skills to respond effectively (e.g., crop diversification and use of alternative water sources); while labor force and educational attainment are human capital that enhances GAC [33]. The social capital that strengthens GAC includes formal and informal rules, trust, and FMIS membership necessary for effective operation of the institution [34]. In specific terms, trust promotes reciprocity among farmers—e.g., altering irrigation rotations during the period of stress—and facilitates the flow of information and resources about crop vulnerability to water stress, pests, and other stressors, as well as place-based interventions. Social capital can sometimes increase vulnerability [35]: for instance, a highly cohesive group of farmers reliant on local knowledge specific to certain conditions can be hesitant to incorporate information as conditions evolve, disregarding scientific information on new risks and potential adaptation.

The physical capital of FMIS to enhance climate-related SAC includes infrastructure such as concrete lining and diversion weirs that reduces inefficiencies, while generic physical capital (e.g., roads, hospitals, and schools) aid not just the FMIS but broader rural communities [36]. Specific natural capital includes alternate water sources from the stream, the local aquifer or mountain groundwater system that may compensate for water shortages. Broader natural capital may include forest cover that meets a range of livelihood needs. Technologies such as groundwater pumping and gabion walls for erosion control are types of physical capital that can reduce climate hazard risks and strengthen SAC.

In GAC terms, financial capital comprises income, access to finance, and income distribution. In Nepal, the ability of FMIS to receive financial support from government agencies, especially after the natural disasters, is a SAC that is crucial for system sustenance. Due to limited funds, complex government bureaucracy [37], and weak FMIS leadership [7], very few FMIS receive government funding for infrastructure rehabilitation. Such support is crucial when FMIS face natural disasters like flooding, landslides, or earthquakes.

Water governance: Effective governance is fundamental for the sustenance of any resource management regime, including irrigation [27]. Among many principles of effective governance, this paper addresses four broad categories: (a) transparency and accountability; (b) equity, inclusiveness, and participatory process; (c) leadership; and (d) multi-functionality. Since FMIS are made functional through collective action based on trust and reciprocity, they are highly sensitive to transparent and accountable governance. A national-level study of FMIS in Nepal revealed that the perception of fairness (represented by the perception of adequate and reliable water supply at head and tail ends of a canal, and by the condition of irrigation infrastructure) is the determining factor for the sustained cooperation of FMIS [38]. Effective governance, facilitated by good leaders, is crucial for climate-change adaptation because it addresses underlying factors that produce vulnerability in the absence of equity, inclusiveness, and deliberation. Leaders build trust with farmers and are capable of performing vital organizational functions [25], including facilitating collective action for canal cleaning, conflict resolution over irrigation deliveries, and resource securitization in the face of risks such as upstream water diversions or from natural factors such as landslides [3]. During natural disasters, leaders play an important role by maintaining cohesiveness, seeking external and internal funding, and mediating multiple risks. Leaders can also balance power dynamics by ensuring inclusiveness of all members in the decisions making processes [25].

Learning: One of the characteristics of a highly adaptive system is its ability to learn from uncertain and changing global-change phenomena. In the context of FMIS, learning occurs at individual and institutional levels [39]. Institutional level learning can be defined as "the process by which the group's learning outcomes are stored in and brought forth from organizational memory, such as rules, procedures, routines, and organizational cultures [39]." Learning occurs effectively when institutions are flexible and permit rule change [41]. In SAC terms, farmers need to integrate both traditional and scientific knowledge on irrigation and promote experimentation through 'learning by doing' [10], especially for cropping practices. As examples of GAC, institutional learning is also influenced by social learning where changes in understanding go beyond the individual level to wider social units or social groups through interactions of actors within the social network [42]. Social learning promotes adaptive capacity by improving collective learning and strengthening trust and relationships [43]. Though learning does not necessarily lead to action and change in behavior it can serve as a platform for sharing information about climate risk and adaptation [44].

Another component of learning that is very relevant to climate adaptation is interaction and inter-linkages with formal and informal institutions including local, regional, national, and international organizations. Informal groups are important because they can help in the exchange of information related to vulnerability and adaptation, and secure resources to build the adaptive capacity [45]. For example, the interaction of FMIS with agricultural extension and irrigation departments can provide avenues for learning about climate adaptation strategies and secure funding opportunities.

3. DISCUSSION

3.1. Linkages between generic and specific adaptive capacities

The SAC and GAC interlink in two noticeable ways. First, SAC in many cases are considered a sub-set of GAC because they concentrate on only one (here, climate risk), among the multiple risks that GAC addresses. GAC can be conceptualized as the underlying, foundational capacity that must be strengthened in order to develop SAC. For example, targeting on climate services for irrigation or building irrigation infrastructure without enhancing managerial capacity and strengthening ties to government or other external sources of information and funding is unlikely to assure long-term adaptation. This implies the need for FMIS-wide prioritization in selecting interventions [46].

Second, there are synergies and tradeoffs between GAC and SAC. When focusing on building infrastructure or a climate-services-knowledge platform, local knowledge systems and unique ingenuities should not be eroded [31]. In terms of synergy, strong leadership can be crucial in formulating rules for climate risk management and procuring infrastructure funds.

3.2. Inter-linkages among the five capitals

In the case of FMIS, the five capital assets also supplement and complement each other. Despite poor physical canal infrastructure, many rural FMIS in Nepal are functioning well due to the strong social capital in the form of collective action, labor contribution, and cooperation [47]. For example, the Raj Kulo of Arghali, Palpa district has one of the complex water governance mechanisms that strengthened the system’s performance despite the inefficient infrastructure conditions [48]. On the other hand, an irrigation system with good infrastructure can fail to function effectively when the social capital is lacking. The erosion of social capital can occur due to inappropriate government policies like state-centric government policies; technology adoption like individual groundwater pumps that discourages the community irrigation; and lack of interest in collective actions and irrigated agriculture [3,49]. Siran Baguwa of

Sindhupalchowk district suffered from poor performance after the farmers at the head-end stopped participating in collective maintenance due to lack of trust [28].

Despite promising developments in SAC for climate-risk response and GAC for foundational capacity building, there are conceptual and operational limits to adaptive capacity for FMIS. Increases in individual or even institutional flexibility (under the learning dimension) do not necessarily lead to increases in adaptive capacity. Higher flexibility may be good in the short term, but the flexibility that leads to uncoordinated action can hinder adaptation in the long run [45]. For example, individual-level groundwater extraction without coordinating at the FMIS- or watershed-level to maintain groundwater balance can degrade long-term sustainability. Hence, there is a need to move from individual or institutional level flexibility to collaborative flexibility through supra-local coordination mechanisms [45].

Another cautionary note is the fact that adaptive capacity is inherent or latent within a system or institution and its effectiveness or failure is not fully apparent until after an influential climatic event [27,45]. Also, identification of adaptive capacity does not necessarily lead to adaptation actions [39], a process that is influenced by individuals' perception of risks, access to resources and entitlements, and socio-cultural factors [22].

4. CONCLUSION AND THE WAY FORWARD

Adaptive capacity is characterized across seven dimensions—the five capital assets, governance, and learning. To understand cross-scale and multi-dimensional linkages, adaptive capacity is further classified into two broad categories: generic and specific. While generic adaptive capacity (GAC) concentrates on capacities to address the multiple global-change drivers, specific adaptive capacity (SAC), as we have taken it here, addresses only climate-induced water risks.

The key SACs necessary for strengthening the response of FMIS to changing climate include knowledge and skills on climate risk management, formal and informal rules, irrigation infrastructure and technologies, and inter- and intra-agency interactions and collaboration. These SACs can only be effective as part of broader GACs, such as governance, trust, and leadership.

From the perspective of policy and practice, it is important not only to identify these capacities but to understand their interconnections including the synergies and trade-offs among multiple capacity dimensions. As climate change impacts become more acute and programs to address impacts and enhance capacity grow more prominent in policy and practice, understanding and operationalizing adaptive capacity will receive greater attention. In order to move from conceptual understanding to support for adaptive actions in practice, generic and specific adaptive capacities must be understood from a holistic perspective and addressed in an integrated way for the long-term adaptation of local FMIS institutions.

METHODOLOGY

The keyword for search included- adaptive capacity, adapt*, farmer managed irrigation, resilience, local institutions, generic adapt*, specific adapt*, determinant adapt*, agricultural water. The peer-reviewed literature was searched for the period 2010-2016 on Web of Science, Google Scholar, and Science Direct. More than 123 articles were downloaded for the given search, of which 78 articles were reviewed in detail because they explained about the characteristics/dimensions of adaptive capacity. Since few articles are published in international journals on FMIS, the literature search for FMIS indicators was extended to national workshop proceedings on FMIS in Nepal and national journals. The seven dimensions of adaptive capacity were short-listed based on their relevance. The criteria are considered relevant when the dimension of adaptive capacity is applicable to FMIS context. For example, the dimension of trust and social is applicable in both the literature on FMIS and adaptive capacity. Learning dimension is not prominent in FMIS literature, but it is incorporated because it is applicable in the local institutional context.

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FIGURES

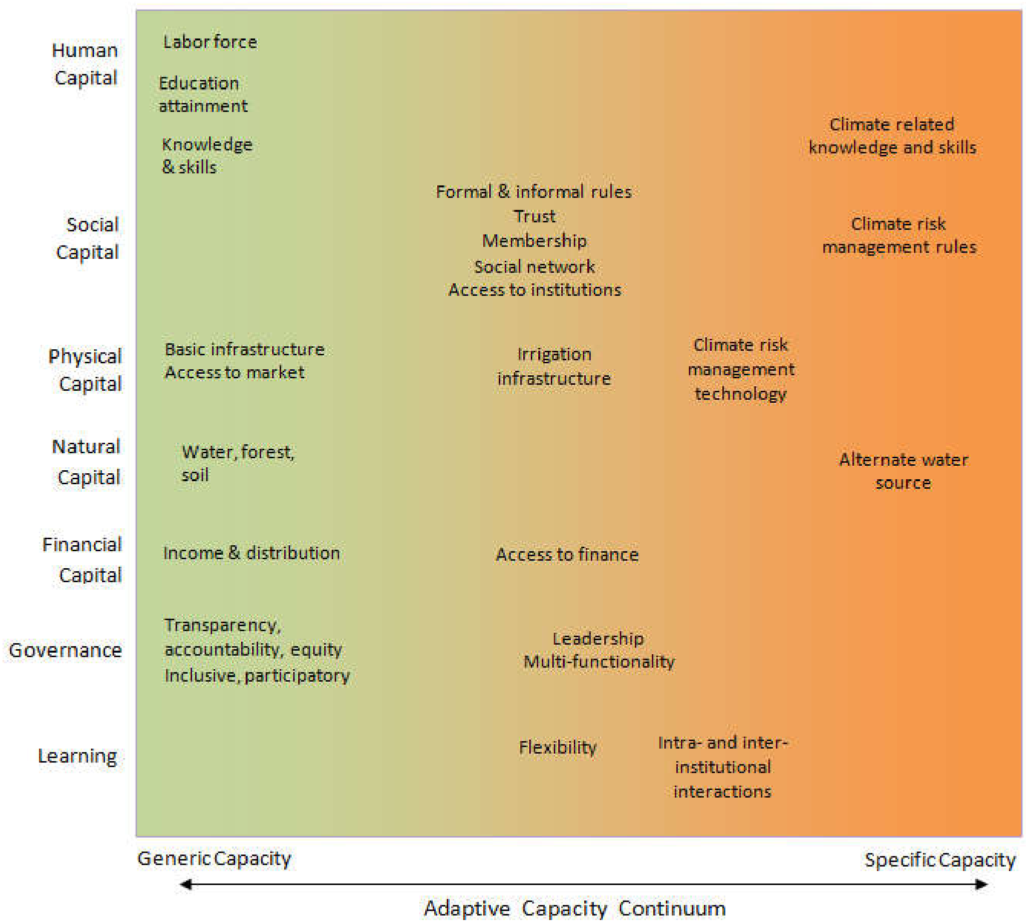

Figure 1: Adaptive capacity continuum

TABLES

Table 1: Generic and specific adaptive capacities

Generic adaptive capacity	Dimensions of generic adaptive capacity	Indicators of generic adaptive capacity	Dimensions of specific adaptive capacity	Indicators of specific adaptive capacity	References
Human capital	Labor force	- Economically active labor population			[50,51]
	Education attainment	- Literacy rate			
	Knowledge and skills	- Years of agriculture and irrigation experience	Knowledge related to climate risk management	- Local knowledge on drought - Crop diversification knowledge - Water conservation knowledge	
Social capital	Formal and informal rules*	- Water distribution, resource sharing & other rules - Cropping intensity head and tail ends - Resource contribution by head/tail end users	Contingency plans for risk management	- Water allocation rules during water shortages	[20,40, 52,53]
	Trust	- Perception of trust	Information sharing	- Information sharing about vulnerability and adaptation strategy	
	Membership	- Membership in FMIS			
	Access to institutions & resources	- Rules on access to irrigation water & WUA			
Physical capital	Basic services infrastructure – health, transportation,	- Distance to road, hospital, and market	Irrigation infrastructure	- Concrete lining - Reservoir	[21,51]

	Market access				
	Irrigation & agriculture technology	- Adoption rate of technology	Climate risk management technology	- Adoption rate of water saving/augmenting technology	
Natural capital	Water source	- Cropping intensity	Water quality and quantity	-Alternate water source -Water available during dry season	[36,54]
	Forest condition	- Forest cover rate			
Financial capital	Income	- Annual income per household			[33]
	Income distribution/ inequality	- Farm size - Gini Coefficient			
	Access to finance	- Account at financial institution	Internal and external financial support	- Support from external agencies	
Governance	Transparency & accountability	- Financial audits - Meetings and disclosure - Graduated sanctions - Monitoring & evaluation			[28,45, 46,52]
	Equity, inclusive and participatory process	- Cropping intensity at head and tail-end - Labor contribution at head and tail-end - Participation in decision making			
	Leadership	- Leadership performance rating			
	Multi-functional Institutions	- Organizational activities	Multiple functions	- Services provided by FMIS	
Learning	Flexibility	- Room for rule change	Intra- and inter institutional interactions	-Meeting with other agencies	[39]
	Collective learning	- Interactions with diverse stakeholders			

* Since most of the rules are informally made by farmers, formal and informal has been categorized in social capital.

APPENDIX B: Institutional strategies for adaptation to water stress in farmer-managed irrigation systems of Nepal[2]

Bhuwan Thapa, Christopher A. Scott

[2] Formatted for submission to *The International Journal of the Commons*

ABSTRACT

Institutions governing common-pool resources have been resilient to global change over the decades. However, we have limited knowledge on how local institutions cope with and adapt to these changes. Using the case of 12 farmer-managed irrigation systems in Central Nepal, this research explores institutional coping and adaptation mechanisms to water stress partly attributed to global change. We find that local irrigation institutions manage water stress using diverse and integrated measures broadly categorized as structural and operational measures. Structural measures include source expansion and infrastructure rehabilitation works whereas water allocation and management rules are examples of operational measures. The effect of these measures on agricultural performance varies by the type of institution implementing these strategies. We also find that different institutional features, such as rules flexibility and leadership, are important for an institution's adaptation to climate change and variability. The study highlights that climate variability and change act as a threat multiplier because they compound the existing threats the system faces from social and economic systems. This article contributes to the literature on adaptation of local institutions in common-pool resource setting by explaining the typology of institutional adaptation and assessing institutional factors for successful adaptation.

Keywords: Farmer-managed irrigation systems (FMIS), institutions, resilience, leadership, common-pool resource governance, self-organization, agriculture.

1. INTRODUCTION

Institutions governing common-pool resources (CPR) including irrigation, fishery, and forestry play an important role in the food and livelihood security of millions of farmers globally. In Nepal alone, 67 percent (645,716 hectare) of total irrigated land that uses surface water sources is managed as farmer-managed irrigation systems (FMIS) (DOI, 2007) where farmers are responsible for overall irrigation management including water appropriation, distribution, canal maintenance, and conflict management through collective action. However, over the recent decade, the urbanization, labor migration, road network expansion, and climate variability and change have added additional stress to the FMIS. Despite these stresses, many FMIS are still functional, but with mixed performance (Bastakoti et al., 2010; Pokharel, 2015), as would be expected of complex adaptive systems. Farmers and communities have coped with and adapted to these changes for generations using indigenous and local knowledge (Chhetri et al., 2013; Yoder,1994). Alteration of water allocation rules, changes in irrigation scheduling, and exchanges of allocated water are some of the common mechanisms used by farmers managing the irrigation system to address the water shortages (Yoder, 1994).

A significant body of literature has been developed over the past few decades on different dimensions of CPR governance seeking to better explain the collective action, adaptive decision-making, and social and institutional learning. The early literature in the 1980's and 1990's focused on self-organization of CPR mostly using the Institutional Analysis and Development (IAD) framework (Bardhan, 2000; Benjamin et al., 1994; Lam, 1996a; Lam & Ostrom, 2010; Ostrom & Benjamin, 1993; Pradhan, 1989b). Given shortcomings in the characterization of dynamic, interactive social and ecological processes, the IAD framework has been reconceptualized and refined to address the robustness of social-ecological systems (Anderies, Janssen, and Ostrom, 2004), the broader social-ecological systems approach (Ostrom, 2011), and coupled infrastructure systems (Anderies et al., 2016; C. A. Scott, Dall'erba, & Caravantes, 2010). Since 1990, the literature on behavioral aspects of CPR governance using field and lab experiments has helped to better theorize human behavior (Janssen, 2015; Janssen and Anderies, 2013).

The effects of multilevel (global, regional, and local) climate and socioeconomic changes on institutional performance and institutional coping and adaptation mechanisms, however, are only slowly emerging (Varela-Ortega et al., 2016; Cárdenas et al., 2017). Cifdaloz et al. (2010) explored the relationship between the robustness of irrigation systems and climatic vulnerability, and demonstrated the tradeoff between vulnerability and robustness. As institutions tune to cope with one shock, they become more vulnerable to other shocks. For example, the changes driven by external policies and market pressures are mediated by local institutions because of flexible rule-making, strong social capital, and trusted local leadership (Bastakoti et al., 2010). A rigorous understanding of the coping and adaptation mechanisms implemented by the FMIS, which remains underdeveloped in the literature, can provide valuable insight into current and future adaptation to climatic and non-climatic changes at different scales.

Using case examples of multiple FMIS in the Gandaki River Basin of Western and Central Nepal, this paper aims to answer three questions: (i) How do FMIS cope with and adapt to water stress? (ii) What are the effects of different institutional strategies on the agricultural performance of the irrigation system? And (iii) What institutional factors contribute to effective water stress management?

The article is organized as follows. We provide a background on FMIS in Nepal and discuss the key terms of water stress and institutional adaptation. The introductory section is followed by a discussion on the temporal dimension of water stress and institutional adaptation strategies implemented by FMIS. Next, we assess irrigation performance for different adaptation measures and explore institutional factors that contribute to effective adaptation. We conclude the paper by assessing the institutional measures taken by FMIS and discuss their impacts on CPR governance.

1.1. Background on farmer-managed irrigation systems

Nepal has a distinct history of irrigation systems managed by communities. Over the last two centuries, Nepalese farmers have constructed irrigation systems deliberately to intensify their agricultural production. This tradition gave birth to farmer-managed irrigation systems (FMIS) that are scattered all over the country (Pradhan, 1989).

It was not until the Government of Nepal started to actively promote irrigation development in the 1980's that it recognized FMIS as an institutional entity (Pradhan, 1989). Currently, irrigation systems in Nepal are managed either as FMIS or as Agency-managed irrigation systems (AIMS). Under AIMS, government personnel are responsible for managing the system with varying levels of farmer participation (Lam, 1996b). In contrast, in FMIS overall irrigation management is performed by the farmers themselves with minimal interference from outside agencies. FMIS only receive occasional financial and technical support from government agencies for infrastructure rehabilitation and institutional strengthening (Pradhan, 1989b). FMIS in Nepal are characterized by their use of low-cost technology appropriate for heterogeneous local conditions, autonomous decision making suited to local contexts, and collective action for the maintenance and operation of irrigation systems.

Despite the primitive infrastructure developed and employed by many FMIS, they are still important for food security and livelihood of Nepalese people. FMIS currently irrigate about 333,000 hectares of agricultural land covering 51 percent of the total surface-water irrigation area (DOI, 2007). About 40 percent of the country's food requirement comes from these irrigation systems (Pradhan, 2012). As Nepal's population is expected to double by 2050, the country will face a significant challenge in meeting the domestic food security. The irrigated agriculture not only increases crop yield by a multiplier of three to four, but also creates local employment opportunities (Smith, 2004). Irrigated agriculture thus contributes to both food and livelihood securities.

1.2. Understanding water stress

Water stress is a commonly used term in agronomy and irrigation engineering. In agronomy, crop water stress measures the water shortage in plants and is derived based on plant canopy, air temperature, and atmospheric vapor pressure deficiency (Alderfasi & Nielsen, 2001; Irmak, Haman, & Bastug, 2000; Jackson, Idso, Reginato, & Pinter, 1981). The Relative Water Supply (RWS) commonly used in irrigation engineering measures the ratio of water supply to the water demand associated with crops grown using existing agricultural practices (Levine, 1982). Similar to the concept of RWS, water stress is defined as the supply of water relative to the farmer's perception of irrigation demand for a crop at a given time period.

The potential causal factors of water stress are climatic variability and change, irrigation infrastructure conditions, FMIS governance, and on-farm water management practices. Nepal has witnessed increasing climatic variability and change over the past few decades. While climate variability measures the variation in the mean state and other statistics of the climate over the long term, measuring the deviations from the long-term mean values are typically called anomalies. Climate change, on the other hand, measures variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer (WMO, 2018). The nationwide study of extreme precipitation trends in Nepal from 1966-2015 showed that there is no definitive country-wide decadal trend in 1-day extreme precipitation peak; however, there is an increase in extreme precipitation events in western mountainous regions and a mixed pattern in other regions including the Gandaki Basin (Talchabhadel et al., 2018). In addition, 32 percent of the total stations in Nepal have crossed the 1-day precipitation threshold estimated to trigger landslides (Figure 1). The study of seasonal precipitation change in the Gandaki River Basin showed a decrease in winter and pre-monsoon precipitation in the hills and a decrease in post-monsoon rainfall in the Trans-Himalaya region (Panthi et al., 2015).

Similarly, the study of temperature trends from 1977 to 1994 showed that Nepal is warming at an average annual rate of about 0.06 ^{o}C per year (Shrestha & Aryal, 2011). More alarming is the fact that warming is more pronounced at higher altitudes, which has resulted in the retreat of major glaciers at the rate of 12-20 meter over the 10 to 15 year period. At the basin scale, precipitation rather than snowmelt has the dominant effect on river discharge in all the basins of Nepal (Alford & Armstrong, 2010). However, the relationship between monsoon and streamflow is variable, which is partly attributed to complex topography and groundwater contributions (Hannah et al., 2005). The instrumental study of river discharge showed an increasing trend for the Narayani River and decreasing trends for the Kali Gandaki, Sapta Koshi, and Koshi basins (Shrestha & Aryal, 2011).

Climatic variability and change can affect irrigated agriculture in several ways. The extreme rainfall events can trigger landslides and flood risks that can damage irrigation diversions, canals and agricultural land (Ostrom et al., 2011). The variability in precipitation events including onset and retreat of the monsoon season can directly influence crop choice decisions and alter crop productivity. For example, rice plantation requires significant water during the pre-monsoon and early monsoon season for land preparation. In Girwari FMIS located near the Narayani River within the Gandaki Basin, farmers perceive that September rainfall, which is critical for flowering and grain formation of rice cultivation, is decreasing; however, the unusual wet September in 2016 caused flood damage rather than alleviating water shortages for crops (Parajuli, 2017). In addition, many irrigation systems use the small seasonal tributaries that are dependent on rainfall for the discharge; however, many of them are drying up and farmers perceive climate change as the main driver (Parajuli, 2017; Poudel & Duex, 2017).

Besides climatic factors, water stress can also result from political, socioeconomic and governance factors. The comparative study of success and failure stories of FMIS in Indrawati River basin of Central Nepal showed that polarization in political factions, poor infrastructure, lack of effective leaders, weak enforcement of existing rules and regulations are some of the main factors contributing to less effective FMIS (Ostrom et al., 2011).

1.3. Institutional coping and adaptation strategies

Based on Anderies et al. (2004), we define institutional adaptation as activities performed to anticipate and respond to external perturbations, in order to initiate structural or functional changes in FMIS and maintain their system performance. Examples of institutional coping mechanisms for water stress management include building temporary dams to increase water availability, improving irrigation infrastructure to prevent leakage, and enforcing rules for equitable and timely delivery of water to all farmers.

The literature on FMIS has identified several attributes supporting institutional adaptation. Some of the attributes are flexible rules, self-enforcement, local knowledge, and institutional nesting (Thapa et al., 2016; Lam and Chiu, 2016). Bastakoti et al. (2010) highlighted the importance of autonomy in decision making, flexibility in rulemaking, individual's trust in local leaders, and strong social capital for responding to market pressures and policy changes. Adaptation strategies are not only affected by institutional characteristics but also by institutional nesting, i.e., multiple tiers of overlapped organizations operating at different spatial scale (Lam and Chiu, 2016). Systems that are tightly nested or institutions that have to follow higher-level authorities for irrigation planning have a limited role in rule crafting and thus are vulnerable to the risks posed by external stressors (Lam and Chiu, 2016). Ostrom (2014) identified the evolution of rules to suit new contexts as another important attribute of institutional adaptation.

The present study contributes to the current literature in two principal ways. First, it provides field-based information on both the structural and operational measures (including rules) that farmers currently implement to respond to water stress. Further, it explores the agricultural performance of these adaptation measures and identifies several pertinent factors that contribute to institutional adaptation including the role of collective action, leadership, and governance.

2. STUDY AREA AND METHODS

The study was conducted in the Gandaki River Basin (GRB) of Central and Western Nepal, with a total catchment area of 46,300 km^2 (Figure 1). Originating in the mountainous region of Central Nepal and Tibet, the Gandaki River provides water for agriculture, households, and energy for one-third of Nepal's 29 million people.

Sample selection of FMIS was done using a two-step process. During the appraisal study, we visited 25 FMIS across the basin to understand the intensity of water stress, note any adaptation implemented, and observe overall system performance. A total of 12 FMIS were selected from 25 systems for a detailed case study based on (i) ecological region—mountains, hills, and Terai (plains); and (ii) water source for irrigation systems—large rivers vs. small- and medium-size rivers (Table 1). The diversity of the ecological region creates heterogeneity in terms of climatic conditions, agricultural productivity, culture, and ethnic composition, which, in turn, influences collective action and innovative adaptation (Gentle and Maraseni, 2012). The type of water source for irrigation determines the nature and extent of water stress and potential adaptation mechanism. All three mountain-region FMIS are located in Mustang which is in the Trans-Himalayan zone of Nepal, characterized by semi-arid, continental climate

(Fort, 2014). The eight hills FMIS are located in Rasuwa, Nuwakot and Dhading districts of Central Nepal. Only one Terai FMIS is selected from Madi, Chitwan.

Based on the precipitation regime, GRB can be divided into four seasons: pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and winter (December to February) (Table 2). The average annual precipitation in the GRB ranges from 152 mm to 549 mm. About 78 percent of the annual precipitation occurs in monsoon season (June-September) with the highest precipitation falling in July and August in all regions; however, the precipitation in the Trans-Himalaya is bi-modal peaking in May and December (Panthi et al., 2015). The monsoon contribution is highest (83 percent) in hills and lowest (32 percent) in the Trans-Himalaya region. The proportion of winter precipitation to the annual amount is the highest in the Trans-Himalaya region (26 percent). Since the river flow is more affected the precipitation than the snow-cover, most of the river receives the increase in flow from June to August and the minimum flow in March and April (Figure 2).

The data on institutional adaptation were collected from September to November 2016 using focus group discussions with the current and previous governing body of the irrigation system called Water User Association (WUA). For each FMIS, 30 to 40 households were surveyed (totaling 379 household surveys) to collect information on agricultural productivity, use of irrigation, and users' perceptions of FMIS governance. I also conducted transect walk in each FMIS where I surveyed the canal from the tail to head section and inspected the condition of irrigation canal, photographed major biophysical risks, estimated intake river category, and the calculated discharge of the river diversion where feasible. The qualitative and quantitative data were coded and analyzed in MS Excel and Stata version 9.2 and version 15.

3. RESULTS

3.1. Water stress: Temporal and spatial dimensions

The study uses farmers' perceptions of the gap between water supply and demand or "deficit water supply" at a particular time for a specified crop as the main indicator of water stress. Even a water-abundant irrigation system can be water stressed at a given time period due to seasonally variable demand and supply of irrigation water. For example, there is a peak water demand for monsoon paddy during land formation and paddy transplantation, which falls during pre- and early- monsoon season that may not provide sufficient water for all farmers (Figure 3). Hence it is necessary to understand the temporal dimension of stress.

The concept of a critical stress period is introduced here and defined as the time period when water stress is significant and institutional responses are necessary to address it. During the critical period, farmers are more actively engaged in irrigation management than other periods. This concept is similar to the notion of critical RWS. The stress is also not homogeneously spread throughout the irrigation system. In many systems, the stress is more concentrated around the tail end of the canal because of over-appropriation at the head-end and seepage loss.

Understanding the critical period is important for adaptation studies in a couple of ways. By looking at farmers' activities during the critical period, we can understand the structural and non-structural (operational) actions they are undertaking to manage the stress. For example, certain water allocation rules are only implemented during water stress period. Since the critical stress period incorporates information on climate variability, water supply, and water demand, its assessment can provide relevant information on climate change adaptation (Fussel, 2007). The study found two critical periods across all the ecological regions, as illustrated in Table 3.

3.2. Institutional strategies to manage water stress

Despite water stress conditions in many FMIS, most farmers have devised institutional strategies to cope with and adapt to the stress. There are four broad categories of institutional approaches implemented by FMIS to tackle water stress: (i) expansion of water sources within the command area by bringing in additional water; (ii) reduction of existing inefficiency in the infrastructure and water distribution mechanisms; (iii) enforcement of rules for equitable water distribution; and, (iv) exchanges of water both within and outside the FMIS. In the literature, these categories fall under the broader typologies of water stress management—water conservation, water allocation, and supply augmentation (Molle, 2004). These strategies are classified as structural and operational measures, where the structural measures are hard path solutions that include system rehabilitation works, while operational measures are soft path solutions that include the institutional rules and mechanisms that are in place to manage water stress (Table 4).

3.3.1. Expanding water sources: FMIS have brought in new water supplies when it is technologically and financially feasible. For example, the source of the Pokharephat FMIS in Nuwakot district has very low discharge (less than 50 liters per seconds) during the dry season mainly because of the seasonal nature of the spring. As a result, the FMIS was sensitive to rainfall variability, which resulted in reduced agricultural productivity for many years. In 2007, a group of farmers mostly comprised of WUA committee members collectively installed a water pump (commonly known as lift irrigation) that lifted water from the perennial Trishuli River up 45 feet to the middle and tail sections of the canal. The water is distributed through the branch canals and pipes based on farmer's demand. The rich history of collective action has facilitated cooperation among farmers for lift irrigation.

In the Trans-Himalaya region, each of the three systems has a storage reservoir above the command area. These reservoirs store water overnight so that farmers can irrigate their fields during the daytime. Each reservoir stores enough water for designated water users to irrigate for one to two days. The reservoir maintenance is generally allocated to either an individual or is done collectively. The reservoir serves multiple purposes. Water can be collected through the night and used by farmers during the daytime without the hassle of going outside in freezing night-time temperature. When the reservoir is opened, it creates enough velocity to discharge the water towards the tail-end of the canal. This is also an example of surge-irrigation that is required for in-field distribution uniformity in sandy soils that characterize the Trans-Himalayan region.

One of the common characteristics of FMIS is the use of local materials for construction of temporary diversion structures on the river. The structure diverts water from the river to the canal intake and is constructed especially during the dry season. Since monsoon rain often washes away the intake dams, most of them are temporary structures constructed using stones, wooden boards, and plastic. We found two systems in the hills that have been using heavy equipment vehicles such as excavators to create the dams. One of the WUA committee members stated "The sand mining that takes place at some distance downstream has contributed to lowering the water level even below the intake structure. For the last 7-8 years, we have had to bring a heavy vehicle to build the temporary dam and divert water towards the intake." The use of machinery is only possible in FMIS that have financial resources to cover the expenses and have road access to intake systems. Use of heavy-equipment vehicles can reduce labor, but requires large financial resources.

3.3.2. Reduce inefficiency through system rehabilitation: Earthen canals, still prevalent in many FMIS, incur seepage losses of up to 20-40%. Over a period of 20 years, all the studied FMIS have rehabilitated at least some sections of their canals using funding from government and non-governmental agencies. The civil works structures can include intake works, canal lining, road crossing structures, and siltation basin as per the local context (Singh, 2010). To prevent water seepage loss, FMIS generally line canals with cement or use high-density polyethylene (HDPE) pipes. HDPE pipes are more common in hills with rugged terrain.

FMIS tend to be opportunity seekers for infrastructure work because it requires large investments. Farmers tend to operate a canal with temporary structures and locally available materials and seek funding from governmental and non-governmental agencies for rehabilitation works. When necessary, FMIS also have acquired funds for infrastructure rehabilitation. For example, in Dhakarjun FMIS in Mustang district, the storage reservoir suddenly broke in 2014. The farmers immediately collected money from all the water users based on their landholding size and rehabilitated the system.

3.3.3. Equitable distribution of available water: The prevailing rule for equitable water allocation is a common mechanism employed by FMIS to manage limited water supplies during the stress period (Yoder, 1994). The allocation rules are generally based on a fixed percentage—the flow of water is divided into fixed proportions by some physical device; a fixed time slot—individuals are assigned fixed time intervals for withdrawal; or a fixed order—individuals take turns in getting water (Tang, 1992). Most systems have adopted rules that are flexible to the available volume of water and are based on fixed order (head to tail).

However, in highly water-stressed systems, we found that time-based allocation was more common than the fixed-order rule (Figure 4). For example, all three FMIS in Mustang district have implemented the time-based provision of water rights. In Phallyak and Dhagarjung, each household has a water right based on the time slot, generally 6-12 hours. In Thangbe, the water right, locally called *pyang,* is based on the irrigable area. The feudal system of local resource and administration governance, called the *mukhiya* system, ensured the strict enforcement of the water allocation rules.

In Gomati and Dhurba Archaletar FMIS in Dhading district, the water-access right was based on labor contribution at the time of irrigation construction. The households that did not contribute labor had to pay a high fee to gain access.

Some systems also had differential water distribution mechanism during water stress period. For example, farmers in Thangbe have access to irrigation water around every 6 days during stress period whereas during the normal period they have access to water every 12 days.

3.3.4. Exchanges of water within and among FMIS: FMIS also exchange water both within and among other FMIS to cope with water stress. In FMIS that have medium to high water stress, there is a fixed water allocation to each farmer, either based on time or landholding. Farmers generally share their water allocations with neighboring farmers in need through informal mechanisms. For example, in Thangbe, Phallyak and Dhagarjung FMIS of Mustang district, farmers generally supply their excess allocated water to neighboring farmers in return for the past or future exchanges based on mutual understanding. . One of the farmers in Dhagarjung told “We often help each other and share the excess water with some of our neighbors; after all, we live in the same village and try to have a good term with each other”. In Radhapur FMIS in Madi, Chitwan, the FMIS have established a mechanism to borrow water from neighboring FMIS during critical water stress period, particularly during the rice plantation season.

3.3. Water stress and institutional arrangements

Since time-based water allocation rules are mostly found in the highly stressed system as shown in Figure 5, the systems that had time-based vs. order-based allocation rules have different institutional arrangements. For our study, we use an aggregate of three dummy variables as an indicator of institutional arrangement—water guards to monitor water allocation, water fees or equivalent, and closed-access to irrigation water. The FMIS with time-based rules had two or even three of the variables of institutional arrangements.

Similarly, good governance is another important feature that determines the overall performance of FMIS. For our study, we defined governance as a cumulative indicator of four variables as perceived by the farmers: rule enforcement, labor mobilization, transparency, and leadership. The four variables are rated 1, 2, or 3 to represent low, medium and high rating respectively. The values are summed and converted into a percentage of the total potential rating. We found high governance scores for systems that had time-based allocation rules. This implies that good governance facilitates the establishments and enforcement of the rules for water governance.

We also found that time-based allocation rules were adopted in FMIS that had a higher percentage of crops grown for commercial purposes. The water has higher monetary value for commercial crops compared to subsistence crops that also motivates farmers to manage it effectively through different institutional mechanisms.

3.4. Institutional adaptation and irrigation performance

The type of institutional adaptation measures also affects irrigation system performance. We found that measures to expand water supplies through lift irrigation and borrowing from neighboring FMIS increases the average crop intensity significantly (Figure 6). Without lift irrigation, Phokarephat FMIS in Nuwakot district was limited to two crops per year. The FMIS in the Trans-Himalaya have the lowest average crop intensity of 1.9 because large plots of agricultural land are barren due to water deficiency and snow cover during the winter season limits the growing season.

In addition, FMIS located in remote areas in hills and mountains have poor access to transportation (e.g., roads and public vehicles) that discourages farmers from doing commercial farming. For example, in Dhurba Archaletar FMIS of Dhading district, farmers could increase the crop intensity if they have better access to road services.

3.5. Institutional factors contributing to effective water-stress management

There are combinations of biophysical and institutional factors—based on local context—that influence the choice of water-stress management strategy. Based on the focus group discussion (FGD), we have identified the following key factors:

3.6.1. Collective action: The first and foremost requirement for a functional FMIS is the farmers' willingness to act collectively. Farmers have to come together to discuss salient irrigation issues and find common solutions. Successful collective action depends upon various factors and has been widely researched (Benjamin et al., 1994; Bardhan, 2000; Dayton-Johnson, 2000, Pokhrel, 2015). Some of the factors are the perception of fairness, reciprocity and trust, homogenous community, group size, and command area. The continued interest of farmers to solve problems collectively forms the basis for collective action on water-stress management. If the majority of farmers are not interested in maintaining the irrigation systems, the FMIS slowly becomes dysfunctional and there is little scope for structural or operational measures. An ex-president of the Pokharephat WUA said, "Now-a-days, farmers are less enthusiastic about the canal maintenance because most of them rely on non-farm income sources including remittance to support their livelihood. The younger generation moves to cities and we old people don't have energy and interest to keep the canal in a good condition."

3.6.2. Economically feasible alternate water sources: In order to pursue source expansion, naturally, there should be an alternative water source that can be extracted in an economically and technologically feasible way. Lift irrigation is only possible in river terraces that are within 30-70 m of the perennial river. In high mountains with steep slopes, this option is economically and geographically unfeasible. Lift irrigation via solar panels is another potential strategy applicable in hills and mountains, but this remains very a costly option in many cases. For example, the farmers in Pokharephat installed a lift irrigation system with significant financial support from a non-government organization. None of the study sites have large, potentially untapped water sources in high mountains and hills. This implies that they either have to depend upon technologies or invest heavily in long-distance aqueduct. Overall, it is apparent that technology choice can have a major implication for common-pool resource governance.

3.6.3. Leadership: Infrastructure rehabilitation requires substantial funding that has to be collected from outside agencies. Over the last two decades, the Government of Nepal (mainly the Department of Irrigation and Department of Agricultural Development) and non-governmental agencies (e.g., CARE Nepal) have made progressive policies to finance canal rehabilitation and strengthen institutions. In order to procure financing, the leaders need to be familiar with the government bureaucracy and be proactive and persistent in securing funds. This attribute will be increasingly important in the future as the intensity and frequency of water stress may increase due to climatic and non-climatic factors.

3.6.4. Good governance: Good governance is the foundation for irrigation management at any given period of time, including the period of water stress. In the context of FMIS in Nepal, some of the main characteristics are leadership, transparency and accountability, inclusive and participatory decision making, and conflict resolution (Thapa et al., 2016; Bastakoti, Shivakoti, and Lebel, 2010). Well-governed systems are able to manage the water stress better because they are more responsive to water shortage concerns, and can ensure effective enforcement of water allocation rules. The WUA committee ensures participatory decision making by organizing regular meetings with the stakeholders. Good leaders who build trust with farmers are capable of performing vital organizational functions including labor mobilization, conflict resolution, and securing internal resources.

4. DISCUSSION

The FMIS have devised innovative strategies based on local agronomy, biophysical environment, and culture. The choice of institutional strategies for water stress management can be limited by multiple factors. For example, water augmentation strategies are limited by the biophysical availability of alternative water source and socioeconomic feasibility of the technological choice. The type of water management rules was strongly influenced by cultural factors in some areas. The influence is noted particularly in the Trans-Himalayan region where natural resources, including irrigation, are managed by *Mukhiya* system. The *mukhiya,* or feudal, system is an indigenous way of governing the village and its resources. The *Mukhiya,* or communal leader, is elected for a fixed term and has the mandate to make all decisions on resource governance, including resource distribution and conflict resolution.

Technology plays an important role in addressing water stress but it also brings challenges for CPR governance. Two unique characteristics of CPR are subtractability (one person's use of the resource diminishes the potential for use by another) and difficulty of exclusion from using the resources (Ostrom et al., 2002). Lift irrigation can alter both these characteristics. Lifting water from the perennial river can actually be considered non-subtractable because lift irrigation only extracts a very minute fraction of the total flow in large rivers (but the situation may change in medium-size rivers). Further, it is relatively easy to exclude the user by charging a fee or setting other criteria. The technology can also alter the labor contribution in irrigation management. Traditional FMIS generally required 2-10 labor days from each household for canal maintenance.

However, lift irrigation requires no household labor contribution because it is done by the pump operator (except the cleaning of tertiary canal that is done by farmers individually).

It is also important to understand the effectiveness of these stress-management strategies on crop productivity. Structural measures of augmenting water or canal lining can add a significant volume of water available to the farmers, particularly located at the tail-end, and help maintain their cropping intensity. On the other hand, institutional rules are important to ensure that water is delivered to the needy farmers. Operational rules are useful to ensure equitable distribution of resources in a timely and adequate manner. Almost all the FMIS in our study have homogenous cropping intensity (except the FMIS in mountainous Mustang district) because of multiple factors – all of them have some form of water allocation and distribution rules and farmers grow less water-consuming varieties (Figure 6).

From an adaptation perspective of local institutions, we note a few important points. In order to understand institutional adaptation, we need to understand at least two elements: 1) when was the action started? and 2) what were the main drivers of the action? (Smit and Skinner, 2002). In terms of the time of origin, most of the operational rules were devised at the time of their establishment. Those rules were established because the systems were water stressed due to small water source and poor infrastructure conditions. Similarly, structural measures, mainly infrastructure rehabilitation, have escalated over the last fifteen years mainly driven by government and non-governmental organizations' effort to modernize FMIS. Hence, we argue that it is difficult to attribute the existence of operational rules and infrastructure rehabilitation to climate change.

However, climate variability and change affects FMIS in various ways. The increasing trend of extreme events increases the flash floods, landslides and debris flow risks that causes damages to the irrigation infrastructure and agricultural land. The change in on-set and off-set of monsoon in some parts of the basin hampers the crop production during that particular season. The FMIS that divert water from small rivers are more vulnerable to climate variability and change than those diverting water from large rivers. Thus, climate variability and change magnifies the existing threats the system faces from water stress and other factors.

5. CONCLUSION

The study identified and characterized multiple institutional strategies implemented by FMIS to cope with and adapt to water stress. Though water stress is prevalent even in water abundant systems, the risk is more significant in FMIS that have small- and medium- size rivers as the water source. Climate variability and change acts as a threat multiplier because it compounds the existing threats the system faces from social and economic systems. Institutions can deploy structural and operational measures to address water stress. Structural measures include source expansion by bringing water from new sources and water conservation through infrastructure rehabilitation works, such as concrete lining. Water allocation rules, provision of water guards, and access to water are some operational measures for water stress management. The choice of a particular measure depends upon multiple factors such as biophysical availability of alternate water sources, leadership and funding availability, and good governance and collective action. Technology can play an important role in reducing water stress but it can also have consequences on key features of CPR governance, including labor mobilization and exclusion of users. Structural measures are more effective in adding a significant volume of water to the command area, however, operational measures are important to ensure that water is distributed equitably and efficiently. Hence, both the structural and operational measures are important and necessary for water stress management. Good governance is the foundation of any institution that helps to operate the infrastructure more effectively and equitably.

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FIGURES

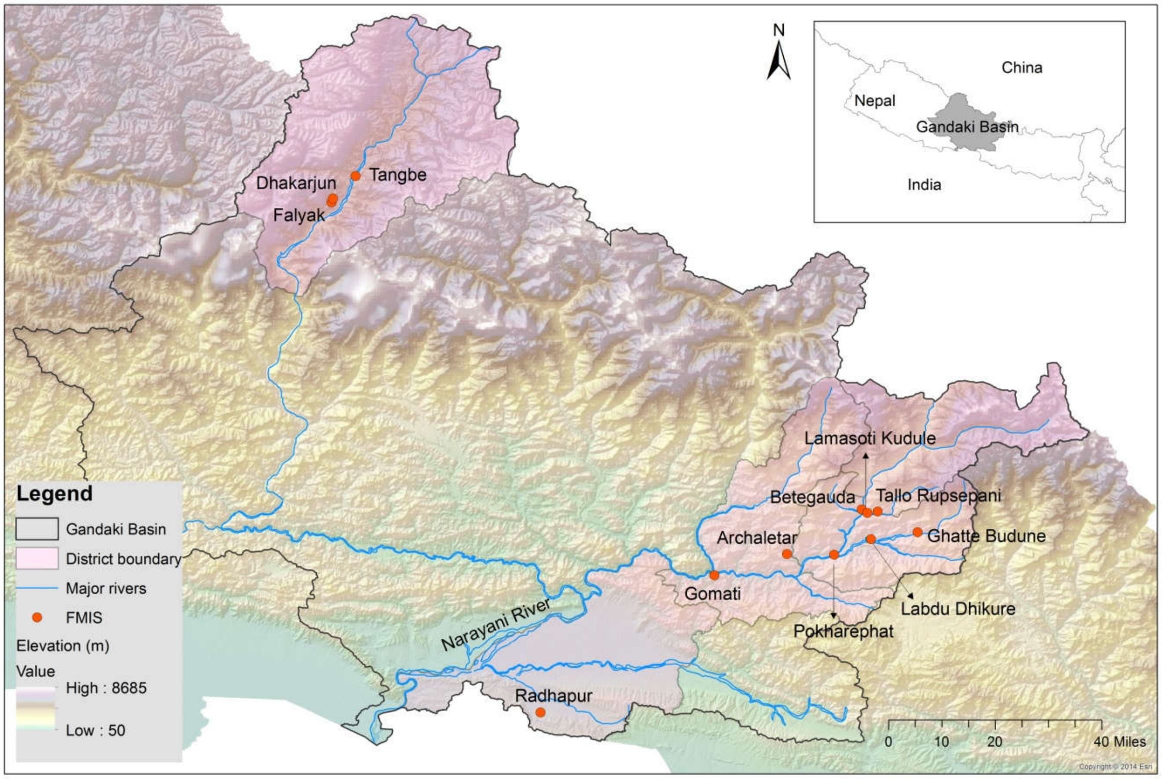

Figure 1: Study sites in the Gandaki River Basin of Nepal (Source: Author)

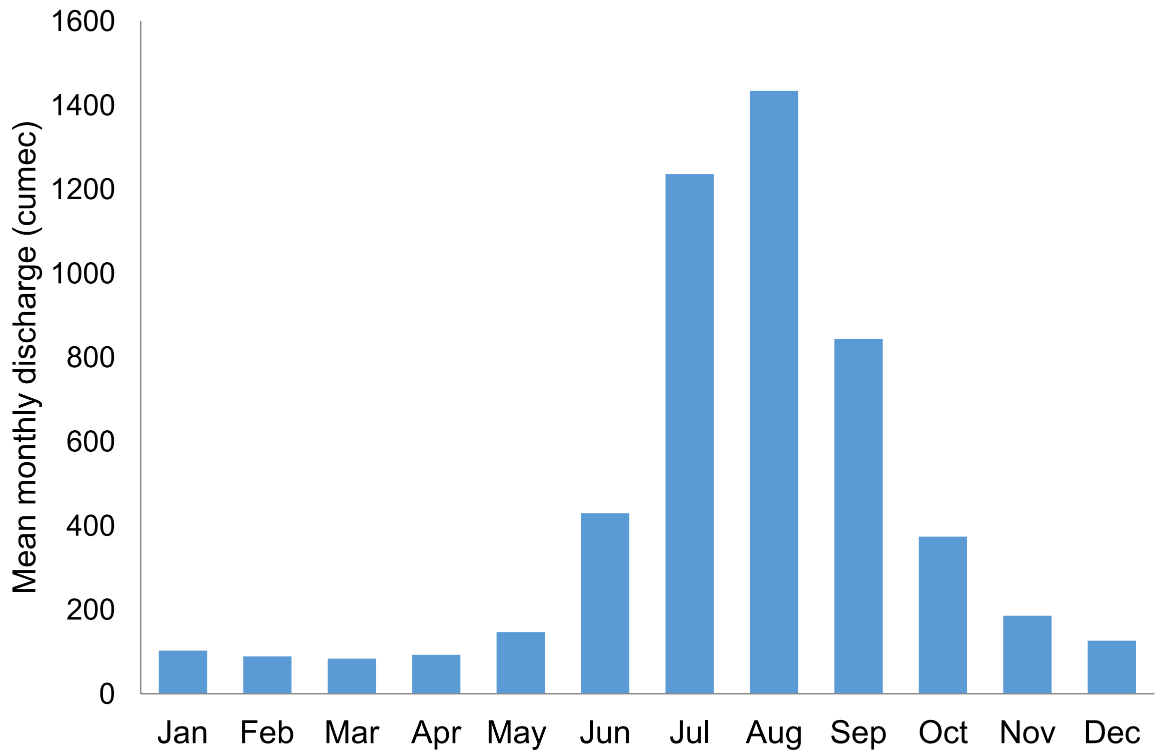

Figure 2: Mean monthly discharge of the Kali Gandaki River (1996-2006) (Bajracharya, Acharya, & Ale, 2011)

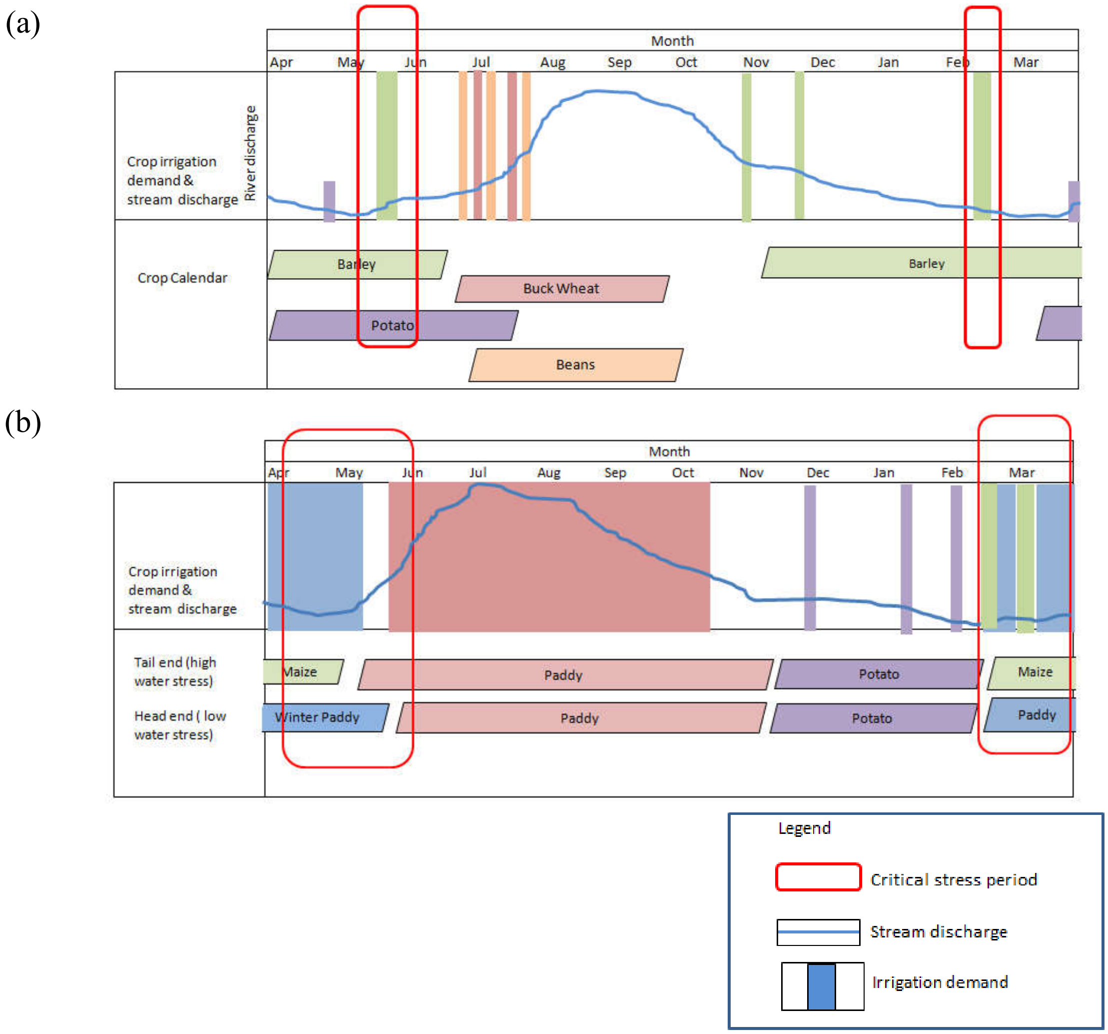

Figure 3: Schematic diagram of irrigation scheduling and river discharge for (a) Trans-Himalaya/Mountain and (b) Hills and Terai farmer-managed irrigation systems (Source: Author)

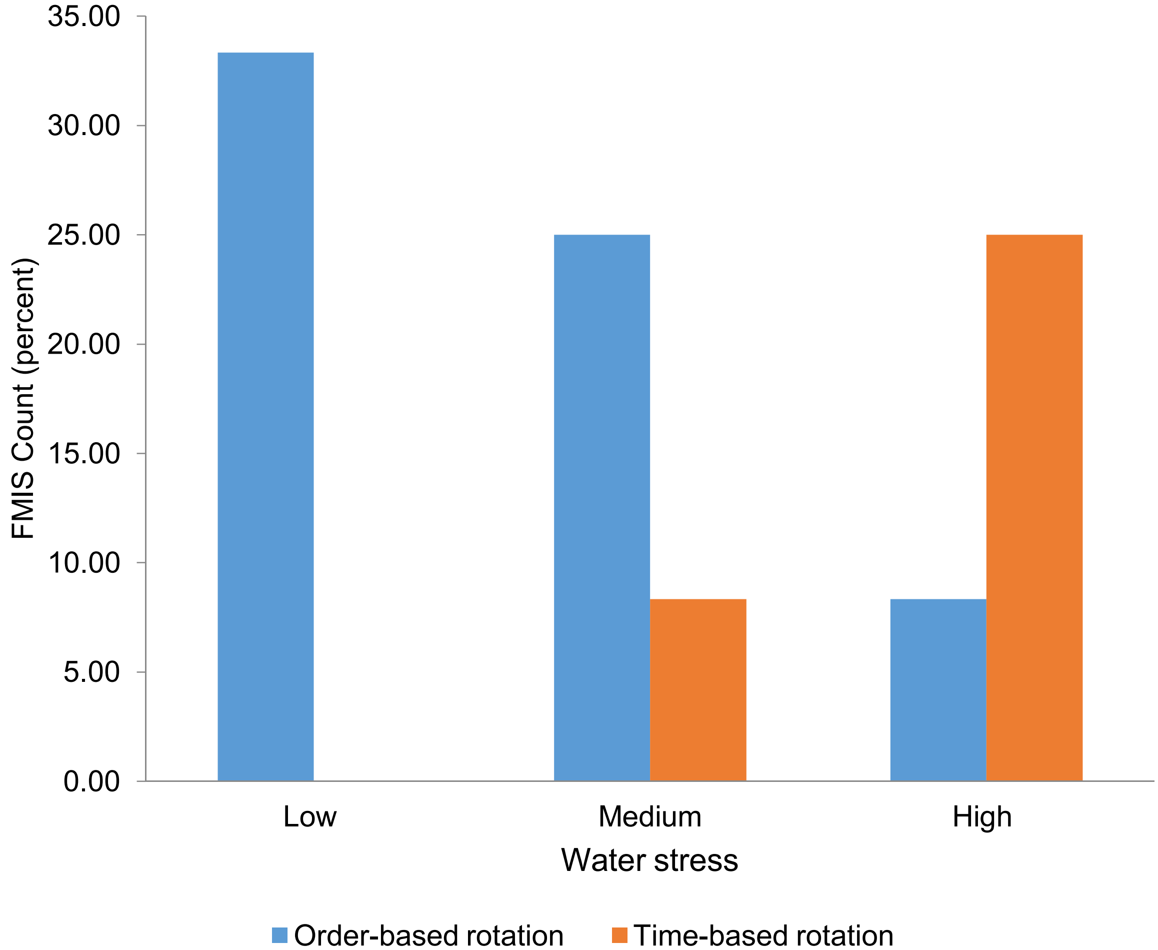

Figure 4: Percentage of farmer-managed irrigation systems with different water allocation and stress level

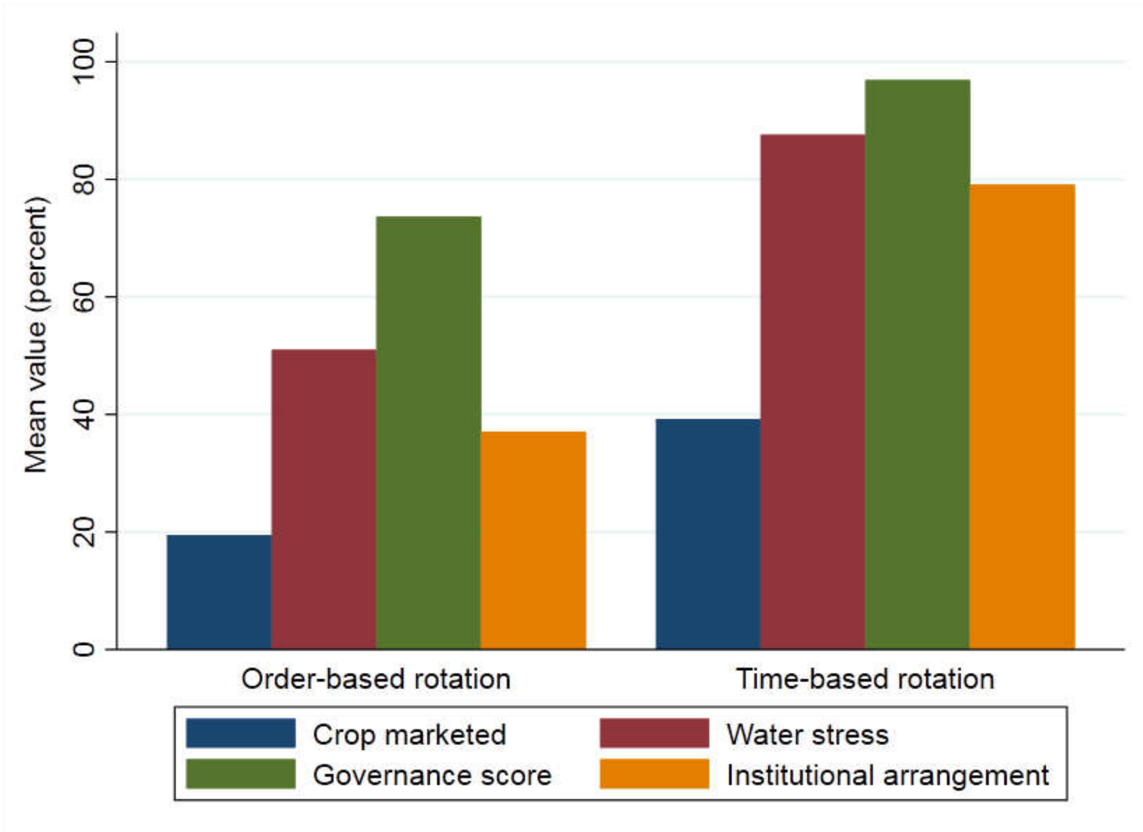

Figure 5: Mean percentage of different parameters in farmer-managed irrigation systems with (a) time-based, and (b) order-based water allocation rules

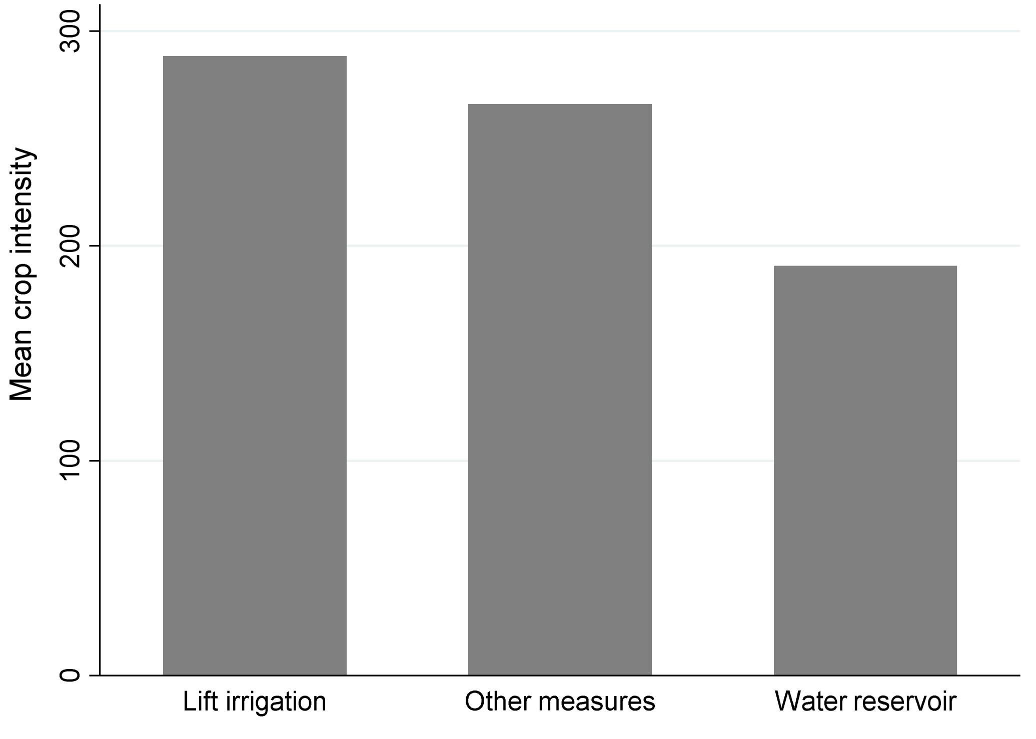

Figure 6: Average crop intensity for different typologies of adaptation

TABLES

Table 1: FMIS parameters by agro-ecological zones

Agro-ecological zone	FMIS Count	Median Command area (ha)	Median total households	Main crops	Median stream discharge (lps)	Ethnic groups
Mountain	3	26	48	Nacked barley, Wheat, potato, beans	400	Homogenous
Hills	8	56.5	162	Paddy, maize, vegetables, mustard	2400	Heterogeneous
Terai	1	26	62	Paddy, maize, mustard	1300	Heterogeneous

Note: lps: leter per second

Table 2: Average seasonal and annual precipitation and their coefficients of variation in agro-ecological zones of the Gandaki River Basin

Agro-ecological zone	Winter (mm)	Pre-monsoon (mm)	Monsoon (mm)	Post-monsoon (mm)	Annual (mm)
Trans-Himalaya	61.7 (56.5)	102.7 (34.0)	342.9 (30.6)	40.1 (133.9)	547.4 (25.0)
Mountain	123.1 (104.6)	198.6 (60.4)	1100.9 (20.8)	73.1 (85.1)	1495.7 (21.5)
Hill	21.4 (60.5)	381.6 (24.9)	2880.9 (11.6)	124.0 (48.3)	3468.6 (10.3)
Terai	46.8 (85.7)	219.7 (36.3)	1601.6 (22.0)	82.6 (81.5)	1950.7 (21.9)
Gandaki River Basin	63.2 (72.6)	225.7 (21.17)	1481.6 (11.8)	79.9 (61.6)	1865.6 (10.7)

(Source: Panthi et al., 2015)

Table 3: Critical water stress period by agro-ecological zones

Agro-ecological zones	Critical water stress period	Sensitive growth periods for water stress
Mountain/Trans-Himalaya	Feb. & Mar.	Crop development period for barley
	May	Ripening stage of barley, high evapotranspiration
Hills & Terai	Early Mar.	Maize plantation & flowering, winter paddy plantation
	Mid-June	Paddy field preparation, plantation

Table 4: Institutional strategies to manage the water stress

Category	Categories	Institutional strategies	Geography	FMIS Cases
Structural	Expand the water sources	Lift irrigation to augment additional water	Hill	6, 12
		Reservoir to store additional water	Mountain, Hill	1,2,3,12
		Temporary dams to increase water inflow at the intake	Hill	8, 11
	Infrastructure rehabilitation	A wide range of infrastructure works	Mountain, Hill, Terai	1-12
Operational	Equitable distribution of available water	Water rotation rules based on time and cultivated area	Mountain, Hill, Terai	1,2,3,8,9, 11
	Exchange of allocated water within FMIS	Informal borrowing of water from other farmers within the FMIS	Mountain	1,2,3
	Exchange of allocated water outside the FMIS	Informal borrowing of water with neighboring FMIS	Terai	11

FMIS Cases: [1] Phallyak, Mustang; [2] Dhagarjung, Mustang; [3] Thangbe, Mustang; [4] Tallo Rupsepani, Rasuwa; [5] Lamasoti Kudule, Rasuwa; [6] Betegauda, Rasuwa; [7] Dhurba Archaletar, Dhading; [8] Labdu Dhikure, Nuwakot; [9] Ghatte Budune, Nuwakot; [10] Gomati, Dhading; [11] Radhapur, Chitwan; [12] Pokharephat, Nuwakot.

APPENDIX C: Assessing multilevel determinants of smallholder crop choice in irrigated agriculture of Central Nepal[3]

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[3] Formatted for submission to *Global Environmental Change*

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ABSTRACT

Change in crop choice is a common adaptation strategy to climate variability and change. However, its drivers are not well understood. We investigate the multilevel determinants of smallholders' crop choice in irrigated agriculture of Central Nepal. We build upon previous studies and consider four levels of determinants: households, farmer-managed irrigation systems, local and regional market systems, and climatic regions. Using primary survey data of 316 farmers from 9 farmer-managed irrigation systems in Trishuli-Narayani sub-basin of Central Nepal, we document that smallholders are more likely to choose rice during the monsoon season if they are more experienced and farm in the irrigation systems that are fed by large rivers. Farmers living in the irrigation systems that are fed by small and medium-size rivers are more likely to choose less water-demanding crops. Market integration is also a key determinant of crop choice. Our findings have important implications for climate resilient adaptation policies.

Keywords: farmer-managed irrigation systems, rice, adaptation, mountain, crop diversification

1. INTRODUCTION

Smallholder farming[6] accounts for 50 percent of the global farmland and more than half of the world's food production (Samberg et al., 2016). In Nepal, 2.7 million farms, with an average landholding of 0.5 hectares, grow up to 70 percent of the country's total food production (Rapsomanikis, 2015; Roka, 2017). In recent decades, however, these farmers have come under increasing stress from urbanization, market integration, competing water demands, and climate variability and change (Bastakoti et al., 2010; Döll, 2002; Pokharel, 2015).

To cope with these challenges, farmers have been adapting their agricultural practices (Chhetri et al., 2013) of which crop choice is one of the most frequently adopted strategies (Dury, Garcia, Reynaud, & Bergez, 2013). Farmers choose the crop according to availability of water resources and other factors. Other coping and adaptation strategies include changing the timing of the crop plantation and switching to water-efficient seed varieties. Crop choice is a dynamic process affected by social, economic, cultural, and biophysical factors (Beckford, 2002; Dury et al., 2013). Since rice is the main staple food for the majority of the population, it is a key component of food security in Nepal. But it is a water-intensive crop. The lowland rice variety, common in Nepal and other Asia countries, is grown in the fields where farmers try to maintain 5-10 centimeter of floodwater on the field for most of the growing season. As a result, it consumes 2 to 3 times more water per hectare than other crops (GRiSP, 2013). In recent decades, Nepal has witnessed changes in precipitation trend (Douglas, 2009; Panthi et al., 2015). In the Gandaki River Basin of Central and Western Nepal, where our study sub-basin is located, there is a decreasing trend of pre-monsoon and winter rainfall in the mountain region.

[6] Farms with less than 0.2-0.5 hectares.

Similarly, while there is no definitive country-wide decadal trend in 1-day extreme precipitation peak from 1966-2015, there is an increase in extreme precipitation events in the western mountainous regions and mixed pattern in other regions including the Gandaki Basin (Talchabhadel et al., 2018). This, along with the market integration at the national and local level, has been discussed as one of the motivations for farmers to choose rice over cash crops such as vegetables (Thapa, Kumar, Roy, & Joshi, 2017). However, to the best of our knowledge, a systematic analysis of the multilevel determinants of crop choice of smallholder farmers is lacking.

In this paper, we analyze and assess the multilevel determinants of farmers' crop choice in irrigated agriculture of Central Nepal. More specifically, we examine the relative importance of household, irrigation system, regional market, and climate characteristics as the determinants of crop choice. Using a survey data of 316 farmers sampled from 9 farmer-managed irrigation systems (FMIS) in Trishuli-Narayani sub-basin, we find that farmers are more likely to choose rice during the monsoon season if they are more experienced and farm in the irrigation systems that are fed by large rivers. FMIS have a unique way of governing irrigation system in Nepal where community members are responsible for overall irrigation management including water appropriation, distribution, canal maintenance, and conflict management through collective action (Thapa et al., 2016). Farmers living in the irrigation systems that are fed by small and medium-size rivers are more likely to choose less water-demanding crops. Market integration is another determinant of crop choice.

The remainder of the paper is organized as follows. In Section 2, we discuss the related studies and outline our theoretical framework guiding the subsequent empirical analysis. The study area and data are described in Section 3. In Section 4, we present our empirical model and discuss the estimation strategy. We present the results in Section 5 followed by the conclusion in Section 6.

2. RELATED STUDIES AND THEORETICAL FRAMEWORK

2.1. Related studies

Studies have explored the determinants of crop choice of smallholder farmers (Arunrat, Wang, Pumijumnong, Sereenonchai, & Cai, 2017; Deressa, Hassan, Ringler, Alemu, & Yesuf, 2009; Warner, Kuzdas, Yglesias, & Childers, 2015; Yang et al., 2017). The general focus has been on the roles of demographic characteristics and socioeconomic status of farmers (Adesina & Zinnah, 1993; Seo & Mendelsohn, 2008), price of agricultural inputs and productivity (De & Chattopadhyay, 2010; J. Dury, Schaller, Garcia, Reynaud, & Bergez, 2012; Greig, 2009; Yang et al., 2017), and access to markets and credits (Below et al., 2012; Deressa et al., 2009; Tambo & Abdoulaye, 2012). Less attention has been paid to the importance of local irrigation institutions (McCord et al., 2017, 2018) and perceptions of climate change (e.g., the perception of temperature and precipitation changes) in household decision making (Jain et al.,2015; and Khanal and Mishra, 2017).

Studies on rice farming and irrigation institutions in Nepal have focused on household and community-level determinants of improved rice seed varieties (Ghimire et al., 2015; Upadhyaya et al., 1993). Upadhyaya et al. (1993) estimate a multinomial model of adoption of improved rice variety and find that the presence of irrigation system as its key determinant. However, they do not consider the institutional characteristics of the irrigation system that is equally important for agricultural productivity (Lam, 1998). In a similar study, Ghimire et al. (2015) estimate a probit model of the adoption of improved rice variety and find that educational attainment, household size, extension services and access to seed varieties as its significant determinants. However, unlike Upadhyaya et al. (1993), they do not consider the role of local irrigation institution at all. A large part of the literature on the governance of common-pool resources in Nepal is devoted to the empirical relationship between the productivity of FMIS and institutional attributes. The general finding is that irrigation institutions managed by farmers are more productive and equitable than those managed by agencies operated under the government entities, also called as agency-managed irrigation system (Lam, 1998; Ostrom & Benjamin, 1993; Pradhan, 1989b). However, it should be noted that these studies were conducted at the irrigation system level. Therefore, their findings cannot be generalized to all farmers. In particular, it is not clear if these findings will hold for smallholder farmers.

Thus, there are two notable gaps in the existing literature. First, although rice is the primary staple food crop in Nepal, in the recent years, increasing numbers of farmers have opted for non-rice crops such as vegetables and citrus fruits. The reasons for this change in crop choice have not been comprehensively examined. In particular, no study to our knowledge has simultaneously considered the roles of household characteristics, irrigation institutions, and climate-related factors. Second, studies on the roles of irrigation institutions, collective action, and system-level water delivery are limited in their scope since they do not account for the potential contributions of hydrological infrastructure that are directly affected by climate variability and change.

This study attempts to fill these gaps in the literature by providing a more comprehensive analysis of the determinants of smallholder farmers' choice of lowland rice during the monsoon season in Central Nepal. We pay a particular attention to the role of water stress[7], which has strong links with climate change and variability observed in Nepal.

2.2. Theoretical framework

We develop a generalized schematic framework (Figure 1) of crop choice. In this framework, the primary outcome – crop choice decision – is influenced by household and socioeconomic factors (e.g., age, education, income, and household size); biophysical and agronomic factors (e.g., climate, slope, and soil type); institutional factors (e.g., farmer-managed irrigation system); and market factors (e.g., distance to market and crop marketed) (Table 1).

Household and socioeconomic factors: Demographic and socioeconomic characteristics of farmers are the first level of factors that influence their agricultural decisions including crop choice. Age, household size, educational attainment, training, income and their sources, and farm size have been identified as important determinants of crop choice and crop diversification (Adesina & Zinnah, 1993; Bezabih & Sarr, 2012; Seo & Mendelsohn, 2008). Younger farmers are more knowledgeable about new practices and are willing to bear risk (Adesina & Zinnah, 1993). The ability to take risks are higher for farmers with larger land holding and household size (Khanal & Mishra,

[7] Water stress refers to supply of water relative to a farmer's perceptions of the irrigation demand for the crop at a given period of time (Yoder, 1994). It is a result of biophysical and climatic changes, infrastructure conditions, institutional rules of water allocation and distribution, and socioeconomic status of farmers.

2017; Langyintuo & Mungoma, 2008). Education, training, and visits by extension services strengthen the farmers' knowledge of new crops and positively affect the crop diversification (Deressa et al., 2009; Tambo & Abdoulaye, 2012).

Biophysical and agronomical factors: The biophysical and agronomical factors such as cropland location, soil type, and slope are significant determinants of crop choice. In Nepal, rice is grown in all agro-ecological zones, from the subtropical climatic region of the lowland Terai and the valley to the higher altitudes of 1,500 and 3,050 meter above sea level – the highest elevations in the world known to grow rice (Chhetri & Easterling, 2010; FAO, 2018b). Our study is located in the hills and Terai regions which are optimally suitable for rice plantation. The location of agricultural land in the irrigation system is another biophysical attribute that determines water scarcity. Generally, tail-end farmers receive less water compared to farmers at the head and middle sections (Lam, 1998). In a hilly area, slope greater than 45 percent is not considered suitable for holding the water required for rice plantation (Chhetri & Easterling, 2010). For moderate and less slopy areas (less than 45 percent), the farmers tend to create terrace (also called *khet*) where the land is bunded (corners of the irrigated land is raised by a few centimeters to hold water) to make it suitable for puddle rice farming (Rana, Garforth, & Sthapit, 2009).

Institutional factors: In Nepal, rice is mostly grown on irrigated plots where irrigation is supplied by FMIS. These irrigation systems are generally built using low-cost technology appropriate for heterogeneous local conditions. Their performance can be measured and assessed by the attributes of farm productivity and delivery of water quality and water quantity (Molden, Sakthivadivel, Perry, De Fraiture, & Kloezen, 1998; Svendsen & Small, 1990). Studies have shown that FMIS with indigenous water management rules provides more reliable sources of adequate water supply than those managed by government agencies, also called agency-managed irrigation systems (AIMS) (Bastakoti & Shivakoti, 2012; Lam, 1998). For example, the rules devised by the farmers for water distribution and allocation are more flexible to local conditions such as soil type and socioeconomic factors than the rules crafted by agency engineers in AIMS who are often located at remote locations and have limited information on the local context.

Market factors: Proximity to market helps farmers in at least two ways. It provides them with easier access to inputs (e.g., hybrid seed, fertilizers, and pesticides). Market proximity also factors into farmers' crop choice. For example, vegetables are more preferred crops among the farmers located closer to market and road networks (Ghimire et al., 2015; Thapa et al., 2017).

3. STUDY AREA AND DATA

The study area is located in the Trishuli-Narayani sub-basin of the Gandaki River Basin (GRB) of Central and Western Nepal, which has a total catchment area of 46,300 km^2 (Figure 2). Originating in the mountainous region of Central Nepal and Tibet, the Trishuli is a major river system providing water for agriculture, households, and energy for millions of people living in the basin and beyond. Agro-ecologically, GRB can be divided into mountains, hills and Terai region.

We purposively chose Trishuli-Narayani sub-basin because of its proximity to Kathmandu. There are about 350 FMIS in Trishuli-Narayani sub-basin (DOI, 2007). From a preliminary survey of 25 FMIS, we randomly selected 9 FMIS based on two considerations: the size of the river used for canal intake and agro-ecological zone (Table 2).

The size of the river used for canal intake directly contributes to water stress. Eight of the FMIS are located in the hilly region and one FMIS is located in the Terai region. Approximately 30-45 households were randomly selected from each FMIS, stratified by its head, middle, and tail sections. The sampling was stratified by the sections of FMIS because farmers at the tail section are generally more water stressed than farmers at the head and middle sections of the irrigation system (Anderies and Janssen, 2011; Lam, 1998).

A comprehensive household survey of farmers was conducted during the post-monsoon season of 2016. In addition, focus group discussion (FGD) was conducted with the FMIS authority that mainly comprised of current and past committee members that manage the FMIS, also called as the Water User Association (WUA). I also conducted a transect walk in each irrigation system, where I surveyed the canal from the tail to head section and inspected the condition of irrigation canal, photographed major biophysical risks, and calculated discharge of the river diversion where feasible.

4. MEASUREMENT AND EMPIRICAL STRATEGY

4.1. Measurement of variables

We are interested in analyzing the multilevel determinants of crop choice. Therefore, our dependent variable of interest is crop choice. The crop choice of a farmer is represented by a binary variable which takes the value of 1 if the farmer's choice during the monsoon season (May – September)[8] of 2016 was rice, and 0 if the choice was other crops.[9] Figure 3 shows the frequency distribution of non-rice crops in the sample. The most frequently chosen non-rice crop is vegetable (i.e., cabbage, cauliflower, tomato, radish, green peas, and bitter gourd, and green Chili pepper).

The predictor variables include household, irrigation institutional, and climatic characteristics. The household variables include age, education, land holding, income source, the location of agricultural land in the irrigation system, and crop intensity. The irrigation system characteristics include the size of the river, which is the irrigation source, and canal infrastructure condition. I also incorporate multidimensional indices to measure institutional rules, WUA performance, and water delivery. Precipitation and temperature trend are also incorporated as regional and global variables.

The precipitation and temperature data were obtained from the Center for Environmental Data Analysis (CEDA)[10]. The monthly total precipitation and average temperature data were obtained from the HadISD dataset (v2.0.2.2017f) for Nepal for the period of 1981-2017. The dataset is at 0.5 ^{o} x 0.5^{o} grid scale. In line with Panthi et al. (2015), we group the data into four seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). Then we use Mann-Kendall test for monotonic trend, a non-parametric method, to calculate the decadal trend (decadal moving average) since it is more suitable for non-normality in a short record and the presence of outliers (Panthi et al., 2015). The tau and Sen's slope

[8] For crop choice, monsoon season also includes May to account for early monsoon planters.
[9] Alternatively, we define crop choice as a categorical variable (1= rice, 2= non-rice crop, 3=fallow land) and estimate a multinomial model of crop choice. The results are presented in appendix, but we note that observations on fallow land is very small (n=21).

[10] http://catalogue.ceda.ac.uk.

values were calculated using Microsoft Excel's XLSTAT function and Stata version 15 (Table 3 and Table 4).

Since farmers are nested within the irrigation system, we construct system level indices to capture the effects of institutional attributes. Following Thapa et al. (2016), we assess irrigation institutions on four dimensions: water distribution and appropriation rules, institutional process and leadership, water delivery, and hydrological infrastructure. Since each dimension has multiple attributes, an index is formulated for each dimension, except the hydrological infrastructure.

Sound infrastructure alone is not sufficient for timely and equitable delivery of water to farmers. Well-crafted rules and enforcement mechanisms can overcome the deficiencies in infrastructure (Uphoff, 2005). For example, rules and norms set out by WUA and enforced through voluntary mechanism can promote behaviors that take into account the collective benefits. These actions help to maintain the overall agricultural productivity despite poor infrastructure. Following Lam (1998), we incorporate three types of rules to construct *institutional rules index* (IRI): irrigation water fee to farmers (F_i), time-based water allocation (R_i)[11], and water guards to deliver water in an effective and timely manner (G_i). The IRI is defined as follows:

$$IRI_i = \sum (F_i + R_i + G_i)$$

Each rule is a dummy variable, which takes the value of 1 if it is present; otherwise 0. Then by construction, IRI_i takes the discrete values between 0 and 3.

One of the common challenges to local institutions is their elite capture and power play that discourages marginal farmers to express their concerns (Iversen et al., 2006;

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[11] The default is order-based water rotation system (e.g., head to tail).

Lund & Saito-Jensen, 2013). The organizational processes such as financial transparency, decision-making processes, and social image of leadership are some of the basic institutional factors that can also foster effective adaptation (Gupta et al., 2010; Thapa et al., 2016). We calculate the institutional process, *Institutional process and leadership index (IPI),* based on the farmer's perception of the leadership and institutional processes, which is measured via four dimensions: labor mobilization ability (L_i), financial transparency (T_i), ability to collect external fund (F_i), and the perception of the social image of the WUA committee members (S_i). The IPI is defined as follows:

$$IPI_i = \sum (L_i + T_i + F_i + S_i)$$

All of the variables are dummy variables. Thus, the *IPI* score ranges between 0 and 4.

The main function of the irrigation system is to deliver water in an adequate, timely and fair manner (Martin & Yoder, 1988; Pradhan, 1989b). Following Lam (1998), we construct a *water delivery index (WDI)* to capture farmers' perception of water delivery. It is based on five considerations: adequacy (A_i), timeliness (T_i), reliability (R_i), deprivation (D_i), and flexibility (F_i). Water adequacy and timeliness refer to farmers' perception of adequate and timely delivery of water. Farmers achieve reliable water supply when they are able to predict the availability of water. Equity measures any deprivation on receiving the water whereas flexibility focuses on alteration of the water allocation rules according to the farmers' need. WDI is defined as:

$$WDI_i = \sum (A_i + T_i + R_i + D_i + F_i)$$

All of the five variables are dummy variables. Thus, the WDP_i of a farmer *i* can take values between 0 and 5.

The water stress level of an irrigation system is directly linked to its water source. FMIS that divert water from large rivers generally have larger volume of water for distribution compared to the irrigation systems that divert water from small- and medium-size rivers. Thus, irrigation systems that rely on small water sources are more likely to be water stressed than those that rely on large sources, which is likely to worsen with climate variability and change.

We capture the effect of water stress on smallholders' crop choice by classifying their water sources into three categories: small-size rivers (lean flow <1,000 liters per seconds), medium-size river (lean flow 1,000 - 10,000 liter per seconds), and large-size rivers (lean flow>10,000 liters per seconds). We also consider the condition of infrastructure, which is captured by a variable representing the percentage of the canal that is concrete.[12]

We include farmers' crop intensity to capture the effects of the agricultural productivity on their crop choice (Table 5). Crop intensity, defined as the fraction of cultivated area that is harvested over a year and measured in percentage (FAO, 2018a), is an indicator of agricultural productivity. For example, a 100 percent crop intensity of a farmer means that all the irrigable land is cropped for one season, or partially cropped over multiple seasons (Lam, 1998). Similarly, a crop intensity of 300 signifies that all agricultural land is harvested three times in a year.

Last but not least, the level of integration with the local and regional market is an important consideration in farmers' crop choice. The share of total annual crop production sold in the market is taken as a proxy for a farmers' level of market

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[12] We dropped the length of command area canal since it is highly correlated with the hydrological infrastructure.

integration. We assume that farmers who are more integrated with the market produce more cash crops to receive higher revenue from the nearby market than those that are less integrated. The positive relationship between market proximity and cash crop has been documented in Nepal (Thapa et al., 2017).

4.2. Empirical model of crop choice

A farmer's crop choice is modeled as an outcome of a multilevel discrete choice process, where crop choice is a binary decision between monsoon rice and other crops. Multilevel models are commonly used for analyzing hierarchical and nested relationships (Goldstein, 2011; McCord et al., 2018). By the nature of our sample design, the farmers are nested at three levels of hierarchies. More specifically, a farmer is nested within a FMIS and the FMIS is nested in one of the four climate regions. Consequently, farmers from the same FMIS and climate region expected to face similar institutional and climatic environment respectively. Multilevel models are also robust for smaller group sizes (Moineddin, Matheson, & Glazier, 2007), which in our case is 9 FMIS and 4 climate regions.

Following Goldstein (2011), we estimate versions of the following basic regression model:

$$y_{ij} = \beta_0 + \beta_1 x_{ij} + (u_{0j} + u_{1j} x_{ij} + e_{0ij})$$

$$var(e_{0ij}) = \sigma_{e0}^2$$

where *j* is for the institutional class (*j*=1....J) and *i* is a farmer (*i* = 1.... n_j). y_{ij} is crop choice, x_{ij} a vector of explanatory variables, u_{0j} & u_{1j} are the fixed residual variables at two levels, and e_{0ij} is the overall residual term.

To compare the results, we also estimate a multilevel multinomial model of farmers' crop choice, where the crop is a categorical variable that takes the value of 1 if the choice is rice, 2 if other crops, and 3 if the choice is fallow land. However, due to a small number of observations on fallow land (n=21), only the results from the discrete choice is discussed in the paper and the result from the multinomial choice model is included in the appendix.

5. RESULTS

Table 6 presents the result from the multilevel discrete model. The following results are very clear. Older farmers are more likely to choose rice than other crops. This is consistent with the previous studies that show that younger farmers are more likely to take risks and adopt new or alternative crops than older farmers (Adesina & Zinnah, 1993; Bezabih & Sarr, 2012; Yang et al., 2017). The educational attainment and training of farmers are not significant factors, suggesting that they are not constraints to adoption of non-rice crops. Farmers are generally switching to vegetable farming or other subsistence crops which do not require significant training. However, these factors may be important for farming crops that require technical skills such as tomato farming in a tunnel or mushroom farming (Lambert & Ozioma, 2011). Landholding size is also not a significant factor, which on the face of it seems contrary to previous findings (Adesina & Zinnah, 1993; Becerril & Abdulai, 2010). But this is a not a surprising result, given that our sample consists mostly of smallholder farmers in the hills (Table 6).

The farmers at the tail-sections of the irrigation systems are less likely to farm rice than those at the head and the middle sections of the systems. This result is quite logical. Farmers at the tail-sections of the irrigation systems generally receive less water due to seepage loss and potential theft by farmers located above them (Anderies & Janssen, 2011; Lam, 1998). A farmer at Tallo Rupsepani FMIS in Rasuwa district said "Since I am at the tail-end, I have to wait for quite long time until the farmers at the head and middle sections of the canal irrigate their plots, as a result, I sometimes hardly get the water on time to prepare my land for rice plantation." Thus, the farmers at the tail-sections of the systems can be expected to choose non-rice crops, requiring less water, due to water shortage and stress exacerbated by climate change and variability.

The crop intensity has a small but positive effect on the choice of rice, which can be attributed to two reasons. First, the farmers who choose other crops may fallow a section of their land for some time in order to accommodate the crop cycle of non-rice crops. For example, in Gomati FMIS, located in the hilly district of Dhading, farmers left their land fallow for a month after harvesting maize in June/July because they intended to sow radish in September/October. Second, as our data shows, some farmers leave part of their agricultural plot fallow for few months because of water scarcity and other factors.

Market integration is a strong determinant of crop choice. First, for one percent increase in the share of total crop production sold in the market, the odds of choosing rice crop decreases by a factor of 0.97. This implies that the rice farmers may be motivated by self-consumption. Conversely, the farmers of non-rice crops may be focusing on cash crops, mainly the vegetables, to be sold in the market. The president of the Gomati WUA, which is located next to the highway to Kathmandu, said, "Most of the farmers in the FMIS used to plant rice, maize, and vegetables for household consumption in the early years of its establishment in 1978. The access to the highway in early 1990's, which connected the village to Kathmandu and two major cities, created greater demand for potato, and many farmers started to plant potato. However, farmers soon realized that vegetable farming (such as tomato, cauliflower, cabbage, and radish) were more profitable than potato, and since then most of the farmers are growing vegetable all year around."

We find that water stress, captured by a categorical variable representing the river size as the source of water supply to FMIS, is indeed a powerful determinant of crop choice. The irrigation system that diverts water from large rivers is more likely to choose rice over other crops, compared to farmers in irrigation system that diverts water from small- and medium- size rivers.

The regions in the study area have statistically significant precipitation and temperature trends but have opposite signs (Table 3 and Table 4). There is a significant increase in monsoon precipitation in all the study areas whereas pre-monsoon precipitation has a statistically significant decreasing trend only in the Terai region. Similarly, the post-monsoon is slightly increasing in some hills and mountainous regions. In contrast, there is a consistently increasing temperature trend in all the study grid cells. For every unit increase in the monsoon precipitation, the odd ratio of choosing rice increases significantly more than that for temperature. The increase in monsoon precipitation increases water availability that, in turn, increases the odds of choosing rice over other crops. Additionally, since rice is a labor-intensive crop, an increase in temperature may accelerate evapotranspiration and discourage farmers from choosing rice. The potential sensitivity of rice yield to temperature could be another explanation.

The institutional rules and WUA performance indices are not significant. These are not surprising results given the lack of variability in the indices of institutional rules (Table 5).

5.1. Further robustness check

The robustness check is conducted in order to see the effect of institutional- and regional- level variables on the individual level coefficients. We find little change in odd ratio after adding the institutional level variables -- river category, concrete canal in percentage, and institutional rules index. Of the three institutional level variables, only river category is statistically significant. When we add institutional variables, three changes occur at household level variables (Table 7, Specification 2) - age of household and interaction effect of crop marketed at tail-end location becomes statistically significant, and the perceived water delivery index becomes statistically insignificant. These changes suggest that institutional characteristics capture the dynamics that are reflected in household characteristics. When regional climatic trends are included, the income from agriculture and crop marketed at the tail section of the irrigation system are rendered insignificant.

6. CONCLUSIONS AND IMPLICATIONS FOR CLIMATE CHANGE ADAPTATION

6.1. Conclusions

We analyze the multilevel determinants of rice crop choice during monsoon season in Central Nepal. Among the household level factors, we find older farmers are more likely to choose rice over non-rice crops. Among the local- or institutional-level factors, the farmers in the irrigation systems that are fed by large rivers are more likely to choose rice over non-rice crops. In contrast, in the irrigation systems that are fed by small- and medium-size rivers, farmers are more likely to choose less water-demanding crops. At the national level, market integration is one of the key determinants of crop choice. The farmers with greater market integration are more likely to choose non-rice crops. We also find that regional precipitation and temperature trends directly affect the irrigation system and farmers' crop choice. The increasing trend of monsoon precipitation positively influences farmers to choose rice while the temperature trend has the opposite effect.

6.2. Implications for climate change adaptation

Future projection of climate variability and change show a significant trend. The mean monsoon precipitation is expected to increase by up to 8 percent with a coefficient of variation from 3 to 13 percent (Kripalani, Oh, Kulkarni, Sabade, & Chaudhari, 2007). In Kaligandaki basin, the it temperature is predicted to rise by over 4 ^{o}C and an increase in average annual precipitation of over 26 percent by the end of 21st century under RCP 8.5 scenario (Bajracharya, Bajracharya, Shrestha, & Maharjan, 2018). In the context of increasing variability and change in Nepal, the following implications for climate change adaptation are clear.

Climate change and variability will *amplify crop choice* in multiple ways. Farmers are more likely to shift from water-intensive crops to less water-demanding crops in irrigation systems that are fed by small rivers. Since small-size rivers are more sensitive to climate change and variability than larger ones and given the fact that the majority of irrigation systems in Nepal are fed by small- and medium-size rivers, millions of smallholder farmers will have to effectively adapt their agricultural practices. In addition, the increase in extreme events will further worsen the frequency and intensity of landslides and flood risks, thus altering the water supply to irrigation systems of all sizes.

Farmers are simultaneously affected by *multilevel drivers of changes* occurring at local, regional and global scales. Climate variability and change is a global scale phenomenon; however, the impacts of climate change will be diverse in Nepal that has sharp topographical variability. Simultaneously, farmers crop choice is also affected by regional and national drivers such as are market integration. The higher profitability from cash crop and lack of adequate water supply and demographic characteristics affect the crop diversification choice.

As water resource is important for crop choice, *the institution will play a significant role* in the effective delivery of the available water to the farmers (see Thapa et al. *in review*). The local institutions such as FMIS have allowed farmers with the flexibility and capacity to make necessary adjustments to changing climatic and resource conditions. The rules and norms devised by these institutions will be vital for future adaptation to climate change as well.

We have witnessed that farmers have been *coping and adapting to multilevel drivers* of change using *two main mechanisms*. At the institutional level, they adapt to the rules and regulations to manage the water effectively (see Thapa et al. *in review*). At the individual level, crop diversification is one of the mechanisms for farmers to cope with and adapt to these changes. Based on existing evidence of coping and adaptation practices, they are likely to pursue autonomous adaptation. However, the effectiveness of these adaptation actions will be determined by multilevel factors, some of which are discussed above.

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FIGURES

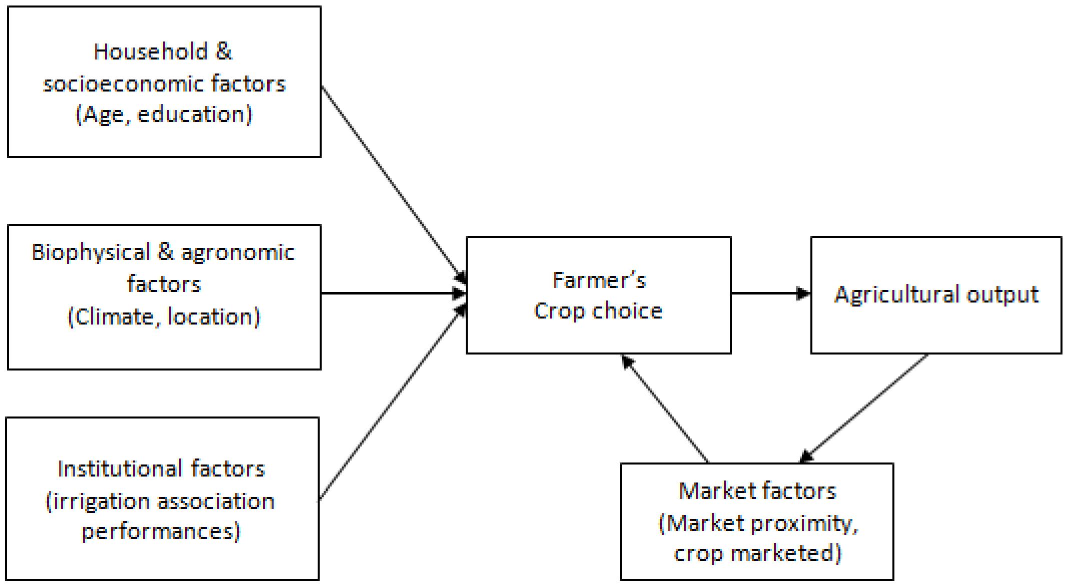

Figure 1: Schematic diagram of key factors affecting farmers' crop choice

(Source: Author)

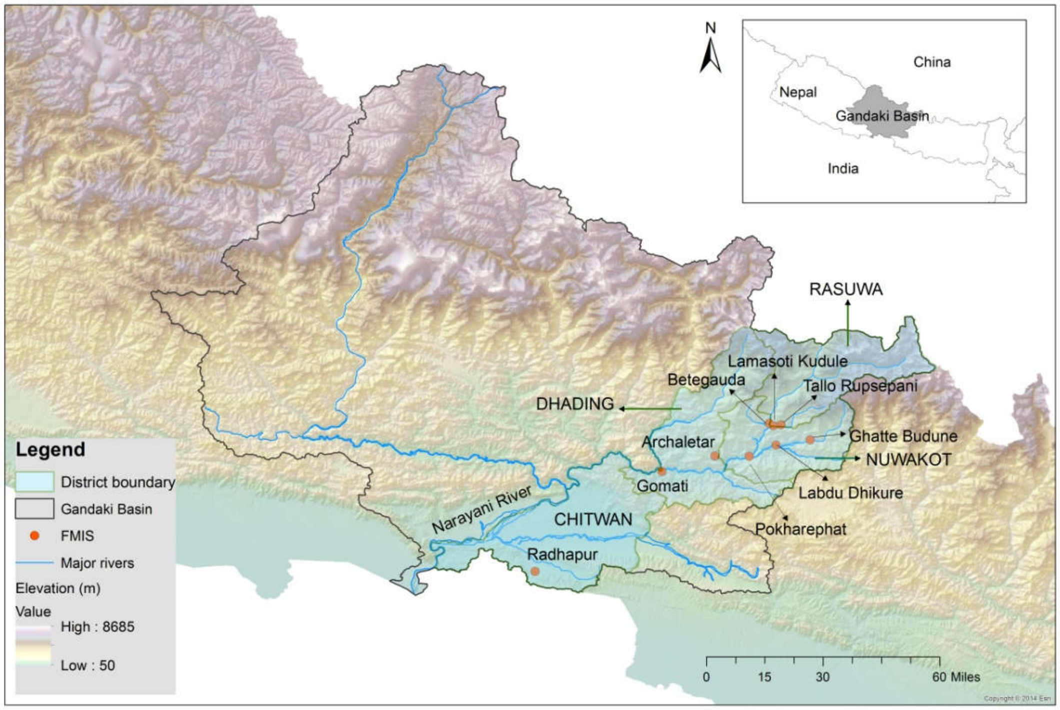

Figure 2: Study area

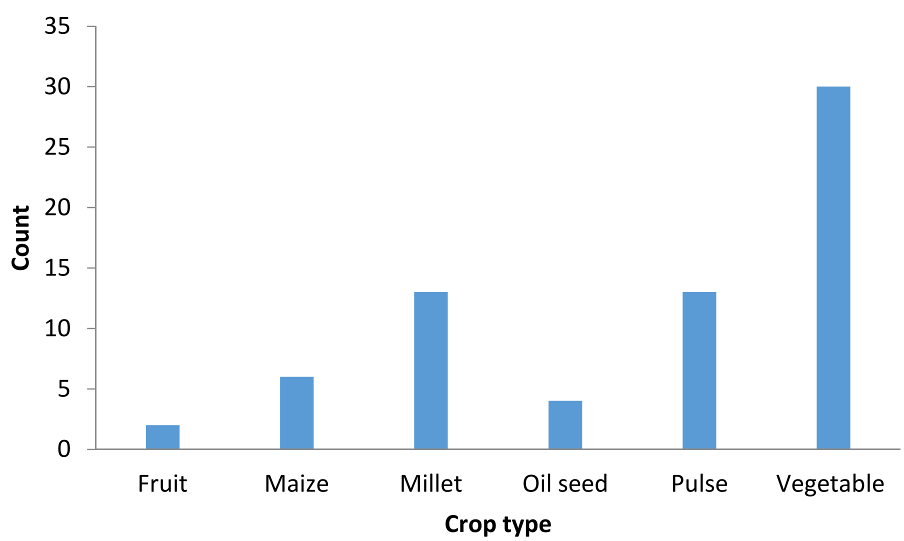

Figure 3: Frequency distribution of non-rice crops

TABLES

Table 1: Description of the key variables

Type	Variables	Description	Hypothesized effect	Associated literature	Coded
Dependent variable: Cropping decision for monsoon 2016	Rice	Farmer plant rice	NA	NA	Binary (1=Rice, 0= Others)
	Other crops	Farmer plant other crops (e.g. vegetables, millet)	NA	NA	Categorical (1= Fallow, 2= Other crop, 3= Rice)
	Fallow	Monsoon crop intensity is less than or equal to 50	NA	NA	
Household (HH) & socioeconomic factors	Age	Age of the head of the household	+	(Adesina & Zinnah, 1993; Seo & Mendelsohn, 2008)	Continuous
	HH size	Total number of people in households	+	(Becerril & Abdulai, 2010; Khanal & Mishra, 2017)	Continuous
	Education	The education level of the head of the household	+	(Below et al., 2012; Bezabih & Sarr, 2012; Deressa et al., 2009; Seo & Mendelsohn, 2008; Yang et al., 2017)	Categorical (1 = No formal education, 2= less than 10th grade of education, 3= 10th grade or higher education)
	Training	Participation in agricultural training in the last 10 years	+	(Deressa et al., 2009; Tambo & Abdoulaye, 2012)	Dummy (1= Yes, 0=No)
	Income from agriculture	Self-reported percentage of income from agriculture	+	(Deressa et al., 2009)	Continuous

	Farm size/land holding size	Total irrigable land holding in *ropani*	+	(Adesina & Zinnah, 1993; Becerril & Abdulai, 2010; Tambo & Abdoulaye, 2012)	Continuous
Biophysical & agronomical factors	Cropland location	Location of the cropland in the irrigation system, the tail-end location as a proxy for water-stressed area	-	(Abdulai, Owusu, & Bakang, 2011; Lam, 1998)	Dummy (1=Tail, 0=Other)
	Crop intensity	The fraction of the cultivated area that is harvested that is calculated as the ratio of the harvested irrigated areas over the area equipped for full irrigation	+	NA	Continuous
	Temperature trend	Change in the mean temperature during monsoon season		(Bezabih & Sarr, 2012; Jain et al., 2015; Moniruzzaman, 2015)	Continuous
	Rainfall trend	Change in the mean rainfall during the monsoon season		(Bezabih & Sarr, 2012; Jain et al., 2015; Moniruzzaman, 2015)	Continuous
Market factors	Travel time to market	Travel time required to travel to nearby marketplace weighted by mode of transportation. The travel by feet is weighted 2.25 times more than that by automobile.	-	(Tambo & Abdoulaye, 2012; Waldman, Blekking, Attari, & Evans, 2017)	Continuous
	Crop marketed	Percentage of total crop production in a year that is sold in the market			Continuous

Institutional factors	Hydrological infrastructure^{WUA}	River category based on estimated lean discharge: small-size river (lean flow <1,000 liters per seconds), medium-size river (lean flow 1,000 - 10,000 liter per seconds), and large-size rivers (lean flow>10,000 liters per seconds)	-	NA	Categorical (1=small, 2=medium, 3=large rivers)
	Institutional rules index^{WUA}	It's the summation of three types of rules and policies of WUA as dummy variables: (i) irrigation water fees, (ii) time-base water allocation rule, (iii) water guards assigned for effective delivery.	NA	(Lam, 1998)	Continuous (Range: 0 to 3)
	Institutional process & leadership index	It is the summation of farmers' perception of four organizational process and institutional leadership: (i) labor mobilization for canal maintenance, (ii) financial transparency, (iii) ability to collect internal and external resources, (iv) perception of the social image. All variables are dummy variables.	-	(Thapa et al., 2016)	Continuous (Range: 0 to 4)

	Water delivery index	It is the summation of farmers' perception of water delivery through four variables: (i) flexibility in water appropriation rules, (ii) timely water delivery, (iii) reliable water delivery, (iv) deprivation of farmers' access to water. All variables are dummy variables.	-	(Lam, 1998)	Continuous (Range: 0 to 4)
Agro-ecology	Terai	Dummy for Terai region	NA	NA	Dummy (0=Other, 1= Terai)

Note: WUA: Institutional level variable

Table 2: Distribution of farmer-managed irrigation systems and households

River Category	Hills		Terai		Total	
	FMIS	Households	FMIS	Households	FMIS	Households
Small	2	51	0	0	2	51
Medium	2	63	1	38	3	101
Large	4	164	0	0	4	164
Total					9	316

Table 3: The Mann-Kendall's tau value for the decadal seasonal trend in precipitation (millimeter/year) in four climate grid-regions of the Gandaki River Basin (1986-2016)

GridID	Pre-monsoon	Monsoon	Post-monsoon	Total monsoon
29	-0.2731**	0.5862***	0.2184	0.0897
40	-0.1914	0.5356***	0.2551**	0.0115
102	-0.1484	0.4942***	0.2230	0.0437
109	-0.0839	0.3793***	0.2919**	-0.0483

*** Trend at α=0.001 level of significance, **Trend at α=0.05 level of significance, * Trend at α=0.10 level of significance.

Table 4: The Mann-Kendall's tau value for the decadal seasonal trend in temperature (^{o}C) in four climate grid-regions of the Gandaki River Basin (1986-2016)

GridID	Pre-monsoon	Monsoon	Post-monsoon
29	0.7204***	0.8698***	0.5194***
40	0.7621***	0.8870***	0.5582***
102	0.7535***	0.8538***	0.5409***
109	0.7720***	0.8624***	0.5856***

*** Trend at α=0.001 level of significance, **Trend at α=0.05 level of significance, * Trend at α=0.10 level of significance.

Table 5: Summary statistics

	Rice (n=253)				Other crop (n=63)			
Variable	Mean	SD	Min	Max	Mean	SD	Min	Max
Age of household head	51.82	13.80	19	79	49.79	11.65	18	76
Education	1.91	0.72	1	3	1.86	0.72	1	3
Training	0.26	0.44	0	1	0.37	0.49	0	1
Agricultural land holding (ropani)	8.62	6.91	1	39	8.39	6.04	1	26
Income from agriculture	82.27	23.37	25	100	73.41	27.89	20	100
Tail-end location	0.26	0.44	0	1	0.41	0.50	0	1
Crop intensity	274.39	44.79	83	420	219.90	77.08	40	400
Crop marketed in percent	22.50	28.04	0	100	33.15	36.72	0	100
Travel time	1.64	1.14	0.5	5	1.94	1.45	0.5	5
River category	2.49	0.70	1	3	1.81	0.67	1	3
Concrete canal in percent	45.55	20.37	20	75	37.30	17.66	20	75
Institutional rules index	1.30	1.15	0	3	1.71	1.14	0	3
WUA performance index	7.48	1.00	4	8	3.24	1.17	0	4
Water delivery index	8.30	1.35	5	10	2.54	1.49	0	5
Decadal monsoon precipitation trend (Tau)	0.48	0.07	0.37931	0.58621	0.48	0.07	0.37931	0.58621
Decadal monsoon temperature trend (Tau)	0.86	0.01	0.85376	0.88698	0.87	0.01	0.85376	0.88698

Table 6: Multilevel determinants of crop choice

Crop choice (1=Rice,0=Other crops)	Odd Ratio	SE
Age of household head	1.03269**	0.018677
Education	0.75736	0.255918
Training	0.611345	0.27992
Agricultural landholding	1.057685	0.03864
Income from agriculture	1.010129	0.008811
Tail-end location	0.017303**	0.035784
Crop marketed	0.973104**	0.011516
Travel time	0.84415	0.169135
River category	16.02565***	1.17E+01
Concrete canal	1.02342	0.033574
Institutional rules index	0.402227	0.265245
WUA performance index	1.242765	0.343859
Water delivery index	1.104347	0.208382
Decadal monsoon precipitation trend (Tau)	7.20E+10**	7.08E+11
Decadal monsoon temperature trend (Tau)	9.48E-27**	2.30E-25
Crop intensity	1.014295***	0.004887
Tail-location x crop marketed	1.02297	0.016562
Tail-location x crop intensity	1.010071	0.00794
Terai dummy	0.056221	1.19E-01
Constant	7.75E+13	5.87E+14
Random effect		
Variance -climate region	4.03E-34	8.14E-18
Variance - FMIS institutions	8.11E-36	2.92E-18
Wald Chi^2 (n)+	58.31	
Log-likelihood	-81.3194	
Number of observations	316	
Number of FMIS institutions	9	
Number of climate regions	4	

*** Significant at 1%, ** Significant at 5%, * Significant at 10%

Table 7: Further robustness check

Binomial model (1=Rice,0=Other crops)	Specification 1		Specification 2		Specification 3	
	Odd ratio	Std. Err.	Odd ratio	Std. Err.	Odd ratio	Std. Err.
Household characteristics						
Age of household head	1.02200	0.01427	1.03030*	0.01848	1.03269*	0.01868
Education	1.36610	0.35533	0.78701	0.25850	0.75736	0.25592
Training	0.62743	0.23010	0.55358	0.24857	0.61135	0.27992
Agricultural landholding (ropani)	1.00182	0.02828	1.05394	0.03828	1.05769	0.03864
Income from agriculture	1.01201*	0.00724	1.01227	0.00896	1.01013	0.00881
Tail-end location	0.34904	0.52973	0.039811*	0.07583	0.017302**	0.03578
Crop intensity	1.01420***	0.00428	1.01454***	0.00491	1.01429***	0.00489
Crop marketed (percent)	0.98223**	0.00726	0.96985***	0.01109	0.97310**	0.01152
Travel time	0.84416	0.10955	0.80047	0.16074	0.84415	0.16913
WUA performance index	0.97096	0.16309	1.04949	0.26071	1.24277	0.34386
Water delivery index	1.48119***	0.17999	1.13804	0.21590	1.10435	0.20838
Tail-location x Crop marketed	1.00285	0.01287	1.02424	0.01584	1.02297	0.01656
Tail-location x crop intensity	1.00316	0.00632	1.00663	0.00737	1.01007	0.00794
Terai dummy	3.40441	2.84543	0.83863	1.17765	0.05622	0.11854
Constant	0.00702***	0.01160	0.00048***	0.00116	2.75E+13	5.87E+14
Institutional characteristics						
River category			15.26793***	9.86745	16.02565***	11.66761
Concrete canal (percent)			0.97980	0.02241	1.02342	0.03357
Institutional rules index			0.63231	0.25344	0.40223	0.26524
Climatic characteristics						
Decadal monsoon precipitation trend (Tau)					7.2 E +10**	7.08E+11
Decadal monsoon temperature trend (Tau)					9.48E-27**	0.00000

APPENDIX D: Key characteristics of the farmer-managed irrigation systems

SN	FMIS Name	VDC/ District	Geog-raphy	Water stress	Water source (river)	HHS	THH	CA *(ha)
1	Phallyak	Kagbeni, Mustang	Mountain	High	Snow-and spring-fed	22	37	60
2	Dhagarjung	Kagbeni, Mustang	Mountain	High	Snow-and spring-fed	16	48	20
3	Thangbe	Tangbe, Mustang	Mountain	High	Snow-and spring-fed	21	62	26
4	Tallo Rupsepani	Bhorle, Rasuwa	Hill	Medium	Spring-fed	21	100	60
5	Lamasoti Kudule	Simle, Rasuwa	Hill	Medium	Spring-fed	40	147	51
6	Betegauda	Banua, Rasuwa	Hill	Low	Glacier-, snow- and spring-fed	31	218	53
7	Dhurba Achaletaar	Khalte, Dhading	Hill	High	Spring-fed	28	160	90
8	Labdu Dhikure	Dhikure, Nuwakot	Hill	Low	Spring-fed	44	1000	260
9	Ghatte Budune	Kharanitar, Nuwakot	Hill	Low	Spring-fed	49	429	260
10	Pokharephat	Khadga-bhyang, Nuwakot	Hill	Low	Glacier-, snow- and spring- fed	34	165	25
11	Gomati	Benighat, Dhading	Hill	Medium	Spring-fed	35	115	43
12	Radhapur	Madi, Chitwan	Terai	Low	Spring-fed	38	35	37

Note: * : Source: DOI, Nepal and household survey; HHS: Household surveyed; THH: Total household in the irrigation system; CA: Cultivable command area in hectare.

APPENDIX E: List of preliminary surveyed farmer-managed irrigation systems

S.N.	FMIS Name	VDC/ District	Geography
1	Falyak	Kagbeni, Mustang	Mountain
2	Dakarjung	Kagbeni, Mustang	Mountain
3	Tangbe	Tangbe, Mustang	Mountain
4	Dange Khole	Chilime, Rasuwa	Hill
5	Tallo Rupsepani	Bhorle, Rasuwa	Hill
6	Bhulbhule	Nilkantha, Dhading	Hill
7	Sera Kulo	Kumpura, Dhading	Hill
8	Kalidaha Bairenitar	Nalang , Dhading	Hill
9	Balaute Kulo	Nalang, Dhading	Hill
10	Pokharephat	Khadgabhyang, Nuwakot	Hill
11	Rochaktar	Benitar, Dhading	Hill
12	Simara	Dhikure, Nuwakot	Hill
13	Dhurba Achaletaar	Khalte, Dhading	Hill
14	Hiramanitar	Haldekalika, Nuwakot	Hill
15	Byapari Raha	Jiling, Nuwakot	Hill
16	Labdu Dhikure	Dhikure, Nuwakot	Hill
17	Lamasoti Kudule	Simle, Rasuwa	Hill
18	Ghatte Budune	Kharanitar, Nuwakot	Hill
19	Gomati	Benighat, Dhading	Hill
20	Simara	Dhikure, Nuwakot	Hill
21	Pitawa	Ratnanagar, Chitwan	Terai
22	Panchakanya	Tadi, Chitwan	Terai
23	Bagauda	Bagauda, Chitwan	Terai
24	Mughai	Madi, Chitwan	Terai
25	Radhapur	Madi, Chitwan	Terai