Institutions governing common-pool resources have survived decades of global change with mixed performance. However, we have limited knowledge on how local institutions cope with and adapt to combined environmental and socio-economic changes. Using the case of 12 farmer-managed irrigation systems (FMIS) in Central and Western Nepal, this paper explores the institutional coping and adaptation mechanisms to water stress. We find that local irrigation institutions manage water stress using diverse and integrated approaches broadly categorized as structural and operational measures. Structural measures include water-source expansion and infrastructure rehabilitation works whereas water re-allocation and drought contingency rules are examples of operational measures. We find that integration of structural and operational measures is more prevalent in highly water-stressed irrigation systems than in less stressed ones. The choice of adaptation strategies has direct implications for agricultural productivity. FMIS that implemented structural measures harvested more crops per year than those systems that adopted only operational strategies or no adaptation strategies. However, the marginal benefit of adopting adaptation measures is particularly pronounced in water-stressed systems. Climate variability and change act as a threat multiplier because they compound the existing threats the FMIS face from social and economic changes. The key to effective integration of structural and operational measures that help FMIS to maintain their productivity during water stress are collective action and governance to overcome biophysical limitations.

Keywords: Farmer-managed irrigation systems; FMIS; institutions; resilience; common-pool resource governance; self-organization; mountain agriculture

1. Introduction
Institutions governing common-pool resources (CPR) including irrigation, fisheries, and forestry play an important role in the food and livelihood security of millions of farmers globally. Irrigation systems managed by communities cover a significant portion of total irrigated area in Asia, particularly in the Himalayas, northern Thailand, Laos, Vietnam, China, Japan, Philippines, and Indonesia (Barker & Molle, 2004). In Nepal alone, 67 percent (645,700 hectares) of total irrigated land that uses surface water sources is managed as farmer-managed irrigation systems (FMIS) where farmers are responsible for the overall irrigation management including water appropriation, distribution, canal maintenance, and conflict management (DOI, 2007). However, over the recent decade, urbanization, labor migration, and climate variability and change have added additional stresses to FMIS. Despite these stresses, many FMIS are still functional, though with mixed performance (Bastakoti, Shivakoti, & Lebel, 2010; Pokharel, 2015). Many systems have developed sophisticated mechanisms to cope with and adapt to global change, as would be expected of complex adaptive systems (Mahon, McConney, & Roy, 2008).
A significant body of literature has been developed over the past few decades on different dimensions of CPR governance seeking to better explain collective action, adaptive decision-making, and social and institutional learning; however, the literature focusing on global change have slowly emerged in the last decade. The early literature in the 1980's and 1990's focused on self-organization of CPR using several social-ecological frameworks that culminated in Institutional Analysis and Development (IAD) (Bardhan, 2000; Benjamin, Lam, Ostrom, & Shivakoti, 1994; W. Lam, 1996; Lam & Ostrom, 2010; Martin & Yoder, 1988; Ostrom & Benjamin, 1993; Pradhan, 1989). Given shortcomings in the characterization of dynamic, interactive social and ecological processes, the IAD framework has been re-conceptualized 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, Janssen, & Schlager, 2016; 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 in collective settings (Janssen, 2015; Janssen and Anderies, 2013). In the last decade, CPR and global change literature have focused understanding the trade-off between resilience and vulnerability and characteristics of adaptive irrigations systems. Cifdaloz et al. (2010) explored the relationship between the robustness of irrigation systems and climatic vulnerability and demonstrated the trade-off between vulnerability and robustness. As institutions tune to cope with one shock, they become more vulnerable to other shocks. In a comparative study of FMIS in Nepal and Thailand, Bastakoti et al. (2010) argued that institutional characteristics such as flexible rule-making, strong social capital, and trusted local leadership help to mediate the changes driven by external policies and market pressures. A rigorous understanding of coping and adaptation mechanisms implemented by 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 two questions: (i) What strategies do FMIS use to cope with and adapt to water stress? and (ii) How do different institutional strategies affect the agricultural productivity of the irrigation system? Here, agricultural productivity is measured in terms of cropping intensity, which is defined as the fraction of cultivated area that is harvested over a year (FAO, 1997). For example, a 1.0 value of cropping intensity means that all the irrigable land is cropped for one season, or partially cropped over multiple seasons (Lam, 1998). Similarly, a cropping intensity value of 3.0 signifies that all agricultural land is harvested three times in a year.

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 temporal and spatial dimension of water stress and institutional adaptation strategies implemented by FMIS. Next, we assess agricultural productivity associated with different adaptation measures and water stress level. We conclude the paper by assessing the institutional adaptation measures taken by FMIS and discuss their implications for CPR governance.

### 1.1. Background on farmer-managed irrigation systems

Nepal has a distinct history of irrigation systems managed by communities. Over at least the last two centuries, Nepalese farmers have constructed irrigation systems deliberately to intensify their agricultural productivity. This tradition gave birth to farmer-managed irrigation systems (FMIS) that are scattered all over the country. 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 (Ostrom, 2014). In contrast, overall irrigation management in FMIS is performed by the farmers themselves with minimal interference from outside agencies. They rely on financial and/or labor contribution by farmers for canal operation and maintenance, while receiving occasional financial and technical support from government agencies for infrastructure rehabilitation and institutional strengthening (Pradhan, 1989). 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 low-cost infrastructure developed and employed by many FMIS, they are still important for food security and livelihood of many Nepalese people. FMIS currently irrigate about 333,000 hectares of agricultural land covering 51 percent of the total surface-water irrigation area (DOI, 2007). They increase crop yield by a multiplier of three to four and also create local employment opportunities (Smith, 2004). 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 domestic food security.

1.2. Effect of climate variability and change on water stress and irrigated agriculture

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 deficit (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 gap between the supply of water and farmers’ perception of irrigation demand for a crop at a given time period.

Climate variability and change is one of the main drivers of water stress in the region. While climate variability measures the variation in the mean state and other statistics of the climate over the long term, 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). Nepal has witnessed a spatially diverse signal of long-term climate and extreme events trends. The study of temperature trends from 1977 to 1994 showed that Nepal is warming at an average annual rate of about 0.06°C per year (Shrestha & Aryal, 2011). More alarming is the fact that warming is 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 (Scott et al., 2019), 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).

Similarly, 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. 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).

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, Lam, Pradhan, & Shivakoti, 2011). The variability in precipitation events including onset and retreat of the monsoon season can directly influence crop choice decisions and alter agricultural 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 unusually 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 that account for FMIS being ineffective in supplying water to meet farmers’ demand (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, Scott, Wester, & Varady, 2016; Lam and Chiu, 2016). Bastakoti et al. (2010) highlighted the importance of autonomy in decision making, flexibility in rulemaking, individuals’ 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. Second, it explores the linkages between water stress, adaptation strategies, governance and agricultural productivity. The integrated understanding of these relationship can help us in devising effective adaptation strategies.

2. Study Area, Data and Methods

2.1. Study area

The study was conducted in the Gandaki River Basin (GRB) of Central and Western Nepal, with a total catchment area of 46,300 km² (Figure 2). 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. Based on agro-ecology, the GRB is divided into four regions: terai which is the flat alluvial plains in the south at elevations below 300 meters, hills upto 3,000 meters including the lower hills of Siwalik located between 300–700 meters, mountains above 3,000 meters in the north, and Trans-Himalaya, a rain-shadow region to the north of the mountains (Frenken, 2012).

The water availability in irrigation systems follows the precipitation pattern in the basin. The GRB has a precipitation pattern with four seasons: pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and winter (December to February) (Table 1). The average annual precipitation in the GRB ranges from 548 mm to 3,469 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 by precipitation than by snowcover, most of the river receives the increase in flow from June to August and the minimum flow in March and April (Figure 1).

Figure 1: Mean monthly discharge of the Kali Gandaki River (1996–2006) (Bajracharya, Acharya, & Ale, 2011).
In order to select the FMIS, we visited 25 FMIS across the basin during an appraisal study in pre-monsoon of 2016 to understand their water stress, adaptation actions, and agricultural productivity. A total of 12 FMIS were selected from 25 systems for in-depth study based on water source for irrigation systems—large, medium, and small-sized rivers, and ecological region—mountains, hills, and terai (Table 2). The size of the irrigation water source strongly influences the nature of water stress and the potential adaptation mechanism. We attempted to include irrigation systems from different eco-regions because there is heterogeneity in terms of climatic conditions, agricultural productivity, culture, and ethnic composition in these eco-regions, which, in turn, influences collective action and adaptation (Gentle and Maraseni, 2012).

We collected data on FMIS through focus group discussion during the post-monsoon season of 2016. A total of 12 focus group discussions (FGD), with one in each FMIS, were conducted with the current and previous governing members of the irrigation system, also referred to as the Water User Association (WUA). Open-ended questionnaires were used to collect information on the history of irrigation system management, water stress period, coping and adaptation strategies, and infrastructure conditions.
For each FMIS, household survey was also conducted using structured questions. Approximately 30–45 households were randomly selected from each FMIS, stratified by the canal’s head, middle, and tail sections. The sampling was stratified 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). From the household survey, we generated two variables: (i) average crop intensity, and (ii) average governance index of the FMIS. Crop intensity was weighted for mountain region in order to account for snow-free months (Chhetri, 2011). The governance index was generated for each FMIS using the summation of three dummy variables: farmer’s perception of WUA ability to mobilize labor, ensure financial transparency, and select office bearers with good social image. For example, a governance score of one means that all the farmers in a FMIS agreed that WUA was good in mobilizing labor, handling finances in transparent way, and selecting leaders with good social image. We also conducted a transect walk in each irrigation system, where we surveyed the canal from the tail to head section and estimated the river discharge using field measurements and farmers’ insight. This information was used to categorize the river size. The qualitative and quantitative data were coded and analyzed in MS Excel and Stata version 15. Other survey results, particularly on household-level adaptation are presented in Thapa & Rahman (in review).

2.3. Methods

Using field observations and institutional FGDs, we first estimated the water stress for each FMIS as discussed below. The degree of water stress (high, medium, low) was assessed using the qualitative ranking based on FGDs and household interaction at head, middle, and tail sections of the canal. From the institutional survey, we identified different adaptation strategies. The relationship between institutional adaptation strategies and agricultural productivity was explored using the average cropping intensity data of each FMIS collected through the household survey.

2.3.1. Water stress

In order to understand the adaptation and its impact on agricultural productivity, it is necessary to evaluate the degree of water stress faced by FMIS. The study uses farmers’ perceptions of the gap between water supply and demand at a particular time for a specified crop as the main indicator of water stress. The irrigation is measured in terms of number of times the crop is irrigated. 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, however the input data are qualitative and based on farmers’ perception of water deficit rather than quantitative field measurement of water volume and crop water demand. The water stress is also not homogeneously spread throughout the irrigation system. In many systems, the stress is more concentrated in the tail section of the canal because of over-appropriation at the head-end and seepage losses before water reaches the tail.

The study found two critical periods across all the ecological regions, as illustrated in Table 3. Since water stress is the result of deficit between perceived demand and supply, the high-water demanding crops can create water stress even in water abundant system. For example, paddy is a very water intensive crop. It requires significant volume of irrigated water during pre-monsoon and monsoon season. As a result, FMIS that are fed by large perennial rivers can also face seasonal water shortages, particularly during the period of pre-monsoon season when the water demand is high for paddy farming (Figure 3). Compared to paddy, vegetables and maize are less water intensive crops.

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

| River Category | Mountains | Hills | Terai | Total |
|----------------|-----------|-------|-------|-------|
|                | FMIS      | Households | FMIS | Households | FMIS | Households | FMIS | Households |
| 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**| **2** | **379**| **5** | **114**| **3** | **114**|

*Note: River category was based on estimated lean flow (liter per second) during the last winter season: Small: <1000 lps, Medium: 1000–10,000 lps, Large: >10,000 lps.*
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. & March                 | Ear formation and early flowing for barley              |
|                       | May & mid-June               | Ripening stage for barley                               |
| Hills & Terai         | March                        | Plantation & flowering for maize, winter paddy plantation|
|                       | April                        | Winter paddy tillering                                  |
|                       | Mid-June                     | Paddy field preparation & plantation                    |

Figure 3: Schematic diagram of crop irrigation use, river discharge and critical water stress period for: (a) Trans-Himalaya/Mountain, and (b) Hills and Terai farmer-managed irrigation systems (Source: Author).

Understanding the critical period is important for adaptation study. 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 insight on climate change adaptation (Fussel, 2007).

3. Results

3.1. Water stress and surface water supply

We found that highly water-stressed FMIS are generally fed by small and medium-sized rivers (Figure 4). In the study area, all the FMIS are solely dependent on a surface-water source, where water availability is directly proportional to the precipitation (Figure 1). These sources receive significant contribution from precipitation and shallow groundwater. As a result, large rivers provide adequate water throughout the season for irrigation diversion, whereas the small- and medium-sized rivers only provide adequate irrigation water during the monsoon season.
3.2. Institutional strategies to manage water stress

Many FMIS have devised a range of institutional strategies to cope with and adapt to water stress. These strategies can be categorized into three broad areas: (i) expansion of water sources by bringing in additional water; (ii) establishment of additional rules for equitable water distribution during stress period; and, (iii) exchanges of water with neighboring FMIS. 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 application of institutional rules and mechanisms that are in place to manage various types of challenges including water stress (Table 4).

3.2.1. Expansion of water sources

FMIS have brought in new water supplies when these are technologically and financially feasible. For example, the source of the Pokharephat FMIS in Nuwakot district has very low discharge (less than 50 liters per second) 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 for lift irrigation that drew water about 45 feet up from the perennial Trishuli River. The water is distributed to the middle and tail sections of the canal using the branch canal and pipes. While the project was financially supported by non-profit organization and local government, the rich history of collective action helped the farmers to initiate the project proposal, seek funding resources, and operate and maintain it after installation.

In the Trans-Himalaya region, all the three systems have storage reservoirs 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.

3.2.2. Separate water rules during stress period

Water allocation and distribution rules are common in FMIS. However, some FMIS have devised additional set of rules for water allocation and distribution during the water stress period. These rules are only active during the stress period. For example, Tangbe FMIS in mountainous region of Mustang district has developed a unique water rotation policy during the water stress period in February and March. During that period, farmers receive water every 6 days whereas during the normal days they receive water every 12 days. This rule is devised to ensure adequate water supply during the high demand period. Similarly, in Labdu Dhikure FMIS of Nuwakot district, the farmers have devised time-based water allocation rule during water stress period of the pre-monsoon season. The tail section of the canal receives water during the night time for certain days in a week while other sections of the canal receive the water during the day time.

Figure 4: Count of FMIS by river size and water stress level.
The day time is allocated to tail-enders so that they can travel to head and middle sections (often a mile or more) to ensure effective water delivery. The rule is aimed at reducing the risky night-time travel by the tail-enders. These rules that suit the local context are only possible when motivated farmers are provided with the capacity and flexibility to devise their own rules.

3.2.3. Exchanges of water among FMIS

FMIS also exchange water with other FMIS to cope with water stress. In Radhapur FMIS in Madi, Chitwan, the FMIS has established a mechanism to borrow and exchange water from a neighboring FMIS during the critical water stress period, particularly during the May/June rice plantation season. An inter-FMIS water exchange mechanism was evident in only this system, and it could partly be attributed to certain biophysical and social settings, such as proximity of the canals and harmonious relationship between the two FMIS communities.

We also noticed different forms and level of collective action in all the FMIS. Some of the qualitative evidence of collective action include farmers' active engagement in canal operation and maintenance including contributing financial and other resources. In all the FMIS except Labdu Dhikure, the farmers contributed their labor for canal maintenance. Labdu Dhikure didn't require labor contribution but collected yearly irrigation fee for the canal operation and maintenance. The cash contribution was established because it is a large system located in the peri-urban area of Nuwakot where the opportunity cost of labor is high. Also, the amount of labor contribution varied by the system. In Trans-Himalaya and hill FMIS where there is continuous damage to the canal from landslides and erosion, farmers contributed around 5–7 days of labor in a year, whereas 1–2 days of labor was contributed in FMIS located in the plain area of hills and terai.

Despite the continued collective action in all the FMIS, many WUA felt that farmers have decreasing enthusiasm for collective action in most of the FMIS in the hills and terai, particularly those located near the peri-urban centers. 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 old people don't have energy and interest to keep the canal in good condition." Based on the informal interaction with the farmers, some of the factors affecting the enthusiasm for collective action are decreasing interest in agriculture due to increasing remittance, labor intensive process, and alternative income sources; weak WUA leadership; and out-migration of young labor population.

### Table 4: Typology of strategies to manage water stress.

| Category          | Categories                                                                 | Institutional strategies                                                                 | Agro-ecological zone | FMIS Cases          |
|-------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|----------------------|---------------------|
| Structural        | Expand water sources                                                       | Lift irrigation to augment water supply                                                   | Hill                 | 6, 12               |
|                   |                                                                            | Reservoir to store additional water                                                       | Mountain, Hill       | 1, 2, 3, 12         |
| Operational       | Water distribution rules                                                    | Additional water distribution rules during water stress period                            | Mountain, Hill,     | 1, 2, 3, 8          |
|                   | Water sharing mechanisms                                                   | Informal borrowing and exchange of water with neighboring FMIS                          | Terai               | 11                  |

FMIS Cases: [1] Phallyak, Mustang; [2] Dhagarjung, Mustang; [3] Thangbe, Mustang; [6] Betegauda, Rasuwa; [8] Labdu Dhikure, Nuwakot; [11] Radhapur, Chitwan; [12] Pokharephat, Nuwakot.

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### 3.3. Water stress, adaptation strategies, agricultural productivity & irrigation governance

In this section, we explore how coping and adaptation strategies are associated with the level of water stress, and how agricultural productivity is distributed across FMIS adopting different types of adaptation strategies.

#### 3.3.1. Water stress and adaptation strategies

We found that high water-stress FMIS have adopted both the structural and operational measures. For example, all the three mountain FMIS have established reservoirs and separate water distribution mechanisms during the stress period. One highly-stressed FMIS in the hills have not established any such mechanisms. Structural measures were also prevalent in low- and medium-stressed FMIS. Two FMIS in
hills with medium- and low-stress levels have implemented lift irrigation to cope with the seasonal water shortages (Figure 5).

We also found that additional water stress management rules were prevalent in less water-stressed FMIS. Labdu Dhikure FMIS in the hill region uses separate water allocation mechanism during the seasonal water stress period of paddy cultivation. Similarly, Radhapur FMIS in the terai area uses informal exchanges of water with its neighboring FMIS during the stress period. Since farmers have the flexibility and capacity to devise their own rules, they are more responsive in devising innovative water allocation rules to address water stress. Unlike structural measures that require significant capital investment, rule-making as an adaptation measure is less resource intensive and easy to implement.

### 3.3.2. Water stress, adaptation strategies and agricultural productivity

We assessed cropping intensity of FMIS implementing different adaptation strategies. We found that adaptation actions have direct implication on agricultural productivity. FMIS that implemented some form of adaptation actions – either structural, operational measures, or both structural and operational measures – were able to maintain cropping intensity of 2.9 compared to FMIS that did not implement any adaptation measures (Figure 6).

However, when we disaggregated the cropping intensity by adaptation action and water stress level, we found that cropping intensity of around 2.8 is maintained by FMIS that implemented some form of adaptation actions at high- and medium water-stress level (Figure 7). Adaptation action helped farmers to

![Figure 5: Count of FMIS using different adaptation strategies by water stress.](image1)

![Figure 6: Average adjusted cropping intensity of FMIS adopting different adaptation strategies.](image2)
maintain the agricultural productivity at all level of water stress. But, we noticed a decreasing gap between adopters and non-adopters as the water stress decreased. There is a wider gap between adopters and non-adopters of adaptation strategies in highly water-stressed FMIS than in those that are less water stressed. In other words, in a highly water-stressed system, non-adopters have significantly lower cropping intensity than non-adopters in systems with less water stress. This implies that the marginal value of the water, measured in terms of agricultural productivity, is higher in high-water stressed system than that in less water stressed system.

3.3.3. Adaptation strategies, agricultural productivity and perceived governance performance
Agricultural productivity is not only affected by the type of adaptation action, but also by the governance performance of FMIS. We accessed the governance performance perceived by the farmers on three characteristics: ability to mobilize labor, transparency in FMIS activities, and social image of the leadership. The index can receive the maximum value of 1 which implies that all the farmers in a FMIS positively responded on all the three variables of the governance score. We found that the governance index for FMIS ranged between 0.67 and 1.0. Most of the FMIS had governance score above 0.85 which implies that most of the farmers in the sampled FMIS were satisfied on these aspects of governance.

We explored the relationship between agricultural productivity and governance score, and found that there is no definitive relationship between them. This could partly be due to small sample size and homogeneity in governance performance. However, FMIS that adopted some form of adaptation measures (operational, structural, or both) had slightly higher governance performance index than those systems that didn’t implement any adaptation actions (Figure 8). In FMIS that only adopted structural measures, an average of 93 percent of the farmers perceived that WUA governance was good. On the other hand, in the FMIS that adopted no adaptation measures, average of 88 percent of the farmers perceived that WUA governance was good.

4. Discussion
We found that many FMIS have adopted some form of adaptation strategies, either structural, operational, or both measures, to cope with and adapt to water stress. The choice of strategy has direct implications for agricultural productivity. Structural adaptation added notable volumes of water to irrigation system; as a result, these interventions can have significant impacts on agricultural productivity. Operational measures, on the other hand, primarily serve to redistribute the available water equitably among farmers, hence, there may be little significant impact on system-level agricultural productivity, except in cases where head-
end farmers were releasing excess water to drains instead of redistributing unused water to middle or tail-end farmers. We also noticed that operational rules are a common mechanism of adaptation to water stress even in less water-stressed FMIS because farmers have the flexibility and capacity to devise the rules to manage water stress. Unlike structural measures that require significant financial capital generally requiring support of external agencies, operational measures are less resource intensive and hence easier to implement. However, the effectiveness of adaptation strategies in terms of maintaining agricultural productivity is not only driven by the type of adaptation actions, but also by other factors, mainly collective action and good governance as discussed below.

Collective action is the backbone of community-driven FMIS actions. 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 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. We noticed significant level of collective action in most of the FMIS, however it fluctuated with time. In Pokharephat FMIS, farmers came together when they were constructing the lift irrigation, however, the level of collective action had gradually eroded after that, partly due to labor out-migration and availability of alternative water and income sources. All the FMIS in Trans-Himalaya had evidence of high level of collective action. They contributed up to 3–6 days in a year for canal maintenance and had even collected money to rehabilitate a reservoir.

We also found that good governance is the foundation for effective irrigation management, particularly during seasonal periods of water stress. In the context of FMIS in Nepal, some of the main characteristics of governance 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. Another characteristic of a good leader that is relevant for adaptation is the ability to seek additional financial resources from different external sources. In the last 20–30 years, government and non-government agencies are actively working to improve the irrigation system, and the leaders play an important role to explore and seek these sources. This characteristic will be more important in future as increase in climate extreme events in future will likely cause more structural damage to the irrigation systems. We also noticed that the form of community governance varies by region and geography.
We noticed a unique form of local governing in Trans-Himalayan region where natural resources including irrigation, are managed by the Mukhiya system, 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. The mukhiya system remains active in all aspects of irrigation governance including water distribution, conflict management, and revenue collection.

FMIS are continuously affected by multiple drivers of change at different levels, however, the role of climate variability and change is distinct. In the context of FMIS, the global level drivers include climate variability and change and globalization; the national level variables include economic liberalization, urban-rural migration, and regional agricultural market integration; and the local-level drivers of change include watershed degradation and competing water demand. We found that climate variability and change act as a threat multiplier in that they exacerbate the existing vulnerability faced by FMIS. For example, climate variability worsens the water stress in FMIS that are fed by small seasonal rivers. Some systems are challenged by the double-exposure effect of out-migration and water stress (O’Brien & Leichenko, 2000). For example, in one of the FMIS that was visited during the appraisal study, many farmers are switching to fruit farming because of labor out-migration and less water availability because fruit farming are relatively less water and labor intensive than cereal crops like paddy and wheat. Climate variability will intensify the water shortages in these FMIS that are already facing multiple stressors.

However, technology can help mitigate the global change impacts to some extent. Technology of lift irrigation and solar pumps can help FMIS to augment water supply. We have noticed two FMIS in the hills that have installed lift irrigation system to augment water supply during water-stress period. We also emphasize that technology is not a panacea for water stress challenge, and it can bring additional challenge particularly for CPR water 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 these characteristics. Lifting water from the perennial river can actually be considered non-subtractable because it 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 per year from each household for canal maintenance. Lift irrigation requires no household labor contribution because it is generally done by the pump operator (except the cleaning of tertiary canal that is done by farmers individually). FMIS may require additional institutional support to mediate better management of these technologies.

Technology and infrastructure interventions also need to be economically and socio-institutionally feasible. For example, lift irrigation that was adopted by one hill FMIS is only possible in river terraces that are within 30–70 m of the perennial river. In high mountains with steep slopes where water needs to be pumped more than 70 meters, this option is prohibitively costly. We found multiple pump systems in Dhading district that lifted water up to 70–100 meters using solar panels, however, all of them were drinking water systems. High cost of maintaining the solar lift irrigation was noted as one of the challenges by these drinking water systems.

While this study has developed a typology of adaptation and linked strategies with water stress level and agricultural productivity, the study had some limitations, chiefly in relation to exclusion of canal rehabilitation as one of the adaptation strategies due to lack of adequate data to analyze the degree and impacts of this strategy. We found that all irrigation systems have rehabilitated the canal in the last 20 years to improve the irrigation distribution efficiency. While this is an important strategy to manage water stress, we did not have adequate ex ante data to demonstrate the water augmentation or head-tail distribution effects of this strategy.

5. Conclusion
The study identified and characterized multiple institutional strategies implemented by FMIS to cope with and adapt to water stress. Furthermore, the study evaluates the impact of water stress on choice of adaptation measures and the role of different types of adaptation measures on agricultural productivity. 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. We developed a typology of coping and adaptation actions under the broad categories of structural and operational measures. Structural measures include hard infrastructure intervention such as construction of reservoirs and lift irrigation systems, whereas soft intervention includes operational rules and water sharing mechanisms between FMIS. We found that the
highly water-stressed FMIS have devised both the structural and operational measures to cope with water stress compared to low- and medium-stressed FMIS. The impact of adaptation measures was noticed in agricultural productivity measures as cropping intensity or the number of harvests per year. The FMIS that installed structural measures had higher cropping intensity than the FMIS that implemented operational or no adaptation measures. The difference in cropping intensity between structural and no-structural measures is more prominent in highly stressed FMIS than less stressed FMIS. The choice of adaptation action is affected by different factors such as degree of collective action, availability of economically and technologically feasible alternative water source and degree of good governance to manage the irrigation system. While climate variability and change acts as threat multipliers because they compound the existing threats the system faces from social and economic systems, the use of technology can help mitigate the water stress to some extent. In addition, the technology deployment can also have negative consequences on the key features of CPR governance, particularly the labor mobilization and exclusion of users. In the context of on-going climate change, FMIS will have to adopt using both the structural and operational measures on the foundation of good collective water governance.

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Competing Interests
The authors have no competing interests to declare.

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