SPATIAL DYNAMICS OF WATER GOVERNANCE AND CROP PRODUCTION IN IRRIGATED SMALLHOLDER AGRICULTURAL SYSTEMS

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Smallholder agriculturalists in semi-arid regions face many challenges to agricultural production. This includes increasingly unpredictable precipitation events. Irrigation plays a role in adapting to these climatic events, as it can salvage harvests by bridging unexpected dry periods. Nevertheless, reliable access to irrigation water is often predicated on effective water management. Institutions shaping water availability are most effective if they are designed in accordance with local environments, are flexible enough to adapt to ever-changing conditions, and are crafted through the input of local-level resource users, among other traits. In this dissertation, I inspect the interplay between water governance, water availability, and smallholder adaptation within a set of communities in the Mount Kenya region. More specifically, three empirical chapters inspect: (1) Smallholder adaptation through one type of on-farm practice, crop diversification; (2) The readjustment of local-level water institutions following a policy shift at the national-level and the resulting impact on water availability; and (3) The contextual drivers of smallholder water availability as well as asymmetries between household-level availability.

Several important findings are revealed. Regarding crop diversification, households that are frequently visited by agricultural extension officers and are located in areas with higher average rainfall also grow a greater number of crops. This suggests a need to ensure that households in drier areas have access to extension education as well as irrigation. Concerning reorientation of local-level institutions following a national policy shift, the willingness to adjust management approaches is often dependent on perceived advantages/disadvantages from changing strategies. Water managers that believe they will be disadvantaged by the policy shift are more reluctant to adopt new water sharing practices and may only alter their management practices if required to do so by regional and national level authorities. Finally, concerning the drivers of household-level water availability, a host of institutional, infrastructural, and biophysical elements influence water delivery, suggesting that in assessing resource provisioning outcomes in social-ecological systems, contextual elements at multiple scales need to be evaluated. This analysis also finds that vast disparities in water availability exist within and across communities, a finding that highlights the need develop new strategies to evaluate asymmetries in resource provisioning.

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Chapter 1: Introduction

1.1. Challenges confronting smallholders and a description of the research agenda

Smallholder farmers in the arid and semi-arid tropics face numerous challenges to agricultural production. Among these, variability of rainfall both within and between seasons is commonly listed as a major environmental obstacle (Cooper et al., 2008), and with a changing climate, smallholders in many semi-arid regions will be confronted by increasingly unpredictable precipitation events (Field et al., 2014). In these semi-arid areas, water security and food security are tightly intertwined since rain-fed agriculture is the most commonly practiced livelihood strategy (SEI, 2005; Cooper et al., 2008). Irrigation introduces an element of flexibility into on-farm operations as it is able to supplement rainfall during unanticipated dry spells and allows smallholders to extend growing seasons (Rockstrom et al., 2010). In this sense, irrigation is an adaptation mechanism that is capable both of reducing smallholder sensitivity to the vagaries of precipitation events and of improving food security (Morton, 2007; Bryan et al., 2009; Bryan et al., 2013). However, water availability is often contingent on effective water governance (Lam, 1998; Pahl-Wostl et al., 2012; Grafton et al., 2013), which includes adaptive (co)management approaches (Huitema et al., 2009). Thus, understanding smallholder livelihood strategies in water-stressed areas requires acknowledgment of a complex array of vulnerabilities faced by smallholders, national and local efforts aimed at devising effective institutions for water management, and the contextual components at the community and household levels that structure water availability.

In this dissertation I investigate smallholder farming strategies and water governance from several angles to account for the various forces affecting household well-being in semi-arid areas. These investigations take the form of three scientific journal articles that account for Chapters 2-4 of the dissertation. Broadly, the collective goals of these three chapters are: **(1)** To understand smallholder vulnerability within a semi-arid agricultural system, as well as adaptive approaches taken by farmers; **(2)** To inspect the influence of national level water policies on water availability within local level user groups, as well as the range of rules crafted by user groups to adjust to external governance changes; and **(3)** To analyze water security at the household level by accounting for elements of the institutional, infrastructural, and biophysical environments that may influence its availability. These goals are pursued through use of data collected within smallholder-operated irrigation systems in the Mount Kenya region, as well as data collected at various offices in Nairobi, Kenya to understand local, regional, and national level water governance efforts.

The remainder of this introductory chapter explores the concepts important to the empirical investigations undertaken in subsequent chapters. This includes the following theoretical topics: smallholder adaptation and vulnerability assessment, particularly in semi-arid agricultural systems; food security; social-ecological systems; and resource governance, including topics related to adaptive (co)management, collective action, and polycentric governance. Chapter 2 explores the concept of vulnerability in the study area and statistically examines an adaptive strategy for reducing vulnerability adopted by smallholders. Chapter 3 studies a national level effort to restructure water governance in Kenya and its influence on local level user groups. Chapter 4 takes a multilevel statistical approach to understand the institutional, biophysical, and infrastructural drivers of household level water delivery. Finally, in Chapter 5 I conclude the dissertation by discussing the contributions made in each of these empirical chapters to the theoretical topics discussed in Chapter 1.

1.2. Background: Major theoretical concepts

1.2.1. Smallholder adaptation in semi-arid systems

Smallholder farmers in semi-arid systems face a number of obstacles in maintaining their subsistence activities. Not only do they encounter challenges posed by the socio-economic systems in which they are situated (Morton, 2007), but given their strong reliance on agriculture to maintain their livelihoods, smallholders are also challenged disproportionately by the current and future impacts of climate change and climate variability (Field et al., 2014). In order to withstand the pressures of climate change and variability, these individuals must develop strategies for adapting to climatic shifts.

The term "adaptation" has been analyzed and debated for decades. Denevan (1983) urged researchers to refrain from describing an action as an "adaptation" if the researcher lacked sufficient observations of adjustments made over time. Likewise, Perramond (2007) emphasized a need to account for the temporal as well as spatial dimensions of "adaptation." He suggested using the term "adaptation" for changes that were certain to be long-term, such as the historic movement of a group of sedentary farmers to an area more favorable for cultivation, while "adaptive tactics" would consist of fleeting adjustments and "adaptive strategies" would consist of those tactics that, over time, materialize into a more systematic strategy. Other scholars have also sought to scrutinize the temporal dimensions of adaptation: Smit et al. (1996) designated short-term changes as "adjustments," while long-term transformations were termed "adaptations;" Batterbury and Forsyth (1999) used the term "adaptive strategy" for short-term changes and "adaptive processes" for changes over the long-term; and Morton (2007) identified "adaptive strategies" as those efforts taken before a system shock and "coping strategies" as efforts taken after an event. In the chapters that follow, I use the term "adaptive strategy" as both

Perramond (2007) and Morton (2007) intended it to be used: a systematic strategy imposed by individuals or communities to mitigate the effect of an event.

In sub-Saharan Africa, smallholders are adapting to a range of well-documented events produced by climate change. These adverse events include mean annual increases in temperature, reduction in precipitation and increased drought stress in many areas, changes to the variability of temperature and precipitation events, reduced crop productivity, and degradation of ecosystems to name a few (Niang et al., 2014). Focusing on precipitation, in each of Africa's major regions (i.e., northern, southern, eastern, and western), climate models suggest a drying signal and/or an increase in precipitation variability as a result of climate change (Giorgi and Lionello, 2008; Orlowsky and Seneviratne, 2012; Cook and Vizy, 2013).

In this dissertation, I concentrate predominately on increased variability of precipitation events and the shifting of rainfall regimes given their influence on water and food security (Rippke et al., 2016), as well as the serious risk they present toward crop harvests in the Mount Kenya region, the primary area of study (Niang et al., 2014). Sivakumar et al. (2004) note that precipitation variability with increased frequencies of drought is the greatest risk posed to African farmers. Variable rainfall is estimated to reduce maize production by 10% on average by 2055, with many locations showing more significant losses (Jones and Thornton, 2003). In East Africa, modeling efforts have found a range of crop yield outcomes as a result of shifting rainfall regimes, with some areas potentially benefitting from changing regimes; however, what must be noted is that farmers in all locations face increasingly unpredictable precipitation events capable of ruining harvests (Thornton et al., 2009; Thornton et al., 2010). It is these unanticipated dry spells and unexpectedly shortened growing seasons to which farmers in the Mount Kenya region must adapt.

1.2.2. Vulnerability assessment in the Mount Kenya region

Vulnerability can be thought of as the degree to which a system is likely to experience harm due to exposure to a hazard (White, 1976). A system's vulnerability is a function of its exposure to the event, sensitivity to the event, and capacity to adapt (Turner et al., 2003; Eakin and Luers, 2006). Polsky et al. (2007) describe these terms as follows: exposure represents, essentially, a quantification of the severity of an event confronted by a system; sensitivity accounts for the instability of a system given its various traits when confronted by an adverse event; and adaptive capacity represents the ability of a system to respond to an adverse event and limit damage. To further explain these concepts, I use the Vulnerability Scoping Diagram (VSD; Figure 1.1) introduced in Polsky et al. (2007) to illustrate the vulnerability of smallholders in the Mount Kenya region.

The VSD was created in an effort to compare the elements of vulnerability across multiple systems. It is used here because it effectively dichotomizes each of the elements of vulnerability into *components* and *measurements*. Components are the features on which to evaluate each of the vulnerability dimensions, while measurements are the observable characteristics of the components.

In the Mount Kenya region, climate change is *exposing* smallholders to rising temperatures, increasingly variable rainfall events, and decreasing streamflow (Figure 1.2). Temperatures within the Ewaso Ng'iro Basin, which is located on the western, northwestern, and northern slopes of Mount Kenya and encompasses the majority of the study area, are expected to increase ~0.4°C per decade for the next fifty years with greater but more variable rainfall (Ericksen et al., 2011). This will have the added effect of reducing river discharge, the product

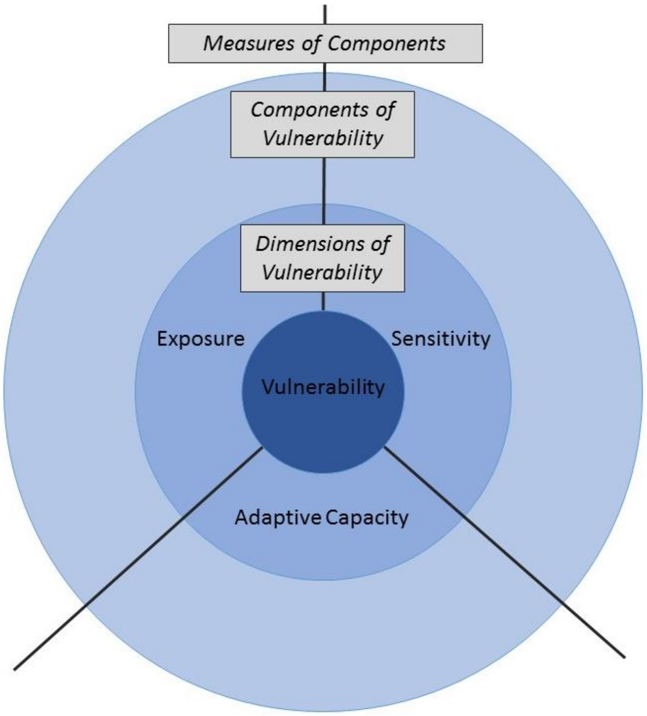


Figure 1.1. The vulnerability scoping diagram.

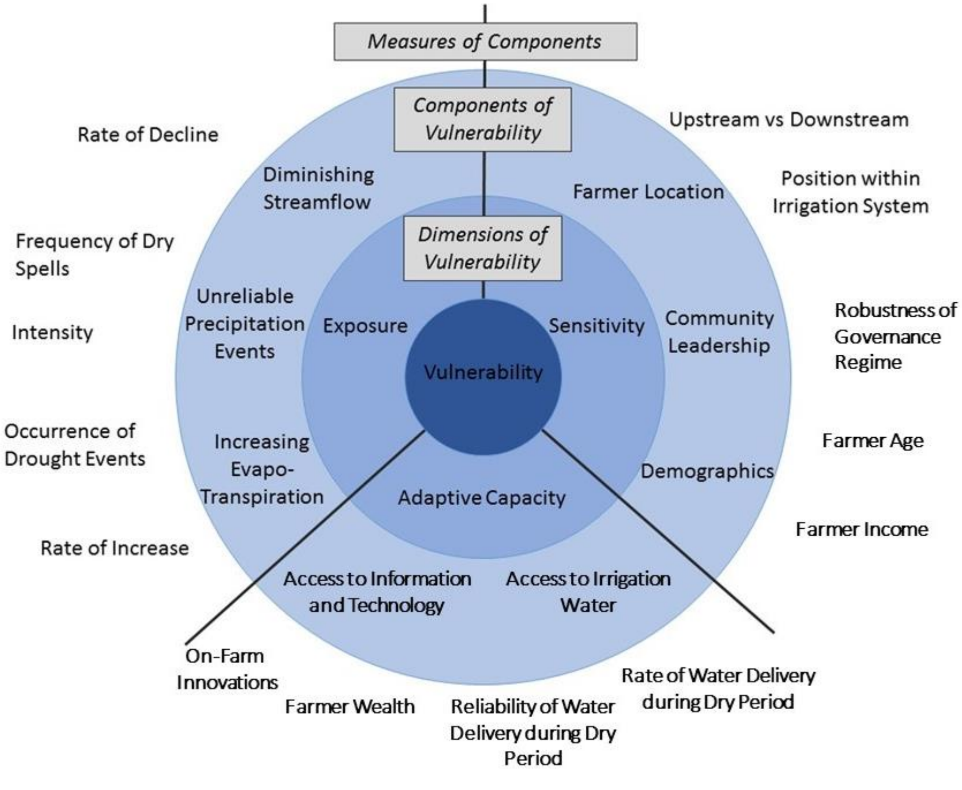


Figure 1.2. The vulnerability scoping diagram with entries related to the Mount Kenya region.

of increased evapotranspiration in the highland locales closer to the headwaters of the study area's rivers and streams (Ericksen et al., 2011).

The *sensitivity* of farmers in the region is dependent on a number of factors. Upstream smallholders may be less sensitive to diminishing streamflow because they are the households that are able to withdraw from rivers first. Further, if a smallholder belongs to an irrigation system, which pipes water directly to the household, the particular position of the farmer within the system may dictate how much water is received and, in turn, the sensitivity to a drought or dry period. Community leadership that allows for public participation and is nested within several levels of decision-making has been shown to be more responsive to the needs of its community when an adverse climatic event occurs (Huitema et al., 2009). For example, an irrigation system with leadership that is in continuous dialogue with its membership may be able to strategize a water rationing program capable of reducing smallholder sensitivity to a particular outcome, such as crop failure. Other individual level attributes, such as income and age, have been shown to influence smallholder proclivity for innovation (Clay et al., 1998; Somda et al., 2002), creating a spectrum of farmer sensitivities to climatic events.

Smallholders may possess a range of assets and techniques that enable their *capacity to adapt* to an adverse event. With respect to a dry spell that occurs unexpectedly during the growing season, irrigation may prove to be effective in avoiding a failed harvest. Rockstrom et al. (2010) discussed the ability of irrigation water to bridge a dry spell or extend a growing season. Additionally, assurance that water will be reliably provided for the purposes of irrigation has been shown to encourage farmer experimentation with different seed varieties, including short maturing varieties that mature during the intervals in which rainfall has historically been present (Deressa et al., 2009; Bryan et al., 2013). In Chapter 4 I investigate the range of contextual factors that influence smallholder access to irrigation water. Other forces such as exposure to new ideas, training, and technical support from extension officers also influence adaptive capacity (Rahm and Huffman, 1984; Ghadim and Pannell, 1999). In Chapter 2 I demonstrate a positive association between exposure to extension officers and smallholder crop diversification, which is an on-farm technique that has been shown to reduce vulnerability to external shocks (Holt-Gimenez, 2002; Tengo and Belfrage, 2004; Lin, 2007; Philpott et al., 2008).

1.2.3. Food production and smallholder livelihoods

Food security, as defined at the World Food Summit in 1996, refers to a situation in which all people have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for a healthy and active life (FAO, 1996). Noteworthy in this definition, as pointed out by Pinstrup-Andersen (2009), is that food *availability* alone does not ensure food security if individuals are unable to *access* and *use* the food nutritiously. Sen (1981) describes food security as a function of entitlements. In his influential book, *Poverty and Famines: An Essay on Entitlement and Deprivation*, Sen notes that an individual's *exchange entitlement*, i.e., the set of commodities that can be acquired given what a person owns, is reliant on his or her *ownership bundle*, i.e., the resource endowment of the individual. Thus, a smallholder with an ownership bundle consisting of several able-bodied family members, a large plot of land, remittances from city-dwelling family members, and access to a nearby market will have an entirely different exchange entitlement compared to a smallholder with an ownership bundle consisting of an elderly spouse, a small kitchen garden, and poor connectivity to markets (Figure 1.3).

Misselhorn (2005) conducted a meta-analysis to understand the drivers of food insecurity. In her study, the insufficiency of food *availability* alone in achieving food security was made clear as the majority of drivers were those that impacted food *access*, not availability. Included within these access-oriented drivers were increases in food prices, unemployment, and poor market access. The leading availability-oriented drivers from this study were insufficient agricultural inputs, absence of property rights, and climatic stressors given their ability to limit agricultural production.

Irrigation is an agricultural input that exposes smallholders to different entitlement sets; for example, an individual with reliable water access as part of their ownership bundle may be able to grow market crops that diversify income sources and improve food security. In this way, water security and food security are tightly interlinked (SEI, 2005; Godfray et al., 2010; Hanjra and Qureshi, 2010). Sen (1989) describes this linkage as one where the absence of agricultural inputs, such as irrigation, produces an entitlement failure that exacerbates food insecurity. The recognition that water security is a fundamental determinant of food security is reflected in conclusions that water scarcity, not the absence of arable land, will be the foremost cause of food insecurity in the coming decades (UNDP, 2006; Falkenmark and Molden, 2008). This dissertation focuses on irrigation – particularly the distribution of irrigation water to smallholders and the management decisions to improve inter- and intra-community access – due to its prominent role in achieving food security.

1.2.4. Social-ecological systems

Water and food security are both products of a range of variables interacting with one another in

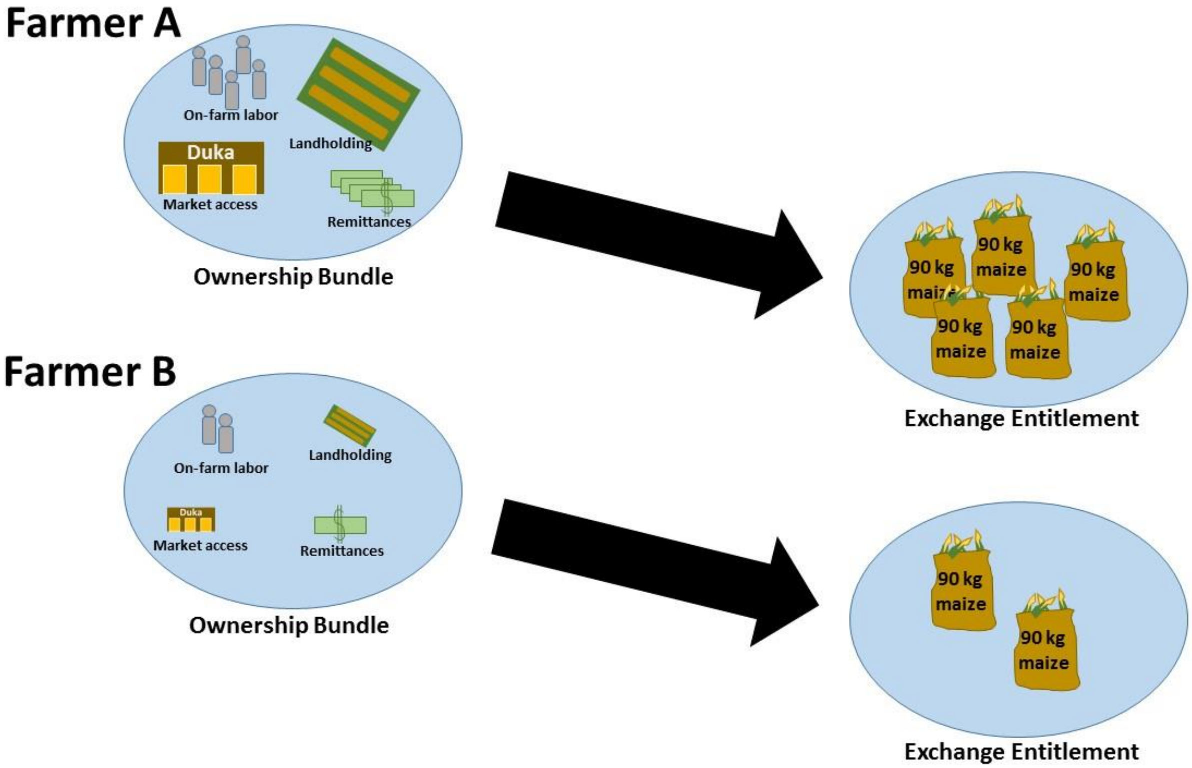


Figure 1.3. Demonstration of the relationship between a smallholder's ownership bundle and their exchange entitlement.

complex ways, often across multiple levels. Viewing these system components and connections as part of a social-ecological system (SES) helps to navigate the complexity. Anderies et al. (2004, 3) describe SESs as "the subset of social systems in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units." They describe the "ecological system" as linked with one or more social systems and consisting of interactive subsystems. Likewise, the "social system" is also described as interdependent with ecological elements and consisting of subsystems.

A range of frameworks have been developed to study SESs, each with their own purpose or outcome of interest. The Vulnerability Framework was developed to incorporate global environmental change and sustainability science perspectives in understanding the vulnerability of coupled human-environment systems (Turner et al., 2003). Liu et al. (2007) developed the

Coupled Human and Natural Systems Framework to emphasize the nesting of coupled systems across spatial and temporal dimensions. Meanwhile, the Resilience Framework was designed to capture the dynamism of connections and feedbacks within social-ecological systems (Holling, 2001). Practitioner-oriented frameworks have also been designed to navigate the complexities of coupled systems. The Human Ecosystems Framework was developed from the Long-Term Ecological Research Program to facilitate resource monitoring and management activities by natural resource agencies (Pickett et al., 2001), while the Ecosystem Services Framework came from the Millennium Ecosystem Assessment program as an effort to standardize comparisons of ecological and economic analyses (MEA, 2005). Given the range of SES frameworks that exist, Binder et al. (2013) reviewed ten of the most commonly used SES frameworks and developed a set of criteria to assist in selecting the appropriate framework for a particular research objective and system.

The SES Framework (Ostrom, 2007) is one of the frameworks mentioned in Binder et al. (2013), and it pursues two primary objectives: 1) to provide an organizing structure to handle the complexity of SESs and 2) to act as a step toward an interdisciplinary science of multilevel systems wherein scholars pose questions related to resource sustainability. I use this framework in Chapter 3 to articulate social and ecological changes in the Mount Kenya region following a shift in water management imposed at the national level. The SES Framework undertakes the ambitious task of classifying a seemingly endless array of contextual variables relevant to coupled systems. This is done by splitting the properties of the system into one of six categories: Resource System (RS), Resource Units (RU), Actors (A), Governance System (GS), the Social, Economic, and Political Settings (S), and the Related Ecosystems (ECO) (Figure 1.4). These first-tier variables, as Ostrom calls them, can be decomposed to second- third- fourth- and fifthtier variables to express finer detail. Figure 1.5 presents a set of common second-tier variables. Through interactions between these components and across multiple levels, important SES outcomes are produced.

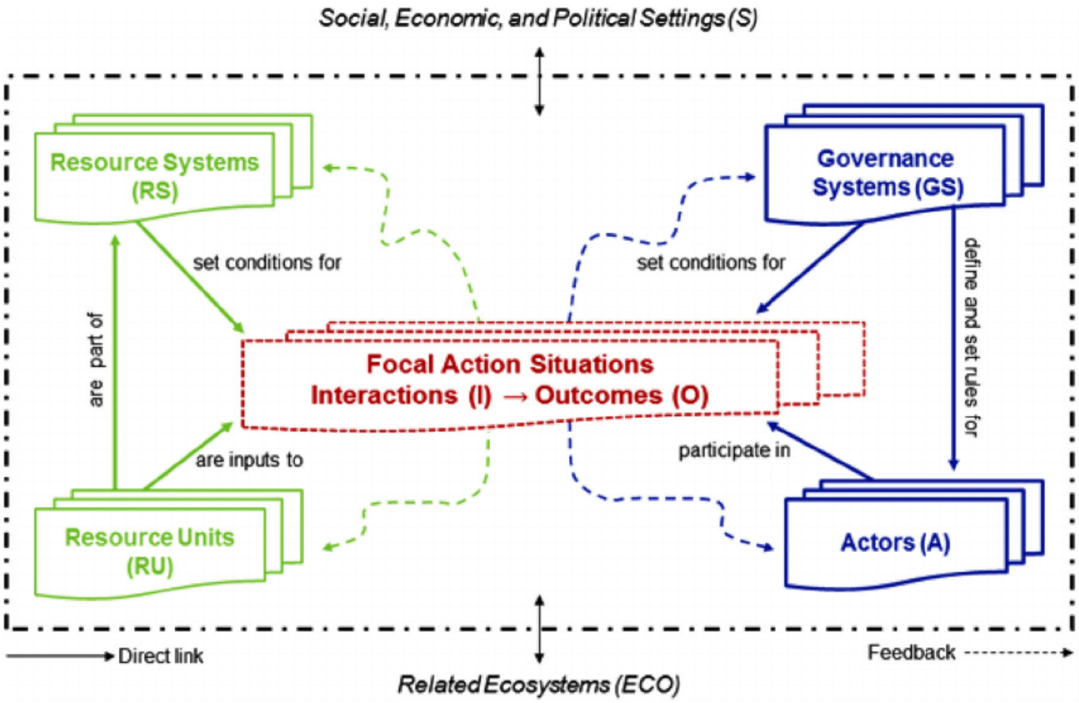


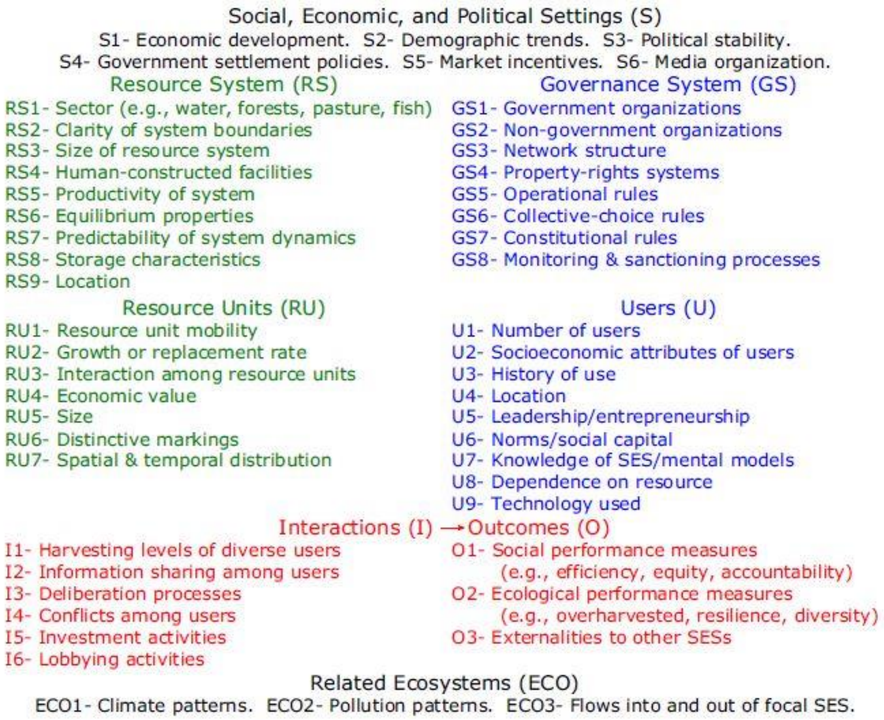
Figure 1.4. The Social-Ecological Systems Framework. *Source: Ostrom (2007).*

1.2.5. Common-pool resource governance

Common-pool resources (CPRs) are those possessing the twin characteristics of (1) subtractability and (2) a high cost of exclusion (Ostrom, 2005). Subtractability refers to the degree to which consumption of the resource by one user detracts from availability to other users. Exclusion refers to the difficulty of restricting access to the resource. Figure 1.6 presents four basic types of goods according to their subtractability and degree of exclusion. A resource such as air is considered to be a public good because (1) the use of it by one person does not make it any less available to another individual and (2) it is generally difficult to exclude someone from its benefits. Water, on the other hand, would be considered a common-pool resource because (1) an individual using the resource subtracts from its overall availability to others and (2) it is generally difficult to exclude others from accessing the resource.

1.2.5.1. Collective action in common-pool resource governance

The sustainability of CPRs is often contingent on whether or not users are able to overcome collective action problems when managing their resource. Collective action problems are created when individual incentives differ from the incentives of the group. For example, as it relates to smallholders reliant on rivers for irrigation, the incentive of an upstream user might be to take as much water from the river as is needed for a successful harvest; however, if all individuals act in the same fashion, the resource will become depleted. Rules accounting for these divergent individual and group interests help to solve commons dilemmas.



Social, Economic, and Political Settings (S)
S1- Economic development. S2- Demographic trends. S3- Political stability.
S4- Government settlement policies. S5- Market incentives. S6- Media organization.

Resource System (RS)
RS1- Sector (e.g., water, forests, pasture, fish)
RS2- Clarity of system boundaries
RS3- Size of resource system
RS4- Human-constructed facilities
RS5- Productivity of system
RS6- Equilibrium properties
RS7- Predictability of system dynamics
RS8- Storage characteristics
RS9- Location

Governance System (GS)
GS1- Government organizations
GS2- Non-government organizations
GS3- Network structure
GS4- Property-rights systems
GS5- Operational rules
GS6- Collective-choice rules
GS7- Constitutional rules
GS8- Monitoring & sanctioning processes

Resource Units (RU)
RU1- Resource unit mobility
RU2- Growth or replacement rate
RU3- Interaction among resource units
RU4- Economic value
RU5- Size
RU6- Distinctive markings
RU7- Spatial & temporal distribution

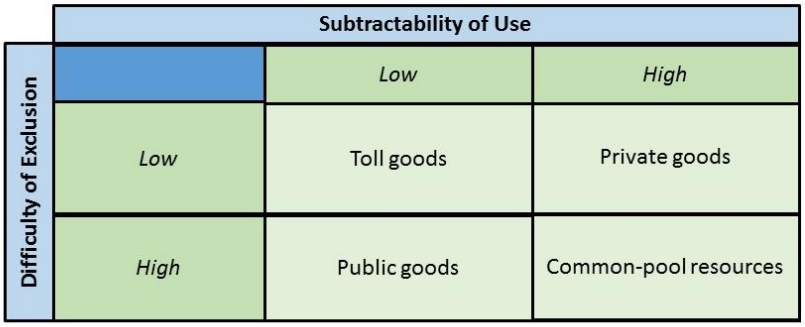
Users (U)
U1- Number of users
U2- Socioeconomic attributes of users
U3- History of use
U4- Location
U5- Leadership/entrepreneurship
U6- Norms/social capital
U7- Knowledge of SES/mental models
U8- Dependence on resource
U9- Technology used

Interactions (I) → Outcomes (O)
I1- Harvesting levels of diverse users
I2- Information sharing among users
I3- Deliberation processes
I4- Conflicts among users
I5- Investment activities
I6- Lobbying activities

O1- Social performance measures
(e.g., efficiency, equity, accountability)
O2- Ecological performance measures
(e.g., overharvested, resilience, diversity)
O3- Externalities to other SESs

Related Ecosystems (ECO)
ECO1- Climate patterns. ECO2- Pollution patterns. ECO3- Flows into and out of focal SES.

Figure 1.5. Common second-tier variables within the SES Framework. *Source: Ostrom (2007).*



Difficulty of Exclusion		Subtractability of Use	
		Low	*High*
	Low	Toll goods	Private goods
	High	Public goods	Common-pool resources

Figure 1.6. Four basic types of goods according to subtractability and difficulty of exclusion.

In terms of why CPR management faces these types of dilemmas, the answer can be found in the very characteristics that distinguish CPRs from other basic types of goods (i.e., their subtractability and the challenge of excluding others from using the resource). Taking irrigation systems again as an example, the challenge of excludability presents the risk of free-riders undermining efforts to maintain the system's infrastructure (Ostrom, 2005). Irrigation systems require considerable labor to provide water to their memberships: trenches must be dug to construct canals or to bury water distribution pipes, repairs need to be made consistently to minimize leakage, and new canals need to be dug if or when an irrigation system's membership expands. If exclusion is costly and it is too difficult to monitor compliance with rules mandating labor contributions, an individual may be able to benefit from the presence of a well-maintained irrigation system without bearing any of the physical and financial cost of its construction and upkeep.

Relatedly, the subtractability of the resource creates its own dilemma. The use of water by an irrigation system member essentially eliminates that water from use by another individual, whether in that same irrigation system or a downstream system. If river water is scarce compared to the demand for the resource, then individuals may be tempted to excessively withdraw water in response to their fear that others will take their share if they do not use it (Ostrom et al., 1994). Allocation rules, therefore, need to exist to effectively eliminate upstream users from taking actions that meet solely their own needs. If left unchecked, these actions create an imbalance between downstream water demand and supply.

Ostrom et al. (1994) described these two types of collective action problems as provision and appropriation dilemmas. Cox and Ross (2011) applied these concepts to irrigation systems by describing provision problems as the temptation to under-provide labor but to benefit from the delivery of water all the same (i.e., the free-rider problem) and the appropriation problem as the overconsumption of water at the expense of others within the same community or catchment. Considerable attention has been given to the particular conditions that challenge the prospect of overcoming provision and appropriation dilemmas. Hardin (1982) found that group size may impinge upon collective efforts since transaction costs associated with organization and coordination increase with additional members. A group of heterogeneous rather than homogeneous water users may also struggle to maintain collective action if distrust, which is expected to be higher within heterogeneous groups, interferes with the ability to establish and abide by water sharing agreements (Walker and Ostrom, 2009). Familiarity with other members and income disparities have also been shown to influence collective action, with members of long-established user groups demonstrating more cooperation (Fujiie et al., 2005) and user groups with greater income disparities showing less cooperation (Ternstrom, 2003). In Chapter 4 I explore several indicators of collective action and their role in producing (un)desirable water delivery outcomes.

1.2.5.2. Adaptive co-management of common-pool resources

Given the dynamic nature of social (e.g., population growth) and biophysical events (e.g., increasingly variable rainfall events), CPR management demands flexibility to keep pace with ever-shifting conditions (Cosens and Williams, 2012). Adaptive management provides for this flexibility by allowing learning and experimentation in policy development, as well as sharing of information between managers and citizens (Lee, 1999). Folke et al. (2005) describe this form of management as that which seeks the outcome of system resilience, or, put differently, a system that is able to absorb natural or social perturbations and continue to maintain essential functioning.

Huitema et al. (2009), in extensively reviewing the resource management literature, identified four institutional characteristics embodied by an adaptive regime. The first characteristic is the existence of multiple centers of power, also referred to as polycentric governance. I will describe the concept of polycentricity in greater detail below. Second, adaptive co-management regimes allow for public participation in the form of collaboration between resource managers and resource users. Decision making may be improved by utilizing information provided by individuals directly affected by management decisions (Folke et al., 2002; Folke et al., 2010). Furthermore, in situations where financial and information resources are scarce, public participation is an essential trait allowing information to be shared in an efficient manner. Third, an experimental approach should be taken by resource managers since information is incomplete and the complexity of SESs leads to uncertainty over time. Resource managers should therefore view their policies as hypotheses and management actions as experiments to test hypotheses (Folke et al., 2005). Finally, management must take place at the resource level. For example, in the case of a river resource, a catchment or basin level authority should exist to manage decisions concerning upstream and downstream water access.

Water governance in the Mount Kenya region exemplifies traits of an adaptive co-management system. Local level irrigation systems are nested within catchment level management groups, which are nested within still broader regions with their own management authorities. This creates an opportunity for rule experimentation across governance regimes at the same level of management and it provides redundancy within the system where failure of a particular function at one level may be offset by another level providing a similar function. These are commonly cited benefits of a polycentric system (Anderson and Ostrom, 2008). Additionally, this type of governance arrangement may facilitate coordination and information transfer between irrigation systems nested within the same catchment, which is particularly important given the need to balance the demand of water by upstream users with the demands of those downstream. Finally, Water Resource Users Associations or WRUAs facilitate rule-making and coordination between irrigation systems at the catchment level, ensuring that water managers consider processes at the appropriate hydrological scale when crafting institutional arrangements. I discuss WRUAs and their role in adaptive co-management in greater detail in Chapter 3.

1.2.5.3. Polycentricity

Huitema et al. (2009) listed polycentric governance as a crucial attribute of a management regime if it is to be sufficiently pliable to adjust to shifting biophysical conditions. The concept of “polycentricity” arose in the early 1960s within the context of metropolitan political units. The dominant idea at the time was that, rather than multiple overlapping political units, a “single dominant center” was a more appropriate form of government, since inefficiencies would arise if multiple units existed, creating duplicated functions (V. Ostrom et al., 1961, p. 831). Essentially, the presence of multiple political units was viewed as too chaotic to be as effective as a single governing unit (Cottrell, 1949).

V. Ostrom et al. (1961) countered this argument by suggesting that a polycentric political system may actually improve the efficiency of government units as they are forced to compete for citizens who have been presented with a variety of public service options from multiple centers of government. Polycentric governance does not, however, simply refer to independence of local authorities to devise their own structures of management, although this is an important component. It also refers to the *interdependence* between institutions and organizations at various levels in a nested or hierarchical structure (Cole, 2011).

Since its application to metropolitan settings, polycentricity has subsequently been extended to resource governance given the nested nature of ecological dilemmas and the potential benefits of building redundancies into resource management (Low et al., 2003). Of the advantages provided by polycentric resource governance, Ostrom (2005) listed the following as particularly important: utilization of local knowledge, inclusion of trusted individuals, usage of knowledge from multiple sources, better adapted rules, reduced monitoring costs, and parallel systems of rule.

With respect to utilization of local knowledge, individuals who interact with a resource on a daily basis will better understand the resource's dynamics compared to a government administrator who may visit the ecosystem only once or twice a year (Folke et al., 2005). For example, the members of an irrigation system relying on a particular river will have a better understanding of their locality's growing and harvesting periods, as well as the timing of rainy seasons that contribute to river levels. Therefore, to ensure that rules are crafted in accordance with local conditions, it is appropriate that local level irrigation system members – or members of any CPR regime, for that matter – have a voice in establishing the river system's governance structure. Additionally, by allowing local user groups to craft and adjust their own rules, as well as to learn from other user groups who are challenged with similar management undertakings, it is presumed that over time user groups will devise better adapted rules, that these rules will improve trustworthiness and reciprocity within the user group, and that enforcement costs will be reduced as those stakeholders who are responsible for monitoring are the same individuals who use the resource and make the rules (Huitema et al., 2009; Pahl-Wostl et al., 2012; Dell'Angelo et al., 2014).

A polycentric system is achieved if, in addition to a commitment to some degree of local level independence, mechanisms are also in place allowing for coordination between local, regional, and national jurisdictions (Baldwin et al., 2016). Creating a degree of interdependence between local, regional, and national levels generates opportunities both for conflicts to be addressed by the most appropriate jurisdiction (e.g., if an irrigation system is unable to resolve a dispute, a regional authority may intervene to make a decision on the dispute) and for large-scale resource systems to be managed by authorities with a wider reach than an individual user group (e.g., a watershed that crosses several irrigation systems). Additionally, interdependent nesting of management authorities often grants a degree of legitimacy to local level user groups, legitimacy that otherwise would not be provided to user groups operating independent of state-sanctioned institutions. Basurto and Ostrom (2009) demonstrated this very idea when exploring two fisheries in the Gulf of California: one that was well-integrated with other jurisdictions and was able to endure when it encountered external threats and a second autonomous group that collapsed when threatened by "roving bandits" of external fishing fleets.

In Chapter 3 I explore several ideas related to polycentric resource governance in the Mount Kenya region. Particularly, I investigate the flexibility afforded by a polycentric system to local user groups in crafting their own institutions. I further examine the ability of user groups to engage in a trial-and-error learning process with other user groups as they grapple with the challenges of devising effective management rules.

1.3. Conclusion

In any SES, a host of contextual elements, including system components and connections, shape various outcomes. In semi-arid agrarian systems, these outcomes include topics such as food and water security, but also other topics related to socioeconomic, migration, and resource conservation outcomes that are omitted from this dissertation. Selecting only a small collection of outcomes and contextual elements to focus on in any SES is an exercise in itself of pragmatism as well as speculation. It is not possible to account for the full range of drivers influencing outcomes within SESs; however, the very complexity of these systems is precisely why rigorous, empirical investigations from multiple disciplinary angles and geographic levels is needed when investigating outcomes such as food and water security.

1.3.1. Summary of empirical chapters

Figure 1.7 offers a conceptual diagram demonstrating the linkages across themes from each of the empirical chapters and Table 1.1 organizes the upcoming chapters according to the research questions addressed in each chapter, the theoretical concepts discussed in the previous sub-sections, the methods used in each chapter, and the particular level(s) of analysis. I focus on three broad research questions in the upcoming chapters:

(RQ1) How do smallholders shape their on-farm cropping strategies to mitigate external threats? What social and biophysical conditions associate with one on-farm risk reducing strategy: crop diversification?

(RQ2) How do local level water managers respond to top-down water governance reform, and do these adjustments align with goals of adaptive management? How do these adjustments influence water provisioning outcomes?

(RQ3) In what ways do the rules-in-use for water management influence the adequacy and reliability of household level water availability? What other elements of a water system, such as the biophysical environment and infrastructural traits, play an important role in driving household level outcomes related to reliable and adequate water availability?

These research questions are investigated within a collection of smallholder irrigation systems, locally referred to as Community Water Projects (CWPs), in the Mount Kenya region. I elaborate upon the study area in each of the following chapters according to its relevance to the particular study.

All chapters relied on primary data collected from two fieldwork campaigns, one in Summer 2012 and a second in Summer 2013. Additionally, Chapter 3 uses archival data collected from various institutions in Nairobi, Kenya. Given the importance of addressing SES puzzles from multiple disciplinary angles, I approach Chapter 2 from the perspective of Vulnerability Science, a science very familiar to Geographers and Anthropologists. In Chapter 2, two separate regressions are employed. In Chapter 3, I engaged in institutional analysis, which is reflected in the qualitative review of survey responses provided by resource managers and the effort to diagnose changes in the make-up of the SES following a national reform to water governance. Finally, I engaged with hydrological data in Chapter 4 and took a quantitative approach to institutional analysis in this chapter, which is reflected by the use of a multi-level regression model to understand household water availability.

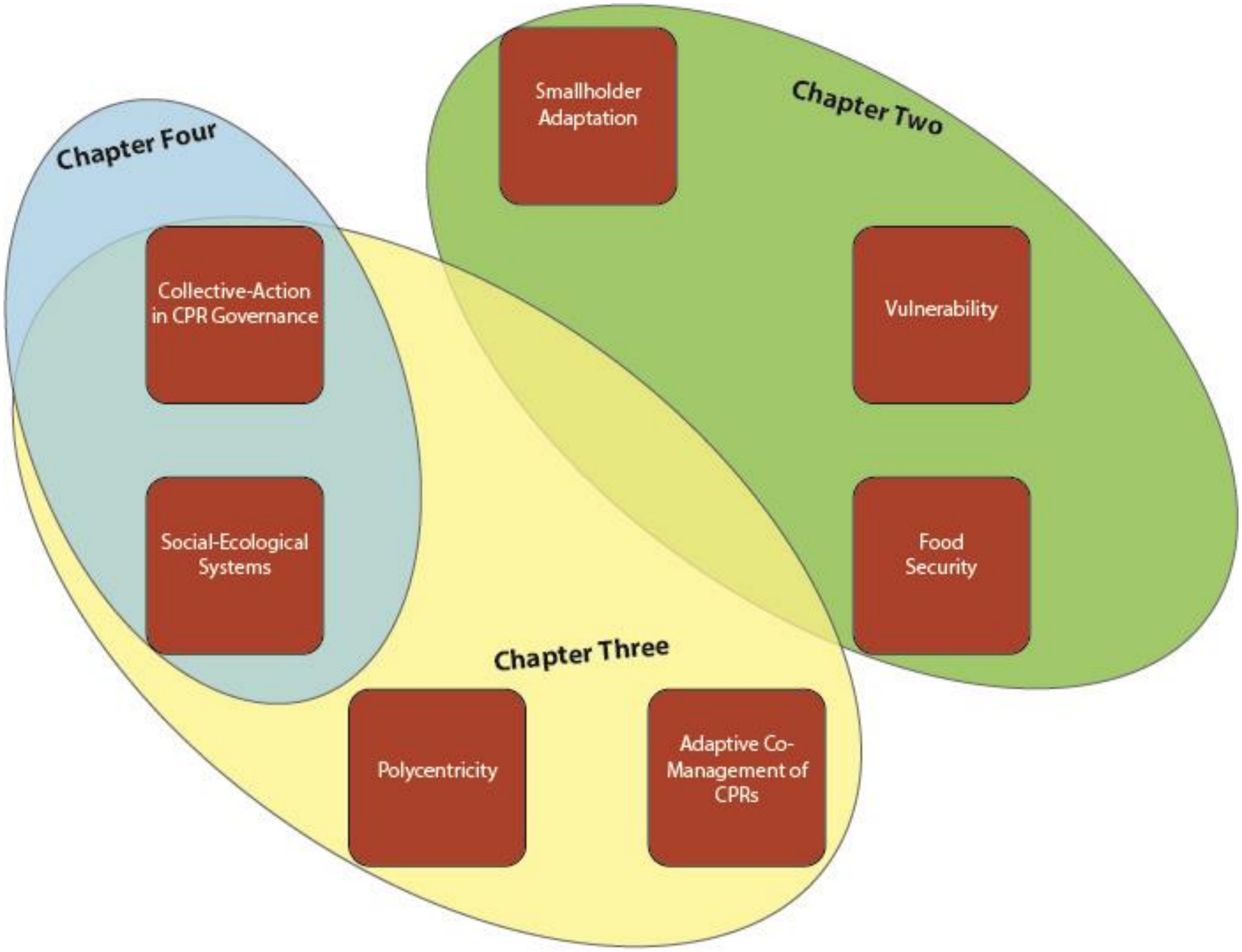


Figure 1.7. Linkages across the empirical chapter themes.

Outcomes related to water governance and smallholder decision making within the Mount Kenya region are explored from several levels. In Chapter 2 I investigate smallholder vulnerability by primarily focusing on household level characteristics and find that household traits such as accessibility and exposure to extension agents associate with smallholder decisions to engage in one type of risk-reducing strategy. Chapter 3 examines water governance by exploring quantitative and qualitative information at the national, catchment, and community levels. In this chapter, I reveal efforts made by irrigation system managers to respond to national level policies; of these actions taken by irrigation system managers, some are unexpected or opposed to findings in the polycentricity literature. And in Chapter 4 I investigate household level water availability by accounting for both household and community level attributes. Significant findings from this chapter include evidence that all irrigation systems within the study area are unable to provide water to their members in an equitable fashion, as well as the discovery that household level water delivery is influenced by a range of elements spanning institutional, infrastructural, and biophysical domains. In taking a multi-level approach to the empirical questions posed in Chapters 2-4, I account for hierarchies within the study area's social, biophysical, and institutional make-up; hierarchies described by Ostrom (2007) as inherent to any SES.

The chapters that follow will demonstrate new findings related to water governance and smallholder decision making within semi-arid systems, particularly smallholder irrigated agricultural systems. I conclude the dissertation by summarizing these findings in Chapter 5 and highlight contributions from the empirical analyses in Chapters 2-4 to several research agendas that I have introduced in Chapter 1, including vulnerability studies, resource governance, and studies of social-ecological systems.

Table 1.1. Summary of empirical chapters

Chapter	Title	Research Question	Theoretical Concepts	Methods	Level(s) of Analysis
2	Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya	RQ1	-Smallholder adaptation -Vulnerability -Food production and smallholder livelihoods	-Standard OLS regression -Ordered logistic regression	Household
3	Polycentric transformation in Kenyan water governance: A dynamic analysis of institutional and social-ecological change	RQ2	-Social-ecological systems -Collective action in CPR governance -Adaptive co-management of CPRs -Polycentricity	-Qualitative analysis -Mann-Whitney-Wilcoxon test	National, Catchment, Community
4	Household level heterogeneity of water resources within common-pool resource systems	RQ3	-Social-ecological systems -Collective action in CPR governance	-Multi-level regression	Community, Household

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Chapter 2: Crop Diversification as a Smallholder Livelihood Strategy within Semi-Arid Agricultural Systems near Mount Kenya

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2.1. Introduction

Climate variability deeply influences livelihoods dependent on agricultural production.

In the semi-arid tropics (SAT), where 22% of the world's population resides, livelihoods are more susceptible to climate fluctuations due to the persistence of high levels of chronic poverty and inadequate food consumption (Falkenmark and Röckstrom, 2008). Surface hydrological dynamics additionally contribute to the vulnerability of smallholder farmers due both to rainfall variability and human- or climate-induced land and water degradation. In Africa, the proportion of arid- and semi-arid lands is expected to increase by 5 to 8% by the 2080s in large part due to depleted water resources (Collier et al., 2008). This is particularly concerning as the greatest impact of such depletion will be in agriculture, the sector that accounts for more than 60% of the African labor force (Collier et al., 2008). Further, it is projected that the area suitable for agriculture, the length of growing seasons, and the yield potential of agricultural lands will decrease. While such changes are expected to vary from country to country, yield reductions may be as high as 50% by 2020, with smallholder farmers being most vulnerable (Boko et al., 2007).

Crop failure in semi-arid systems results from challenges such as pest outbreaks, insufficient rainfall, or in some cases excessive rainfall. When crop yields decline or fail, farmers adopt a variety of strategies to maintain their livelihoods. However, the adaptation opportunities available to semi-arid smallholder farmers are limited for a number of reasons. Dry spells may require some amount of irrigation to bridge to periods of higher rainfall. But in many locations, water harvesting strategies and irrigation infrastructure do not provide sufficient water to continue cultivation during dry periods. Household conditions including income and farm size may limit the ability to experiment with adaptation strategies such as growing market-oriented crops and diversifying income through off-farm employment given the household's inability to tolerate a failed endeavor. Finally, isolation from other villages and urban centers or poor infrastructure reduces connectivity to extension agents and may thereby diminish information flow concerning water conservation techniques and cultivation of drought-tolerant varieties. Challenges to semi-arid agriculture should therefore be recognized when exploring farmer adaptation strategies given the complex set of social and ecological conditions that influence the farmer decision-making process.

Crop diversification is one strategy households may employ to reduce their vulnerability to external stressors, such as climate change (Altieri, 2004; Baumgartner and Quaas, 2010; Lin, 2011). The term *vulnerability* should be understood as a function of three dimensions: *exposure* to social and/or environmental stresses, associated *sensitivities*, and related *adaptive capacities* (Polsky et al. 2007, p. 473). For example, from this perspective a community of smallholders could be equally *exposed* to a drought, yet household harvest *sensitivity* to the drought would vary depending on cropping strategies as soil moisture within monoculture fields has been shown to be lower compared to polyculture fields that make use of multi-storied crops and shade trees (Lin 2007), translating to a relatively larger harvest from the polyculture system. Additionally, crop diversification provides access to multiple markets and may introduce farmers to new cultivation techniques thus improving *adaptive capacity* in the face of adverse market and/or climatic events. Taken together, growing a diverse array of crops can lessen household vulnerability to adverse conditions.

Examples of crop diversification include polycultures, agroforestry systems, and crop rotation systems, with diversity evident in form (e.g. genetic, species, structural), function (e.g. pest suppression, increased production), and scale (temporal and spatial) (Lin, 2011). One of the primary advantages of crop diversification is enhanced ecosystem functioning and resilience.

Because different species occupy a multitude of niches while performing duplicative functions, redundancy is built into the system (Vandermeer et al., 1998; Lin, 2011). Such redundancies may allow for sustained ecosystem functioning over time, since species respond differently to environmental fluctuations, and the presence of multiple species performing similar functions better ensures that, if one species is unable to perform a specific role, another can be substituted. This benefit of diversification, linked to the insurance hypothesis, maintains that biodiversity provides a buffer against environmental fluctuations (Yachi and Loreau, 1999). The significance of on-the-farm crop diversification has additionally been extended to market-oriented smallholders (Bradshaw et al., 2004; Fraser et al., 2005). By growing a diverse array of crops and by maintaining links to multiple markets in a range of locations, a smallholder farmer is better able to ensure a marketable harvest and can buffer against adverse market events by, for example, taking a harvest to an alternative market if the initial market has been over-supplied with of particular crop.

Though crop diversification may reduce farmers' vulnerability to climate and market variability, dissimilarities in individual characteristics and social and biophysical conditions can impact the level of diversification across a landscape (Altieri, 1995). Land suitability, income level, risk avoidance, contact with extension officers, and social norms are potential determinants of crop diversification at a narrowed scope (Cutforth et al., 2001; Di Falco and Perrings, 2003). Across semi-arid upland-lowland environments, however, these determinants may change rapidly over short distances. Orographic lifting, for instance, creates disparities in precipitation levels (i.e. growing conditions) between relatively proximal locations. In the process, these dissimilarities may lead to varying income levels and livelihood activities, for example, as favorable growing conditions may spur successful cropping while individuals in drier regions may resort to less profitable alternatives. The rapidly changing abiotic factors across such environmental gradients often influence plant species diversity (Loreau, 1998; Loreau et al., 2001), with positive linear relationships between rainfall conditions and species diversity existing in some locations (Gentry, 1988).

Multiple studies have inspected how planting strategies and, accordingly, crop species diversity, are affected by farm-level abiotic conditions, such as rainfall, as well as socioeconomic conditions, household demographics, farmer experiences, and community-level characteristics (Napier and Camboni, 1993; Jarvis and Hodgkin, 2000; Neill and Lee, 2001; Ryan et al., 2003; Degrande et al., 2006). Further, a growing body of literature is concerned with understanding the management and improvement of agrobiodiversity in the context of changing conditions, such as mechanized monoculture farming, household member migrations, climate change, and development or alteration of irrigation systems (Zimmerer 2010a; Zimmerer 2011; Khumalo et al. 2012). In this context, irrigation can improve agrobiodiversity by allowing crops with different maturation periods to be cultivated through extension of growing seasons (Zimmerer 2014), yet a decrease in diversity as well as crop failures may also result if the governance or design of the irrigation infrastructure are unsatisfactorily altered for the needs of a community (Zimmerer 2011). The area of study in our analysis has experienced significant change in the past century, including irrigation practices, which will be explained in section 2.2. Social and ecological differences as well as varying trajectories of change throughout the study area have created a distinctly heterogeneous landscape in terms of biophysical and social traits. These local traits, upon which global forces of change operate, interact with agricultural management, on-the-farm biological diversity, and, in the process, smallholder vulnerability to fluctuating climatic and social conditions (Zimmerer 2010b). We intend to explore crop diversification practices across this heterogeneous landscape, and in the process contribute to the growing body of literature inspecting social and ecological vulnerability in the face of global change pressures.

The purpose of this paper is to examine the crop diversification practices of households within a semi-arid upland-lowland system where biophysical conditions, social conditions, and features such as the capacity to irrigate vary. Irrigation presents an important capacity to support agricultural production in marginal environments, but there are diverse ways that farmers utilize this capacity at the farm level to maintain or enhance crop diversification. We focus on spatial rather than temporal crop diversity as the data employed in our analysis span a single growing season. The study takes place across a landscape spanning eight community irrigation projects on Mount Kenya's northwestern slopes. This study area is emblematic of semi-arid mountain environments exhibiting environmental gradients affecting land use suitability. A total of 315 households in eight community irrigation projects were surveyed to examine differences in crop diversification in the context of various social and environmental factors. The communities range from the lower slopes of Mount Kenya (2099 – 1805 m a.s.l.) to the Laikipia plateau (1799 – 1792 m a.s.l.) to the semi-arid to arid rangelands (1634 – 1617 m a.s.l.). By exploring crop diversity across a distinct semi-arid gradient, we will investigate the influence of varying social and biophysical conditions on cultivation strategies and, in the process, contribute to a growing research area concerning techniques to reduce vulnerability within irrigation systems. We hypothesize that the study area locations that are "upstream," or at a higher elevation, will have greater crop diversity levels due to more favorable biophysical conditions (i.e. higher potential annual precipitation and less reliance on irrigation to sustain adequate crop growth), and that, in easily accessible locations, frequent exposure to agricultural extension officers will increase diversification.

2.1.1. Background: Reduced vulnerability through crop diversification

Agriculturalists in the SAT face a number of sociopolitical and environmental challenges. Most notable among the environmental challenges are between and within season rainfall variability, low and deteriorating levels of soil organic matter, and high evapotranspiration rates (Ayuk, 2001; Rockström and Barron, 2007; Cooper et al., 2008). Crop diversification has the potential to enhance resilience in agricultural systems (Heal, 2000), particularly on lands considered marginal for production (Ewel, 1999). Resilience, here, refers to the capacity of a system to maintain structure and function following a perturbation, without necessarily returning to a particular reference state (Holling, 1973). Thus, a resilient agricultural system is one that continues to provide services, such as nutrient cycling and food production, despite the presence of external stressors, such as extreme climatic events or the presence of pests (Lin, 2011). Recent research has demonstrated that crop diversification practices help buffer microclimatic fluctuations (e.g. Holt-Giménez, 2002; Tengo and Belfrage, 2004; Lin, 2007; Philpott et al., 2008) and increase the suppression of pests and diseases (e.g. Mitchell et al., 2002; Perfecto et al., 2004), while also enhancing production stability and the provision of diverse livelihood benefits to farmers (e.g. Moguel and Toledo, 1999; Peeters et al., 2003; Méndez et al., 2007).

The resilience of diversified systems, such as polycultures and agroforestry systems[1], to extreme climatic events is commonly linked to modifications in farm-level microhabitats. For example, in comparing the resilience of farms to hurricane impacts (e.g. Hurricane Mitch in 1998) in Nicaragua and Honduras, Holt-Giménez (2002) found that “agroecological” farms (or farms that used more sustainable land management practices, such as contour farming,

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[1] Polycultures are characterized by two or more crop species grown on the same field while agroforestry systems are characterized by the growing of trees and crops on the same field. In both systems, wide variability exists in the spatial and temporal arrangement of crops and trees (Lin, 2011).

intercropping, vegetative strips, and agroforestry) had more topsoil, higher field moisture levels, and lower economic losses than conventional farms following disturbance. Research by Philpott et al. (2008) in Chiapas, Mexico further demonstrates the importance of vegetative complexity in buffering against extreme storm and wind events. The authors examined the relative impact of topographic and biophysical characteristics (e.g. aspect, slope, elevation, canopy cover, vegetation structure) on predicting economic and landslide damage associated with Hurricane Stan in 2005. They found that reductions in farm-level vegetative complexity correlated with increased probability of landslides at the farm and landscape level.

Additional research by Lin (2007) demonstrates the importance of multistoried shade trees in producing microclimates that buffer temperature and humidity fluctuations, thereby improving growing conditions. In comparing the microclimate and soil moisture data of coffee systems with varying degrees of shade cover, Lin (2007) found that fluctuations in temperature, humidity, and solar radiation increased as shade cover decreased. The presence of shade trees helped control or limit climatic extremes, which enabled better management of plant physiological processes, including reduced loss of water through evapotranspiration. The positive impact of biodiverse systems relative to more modern, intensive agricultural systems was also demonstrated by Tengo and Belfrage (2004) in Sweden and Tanzania. The authors found that more traditional land management practices, particularly those that incorporated wild varieties suitable for local conditions, had a higher capacity to adapt to climatic extremes. Further, systems with greater spatial and temporal complexity, such as polycultures and intercropping systems, were shown to regulate pest outbreaks and enhance water conservation, which limited the impact of seasonal drought.

Finally, in the context of global change, the importance of crop biodiversity increases as commercial agriculture tends toward large, monoculture systems. These monoculture systems are generally associated with increased use of costly inputs for crop maintenance (e.g. irrigation, synthetic fertilizers, pesticides) and reduced diversity of crop varieties. Given losses of diversity, any major natural shock to the agricultural system may cause severe and irreversible damage to the system. Though crop diversification is not a panacea for reducing vulnerability to climatic variability, it has the *potential* to increase production and promote ecosystem stability on marginal or degraded lands. Additional to the benefits outlined above, diversified systems can aid in the cycling of water and nutrients. For example, intercropping with leguminous crops and trees has been shown to improve use of space, rooting ability and water use efficiency, and nutrient uptake on lands with poor soil quality (Morris and Garrity, 1993; Lithourgidis et al., 2011). Because inorganic fertilizers contribute to nitrate pollution and eutrophication (among other environmental consequences), intercropping with legumes can provide an alternative, sustainable way of introducing biological nitrogen fixation into the system (Fustec et al., 2010; Lithourgidis et al., 2011).

2.1.2. Background: Crop diversity and agricultural innovation

Extensive attention has been given to agricultural innovation and adoption (e.g. Feder and Umali, 1993; Saha et al., 1994; Diederen et al., 2003; Knowler and Bradshaw, 2007; Shiferaw et al., 2009). This body of literature typically investigates farmer adoption of technological innovations or practices as a utility maximization process subject to micro-level and macro-level constraints (Feder et al., 1985). Factors affecting adoption can be grouped under four categories: human capital, structural, institutional, and environmental (D’Souza et al., 1993), with variables such as age and education grouped under *human capital* characteristics, farm size and off-farm employment under *structural* characteristics, participation in government programs under *institutional* characteristics, and rainfall and soil quality under *environmental* characteristics. These variables are then used to identify patterns of adoption behavior at micro- and macro-scales, and to verify or refute hypothesized relationships regarding new technology use and farm-level or firm-level (aggregate) characteristics.

Studies investigating sustainable agricultural practices, such as crop diversification, have also utilized the technology adoption literature. While justifying their use of this literature in formulating an econometric model, D'Souza et al. (1993, p. 160) state that "the adoption of a sustainable agriculture system can be expected to be influenced by the same characteristics as those that influence adoption of conventional technologies." Similarly, studies inspecting adoption of sustainable agriculture techniques such as conservation tillage and no-till techniques (e.g. Gould et al., 1989; Pautsch et al., 2000; D'Emden et al., 2008), the use of cover crops (e.g. Neill and Lee, 2001), and the use of organic input or low-input practices (e.g. Saltiel et al., 1994; Clay et al., 1998; Parra Lopez and Calatrava Requena, 2005; Genius et al., 2006) have assembled their analyses utilizing previous research on technology adoption. Likewise, we use the technology adoption literature to provide a framework for our analysis, a strategy applied less frequently in studying crop diversification compared to other sustainable agricultural practices.

We have chosen to conduct our study of crop diversification strategies within a semi-arid environment given the unique precipitation-related exposures present in these systems, and the role that these exposures may play in a household's ability to diversify. Additionally, our study takes place within an upland-lowland system to capture not only differences in climatic conditions and how these differences influence crop diversity levels, but also to better understand how differing social conditions influence crop diversification. Mount Kenya's environmental gradient, which captures varying biophysical conditions, as well as multiple socioeconomic levels, farming strategies, and ethnic groups, allows this to be achieved.

2.2. Social and environmental conditions in the Upper Ewaso Ng'iro Basin

Up to the early 1900s, Mount Kenya's Upper Ewaso Ng'iro Basin, which encloses on the mountain's northwest foot slopes and extends to the semi-arid plains of the Laikipia plateau before giving way to semi-arid and arid lowlands, was predominately occupied by Maasai and Samburu pastoralists (Wiesmann et al., 2000). During the colonial era, the lower slopes of Mount Kenya and the Laikipia plateau transitioned to large ranches and farms owned by white settlers. Following independence, many of the large agropastoral landholdings were subdivided into small plots of land where agropastoral systems persist. The basin has experienced a rapid increase in population since the colonial era as a population that stood at approximately 50,000 in 1960 rose to 500,000 in 2000 (Ngigi et al., 2007). This increase was largely driven by immigration from nearby densely populated areas, often people of Kikuyu or Meru origin from Kenya's Central Province seeking available farmland (Kunzi et al., 1998). The resulting social make-up of the once pastoral-centered Upper Ewaso Ng'iro Basin is as follows: densely settled smallholder and larger commercial operations with urban centers (populations ranging from 2500 to 30,000 people) on the lower slopes of the mountain, less densely settled smallholder farming operations on the Laikipia plateau, and pastoralists on the edge of the plateau as well as the more marginal arid lowlands (Wiesmann et al., 2000). Thus, a distinct "social gradient" exists in the basin from the upper slopes of Mount Kenya to the lowlands beyond the Laikipia plateau. This “social gradient” is characterized by variability in landholding density, landholding size, and ethnic groupings, among other qualities (as described in section 2.2.1).

Similarly, as is typical in an upland-lowland system, a strong precipitation gradient exists in the basin. At the peak of Mount Kenya (~ 5200 m a.s.l.), rainfall amounts to 2000 mm yr^{-1}, while at Archer’s Post (862 m a.s.l.), the outlet of the Ewaso Ng’iro River in the north of the basin, rainfall may total only 200 mm yr^{-1} (Ngigi et al., 2007). Climatic zones thus progress from humid to semi-arid to arid with advancement first from the slopes of Mount Kenya, then to the Laikipia plateau, and finally to the northern lowlands. Average temperatures in the basin likewise range from 10˚C to 24˚C, with evaporation loss being a major obstacle to agriculture in the lowlands (Liniger et al., 1998).

Our analysis takes place in an upland-lowland social-ecological system embedded within the larger Upper Ewaso Ng’iro Basin system (Figure 2.1). The study area exhibits social conditions and a climatic gradient not unlike the larger basin.

2.2.1. The study site: Eight riparian communities

Figure 2.1 identifies the eight riparian community irrigation projects surveyed for this analysis, as well as Nanyuki Town, the primary economic center within the study area. These irrigation projects encompass an area of approximately 1250 km^2 and are positioned along three major rivers of the Upper Ewaso Ng’iro Basin: the Likii, the Nanyuki, and the Ewaso Ng’iro. The upstream irrigation projects, those drawing their water from the Likii River, represent five of the nine projects occupying the Likii subcatchment (positioned within the larger Upper Ewaso Ng’iro Basin). These projects belong to the Likii Water Resource Users Association (Likii WRUA), which was established to allow for subcatchment-level management of water resources

(LWRUA, 2009). Each of these irrigation projects has a single intake where water is then directed to users through a network of pipes. Within the Likii subcatchment, rainfall ranges from 1100 mm yr^{-1} in the humid areas to 750 mm yr^{-1} in the semi-arid locales at the foot of the subcatchment. The number of documented river water extraction points within the subcatchment more than doubled from 1997 to 2004, giving way to concerns of water scarcity (LRWUA, 2004). This has largely been driven by an increasing population as well as growth of the subcatchment's horticultural enterprises.

The Kikuyu and Meru ethnic groups are most prevalent within the Likii subcatchment, with Meru people mostly residing within the irrigation projects nearest Mount Kenya (i.e. Miarage A and Murimi). Landholdings are typically two acres in size and consist of several dwelling structures, a structure for livestock, and fields for cultivation. Some farmers with greater wealth may own additional acres; however, land redistribution and subsequent subdivisions following independence have resulted in landholdings of two acres as the norm within the Likii subcatchment. These farm units are being further subdivided as multiple generations inhabit a single household. This further strains the available land and water resources.

Many Meru and Kikuyu farmers in the Likii subcatchment are settlers from areas of higher agricultural potential, such as the lands surrounding Meru Town and Nyeri Town (personal correspondence). With them, they may bring a desire to cultivate crops more suitable to their previous residences, but most continue to grow the staple crops of maize, beans, and potatoes. These staple crops are first and foremost grown for consumption. A surplus may be taken to market, but aside from market crops such as cabbage, snow peas, and tomatoes, the familial unit consumes what is harvested.

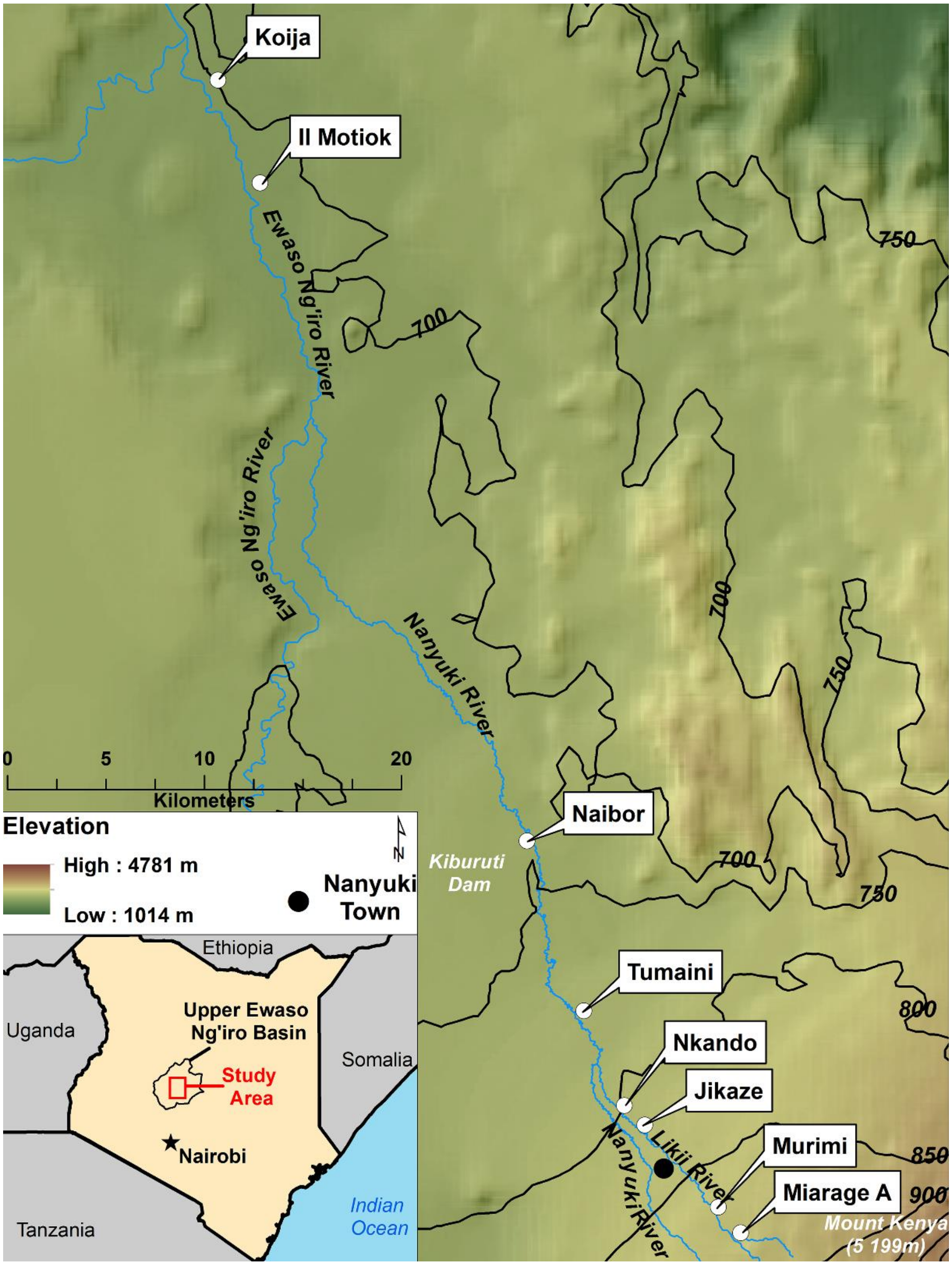

Figure 2.1. Study area of the 8 irrigation communities.

Naibor represents the midstream irrigation project and is located along the Nanyuki River following its confluence with the Likii. Pastoralism is common here (Huho et al., 2012), but many sedentary farmers also exist. As opposed to the irrigation projects within the Likii subcatchment where a single intake acts as the source of river water for the community, river water extraction within the Naibor irrigation project is direct, meaning that individual farmers withdraw water from the Nanyuki River. Additionally, a collection of farmers receive water from the Kiburuti Dam, a dam project initiated by Kenya's Ministry of Agriculture, rather than the Nanyuki River. These farmers also directly withdraw water from the dam, typically through the use of fuel-powered pumps. Data provided by WorldClim (see Hijmans et al., 2005) suggests average yearly rainfall here to be between 700 mm and 715 mm and average temperature to be ~17˚C.

The Kikuyu tribe makes up the majority of sedentary farmers in Naibor. According to surveys conducted during the summer of 2012, which will be described further below, landholdings size, on average, are slightly greater than one acre. This reduction in size compared to landholdings within the Likii subcatchment is partly due to the small plots surrounding the Kiburuti Dam. Members of the Maasai tribe, while present in this area, were not interviewed unless their livelihood strategy was one of sedentary farming.

The downstream communities of Il Motiok and Koija are Maasai group ranches where farming operations only take place on the banks of the Ewaso Ng'iro River. Livestock herding is the chief livelihood practice in these communities with sedentary farming being a relatively recent phenomenon. Promotion and development of farming operations resulted through efforts by NGOs in 2010; however, farmers have expressed frustrations stemming from low rainfall, difficulties with wildlife, and the high costs associated with machinery and agricultural inputs (personal correspondence). River water extraction within these irrigation projects is performed by the individual and typically involves foot pumps, fuel-powered pumps, or simply abstracting water with buckets. Data provided by WorldClim suggests average yearly rainfall ranges from 685 mm to 715 mm, while average temperatures range from 18 to 19°C.

Temporary dwellings are kept near the river to manage the fields and protect crops from wildlife, namely elephants and monkeys. Permanent *manyattas* (family compounds) are set back from the Ewaso Ng'iro River a distance of approximately 2 to 4 kilometers. When visiting the Koija and Il Motiok sites during the summer of 2012, the authors witnessed several fields that had been abandoned – examples of the frustrations expressed concerning sedentary farming and coping with the challenges of developing a new livelihood practice. The 2012 fieldwork data revealed that riparian fields are, on average, one acre in size in Il Motiok and 0.50 acres in Koija.

2.3. Methods

The process for collecting the primary data, variable selection, and the quantitative techniques are described below.

2.3.1. Data collection procedures and description of sample

Household-level and community irrigation project-level data were collected during the summer of 2012. Household surveys were administered to gather information regarding household-level demographics, water use, agricultural practices, reliance on irrigation, and attributes of the irrigation project to which the household belonged. These surveys had a duration of approximately 45 minutes. Irrigation project-level surveys were administered to the managers of the projects to better understand water rationing strategies, rules governing river water extraction, and relationships between other irrigation projects. The project-level surveys had a duration of one hour. The analyses within this study employ only the household-level data;

however, information obtained from the community irrigation project manager surveys helped to contextualize results.

In all irrigation projects, selection of households was done in such a fashion that after completing a survey, the next two homesteads would be skipped before stopping at the third homestead to conduct the next survey. This was done to obtain a more representative sample of households within the community irrigation projects. A total of 315 surveys were administered. Table 2.1 provides attributes of surveyed households as well as the irrigation projects themselves, with information grouped by irrigation project.

Table 2.1. Attributes of water and irrigation projects.

	Num. of inter-views	Num. of HHs with tribes traditionally practicing sedentary ag.	Num of HHs with tribes traditionally practicing pastoralism	WPIP average size of household	WPIP average change in land irrigated in past 5 years	WPIP average number of years farming	Average elevation (m a.s.l.)
Miarage A	42	42	0	4.6	*No change*	18	2088
Murimi	47	47	0	4.4	*No change*	12	2008
Jikaze	18	15	3	4.8	*Slight decrease*	17	1938
Nkando	41	41	0	4.8	*No change*	15	1899
Tumaini	51	49	2	4.8	*No change*	25	1836
Naibor	57	49	8	5.0	*Slight increase*	15	1794
Il Motiok	24	0	24	5.7	*Slight increase*	2	1624
Koija	35	0	35	4.9	*Slight in*	1	1618

A representative sample of at least 35 households per project were visited in the larger irrigation projects. In the smaller projects of Jikaze and Il Motiok, 18 and 24 households were visited, respectively. This represented more than 50% of total members in both of these irrigation projects. All households were located near one of the main rivers within the study area (i.e. the Likii, Nanyuki, or Ewaso Ng'iro River), or in the case of the Kiburuti Dam, households were located near the dam. Within the two downstream communities of Il Motiok and Koija, temporary dwellings were kept near the riparian fields, while permanent *manyattas* were set back several kilometers from the river. To get a representative sample within these two communities, one surveying group visited the permanent homesteads while two other surveying groups visited the temporary riparian dwellings.

2.3.2. Variables for analysis and hypotheses

Whether spatial crop diversity is studied at the genetic or species level, the outcome of reduced vulnerability from greater diversity remains since redundancy is built into the agricultural system through various levels of diversity (Vandermeer et al., 1998). The household-level surveys only collected information on the crop species grown, not the genetic variety of crops. As a result, attention is given to the species level. The crops grown in the study area offer many agroecological benefits when grown together (see Table 2.2), and the dependent variable *CropType* was constructed to capture these benefits of diversification at the household level.

To construct the *CropType* variable, a homestead's crops were grouped into one of eight categories: cereal, legume, root vegetable, fodder grass, fruit/fruit tree, leafy green vegetable, stimulant/hallucinogen, and sugar-rich grass. One point was awarded for each crop type grown, which resulted in a variable ranging from 1 (a farm growing one crop or one crop type) to 8 (a farm growing at least one of each crop type). Thus, a homestead growing onions, carrots, maize, mixed beans, and bananas would have a score of 4 (*root vegetable*: onions and carrots; *legumes*: mixed beans; *cereal*: maize; *fruit*: banana trees). After grouping all crops into the eight categories, household fields that were less than or equal to 0.125 acres were removed from the analysis to avoid capturing the smallest gardens (i.e. kitchen gardens). This resulted in 16% of the initial 1181 fields being dropped from the analysis. While kitchen gardens are important to maintaining livelihoods, our analysis seeks to examine the fields that impose a greater demand on labor and agricultural inputs.

The *CropType* variable is, in essence, a measure of farm-level species richness during a single growing season with species grouped by type to emphasize agroecological benefits. A second representation of species richness is captured by an additional dependent variable, *FrequencyGrown*. Of the households surveyed, maize, potatoes, and mixed beans accounted for more than 60% of all crops grown. This variable groups maize, potatoes, and mixed beans together and awards only one point for growing one, two, or all three of these crops. These three crops are grouped since each is a staple food item and, we believe, each yields similar (i.e. minimal) market opportunities. Therefore, the vulnerability-reducing capacity of each of these three crops likely remains similar whether a household grows one, two, or all three crops. An additional point is awarded for each less commonly grown crop. Therefore, an agricultural system consisting of maize, mixed beans, tomatoes, mangoes, and spinach would have a species richness value of 4, since maize and mixed beans, together, are counted only once. Like *CropType*, the smallest fields, those less than or equal to 0.125 acres, were eliminated when constructing the *FrequencyGrown* variable.

A metric of species richness offers an adequate alternative to proportional abundance measures of diversity, such as the Shannon or Simpson indices of diversity, but detail is compromised using a richness index. The two separate dependent variables were constructed to mend this by examining diversity from two perspectives: an agroecological perspective and a

Table 2.2. Agroecological benefits by crop type and qualities of crops within the study area.

Crop type	Crops grown in study area	Benefit
Grain	Maize, sorghum, rice, millet, wheat	Intercropped with nitrogen-fixing crops to increase production; large biomass producing cover crop; extensive rooting structure; *staple food crop*
Legume	Groundnut, soybeans, mixed beans, Bambara nuts, cowpeas, velvet beans, peas	Contribute to nitrogen fixation; used as cover crop to reduce water loss; pest suppression properties; *staple food crop*
Root vegetable	Irish potatoes, sweet potatoes, cassava, onions, carrots	Efficient use of space – food source and rooting structure are one and the same; *staple food crop*
Stimulant/hallucinogen	Tobacco, miraa	Provides temperature regulation and reduces water loss by providing shade in the case of miraa; commercial crop
Fodder grass	Hay, napier grass, Rhodes grass	Used frequently in mulching to improve soil cover; reduces soil erosion and acts as a windbreak when planted on field perimeter; promotes pest regulation; *critical component of integrated livestock-agricultural systems*
Sugar-rich grass	Sugarcane	Some varieties capable of fixing nitrogen; *grown in small quantities for domestic consumption*
Fruit tree/fruit shrub/fruit	Tangerine, orange, banana, guava, pawpaw, avocado, water melon, mango, tomatoes	Provides temperature regulation and reduces water loss by providing shade; extensive rooting structure; *some crops provide large economic returns, particularly tomatoes*
Leafy green vegetable	Cabbage, spinach, kales	Improved yields from integration into intercropped systems; efficient use of space; *cabbage is often grown for market*

Note: Information in italics pertains specifically to the study area, although the information may also be consistent with other locations.

more straight-forward count of the different species grown. The independent variables used in the analysis, as well as the hypotheses, remain the same regardless of the dependent variable.

The independent variables listed in Table 2.3 were chosen based on a review of studies inspecting agricultural innovation and adoption of agroecological practices, namely Ghadim and Pannell (1999), Pannell et al. (2006), and Knowler and Bradshaw (2007). These variables are consistent with the technology adoption literature, since adoption of sustainable agricultural practices can be expected to be guided by the same factors as those influencing adoption of technologies in agricultural systems (D’Souza et al., 1993). Because we are motivated by the distinct and differing conditions across the study area’s gradient, the variables have also been summarized by community irrigation project (Table 2.4). Aside from the precipitation variable, all variables were derived from the household survey. Precipitation data were obtained from WorldClim (see Hijmans et al., 2005).

Table 2.5 provides the predicted relationships between the dependent variables and the independent variables, as well as explanations for these relationships. In the case of both dependent variables (i.e. *CropType* and *FrequencyGrown*), the expected relationships with the independent variables are thought to be identical.

2.3.3. Analysis

To analyze the effects of the independent variables on both *CropType* and *FrequencyGrown*, two sets of regression models were run, one for each dependent variable. Other than this, the models were identical. Each model included all independent variables mentioned previously to create the following equations (see Table 2.3 for variable descriptions):

$$(1)\quad CropType_i = \beta_0 + \beta_1 Precip + \beta_2 HH12yr_i + \beta_3 1ncome_i + \beta_4 Age_i + \beta_5 Loc_i + \beta_6 Extension_i + \beta_7 Edu_i + \beta_8 Offfarm_i + \beta_9 Fldsize_i + \varepsilon_{it}$$

$$(2)\ \ FrequencyGrown_i = \beta_0 + \beta_1 Precip + \beta_2 HH12yr_i + \beta_3 1ncome_i + \beta_4 Age_i + \beta_5 Loc_i + \beta_6 Extension_i + \beta_7 Edu_i + \beta_8 Offfarm_i + \beta_9 Fldsize_i + \varepsilon_{it}$$

Both ordered logistic and standard ordinary least squares were used to estimate the models, and similar results were produced with each technique (only the results of the OLS models are presented). Diagnostic tests following the regressions did not reveal any large problems with the data. Several outliers were identified in the *FrequencyGrown* model and there was evidence for heteroskedasticity in both models, but correcting for these possible problems did not substantively change the results of the models.

2.4. Results

Table 2.6 shows the results of the OLS regressions for both models. For the model with CropType as the dependent variable, the only independent variable that was significant was the Precip variable, which was extremely significant. The direction of this variable was also as predicted, with more precipitation associated with increased crop diversity. On average, an increase in one standard deviation of this variable led to a 0.42 increase in the CropType variable (or 37.5% of its own standard deviation). Considering that the average of the CropType variable is 3 (with a range from 0 to 6), we judge the Precip variable then to have a moderate effect size. The rest of the variables were not significant at the 5% or 10% levels, nor were any of them close to either threshold.

For the FrequencyGrown model, the Precip variable was highly significant as was the Fldsize variable. The Income and Extension variables were also significant at the 5% and 10% levels, respectively. The p values of the HH12yr and Offfarm variables were also much closer to the threshold for significance than either were in the CropType model. The effect size for the Precip variable was smaller in this model (with its standard deviation change associated with an

Table 2.3. Summary of variables used for analysis.

Variable	Variable description	Variable type	Max	Min	Avg
CropType	Number of different crop types grown by the household. See section 2.3.2. for further information regarding construction of this variable.	Ratio	6	0	2.936
FrequencyGrown	Number of different crops grown by the household. See section 2.3.2. for further information regarding construction of this variable.	Ratio	8	0	2.168
Precip	The average annual precipitation at the location of the homestead unit as provided by World Resources Institute (in millimeters).	Ratio	886	685	791.15
HH12yr	The number of members within the household who are 12 years old or older.	Ratio	9	1	3.55
Income	The total yearly income summing the incomes of all members of the household (in Kenyan shillings).	Ratio	1,428,000	0	167,431
Age	The age of the household head as identified through the survey.	Ratio	92	16	46.2
Loc	The number of years that the household head has been farming at the current location.	Ratio	53	1	15
Extension	Whether or not a member of the household met with or attended workshops with an agricultural extension officer within the previous year.	Binary	1 *(yes)*	0 *(no)*	0.29
Edu	The highest level of education obtained by the household head categorized by *no education*, *some primary education*, *completed primary*, *some secondary*, *completed secondary*, *certificate level*, and *some college/university*.	Ordinal	6 *(some college)*	0 *(none)*	2 *(finished primary school)*
Offfarm	The number of household members who derive their income from an off-farm source.	Ratio	3	0	0.58
Fldsize	The sum of the acreage of all the fields possessed by the household that were being cultivated at the time of the interview or were fallow either at the time of the interview or the previous year (in acres).	Ratio	7.25	0.25	1.35

Table 2.4. Average value of variables by WPIP.

	Miarage A	Murimi	Jikaze	Nkando	Tumaini	Naibor	Il Motiok	Koija
CropType	3.462	3.333	3.187	3.342	3.021	2.189	2.500	2.600
Freq.Grown	2.513	2.250	2.375	2.711	1.896	1.887	1.800	2.000
Precip	882.72 mm	874.14 mm	809.25 mm	803.16 mm	775.56 mm	737.57 mm	714.40 mm	718.5 mm
HH12yr	3.5	3.3	4.1	3.7	3.9	3.5	3.2	3.4
Income	182,789 Ksh	171,794 Ksh	309,962 Ksh	236,096 Ksh	133,516 Ksh	149,422 Ksh	139,060 Ksh	84,226 Ksh
Age	47.9	47.7	48.3	45.3	55.7	42.0	35.4	38.9
Loc	18.7 years	12.5 years	17.4 years	15.3 years	25.5 years	15.4 years	2.1 years	2.0 years
Extension (% of households visited by extension officers)	28.2%	19.4%	0%	36.3%	44.9%	29.4%	16.2%	10.9 %
Edu	Some second school	Finished prim. school	Finish second. school	Some second. school	Finished prim. school	Finished prim. School	No educ.	No educ.
Offfarm	0.41	0.53	1.13	0.89	0.63	0.64	0.30	0.20
Fldsize	1.92 acres	1.28 acres	1.44 acres	1.36 acres	1.68 acres	1.14 acres	1.18 acres	0.54 acres

Table 2.5. Hypothesized relationships.

Variable	Hypothesized relationship with dependent variables	Explanation
Precip	+	Locations with higher rainfall levels represent locations where environmental conditions support more numerous plant species (Gentry 1988).
HH12yr	+	If a household has additional family members capable of working on the farm, the risk of trying new techniques, including new crops and agroecological techniques, will decrease (Schmitt 1991; Ghadim and Pannell 1999).
Income	+	The adoption of new techniques requires sufficient financial security (Somda et al. 2002).
Age	-	Increasing age may cause farmers to become more risk averse discouraging against new techniques (Clay et al. 1998).
Loc	+	The experience of the homestead with the local farming conditions will increase willingness to trial new techniques (Knowler and Bradshaw 2007 for summary of viewpoints).
Extension	+	Exposure to new ideas, training, technical support, and logistical support will put farmers in a better position to adopt new crops and techniques (Rahm and Huffman 1984).
Edu	+	Education reduces risk-aversion and leads to household heads being more inclined to adopt new farming strategies (Knight et al. 2003).
Offfarm	-	Less labor available on the farm will discourage farmers from adopting new strategies since human capital will be drawn down (Knowler and Bradshaw 2007 for summary of viewpoints).
Fldsize	+	Larger landholdings may be indicative of a farmer’s willingness to take on the risks of investing in new techniques and new technologies (Nkonya et al. 1997).

Table 2.6. Ordinary least squares regression results

	CropType model	FrequencyGrown model
Precip	0.007 [a]	0.004 [a]
	(0.001)	(0.001)
HH12yr	0.057	0.071
	(0.044)	(0.047)
Income	0.002	0.008 [b]
	(0.003)	(0.004)
Age	-0.004	0.000
	(0.005)	(0.006)
Loc	0.003	-0.004
	(0.007)	(0.007)
Extension	0.166	0.277 [c]
	(0.156)	(0.164)
Edu	-0.015	-0.021
	(0.047)	(0.049)
Offfarm	-0.072	-0.162
	(0.107)	(0.112)
Fldsize	0.042	0.186 [a]
	(0.062)	(0.065)
N	265	265
R^2	0.165	0.147

[a] Statistical significance indicated at the 0.01 level
[b] Statistical significance indicated at the 0.05 level
[c] Statistical significance indicated at the 0.10 level

average 22% of a standard deviation change in the FrequencyGrown variable). The effect sizes of the other significant variables were moderate to small: using the same formula, one standard deviation change in the Income, Fldsize, and Extension variables on average led to 14%, 17.5%, and 10% of a standard deviation change in the FrequencyGrown variable, respectively. For each of these variables, the direction of the relationship was as hypothesized (positive).

2.5. Discussion

2.5.1. Understanding crop diversification in a semi-arid agricultural system

Strategies for adopting cropping practices are manifold. Benefits such as increased productivity, market returns from innovation, ability to cope with adverse climatic and market events, food security, and maintaining traditional practices all may influence crop choices.

Maize, beans, and potatoes are staple crops within Kikuyu and Meru diets, so it was not surprising that these three crops accounted for more than 60% of all crop observations within the study area. In Il Motiok and Koija, where the Maasai have traditionally led a subsistence lifestyle centered on pastoralism, the recent emphasis on sedentary farming has increased the presence of maize, beans, and potatoes here as well. In all locations, more than anything else, the presence of the three staple crops results from a desire to achieve food security and, in the upstream communities, to maintain a traditional diet. No farmers stated that these three staple crops were being grown solely for market.

Tengo and Belfrage (2004) found that smallholder farmers adjusted their management practices in accordance with ecological conditions and to account for recurrent climatic disturbances. Conversations with farmers surveyed in this study revealed a range of considerations for ecological conditions. For example, when describing the rationale for intercropping, some farmers expressed the ecological benefits of pest management, and improved soil quality, as well as efficient use of space. However, others who were also intercropping expressed a desire to move away from the practice in favor of monocropping, and that they were intercropping simply because that was the traditional practice used in the area. Therefore, deployment of agroecological practices, such as crop diversification, was not solely the outcome of consciously seeking stability in the face of adverse conditions. In some cases, the decision was made due to the choices of neighbors, friends, or family members. In other cases, such as the one described above, the farmer may eventually transition away from some agroecological practices if it is believed that a different agricultural management scheme may yield better results. These scenarios demonstrate that agroecological management decisions arise from consideration of multiple factors, which must be kept in mind when interpreting the study results. Additionally, directionalities of the relationships from our analysis have not been thoroughly defined. In this section, we show and posit explanations for relationships, however, we leave more rigorous testing of causal relationships to future work where we also intend to employ a longitudinal data set to better understand spatial as well as temporal semi-arid agricultural practices.

Both the *CropType* and the *FrequencyGrown* models explain roughly the same amount of variation within their respective dependent variables. As mentioned in section 2.4, the *FrequencyGrown* model found significant relationships with four of the independent variables, while the *CropType* model found only one significant relationship. This may reflect the fact that the dependent variable in the *FrequencyGrown* model is a much more conventional measure of crop diversity, or that using the technology adoption literature to guide selection of independent variables is more appropriate when the response variable is a conventional measure of crop diversity. Studies such as Isakson (2007) have used strict richness measures when the data did not lend themselves to a measure of proportional abundance (e.g. Simpson or Shannon indices of diversity). To our knowledge, a richness measure that also attempts to account for agroecological function by grouping crops by type (i.e. the *CropType* model) has not been used previously. Had the results of the *CropType* model been more notable, or had the model clearly outperformed *FrequencyGrown*, evidence may have existed that farmers were considering the interrelatedness of crop functions in their cultivation practices. It certainly remains a possibility that farmers do consider these agroecological functions when making cultivation decisions, but it is not being captured by grouping crops by type. Given that the *FrequencyGrown* model performed better in terms of identifying significant relationships, we focus our remaining discussion on this model.

All significant independent variables for the *FrequencyGrown* model were in the hypothesized direction, as shown in Table 2.5. The technology adoption research (e.g. Feder, 1982; Feder et al., 1985; Rogers, 1995) has been used in the study of multiple sustainable agricultural practices; a similar level of effectiveness in explaining the farm-level characteristics contributing to crop diversification was found when applying the technology adoption literature. The *Precip* variable was highly significant and indicated that increasing precipitation resulted in greater crop diversification. This was not surprising as suitability of growing conditions in the study area improves with increased rainfall. Smallholder farmers in locations with higher precipitation levels may need to rely less on irrigation infrastructure and water harvesting practices since dry spells may be less frequent and less severe. It should also be recognized that the precipitation variable is acting as a proxy for other environmental conditions, an observation that was made by Samberg et al. (2010) in their study of the diversity of crop species and crop varieties in Ethiopia's highlands. Elevation and temperature would both likely produce a comparable effect as, similar to precipitation, both show a continuous, steady, unidirectional trend with advancement along the mountain slopes. Thus, the precipitation variable is capturing Mount Kenya's leeward environmental gradient.

Household income had a small but positive effect on crop diversity levels. Wealthier farmers may deem the practice of growing a diverse array of crops, some crops less commonly grown than others, a less risky endeavor compared to farmers with relatively low income. This is due to the ability of a wealthier farmer to better absorb the consequences of a failed cultivation venture since investment in the uncertain endeavor constitutes a smaller proportion of overall wealth. Farmers with greater wealth can additionally invest in new equipment and labor that facilitates planting and maintaining multiple crop types. For example, drip irrigation kits are commonly used when growing tomatoes in the study area. The cost of these kits and the additional labor needed to maintain intensive horticultural endeavors may preclude some farmers from cultivating tomatoes. The household surveys reveal that the average income of farmers who have at least one field in which tomatoes are grown is 183,000 Ksh, while the average income of farmers growing sweet potatoes, a less capital-intensive crop, is 152,000 Ksh. If not for some small-scale growers of tomatoes, this disparity would be much greater due to the presence of several wealthier farmers with large greenhouses dedicated to tomato production.

In the case of interactions with agricultural extension officers, the relationship is also consistent with much of the findings from the technology adoption literature, since it suggests that exposure to new techniques and strategies provided by extension officers will lead to a greater diversity of planted crops. Here, accessibility may be an influencing factor. Extension officers are more likely to visit locations made more accessible via better road networks or proximity to economic centers. The more accessible community irrigation projects are those located in the middle and lower zones of the Likii WRUA (i.e. Jikaze, Nkando, and Tumaini), as well as Naibor. A closer inspection of the agricultural extension variable indeed reveals that the more accessible Nkando, Tumaini, and Naibor irrigation projects were more consistently visited by extension officers (36% of surveyed households in Nkando, 45% in Tumaini, and 29% in Naibor). Surprisingly, the Jikaze project, which is located closer to Nanyuki Town than any other irrigation project, recorded zero visits by extension officers. One possible explanation for this is the disproportionate number of civil servants within the Jikaze project, which leads to many Jikaze members being financially better-off when compared to members of other irrigation projects. Extension services therefore are possibly being directed away from Jikaze toward other irrigation projects in greater need of these services. Of the households surveyed in the remote downstream irrigation projects of Il Motiok and Koija, 16% of households in Il Motiok and 11% of households in Koija had been visited by an extension officer within the previous year. These were the lowest values aside from the value recorded for Jikaze. For farmers in these two irrigation projects, low exposure to extension officers further challenges the smallholders since sedentary farming was only widely adopted in 2010 and assistance is likely needed in order to inform farming decisions.

Finally, field size had a positive relationship with *FrequencyGrown*. Feder et al. (1985) point out that the relationship between farm size and adoption of practices is less distinct than is the case with other farm-level characteristics, since landholdings, in actuality, may act as a surrogate for such factors as access to credit, risk aversion, access to scarce inputs, and access to information, thereby clouding the relationship. Studies such as Clay et al. (1998) have in fact found a negative relationship between field size and adoption of new practices. One possible explanation for the positive relationship found in our study is that farmers with larger landholdings may have more cultivatable space to experiment with new crops. Thus, if the area dedicated to a new crop is a relatively small proportion of the overall landholding size, the household is better able to withstand failed experimentation if much of the land continues to yield a harvest from other reliable, commonly grown crop species. This explanation clearly links size of landholdings with ability to tolerate risk.

2.5.2. Crop diversification trends across both the upland-lowland gradient and in the context of changing conditions

Our analysis aimed to capture information about crop diversification practices across a heterogeneous biophysical and social landscape to both investigate influencing factors to crop diversification in general and to further the understanding of practices aimed at reducing vulnerability in semi-arid agricultural irrigation systems experiencing significant change. The study area encompassed multiple agroclimatic zones: the Miarage A and Murimi irrigation projects exist near the *semi-humid* and *semi-humid to semi-arid* interface; Nkando and Jikaze are located within the *semi-humid to semi-arid* zone; Tumaini is positioned at the interface with the *semi-arid* zone; and Naibor, Il Motiok, and Koija are located within the *semi-arid* zone, with the latter two approaching the *arid* agroclimatic zone. Additionally, the study incorporated multiple ethnic groups with different socioeconomic levels. Finally, by conducting the study within a semi-arid environment where rain-fed agriculture is practiced and irrigation needed during dry periods, we gain insight to crop diversification strategies in regions of fluctuating rainfall potential. By incorporating these features, the following trends were identified.

First, wealth, which had a positive influence on crop diversity, not surprisingly appears to be influenced by opportunities for employment. The wealthiest irrigation projects (i.e. Jikaze and Nkando) are both located near Nanyuki Town. Miarage A and Murimi suffer from road infrastructure that is virtually impassable during the rainy season, which reduces market access, and Il Motiok and Koija have very limited access to paid employment opportunities and educational services due to their isolation. So, while crop diversity is influenced by wealth, cultivation decisions may more broadly be a product of accessibility to markets as well as employment and educational opportunities. With improved accessibility comes increased income, which allows farmers to experiment with crop diversification strategies. Second, as mentioned earlier, visitations from extension officers (or lack thereof) may similarly be a product of accessibility. This was a major advantage of conducting the analysis across irrigation projects ranging from very accessible to minimally accessible, since the survey data bear out this pattern nearly perfectly. As evident in Table 2.4, the irrigation projects near Nanyuki, aside from Jikaze (to which a hypothesis was offered in section 2.5.1), had the greatest percentage of households visited by extension officers, while Il Motiok and Koija had few visitations. Miarage A and Murimi, however, are much closer to Nanyuki than both Tumaini and Naibor, yet a smaller percentage of households were visited in these two projects, especially in the case of Murimi. This again lends itself to the role accessibility plays in crop diversity outcomes since Tumaini and Naibor, despite being further from the primary economic center, are more reachable for extension officers given the relatively well-maintained road along which they reside. Third, despite the poor infrastructure and relative inaccessibility within the uppermost irrigation projects of Miarage A and Murimi, some of the highest crop species richness counts were found in these areas. Employment opportunities and accessibility cannot alone be explaining diversity. This seems to suggest that even with limited market access, comparably fewer employment opportunities, and less frequent visits by extension officers, favorable growing conditions (as exhibited by higher potential precipitation in these projects) outweigh potential disadvantages that arise from inaccessibility. Fourth and finally, aside from Tumaini, the other irrigation projects within the Likii WRUA (i.e. Miarage A, Murimi, Jikaze, and Nkando) had the greatest levels of crop diversity within the study area (Table 2.4). Admittedly, these irrigation projects experience more favorable growing conditions than the projects outside of the Likii WRUA, but the attention given to irrigation infrastructure within the WRUA (see section 2.2.1) may also be influencing crop species diversity as the well-maintained irrigation infrastructure within the WRUA allows smallholders to better tolerate dry periods. This ability to bridge to wet periods by irrigating during dry spells is an important element in semi-arid agriculture. This will be explored further in future research.

Smallholder farmers therefore are influenced by income levels and extension officers when making cultivation decisions, but greater levels of crop diversification appear to take place irrespective of these influences when biophysical conditions, and possibly irrigation infrastructure, allow. In Il Motiok and Koija, relative inaccessibility and limited employment opportunities coupled with unfavorable growing conditions led to lower crop diversity. These two irrigation projects also represent a collection of relatively new agriculturalists, which may lead to conservative cropping strategies (e.g. cultivating only maize, beans, and potatoes). The heterogeneity of conditions therefore suggests the importance of accessibility and climatic conditions in crop diversification, with favorable climatic conditions capable of outweighing limitations posed by poor road networks and isolation (i.e. separation from villages and towns capable of providing opportunities not offered in a smallholder's home village).

Zimmerer (2014) inspected agrobiodiversity of smallholder farmers facing changes to their "cultural landscape" presented by proximate and more distant forces, such as decision-making regarding irrigation infrastructure, peri-urban influences, and out-migration to different regions and countries. Farmers within the Mount Kenya upland-lowland irrigated agricultural landscape similarly face challenges from a variety of sources when seeking to reduce vulnerability through crop diversification strategies. The reliable provision of water likely played a role in the higher levels of crop diversity within the Likii WRUA (aside from Tumaini). However, even within the Likii WRUA irrigation projects there is great variability in the quantity of water supplied to households; a source of frustration for some members. This, to a certain extent, is the result of a mostly one-size-fits-all approach taken in WRUA development and in the formal recognition of WRUAs by Kenya’s Water Resources Management Authority. Overreaching of outside forces in irrigation system development has been shown to influence not only overall performance of an irrigation system (Lam 1996), but also agrobiodiversity outcomes (Zimmerer 2011). Future work will inspect the institutions governing water use and provision in the study area and the fostered outcomes, but preliminary assessment indicates limited tailoring of irrigation project decision-making to local conditions.

Population growth, as discussed in section 2.2, has also played a role in altering the social-ecological setting and, in the process, potential diversification levels. For example, sensing an inability to reliably provide farmers with water, irrigation projects may limit the number of total members (as Jikaze has done). For those who are not members at the time of this decision, and who are unable to receive service from another irrigation project, irrigation opportunities become much less certain. Under these occasions cultivating a diverse array of crops may no longer be possible due to an inability to span dry periods or extend the growing season.

While a more exhaustive list of proximate and distal causes of change within the studied landscape certainly exists, the two previously mentioned (i.e. WRUA development and population growth) provide examples of the pressures faced by smallholder irrigated agricultural systems in maintaining and improving agricultural outcomes, such as crop diversity.

2.6. Conclusions

This research demonstrated the influence of income, exposure to extension officers, field size, and precipitation on crop diversity levels in semi-arid farming systems. It was then followed by a discussion that included acknowledgement of forces of change within the irrigation projects. Of particular note in our research is the role agricultural extension officers may play in promoting crop diversification strategies and other sustainable agricultural techniques. Assuming institutional willingness to provide such services is present, engagement with extension officers may require new strategies aimed at enhancing interactions with distant and/or difficult-to-reach smallholders. The use of mobile technologies to communicate with farmers about alternative and sustainable production strategies is one such example.

In our research, more remote areas exhibited lower income levels and less connection to extension officers, while more accessible locations had better connection to extension officers and higher income levels. These elements appear important with respect to crop diversification as farmers in more accessible irrigation projects demonstrated higher levels of crop diversification. That said, farmers may be able to counter the disadvantages of their remoteness or isolation when growing conditions are favorable and when irrigation can take place during dry spells. The upland irrigation projects offer an example of this as, despite the poor road infrastructure in these irrigation projects, higher precipitation levels and reliable provision of water for irrigation purposes appear to allow for a more diverse array of crops to be grown. These findings highlight biophysical, social, and institutional characteristics that may influence engagement in sustainable cultivation strategies within semi-arid agricultural systems. Further, several processes, such as improved exposure to extension officers, have been suggested that may influence adoption of sustainable farming practices.

Finally, it must be noted that smallholders are keenly aware of their own vulnerabilities. Recognition exists that precipitation events in the Mount Kenya region have become more variable and that river discharge in many rivers has decreased. To this end, it is not that smallholders need extension officers to inform them of these threats; rather, extension officers may provide valuable training in terms of water conservation techniques or strategies for diversifying income sources. Thus, the role of the extension agent is one of exposing smallholders to risk-reducing strategies as they face increasingly unpredictable growing conditions.

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Chapter 3: Polycentric transformation in Kenyan water governance: A dynamic analysis of institutional and social-ecological change

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3.1. Introduction

In 2002, Kenya began to transition from a highly centralized system of water governance to one demonstrating a polycentric order. The country's current regime includes several features that scholars associate with polycentricity and have proposed should lead to effective water management in terms of equitable water distribution and coordination between multiple decision-makers. Independent groups of local users are allowed to devise their own water allocation rules in response to changing ecological conditions. Local users also participate in regional, watershed-delineated users' associations that coordinate use throughout a watershed's catchment and impose regionally appropriate restrictions on water use during times of scarcity. Throughout Kenya, user groups are part of an overarching system of national laws that coordinates water governance between local, regional, and national actors.

The Kenya case allows us to examine two areas of research on polycentricity that are rarely addressed. First, we inspect a deliberate national government effort in transitioning toward polycentric resource governance, which few have investigated (exceptions include Andersson & Ostrom, 2008; Baldwin, Washington-Ottombre, Dell'Angelo, Cole, & Evans 2016). Second, while many polycentricity scholars have developed propositions about why polycentric structures result in improved natural resource governance, few of these propositions have been empirically tested. Therefore, we move beyond a descriptive analysis of the governance structure to investigate whether Kenya's reforms have produced the beneficial outcomes predicted by theory.

In this paper, we combine data from fieldwork and archival research to ask: In a particular social-ecological system, how have actor roles and local level rules adjusted following the 2002 top-down reform? More specifically, to what extent do Kenya's post-reform governance outcomes reflect the benefits predicted by polycentricity theorists? With respect to this research question, we test two hypotheses:

> **Hypothesis 1**: In the post-reform period, user groups will experiment with new approaches to governance by adjusting their rules.
>
> **Hypothesis 2**: Some of this experimentation will correlate with improved local conditions.

In addition to directly testing the above hypotheses, we also draw on survey evidence to examine the way that communication and coordination within Kenya's polycentric system has affected governance within user groups. This inspection provides an opportunity to empirically examine the alignment of formal and informal outcomes with the theorized traits of a polycentric system. Our investigation will focus on a social-ecological system (SES) within Kenya's Upper Ewaso Ng'iro basin on the northern and northwestern slopes of Mount Kenya.

In order to document regional and national level drivers leading to water reform, as well as changes to key subsystem variables (i.e., resource system, resource units, governance system, and actors) following reform, we use a new framework: the "combined IAD-SES framework," which was recently developed by scholars affiliated with the Ostrom Workshop of Indiana University (see Cole, Epstein, & McGinnis, 2014). This framework allows us to capture complex social, biophysical, and institutional arrangements and interactions at the regional and national level and explain the Government of Kenya's transition from top-down water governance to an approach in which responsibilities are distributed across multiple levels.

The structure of the remainder of the paper is as follows. First, we review the literature on polycentricity, identifying the key features of polycentric systems and the theoretical mechanisms by which these features might be expected to lead to improved natural resource governance. Next, the combined IAD-SES framework is described and used to briefly explain the Government of Kenya's transition from centralized to multi-level water governance. The study site is then described, followed by an explanation of the data and methods used in our empirical analysis. We then inspect post-reform governance outcomes, including rules-in-use, at the community and catchment level within the Upper Ewaso Ng'iro basin as of the summer of 2013. Finally, we discuss our empirical findings and their conformance with polycentricity theory.

3.1.1. Polycentricity

Polycentricity was first proposed as a possible approach to governance in the early 1960s. At the time, many metropolitan areas included city, county, and suburban jurisdictions, as well as the presence of state and federal agencies with specialized but limited authority in particular policy areas. Scholars of government tended to presume that such overlapping jurisdictions were chaotic at best and pathological at worst, and called for consolidation of service provision to improve efficiency (Cottrell, 1949; Aligica and Tarko, 2012). V. Ostrom, Tiebout, & Warren (1961) countered this argument by proposing that consolidated approaches to service provision were likely to be inefficient, because such "one size fits all" approaches could not account for divergent preferences among different groups of citizens, or differing economies of scale among different public services. In contrast, polycentric systems – with "many centers of decision-making which are formally independent of each other" – might actually improve efficiency (V. Ostrom, Tiebout, & Warren, 1961, p. 831).

In the decades since, a growing number of scholars have further developed the concept of polycentric governance, both theoretically and empirically. Much of this literature focuses on polycentric approaches to natural resource governance and development. Not unlike government scholars of the 1960s, many development scholars in the immediate post-colonial period tended to presume that centralized government control was necessary to ensure efficient use of natural resources (e.g., Scott, 1998; Shivakoti & Ostrom, 2001). Numerous scholars – including, most famously, Elinor Ostrom – countered this presumption through empirical documentation of cases in which local resource users were able to manage resources effectively (Ostrom 1990; 1999; Agrawal & Gibson, 1999). As these cases have accumulated, the concept of polycentricity has developed beyond the original conception proposed by V. Ostrom, Tiebout, and Warren.

Polycentricity has been defined in numerous ways, and not all scholars agree about what makes a particular governance system "polycentric," although studies have tended to converge around a few key characteristics. First, polycentric systems always involve multiple, independent centers of decision-making (Andersson & Ostrom, 2008). Polycentricity is distinct from decentralization, however, in that mechanisms for coordination and cooperation between decision centers are crucial features of polycentric regimes (Pahl-Wostl & Kneiper 2014). Polycentric systems also feature overlapping jurisdictions that create partially redundant institutions (da Silveira & Richards 2013; McGinnis 1999). Overlap can be geographic, perhaps in the form of nested decision centers (Andersson & Ostrom, 2008), or may be functional, where multiple decision centers have authority in a given policy area (Galaz et al., 2012).

Moreover, many scholars of polycentricity have asserted, either implicitly or explicitly, that these structural features give rise to good governance outcomes. For example, the presence of multiple, independent decision centers is thought to allow local decision centers to experiment with informal rules governing resource use, suggesting the possibility of innovation and learning (Andersson & Ostrom, 2008). It also allows local groups to devise rules that respond and adapt to local conditions, theoretically making polycentric systems more resilient to ecological shocks (Galaz et al., 2012). Because local actors best understand local needs and conditions, they may be better-positioned to craft informal rules that meet localized needs more efficiently and equitably than government administrators' formal rules (Ribot, Agrawal, & Larson, 2006; Folke, Hahn, Olsson, & Norberg, 2005).

Perhaps more important, however, coordination and overlapping authority among these independent decision centers can enable mutual adjustment among decision centers (V. Ostrom, 1999). Indeed, mechanisms for communication and coordination distinguish between polycentric systems and those that are decentralized (Andersson & Ostrom, 2008; Pahl-Wostl & Knieper, 2014). Such coordination might, for example, allow local user groups to communicate with regional or national policy makers, giving them a "voice" in policy matters that can help improve outcomes (Andersson & Ostrom, 2008). Coordination can also be crucial where multiple local user groups are nested within a shared water basin, forest system, or fishery. Coordination and overlapping authority allows user groups to communicate and adjust their use in ways that benefit the system as a whole, essentially enabling collective action at multiple levels of governance (Cole & McGinnis, 2014).

It is not a foregone conclusion, however, that polycentric governance structures will always give rise to the beneficial governance outcomes predicted by theory. Indeed, V. Ostrom, Tiebout, and Warren (1961) were cautious to note that independent centers of decision making may not inevitably give rise to "orderly outcomes"; instead, this is an empirical question (p. 831). Recently, a number of studies have provided empirical evidence that polycentric governance regimes tend to have high performance (Ostrom 1999; Basurto & Ostrom 2009; Pahl-Wostl, Lebel, Knieper, and Nikitina, 2012), particularly when compared with non-polycentric or less-polycentric systems (Pahl-Wostl & Kneiper 2014; da Silveira & Richards, 2013). There has been limited empirical testing, however, of the theoretical propositions that scholars have developed to explain the apparent success of polycentric systems, including experimentation with informal rules and adaptation to local conditions.

In this article, we undertake such empirical testing. We examine a system – water and irrigation governance in Kenya – that has recently adopted reforms instating the three basic features of polycentricity: multiple decision centers at the local, water basin, and national levels; overlapping authority among these decision centers; and formal and informal mechanisms of coordination and communication between these decision centers. Within that system, we examine processes and behaviors adopted by water users, focusing in particular on whether Kenya's polycentric structure gives rise to processes and behaviors predicted by polycentricity theory, such as local groups experimenting with new rules and adoption of rules in response to local conditions.

The Kenyan case is particularly interesting because whereas most previous studies have focused on polycentric governance systems that evolved over time, some of the structural elements that create a polycentric system in Kenya are the result of national policy changes due to reforms in 2002. Kenya has always had local and national centers of decision making, but the 2002 reforms formalized the creation of regional (water basin level) decision centers, created several formal mechanisms for coordination between local, regional, and national level decision units, and prescribed overlapping authority over water allocation between these decision units. As a result, the Kenyan case provides the researcher with a rare opportunity to examine whether polycentric structures, imposed by national actors, give rise to the local-level behaviors and processes predicted by polycentricity theorists.

We turn now to a description of the Government of Kenya's transition from monocentric to polycentric water governance, which is aided by use of the combined IAD-SES framework.

3.2. Transformation from monocentric to polycentric governance

The water governance structure that presently exists in Kenya was largely put in place following the 2002 Water Act (Liniger et al., 2005). A number of drivers led to water reform, and since reform, significant changes have occurred with respect to the governance system, actor roles, and efforts to match governance responsibilities with hydrological borders. We briefly document these drivers and post-reform changes at the national level using the combined IAD-SES framework.

3.2.1. The combined IAD-SES framework

The institutional analysis and development (IAD) framework, first described in publication in 1982 (Kiser & Ostrom, 1982), places action situation(s) at its center and uses exogenous biophysical conditions, community attributes, rules used by participants, and interactions among actors and their environments to explain decision-making within action situations (Figure 3.1a). Further, decision-making is influenced by the positions held by participants, the allowable actions, information availability, and the costs and benefits of decisions within the action situation. The framework has been described by some as one of the most important institutional analytical frameworks in policy sciences (Sabatier, 2007), and since its development, has been extended to a large and diverse number of empirical settings, including international development (e.g., Gordillo & Andersson, 2004), industrial regulation (e.g., Schaaf, 1989), banking reforms (e.g., Polski, 2003), land tenure (e.g., Mwangi, 2003), problems related to the water-energy-food nexus (e.g., Villamayor-Tomas et al., 2015), environmental conflicts (e.g., Dell'Angelo, 2012), and participation analysis (e.g., Bixler, Dell'Angelo, Mfune, & Roba, *Forthcoming*).

Like the IAD framework, the more recently-developed social-ecological systems (SES) framework is structured around a central action situation (Figure 3.1b). First elaborated in Ostrom (2007), the SES framework seeks to identify components of and interactions between resource systems, resource units, actors, and governance systems in producing social-ecological outcomes (McGinnis & Ostrom, 2014). The SES framework operates as a diagnostic tool as it proposes a set of second- and third-tier variables for analysis of SESs (Table 3.1), and in this way further elaborates upon elements originally appearing in the IAD framework. Since its inception, the SES framework has been applied to a variety of social-ecological settings, such as fisheries (e.g., Gutiérrez, Hilborn, & Defeo, 2011; Cinner et al., 2012; Basurto, Gelcich, & Ostrom, 2013), forests (e.g., Fleischman et al., 2010), and water and irrigation (Madrigal, Alpízar & Schlüter, 2011; Ostrom, 2011; Cox, 2014).

Despite the utility of the IAD and SES frameworks in studying, among other things, the sustainability of SESs, each has been criticized for perceived shortcomings: the IAD for insufficient attention to natural systems, and the SES for its inability to provide more than a static list of system components. Recognizing these shortcomings, Cole, Epstein, & McGinnis

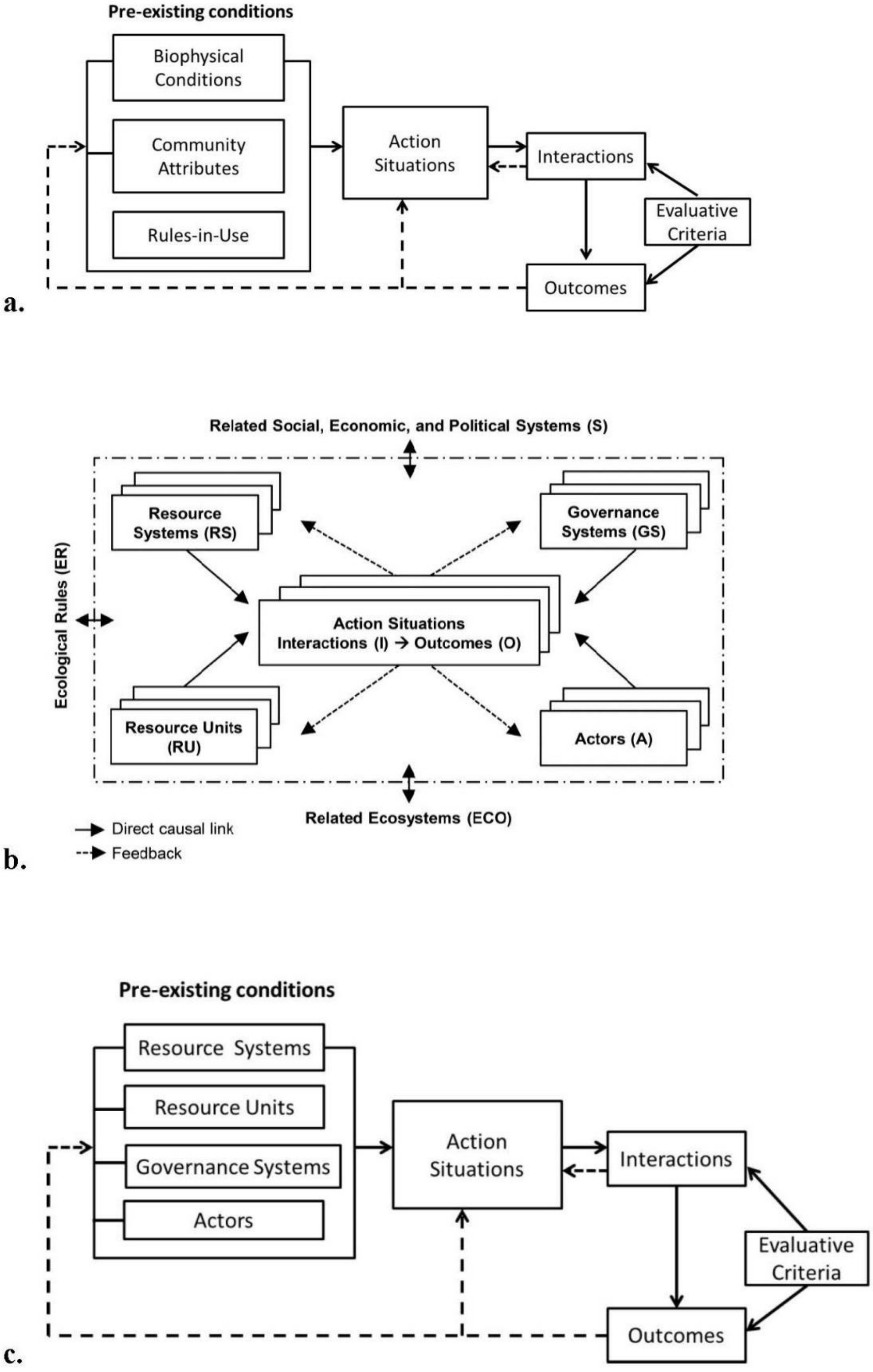

Figure 3.1. (a) The IAD Framework, (b) the SES Framework, and (c) the Combined IAD-SES Framework. *Source: Adapted from Cole et al. (2014).*

Table 3.1. Second- and third-tier SES variables

Resource Systems	**Resource Units**	**Governance Systems**	**Actors**
RS1 Sector	**RU1** Resource unit mobility	**GS1** Government organizations	**A1** Number of users
RS2 Clarity of system boundaries	**RU2** Growth or replacement rate	**GS2** Nongovernment organizations	**A2** Socioeconomic attributes of users **a)** Economic **b)** Cultural
RS3 Size of resource system **a)** Area **b)** Volume	**RU3** Interaction among resource units **a)** Strong to weak **b)** Predatory or symbiotic	**GS3** Network structure **a)** Centrality **b)** Modularity **c)** Connectivity **d)** Number of levels	**A3** History of use
RS4 Human-constructed facilities	**RU4** Economic value	**GS4** Property-rights systems **a)** Private **b)** Public **c)** Common **d)** Mixed	**A4** Location
RS5 Productivity of system	**RU5** Number of units	**GS5** Operational rules	**A5** Leadership / entrepreneurship
RS6 Equilibrium properties **a)** Recharge dynamics **b)** Recharge rate **c)** Number of equilibria **d)** Feedbacks **i)** Positive **ii)** Negative	**RU6** Distinctive markings	**GS6** Collective-choice rules	**A6** Norms / social capital
RS7 Predictability of system dynamics	**RU7** Spatial and temporal distribution **a)** Spatial heterogeneity **b)** Temporal heterogeneity	**GS7** Constitutional rules	**A7** Knowledge of SES / mental models
RS8 Storage characteristics		**GS8** Monitoring and sanctioning processes	**A8** Importance of resource
RS9 Location			**A9** Technology used

(2014) devised the "combined IAD-SES framework," which integrates the SES variables entirely into the IAD framework (Figure 1c). The combined IAD-SES framework, therefore, allows the user to employ a multi-level analysis tool that recognizes the major sub-systems of an SES (i.e., the SES framework) in a dynamic manner where temporal institutional variations are accounted for (i.e., the IAD framework). Given these strengths, this framework appears well-suited for detailing the drivers of institutional reform and the outcomes produced through such a reform.

We have chosen to employ the combined IAD-SES framework to detail Kenya's water reform for several reasons. First, separately the IAD and SES frameworks are both meant to incorporate feedback mechanisms; however, in the case of the SES, these mechanisms are not readily identifiable. Using the newly developed framework we are able to identify not only the existing conditions from the social and ecological realms at the first time step, but also those produced following treatment at a second interval. Second, the interaction of adjacent action situations in producing outcomes has been well-developed within the IAD framework (McGinnis, 2011), but by employing the combined IAD-SES framework, the user's attention is readdressed from looking primarily at outcomes produced from actor preferences and institutional arrangements to the role of broader sub-systems in achieving social-ecological outcomes. Finally, as we will highlight, the institutional arrangements within the Kenya context are particularly complex, and to understand the transformation from one governance regime to another, a framework characterizing not only the breadth of interactions across time points but also the depth of interactions at a single time point, such as multi-level dynamics, is particularly useful. We believe the combined IAD-SES framework has been well-developed for this purpose.

In describing Kenya's water management reform, we primarily employ information retrieved during the summer of 2013 from the Kenyan National Archives, the University of Nairobi, and the Ministry of Water and Irrigation. We focus on the period beginning just before the 2002 reform and ending at the time of data collection (i.e., 2013). Explanations for variable selection before and after the 2002 reform, as well as action situation dynamics are detailed in the Appendix.

3.2.2. Application of the combined IAD-SES framework: Explaining reform

In the early and mid-1960s as Kenya emerged from colonial rule, the government retained many of the water governance strategies that were put in place by the British. The centralized approach established during colonial rule was poorly suited for the conditions in Kenya and was eventually superseded by reforms at the turn of the twenty-first century (Baldwin, Washington-Ottombre, Dell'Angelo, Cole, & Evans, 2016). Among other features, these reforms represent a shift from top-down water governance to a polycentric approach by creating decision centers at multiple levels and providing for coordination between regional and local actors. In the paragraphs that follow, we describe the resource system, actors, and governance system in place prior to the 2002 reform. We go on to analyze the way these variables affected appropriation, rulemaking, monitoring, and conflict resolution. We conclude with a discussion of resource and governance outcomes as of 2013. Table 3.2 summarizes each of the SES sub-systems at two time points, while Figure 3.2 uses the combined IAD-SES framework to dynamically capture forces motivating change, as well as the outcomes produced.

3.2.2.1. Pre-existing conditions before water reform

By the late 1990s, the groundwork for water reform was already being laid as, in response to a largely failing national system, NGOs, government representatives, community water projects (CWPs), and individual smallholders created an informal Water Users' Association (WUA)

Table 3.2. Key SES variables at two time points.

Variable (code)	Time point 1 – late 1990s	Time point 2 – 2013	Summary of subsystem
Resource System (RS)			
Clarity of hydrological boundaries (RS2)	Clearly defined	Clearly defined	From 1964 to the late 1990s, despite the clarity of hydrological boundaries, water administration took place along political boundaries, which did not compel resource users to consider downstream individuals (A6). Following the 2002 water reform, water management matches hydrological boundaries, which has contributed to improved downstream water access in some locations.
Streamflow trend (RS5)	Decreasing	Decreasing, but reports of improved downstream river water access in some locations	
Actors (A)			
Leadership (A5)	Leadership poorly aligned with biophysical units and limited in its consideration of local conditions. Informal user groups providing model for reform in late 1990s	Leadership recognized at multiple biophysical units	Smallholder farmers throughout Kenya are highly reliant on surface water for irrigation purposes. Before the 2002 reform, downstream users were severely disadvantaged due to the poor fit between hydrological scales and governance units, which did not compel upstream users to be overly aware of the catchment-wide consequences of their actions. After reform, leadership became better aligned with hydrological
Norms (A6)	Minimal consideration of downstream users	Increased awareness of downstream users	
Resource dependence (A8)	High resource dependence	High resource dependence	

			scales and has improved water access in some downstream locations.
Governance System (GS)			
Government organizations (GS1a)	Water Apportionment Board, Water Bailiffs	Water Resources Management Authority, Water Resource Users Association	Kenya shifted from a top-down, monocentric style of water management to one with multiple levels corresponding with various hydrological scales after the 2002 reform. This put in place WRMA and the WRUAs as regional and catchment level managers of water and replaced the WAB and the Water Bailiffs. With the creation of WRUAs, connectivity between governing units improved, since local water users serve on each WRUA's management committee, and WRUAs work closely with their corresponding WRMA office. In turn, this has improved the presence of monitoring personnel and led to rules-in-use aimed at equitably appropriating water between upstream and downstream users
Network structure (GS3a)	Formal structure: Top-down	Formal structure: Multi-level	
Connectivity between governing units (GS3b)	Minimal connectivity	Improved connectivity	
Water appropriation operational rules (GS5a)	Nairobi and region-based permit system. Ineffective operational rules for water appropriation between upstream and downstream users	Regional WRMA offices responsible for issuing water use permits. Operational rules for water appropriation between upstream and downstream users put in place by WRMA and WRUA.	
Monitoring (GS8)	Water Apportionment Board personnel and Water Bailiffs significantly underfunded leading to poor monitoring	Local monitoring personnel in the form of WRUA representatives and, in some cases, WRMA staff	

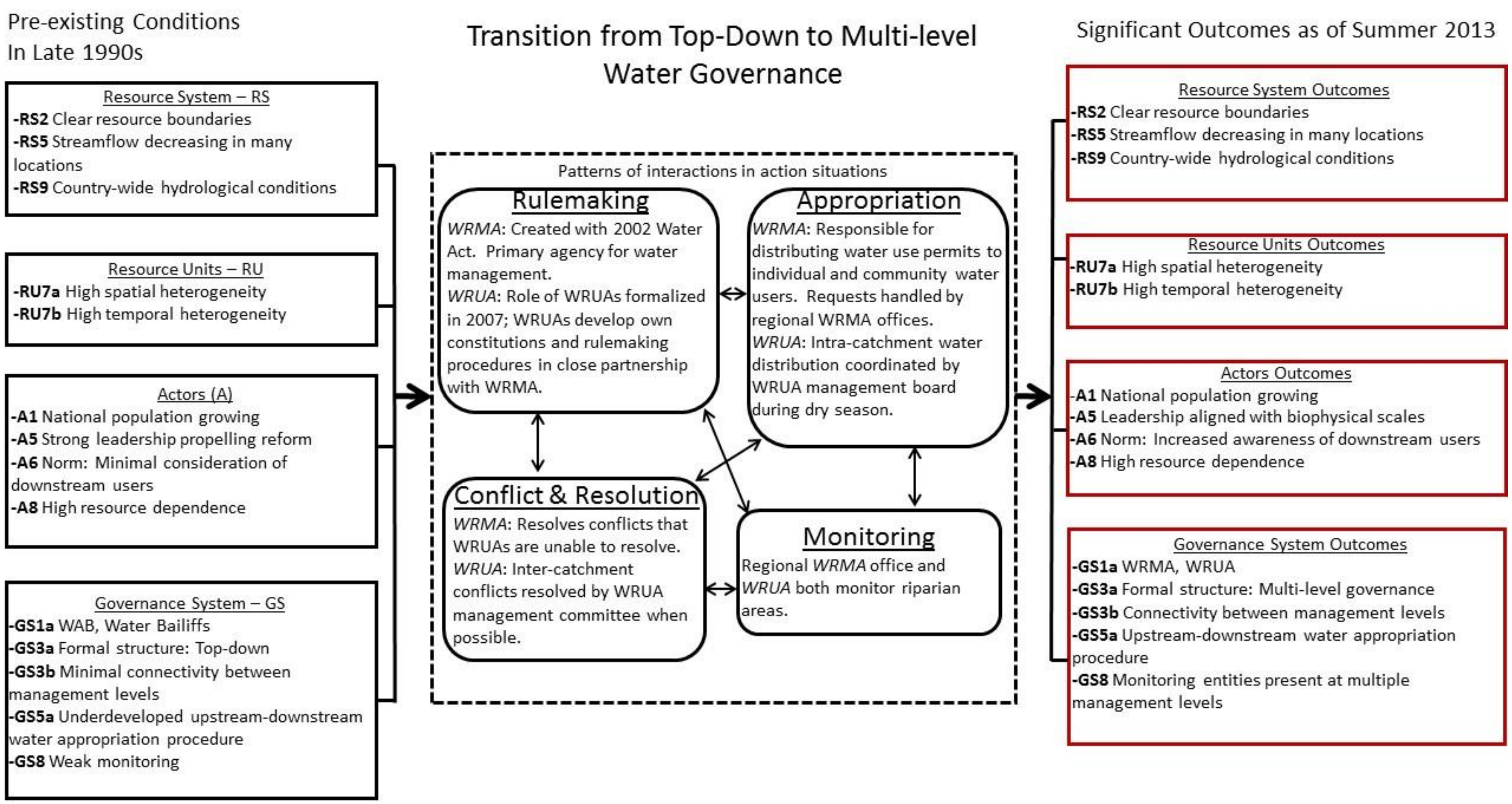

Figure 3.2. Application of the combined IAD-SES framework: Kenya’s transition from monocentric to multilevel water governance.

within Kenya’s Likii River catchment (A5 in Figure 3.2 – left hand side variables) to coordinate upstream-downstream water uses, share information, and resolve disputes (Liniger, Gikonyo, Kiteme, & Wiesmann, 2005). This WUA would later be the model for catchment level user groups following reform (described below). The immediate impetus for these actors in establishing the Likii WUA was a rash of upstream-downstream water conflicts fueled by excessive upstream river water withdrawals. However, the less apparent drivers – although more universal throughout the country – had existed since the colonial era. We now explain these drivers.

The Nairobi-based Water Apportionment Board (WAB; GS1a) had several critical responsibilities during British rule and in the years following independence, including permit issuance, sanctioning of water misuse, and placing restrictions on use during periods of scarcity. While the WAB was a national agency based in Nairobi, reforms in the 1970s increased participation by local officials, primarily by opening numerous Water Bailiff offices throughout Kenya to issue permits and monitor permit compliance (GS1a; Kenya Water Apportionment Board, 1972). These efforts were largely ineffective, however, as final authority remained with the central government. In fact, these adjustments led to a less-efficient permitting process: water users now needed to obtain permits from both local and national officials, and this process could take years to complete (Kenya Ministry of Water Development, 1983). The regional Water Bailiff offices were also significantly underfunded and often lacked the financial means to patrol riparian locations for non-permitted water users (GS8). If water users chose to avoid the permitting process, they ran little risk of detection. Thus, despite efforts to bolster local water governance, Kenya retained a largely ineffective top-down system of management (GS3a) with poor coordination across governance levels (GS3b) up to the turn of the twenty-first century.

Compounding these inefficiencies were incongruities between the hydrological system itself and the individuals charged with officiating the resource system. In their efforts to monitor water use and issue abstraction permits, Water Bailiffs were assigned to jurisdictions based on political (district) boundaries. This complicated management efforts since these water officials had no reason to consider the effects of upstream water use on downstream users so long as the downstream users were within another district (GS5a). Therefore, despite the clear natural borders (RS2) of the hydrological system (i.e., catchment areas), the management of water use led to opaque understandings of downstream water needs (A6); the result of which were frequent downstream water shortages, particularly during dry periods (A8 and RS5; Liniger, Gikonyo, Kiteme, & Wiesmann, 2005).

3.2.2.2. Kenya's 2002 water reform

As these water shortages intensified, efforts took place at both the regional and national levels to reform water management. An informal WUA was established in the Likii River catchment to coordinate use among water users. Following the initial success of this WUA, the Government of Kenya incorporated the WUA concept in its reforms by encouraging the creation of formal Water Resource Users Associations (WRUAs), which would become independent decision units at the catchment level. National reforms also created a Water Resources Management Authority (WRMA), responsible for developing overall policy strategies for Kenya, as well as for certain appropriation, conflict resolution, and monitoring activities. The reforms also delineated overlapping and shared responsibilities for rulemaking, appropriation, monitoring, and conflict resolution at the community, WRUA, and national levels. Thus, a multi-level system took hold in which individual or community water users were nested within WRUAs, which were further nested within a WRMA region.

With the opening of regional offices within each of Kenya's water basins, WRMA officials were able to better enforce policy changes enacted after the water reform. From a water appropriation perspective, WRMA now requires users to obtain permits from one of these regional offices, or if the individual belongs to a community user group, the user group needs to collectively possess a WRMA permit. Further, an overlap between the responsibilities of WRMA and WRUA exists since WRMA must consult with the WRUAs on permit issuance. These permits formally limit the timing and quantity of water abstracted, and, in times of water scarcity, require a percentage of water to pass through the catchment to downstream users. Monitoring compliance with the terms of these permits is shared between WRMA personnel and members of the WRUA. Additionally, if the permit terms are violated or disputes arise between upstream-downstream users within the same catchment, WRUA and WRMA may share conflict resolution responsibilities. In cases where upstream-downstream conflicts occur across catchments, WRMA becomes the primary entity responsible for conflict resolution, creating an overlap of authority between WRUAs and WRMA.

The WRUAs did not become formally recognized as catchment level users associations until 2007; nonetheless, informal WUAs were present in multiple catchments before 2007 and these informal groups provided a blueprint upon which the WRUAs that existed as of 2013 were crafted (Baldwin, Washington-Ottombre, Dell'Angelo, Cole, & Evans, 2016). A WRUA encompasses all members of a particular catchment that possess a WRMA water use permit, and they operate as truly representative entities, as the management committee for each WRUA is made up of members from the catchment: representatives from community user groups, CEOs of large-scale farms, and individual riparian households, among others make up the WRUA management committee.

The primary role of a WRUA is to prevent and resolve conflicts between water users within a catchment area (WRMA & WSTF, 2009), and to this end, they share many responsibilities with the regional WRMA office. In terms of rulemaking, WRUAs are allowed to devise their own constitutions; yet, this is done in partnership with WRMA, often using a template approved by WRMA. Their closest partnership with WRMA, however, arguably occurs with respect to water appropriation during the dry season. As river water becomes scarce, WRUAs are expected to devise a schedule of appropriation amongst the catchment members. This requires members to keep their river intakes shut on all days that they are not scheduled to receive water. In theory, this program allows a percentage of water to reach downstream users, even during the dry season. Crafting the schedule of appropriation is often done in close consultation with WRMA officials and requires WRMA's approval before implementation. Likewise, monitoring compliance with the dry season regulations and resolving conflicts as they arise is also typically shared between WRUA and WRMA personnel; yet, WRUAs may entirely defer conflict resolution duties to WRMA if the offense or grievance is deemed best handled at a higher level of governance.

3.2.2.3. Conditions as of the summer of 2013

Following this national level effort to reorient water governance institutions and actor roles, SES conditions as of 2013 indicate that certain features of polycentric governance and adaptive co-management of water resources now exist in Kenya (GS3a in Figure 3.2 – right hand side variables). Adaptive co-management suggests that governance responsibilities are most effective when the scope of influence aligns with hydrological borders (Huitema et al., 2009). With the creation of WRUAs, water use activities within and across catchments became better coordinated, particularly during the dry season (GS3b and GS5a), and individual water users became increasingly aware of the consequences of their activities on other actors within and outside their catchment (A6). Our own interviews suggest that, despite these coordination efforts within catchments, the effectiveness of WRUAs in alleviating water disparities have been mixed: some downstream users continue to object to excessive upstream water use, while others feel that post-reform water availability has improved (RS5).

In terms of monitoring (GS8), the 2002 reform has created redundancies in some catchments, a trait of polycentric governance. Regional WRMA personnel will patrol riparian zones in search of unauthorized pumping, an effort that is also performed by members of the WRUA particularly when the dry season appropriation schedule has been imposed. This duplication of duties creates a safety net where a failure on the part of one institution is alleviated by the presence of another. While WRMA personnel may not be as prominent in some catchments compared to others, the very presence of a catchment level governance entity (i.e., the WRUA) suggests leadership will be familiar with local conditions (A5), another important element of adaptive co-management (Huitema et al., 2009).

With the formal transition from monocentric to multi-level management described, we now analyze the outcomes of this nationally imposed polycentric shift on a SES within Kenya’s Upper Ewaso Ng’iro basin. We begin by describing the SES of interest and then move on to a description of the data used before inspecting the outcomes of reform.

3.3. Study area

3.3.1. The Upper Ewaso Ng'iro basin

Both a climatic and social gradient exists in the Upper Ewaso Ng'iro basin (McCord, Cox, Schmitt-Harsh, & Evans, 2015). Nested within the basin are twenty-five community water projects (CWPs) where fieldwork was conducted. These CWPs span an area of approximately 1800 km^2 and are located predominately on Mount Kenya's leeward side within five WRUAs (Figure 3.3). The CWPs nearest Mount Kenya, on average, receive greater precipitation totals; however, rainfall events across the region are variable. Throughout much of the study area, either a bimodal or trimodal rainfall pattern exists, with rainy seasons taking place from April to June, October to December, and a more unpredictable rainy season occurring from July to August under the trimodal pattern (Ericksen et al., 2011). This seasonality results in significant variability of surface water availability.

In addition to the study area's environmental gradient, a "social gradient" is also present. Until the early 1900s, much of the study area was occupied by Maasai and Samburu pastoralists (Wiesmann, Gichuki, Kiteme, & Liniger, 2000). Large ranches and farms owned by white settlers that were established during the colonial era (i.e., starting at the turn of the twentieth century) have today largely transitioned to Kikuyu- or Meru-owned small-scale farms, although some large landholdings remain. Many of these large landholdings have been transformed into highly technical horticultural operations producing for international markets (Wiesmann, Gichuki, Kiteme, & Liniger, 2000). The Maasai and Samburu pastoralists, who once dominated the area, have largely been pushed north to the marginal arid and semi-arid rangelands (Kiteme, Wiesmann, Künzi, & Mathuva, 1998).

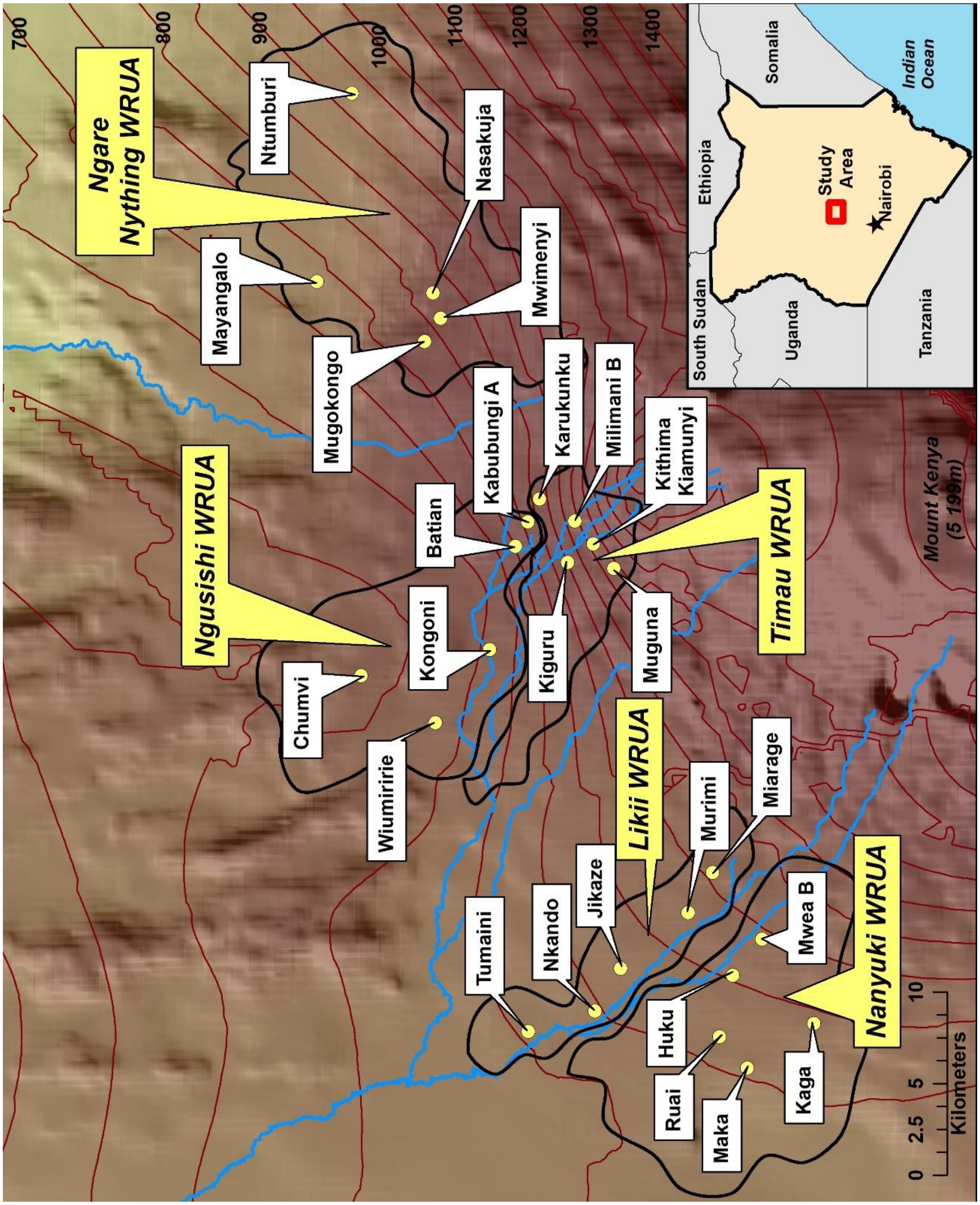

Figure 3.3. Study area. *Notes: Isohyets represent average precipitation (mm) to demonstrate the region's environmental gradient. Boundaries of WRUAs are approximations. Locations of water projects are represented by the centroid of the water project.*

Population growth within the Upper Ewaso Ng'iro basin, which witnessed an increase from 50,000 in 1960 to approximately 500,000 in 2000 according to Ngigi, Savenije, & Gichuki (2007), as well as increases in the number of smallholder farmers, typify the trend throughout much of Kenya during the post-colonial era. These growth processes were encouraged by the Government of Kenya's subdivision of former British ranches to be used for smallholder farms, as well as immigration from nearby densely populated areas in search of locations with high agricultural potential. In the process, population growth has added new pressures to land and water resources. As evidence, multiple rivers within the Upper Ewaso Ng'iro basin have experienced decreasing flows since the early 1960s (Liniger, Gikonyo, Kiteme, & Wiesmann, 2005). In some areas, the decrease in river water availability has shifted livelihood practices from smallholder sedentary agriculture to pastoralism.

3.3.2. The community water projects

Community water projects (CWPs) are small, member-based irrigation infrastructure projects that allow smallholders to access irrigation water (although the primary goal of CWPs is to provide water for domestic use). Many CWPs were initially funded by government programs or donors, with subsequent management and infrastructure improvements undertaken by the CWP's membership. Some CWPs date back to the colonial era, although the number of CWPs increased rapidly in the post-colonial period supported by government programs aimed at increasing small-scale agriculture.

We focus our attention on twenty-five CWPs within the Upper Ewaso Ng'iro basin. Each of the twenty-five CWPs has an intake from either one of the study area's major rivers or from a natural spring as is the case with the CWPs in the Ngusishi WRUA (refer to Figure 3.3). Intakes can be closed during periods of rationing between CWPs in the same WRUA. After flowing through the intake, water is then gravity-fed to households through a series of buried pipes. CWPs vary in their water use restrictions, as some only allow for irrigation of small plots of land, while others are more flexible. Typically this is influenced by the number of members within a CWP, which is highly variable and can be related to population growth within an area, as well as decisions made by the CWP's management committee to either restrict membership or allow membership growth.

Community water projects have long exhibited autonomy in crafting their own institutions, a tradition dating to the colonial era. Important differences therefore exist in management strategies, including water appropriation strategies during the wet and dry seasons. CWP management committees make decisions as to whether or not a CWP will institute a rotation schedule (i.e., alternating water delivery between separate CWP distribution lines on a day-to-day basis) during the wet season and how dry season water shortages will be managed. These decisions are typically influenced by the number of members within a CWP. It is not uncommon for larger CWPs to enforce a wet season rotation in which households receive water three or fewer times in a week, while CWPs with smaller memberships may be able to forgo a rotation program during periods of high river levels. When river levels decrease in the dry season, household level water availability is typically restricted in both large and small CWPs.

3.4. Data and methods

We use three types of data for this study: survey responses, household level water flow measurements, and archival research. Surveys were administered to members of the CWP management committee, which included a set of chairperson surveys (i.e., the manager of the water project; N=25), a set of care taker surveys (N=19), and a collective survey of the CWP's chairperson, vice-chairperson, secretary, vice-secretary, and treasurer (N=19). Responses from the chairperson surveys revealed the historical context, rules and monitoring policies, and water rotation and rationing strategies within each CWP. Care taker surveys offered insight into the infrastructural design and repairs made to each CWP's pipe network. And the collective survey with the CWP management committee was used to better understand group decision-making.

Household level water flow was measured on a weekly basis from July 2013 to January 2014. In smaller CWPs, ten households were measured on a weekly basis, while in larger CWPs, twenty households were measured weekly. Using a stopwatch, measurements were taken by timing the duration to fill an 18L bucket; measurements were then converted to liters per minute. In so doing, we have obtained a temporal record of weekly flow measurements in each CWP. The large amount of sediment in the CWP pipes prohibited the use of flow sensors to measure household level water flow.

Archival research provided an understanding of Kenya's legal water institutions. This research was conducted in Nairobi during June 2013 in the Kenyan National Archives, the University of Nairobi, and Kenya's Ministry of Water and Irrigation, and includes statutes, regulations, and historic documents from Ministry of Water and Irrigation field offices. These three sets of data (i.e., the survey responses, the household-level water flow measurements, and the archival research) will be used in the next section to inspect post-reform experimentation with rule changes and how these rule changes correlate with location conditions.

3.5. Polycentric transition outcomes: Inspection of the Upper Ewaso Ng'iro basin SES

3.5.1. Hypothesis testing

In examining the outcomes of water reform, we focus particularly on the rules-in-use within each CWP. We attempt to link CWP governance strategies with propositions from the polycentricity literature and hypothesize the following: First, in the post-reform period, user groups will experiment with new approaches to governance by adjusting their rules (hypothesis 1), and second, some of this experimentation will correlate with improved local conditions (hypothesis 2). We begin our examination of the outcomes following water reform by describing a case in which rule changes have clearly led to an outcome that polycentricity theorists would view as favorable. This is followed with additional evidence (or lack thereof) of outcomes predicted by polycentricity theory.

Monitoring and maintenance roles within CWPs are an element that appear to have been adjusted within at least one WRUA following the 2002 reform. CWPs typically employ a care taker who is responsible for inspecting CWP pipe lines for leaks, responding to complaints of poor water flow by members, monitoring to ensure that no members are taking water illegally, and disconnecting members if rules are violated. However, in the Ngusishi WRUA, CWP monitoring rules differ from the other four WRUAs. Rather than the CWPs of the Ngusishi WRUA employing care takers, *scouts* are provided by the WRUA to monitor water use activities along the CWPs' main lines. This stands in stark contrast to the other four WRUAs where WRUA officials only patrol the riparian zones, not the CWP's infrastructure. Scouts also make repairs to the main line(s). All sublines and some main lines within the Ngusishi CWPs are also maintained and monitored by representatives from the households along that particular line.

It is unclear if the scout system employed in the Ngusishi WRUA is preferable to the care taker system within the other four WRUAs. The CWP may benefit by avoiding the cost of employing an individual within the monitor/maintenance position, since the WRUA pays for the scout; however, the scout may also be seen as an “outsider” and not trusted to the same degree as the care takers within the other WRUAs. A natural experiment may well take place in which other WRUAs trial the approach taken by the Ngusishi WRUA. This experimentation with monitoring obligations in the Ngusishi WRUA confirms our first hypothesis. Additional examples of rule adjustments and experimentation are now explored, as well as the proficiency of experimentation efforts in adapting to local conditions (i.e., hypothesis 2).

To better understand other rule adjustments in response to the 2002 water reform, further background is necessary. The WRUAs and WRMA leverage considerable influence with respect to catchment level water appropriation, particularly during the dry season. If a WRUA has directed a catchment’s member groups to follow the agreed upon appropriation schedule, a CWP’s river intake is expected to only be open during the days in which that particular CWP is scheduled to receive water. Before the 2002 Water Act, rationing between CWPs was absent since formal catchment level regulations did not exist. CWPs had little reason to consider the volume of water withdrawn from the river and upstream CWPs were the *de facto* beneficiaries. Some upstream CWP chairpersons have expressed their longing for the pre-WRUA period, claiming that water rationing has forced them to devise new rotation schedules (or alter existing schedules) within their CWPs, and that these changes have obstructed their abilities to meet the household consumption and irrigation needs of members.

In response, certain CWPs have adjusted their rules-in-use, particularly rules regarding new membership. As of the summer of 2013, eight of the twenty-five CWPs had capped their membership (Table 3.3). In many cases this was a recent decision made by management committees as they struggled to meet the needs of their members in the face of increasing population and water provisioning restrictions. Membership control represents a response to water scarcity and a divergence in the rules-in-use found among the twenty-five CWPs. It also suggests a divergence in water allocation outcomes. To explore this, we have calculated a single coefficient of variation (CV) value of pipe network water flow for each CWP using the household level water flow data from July 2013 to January 2014 (Table 3.3). To estimate the CV of water flow, the mean flow over time was calculated for each household within each CWP. The average of all household mean flows was calculated as well as the standard deviation of the household mean flows. The CWP level CV of flow was then generated by dividing the standard deviation of CWP flow by average flow. We have grouped CWPs, as well as their CV of water flow, according to their decision to either cap membership or allow membership to grow. This allows us to compare the two groups based on summation of their CV of water flow ranks using a Mann-Whitney-Wilcoxon test.

This comparison of rank sums suggests that the difference between CV of water flow for CWPs that have capped membership compared to those allowing membership to grow is statistically significant, and that variability is significantly higher in CWPs that allow new members to join compared to those that have limited their membership (Table 3.4). Thus, households within CWPs that have capped their memberships appear to receive more predictable water delivery. While other factors such as population and infrastructural components almost certainly affect this relationship, the statistical significance of this test suggests that institutions play a role in influencing water allocation outcomes as well. This tends to confirm our hypothesis that experimentation with rules-in-use can lead to successful adaptation to local conditions (i.e., hypothesis 2).

Table 3.3. Community water project change in CWP membership and CV of water flow

CWP	WRUA	Membership capped	CV of water flow[1]
Jikaze	Likii	Yes	0.1935
Miarage		No	0.2592
Murimi		No	0.1824
Nkando		No	0.2066
Tumaini		No	0.2568
Huku	Nanyuki	No	0.1223
Kaga		No	0.5470
Maka		No	0.1860
Mwea B		No	0.4953
Ruai		No	0.4492
Batian	Ngusishi	No	0.8262
Chumvi		No	0.5220
Kabubungi		Yes	0.1201
Kongoni		Yes	0.3022
Wiumiririe		No	0.3747
Mayangalo	Ngare Nything	No	0.8044
Mugokongo		Yes	0.1985
Mwimenyi A		No	0.2230
Nasakuja		No	0.3220
Ntumburi		No	0.3593
Karukunku	Timau	Yes	0.1145
Kiguru		No	0.0773
Kithima-Kiamunyi		Yes	0.1690
Milimani B		Yes	0.1695
Muguna		Yes	0.4641

Notes: [1]Calculated from weekly household-level measurements taken from July 2013 to January 2014. Household-level measurements started on a rolling basis where the first CWP visited (i.e., Nkando) had its first measurements taken on July 8, 2013, while the final CWP visited (i.e., Kiguru) had its first measurements taken on September 9, 2013. Thus, the overall total number of visits to each CWP are not equal.

Table 3.4. MWW test results

Change in CWP membership in past 5 years	Number of CWPs	Rank sum	Expected rank sum
No Change (capped membership)	8	70	104
Increase	17	255	221
Total	25	325	325

Notes: The test was significant at a critical value of 0.05. The group of CWPs that have capped their memberships (8 CWPs) have actual rank sums that are lower than their expected rank sum and lower than the actual rank sums of the group of CWPs that are allowing membership to increase (17 CWPs). Thus, the CWPs that have capped their memberships have a lower rank in variability of water flow.

3.5.2. Coordination among local and regional actors

In addition to testing the above hypotheses, we also examine some ways that Kenya's reforms have created or encouraged coordination among multiple levels of management, and how these coordination mechanisms have affected CWP governance. The most notable post-reform coordination mechanism exists between CWPs and their respective WRUA. At the local level, the CWP membership elects the individuals who serve on the management board, including the CWP's chairperson. Along with water use decision-making obligations within the CWP, the chairperson also serves on the WRUA's management committee, which makes catchment-wide decisions concerning water appropriation, monitoring, and sanctioning. Thus, coordination between the CWP and WRUA legislative bodies is directly linked by the representative procedure that elects each of the CWP's chairpersons. This process suggests more active and effective dialogue between WRUAs and CWPs, and that CWPs coordinate with WRUA officials when management concerns span community boundaries. For instance, twenty-four of the twenty-five CWP representatives stated that coordination with WRUA helps to prevent conflicts, and fifteen of these individuals claimed that, of the higher levels of governance, WRUAs are most frequently relied upon to handle disputes between CWPs.

This increased level of coordination between CWPs and WRUAs – as well as between CWPs in the same catchment – has been accompanied by adjustments in institutional and physical infrastructure to ensure that WRUAs are achieving their goal of improving the quantity of water resources to all members of the catchment. For example, both the WRUA and WRMA now expect all CWPs to have a flow-measuring device near their river intake position, and will impose fines if devices are not installed. Similarly, to ensure that all CWPs withdraw an equal amount of water, WRUAs now tend to require that all CWPs install uniform (6 inch) intake pipes. In addition, WRMA (in partnership with the WRUA) has increased the frequency with which it assesses penalties to CWPs withdrawing water in excess of permits. These new requirements and fees improve efforts to guarantee catchment-wide water access, but they also burden communities with additional financial obligations and water use restrictions. Some CWP chairpersons expressed frustrations related to the increased fees following the 2002 Water Act. One chairperson described the reform as operating in a "commercial way" that has precluded the "normal person" from accessing water if they cannot afford it. Another claimed that the 2002 reform "has not been good" since it has increased costs within CWPs. These and other CWP leaders explained that they have been forced to raise fees in response to the increased financial burden, and in some cases CWPs have increased their memberships to help pay the increased fees.

3.6. Discussion

The preceding analysis of Kenya's water reform demonstrates that the government has deliberately created the basic features of a polycentric system: multiple, independent decision centers at the CWP, WRUA, and WRMA levels; overlapping authority over several aspects of water governance; and mechanisms for coordination between governance levels. Arguably, however, the more interesting question is how these changes have affected governance on-the-ground among and between local CWPs and WRUAs, particularly with respect to rule adjustment and experimentation, as well as the emergence of new forms of collective action.

The 2002 reform appears to have provided a stimulus for all CWPs within the Upper Ewaso Ng'iro SES to experiment with their rules-in-use in order to meet the needs of their members. While CWPs had the authority to make their own rules before 2002, the rule experimentation that is now taking place is fundamentally different given that CWPs now occupy rule-making space with their WRUA, as well as WRMA. A CWP that is nested within a WRMA-approved WRUA – as is the case with all of the CWPs in this study – has representatives who participate in catchment level decision-making about permit issuance, regional scale water allocation, and water conservation strategies. This representation gives CWP leaders a level of legitimacy that they lacked in the past. However, it also requires CWP chairpersons to balance the wants of their members with the requirements specified at higher levels of management. This is precisely where the decision of some CWPs to limit their memberships has originated, since WRUAs mandate a percentage of river water reach downstream users. While balancing the requirements of the WRUA with the wants of CWP members can be challenging, it is important to recognize that by taking on these challenges, CWPs are now provided with a path toward user group legitimacy, an important trait of a polycentric system and a trait that was glaringly absent before the 2002 reform.

The literature on polycentricity also suggests that coordination between local, regional, and national actors should encourage mutual adjustments and the undertaking of collective action at multiple levels. Our examination of the Upper Ewaso Ng'iro basin shows that, post-reform, CWPs are reducing their water use to ensure water availability for downstream users. However, they are doing so to comply with rules imposed upon CWPs in a top-down fashion, with some resistance from CWP managers. It thus may be premature to consider water allocation arrangements within WRUAs to be "collective action" in the classic sense; WRUA members communicate and coordinate their water use, but actual reductions in CWPs' water allocations have come about due to formal legal requirements rather than due to bottom-up strategies.

Nonetheless, the coordination mechanisms created by the reforms – particularly the creation of the WRUAs – have helped to ensure that CWPs will comply with the requirements and that the mandates will achieve the intended result of increased water availability.

Key understandings with respect to the literature on polycentricity have been revealed from this study. We have found evidence that a deliberate push for polycentric resource management *can* encourage local decision-making and rule experimentation, especially as local chairpersons respond to policy changes from decision-makers at higher levels of management. While additional experimentation may occur over time, we conclude that Kenya's top-down reforms *allow*, rather than *encourage*, experimentation, adaptation, and learning.

Similarly, while CWPs have autonomy to craft their own rules, this is primarily limited to internal matters, and WRMA retains the right to impose rules in top-down fashion – for example, mandating certain infrastructure investments. However, it appears that local level rule diversification would actually be quite minimal within the twenty-five CWPs without these top-down policy-induced changes. Additionally, it is possible that simply not enough time has elapsed since the 2002 Water Act, and that with the passage of time more experimentation will naturally occur. In this vein, we may be witnessing the less-than-optimal institutions established by local resource managers as they grapple with the complexity of their system (Ostrom, 2005).

Finally, our examination of the twenty-five CWPs, and their respective WRUAs, suggests that a polycentric system is developing not solely on paper, but on-the-ground as well. Yet, while some beneficial conditions have arisen following the 2002 reform, other governance outcomes predicted by theorists have been slow to emerge, and the actual benefits of these outcomes may fall somewhat short of those predicted by theory. It additionally remains to be seen whether the conditions in our study area are pervasive across Kenya and whether other CWPs have experienced a similar level of interaction with regional and national actors.

3.7. Conclusion

This study set out to identify how actor roles and local level rules have changed following the 2002 water reform, and to determine the extent to which the post-reform governance outcomes reflect benefits predicted by polycentricity theorists. With regards to this inquiry, we hypothesized the following: (1) In the post-reform period, user groups will experiment with new approaches to governance by adjusting their rules, and (2) some of this experimentation will correlate with improved local conditions.

We found evidence – albeit limited – in support of these hypotheses. Kenya's polycentric shift may have provided a "shock" which led to rule changes and a divergence in rules-in-use employed by CWP chairpersons, particularly those rules related to user group membership and monitoring. These adjustments appear to be ongoing and indicate some amount of experimentation with management strategies. We also found evidence that the coordination mechanisms created by the reforms have prompted CWPs to curtail water use to the benefit of other CWPs; however, this has largely occurred by way of a top-down approach that may not fully match theorists' predictions about collective action.

By taking an empirical approach, this study has addressed critical questions concerning the institutional dynamics that are involved in a national water governance polycentric transition. In the process, it has raised topics that are ripe for future research, including the different and often contradictory features of polycentric reforms and the barriers to on-the-ground deployment of polycentric principles when, formally, multiple centers of governance exist. Further investigation into these topics will advance the governance community's understandings of polycentric resource governance.

Appendix

Selection of variables to be included in the combined IAD-SES framework at the pre-reform time step was guided by the following steps:

1. An understanding of the water management system as of 2013 was obtained through review of information gathered during archival research. From this understanding, we worked backwards to the time step just before 2002 reform to identify SES framework variables where it was possible to make a causal connection to 2013 outcomes.
2. In identifying these pre-reform SES variables, we first focused on isolating second-tier variables for each subsystem that could either help characterize the pre-reform landscape, or function as a direct driver of reform, or both.
    a. Before selecting a variable, a "yes" response was required of the following question: "Is this variable critical to understanding the SES in the context of Kenyan water governance, or is this variable a driver of water policy reform?"
3. Where greater detail was needed, we unpacked the identified attributes into third-tier variables by repeating steps 2 and 2a for each variable previously identified.

To characterize the dynamics within the adjacent action situations that produced the post-reform conditions, we adhered to the following steps:

1. An assessment was made of which broad action situations processes could be reasonably articulated using the pre-existing conditions from the pre-reform time step.
2. Given our understanding of the water management system as of 2013, a narrowing of potential action situations was performed by identifying decision-making processes that reasonably led to the 2013 conditions.

3. In order to demonstrate the connectivity within the adjacent action situations, the elements identified for each action situation needed to both influence and be influenced by the other decision-making strategies within the web of action situations.

Selection of the combined IAD-SES framework post-reform conditions was guided by the following steps:

1. Tracking the steps of reform from pre-reform conditions to the adjacent action situations, an assessment was made of the SES framework variables that were directly altered during this course of development.
2. After acknowledging these second- and third-tier variables, we further detailed the post-reform conditions by referring to information collected through 2013 archival research.

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Chapter 4: Household level heterogeneity of water resources within common-pool resource systems

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4.1. Introduction

Management of common-pool resources (CPRs), such as forests, pastures, irrigation systems, and fisheries, has attracted the attention of scholars for decades. Initial warnings were of resource exhaustion for those CPRs that were neither publicly nor privately owned (Gordon 1954, Scott 1955, G. Hardin 1968). In the 1980s, a number of case studies demonstrated the ability of local level resource users to self-organize and collectively manage CPRs, thereby challenging the speculations of earlier scholars. While insightful as to the ability of users to work together to manage a CPR, a consistent set of rules utilized in cases of successful management was not discovered (Ostrom 2005). What was synthesized, however, were eight fundamental "design principles" underlying the ability of resource users to form trust in one another and sustain collective-action in resource management (Ostrom 1990). Local systems of natural resource governance embodying some, but not necessarily all, of these traits would be more likely to endure over the long-term.

Since the introduction of Ostrom's design principles, many diagnostic analyses have been conducted using these principles to query the sustainability of particular management regimes within diverse social-ecological systems (SESs; e.g., Morrow and Hull 1996, Coop and Brunckhorst 1999, Tucker 1999, Basurto and Ostrom 2009, Dell'Angelo et al. 2016). Irrigation systems are particularly reliant on robust institutional structures given the challenge of achieving water equity between head-end and tail-end members of the system. We define institutions as the set of rules that are actually used by a group of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially others (Ostrom 1992). Demonstrating the importance of institutions, Ostrom and Gardner (1993) revealed that even in irrigation systems where the physical infrastructure is new and well designed, water delivery inequities may be greater compared to systems with less sophisticated infrastructure but better crafted institutions.

Despite the importance of effective water management rules, some have recently expressed concerns that the persistent focus on institutional arrangements has over-shadowed the role of technology and the environment in producing resource outcomes (Anderies et al. 2016). Inter-connections between technological, environmental, social, economic, and institutional processes are important to consider in any SES, but irrigation systems demand particular attention to be given to technological traits (i.e., water distribution infrastructure). For example, the frequency of repairs to water distribution lines, the age of infrastructure, and the decision to expand the footprint of the irrigation system by adding new distribution lines all may play a significant role in water delivery. As a result, we use the term “coupled infrastructure system” (CIS) to denote our unit of analysis. A CIS accounts for soft human-made (institutions), physical human-made (technology) and natural (e.g., biophysical elements) infrastructures and, by explicitly acknowledging a broad array of social and physical elements, it helps to identify the inter-relations that produce resource outcomes, including water delivery within irrigation systems (Anderies et al. 2016). In this manuscript we treat the term “CIS” as synonymous with “SES.” This is strategic given the infrastructure-heavy nature of our area of study and the utility of this term in structuring our analysis. We also use the term “CIS” in an effort to further caution against inadequate treatment of system traits in favor of others, much like the warning provided by Anderies et al. (2016).

In understanding water delivery and asymmetries between irrigation system members, the tendency has been to rely on proxies for water distribution aggregated to either an intra-system level, such as the head- and tail-end of the system, or to the level of the irrigation system as a whole. For example, Lam (1996) assessed water delivery at the head-end and tail-end of multiple Nepalese irrigation systems through member self-reportings of water availability. Cox and Ross (2011) used agricultural productivity, measured through remotely sensed images, at the irrigation system level to assess cooperative efforts of members that facilitated adequate water delivery. While these studies offer valuable insights in terms of system-wide outcomes produced by particular governance arrangements, the aggregation of performance measures may overlook dynamics occurring at a finer scale and the reliance on proxies may undermine a fuller understanding of the performance measures truly under investigation, such as water delivery and equity.

In this study, we rely on household level measurements of water delivery from twenty-five irrigation systems on the northern and northwestern slopes of Mount Kenya. These measurements are used to understand how elements of the CIS – that is, the institutional, technological (i.e., physical water distribution infrastructure), and biophysical infrastructures – contribute to water delivery outcomes in the form of the average rate of household water delivery and the variability of household water delivery. Our goal with this research is to both investigate CIS traits that associate with household-level water delivery and to consider water delivery asymmetries that exist among households belonging to irrigation systems. In this vein, we seek to address the following research questions:

1) How do elements of the CIS influence household level water delivery outcomes within smallholder-operated irrigation systems?
2) How does the amount of water delivered and the reliability of delivery differ among members of the same irrigation system, as well as between irrigation systems?

By making use of data expressly collected to understand water delivery outcomes, our results are informed by the same information that water managers within the irrigation systems, unfortunately, mostly lack. Reasons for this absence of data held by decision-makers are both financial and technological. Many irrigation system managers have encouraged farmer participation and zonal representation within their respective systems as a strategy to promote equitable outcomes in the absence of direct measurements of water delivery. We explore these efforts in the Discussion of the study. Before doing this, we provide background information on the limited presence of ecology in SES studies and the need to employ ecological indicators when assessing irrigation system performance. We then describe the study area as well as our methods for data collection and statistical analysis. The results of the analysis are then presented before entering into a final discussion.

4.1.1. The role of *ecology* in assessing performance of irrigation systems

Research on CPRs is a challenging endeavor. Assessing the sustainability of these systems entails a recognition of complexity in the form of linear and non-linear system feedbacks across multiple spatial and temporal scales (Berkes 2002, Young 2002). Analytical tools such as the Social-Ecological Systems Framework (Ostrom 2007) have been developed to navigate SES complexity. Yet, the SES Framework as well as SES research more generally have typically given uneven attention to its two constituent parts, with social components and processes receiving greater attention than the ecological domain (Epstein et al. 2013, Vogt et al. 2015). Rissman and Gillon (2016: 7) reviewed 120 SES articles and concluded that "better integration of ecology is needed in SES research." This systematic review also found that it was more common in studies with an independent variable-dependent variable connection for the outcome to be a social indicator, often a socioeconomic variable. This is likely due to the relative dominance of social scientists in SES research and the common emphasis given toward understanding how resource availability influences human decision-making and socio-economic status (Epstein et al. 2013). What is important to note here, however, is that the greater the separation between the actual resource outcome, such as water distribution equity within an irrigation system, and the dependent variable used as a proxy for performance, such as household income, the greater the opportunity for an intervening variable to skew the direct understanding of resource system performance (Small and Svendsen 1990).

To re-adjust the balance between social and ecological elements in SES research and avoid errors imposed by intervening variables in analyses establishing an independent variable-dependent variable connection, we describe several ecological performance indicators to evaluate irrigation systems. In this study, "ecological" is meant to include both environmental and ecological variables, a grouping common in the SES literature. The term "performance" is meant to indicate household level outcomes that can be measured by their equitability, efficiency, or ability to support livelihood security (Berkes and Folke 1994). Civil engineering studies, in research concentrating on rural development, have paid extensive attention to issues of water delivery within a range of systems. Molden and Gates (1990) provided definitions for several measures of irrigation system performance. The authors identified measures of adequacy (i.e., delivery of the necessary amount of water over an area served by the irrigation system), efficiency (i.e., conservation of water by ensuring that water deliveries equal water requirements), dependability (i.e., the temporal variability in the amount of water delivered compared to the amount required), and equity (i.e., the spatial variability in the amount of water delivered compared to the amount required) as indicators of irrigation system performance. Relying on multiple field measurements of water flow at various times and locations, the authors then applied these measures to evaluate performance of irrigation systems in Sri Lanka and Egypt.

In this study we use household level measurements of water delivery to assess the dependability of water flow (i.e., the variation in water delivery) and the adequacy of water flow (i.e., the average flow rate). Directly employing ecological indicators of irrigation system performance reduces the potential for intervening variables to complicate our assessment of the contextual drivers influencing water delivery in a collection of irrigation systems in the Mount Kenya region.

4.2. Study area

The twenty-five irrigation systems, known as community water projects (CWPs) in the area of study, are found on the northern and northwestern slopes of Mount Kenya in the Upper Ewaso Ng'iro basin (Figure 4.1). Over very short distances, the conditions within the basin change significantly: precipitation dramatically decreases from atop Mount Kenya to the northwestern reaches of the study area, and, moving from the CWPs closest to the mountain to those further downstream, livelihood practices transition from sedentary farming to practices more focused on pastoralism (McCord et al. 2015). Smallholders primarily rely on rainfall when cultivating crops, but utilize irrigation water provided by their CWP to supplement rainfall, extend growing seasons, and span dry spells. The basin's population grew from 50,000 in 1960 to 500,000 in 2000 (Ngigi et al. 2007), which in turn reduced streamflow in the basin's major rivers (Liniger et al. 2005).

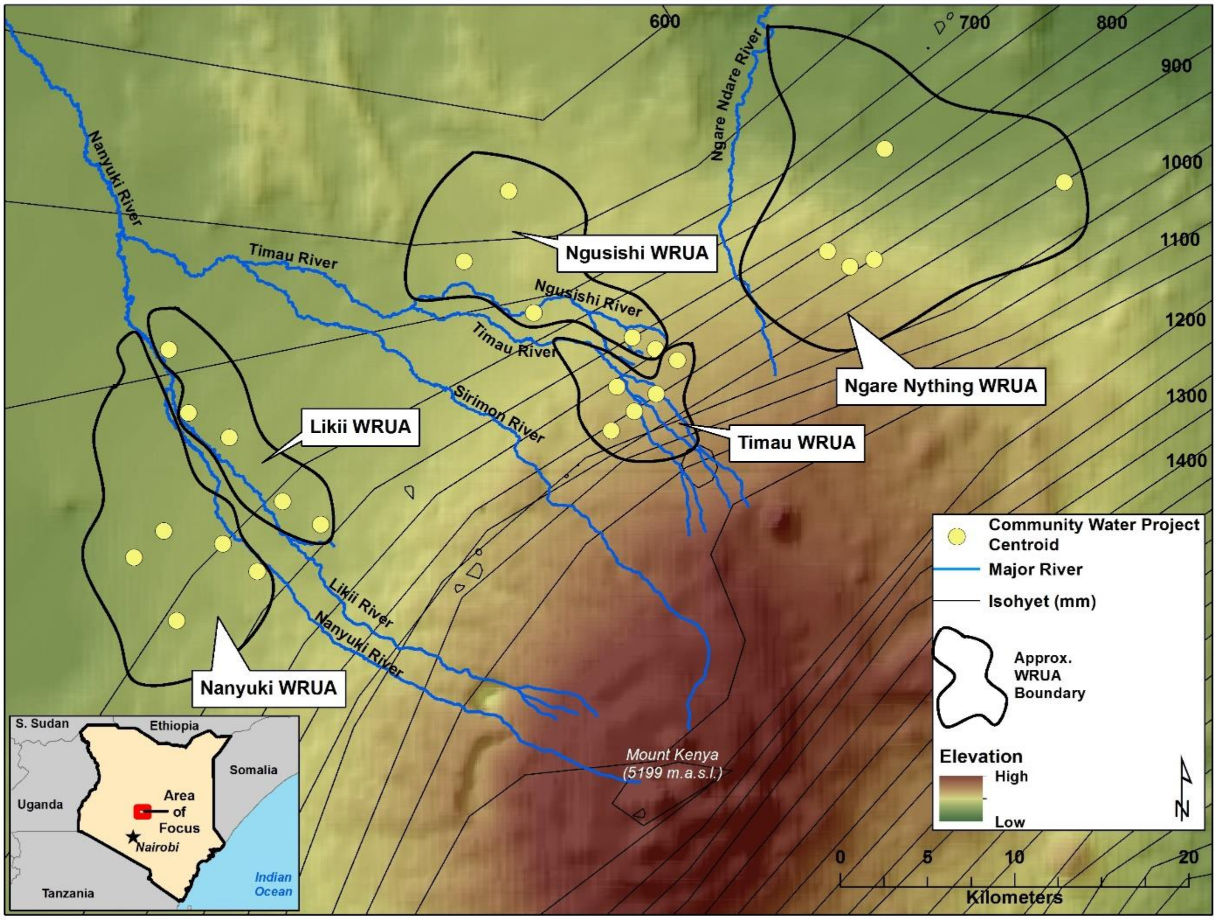


Figure 4.1. Study area. *Note: WRUA boundaries have been approximated. CWP locations are presented with their centroids. Isohyets represent average yearly precipitation in millimeters.*

4.2.1. The coupled infrastructure system: Physical human-made infrastructure traits of the CWPs

All CWPs receive their water from one of the major rivers within the study area, or, in some cases, a natural spring. The CWPs are typically located several kilometers from their water source and rely on polyvinyl chloride (PVC) pipes ranging in size from three to eight inches to carry water from the source to the CWP head-end. Once in the CWP, water is either held in a large tank or reservoir, or it is gravity-fed through a network of PVC pipes making up the distribution lines of the irrigation system (Figure 4.2). Water is then fed from these pipes to each homestead through individual household lines; note that the individual household lines are not shown in Figure 4.2. The distribution lines of the CWP are buried and range in diameter in order to maintain pressure. Water held in the CWP's tank or reservoir is often released to households during times of water scarcity. The water distribution networks under investigation here differ from the irrigation systems in studies such as Lam (1996, 1998), which utilize open and often unlined ditches to transport water.

Physical human-made infrastructure characteristics vary greatly across the CWPs (Table 4.1). Age of the CWP and the number of distribution lines are two such examples. The oldest CWP was established in the early 1970s and began running water to its members in 1980, while the youngest was formed in 2008 and only began distributing water to its members in 2011. Depending on the level of maintenance given to distribution lines, pipes within older CWPs may be more susceptible to leakage and result in less reliable household flow. The number of distribution lines range from a complex configuration of twenty-five lines (this is the CWP shown in Figure 4.2) to a single, straight conduit with households affixed at various points.

4.2.2. The coupled infrastructure system: Institutional infrastructure traits of the CWPs

Water governance in the Upper Ewaso Ng'iro basin, as well as throughout Kenya, is multilevel: Water Resource Users Associations (WRUAs) oversee activities at the subcatchment level and generally coordinate water withdrawals from a single river or spring (see Figure 4.1), while CWPs manage water operations within their communities. A WRUA creates a forum for the CWPs of a particular subcatchment to communicate, monitor water use, and resolve conflicts (Dell'Angelo et al. 2014). WRUAs play an important role during dry periods as they coordinate water rationing schedules among the CWPs of their subcatchment and ensure that a community only takes water when they are scheduled to do so. These dry periods typically occur in January and February and during a longer episode from late July to September. In some subcatchments, WRUA personnel periodically patrol the riparian zone to assess water levels and safeguard against excessive withdrawals. Despite the importance of WRUAs in water management, our analysis here focuses primarily on water management at the community level, thus concentrating on the institutions devised by CWP management committees. More detailed attention is given to WRUAs in Baldwin et al. (2016).

The management committee of a CWP, typically consisting of a chairperson, vice-chairperson, secretary, treasurer, and other individuals elected to represent households belonging to particular sections of the CWP, is responsible for designing procedures that ensure household water availability both during the wet and dry seasons. In the absence of water meters affixed to distribution lines to provide flow readings, which are absent from CWPs due both to financial reasons and obstruction concerns stemming from the large amount of sediment in pipes, the management committee relies on zonal representatives to report household level water delivery concerns (McCord et al. 2016). All twenty-five CWPs utilize some form of information transfer from these representatives to the management committee in order to prioritize maintenance activities and to resolve concerns of poor water delivery, such as low or unreliable flow. System maintenance is typically carried out by a paid employee of the CWP known as the caretaker.

Aside from relying on representatives from particular branches in the CWP to report water concerns, the management committee also crafts water use and membership rules to take on collective action challenges – i.e., the difficulties that arise due to dissimilarities between individual and group incentives. These challenges may take the form of appropriation dilemmas,

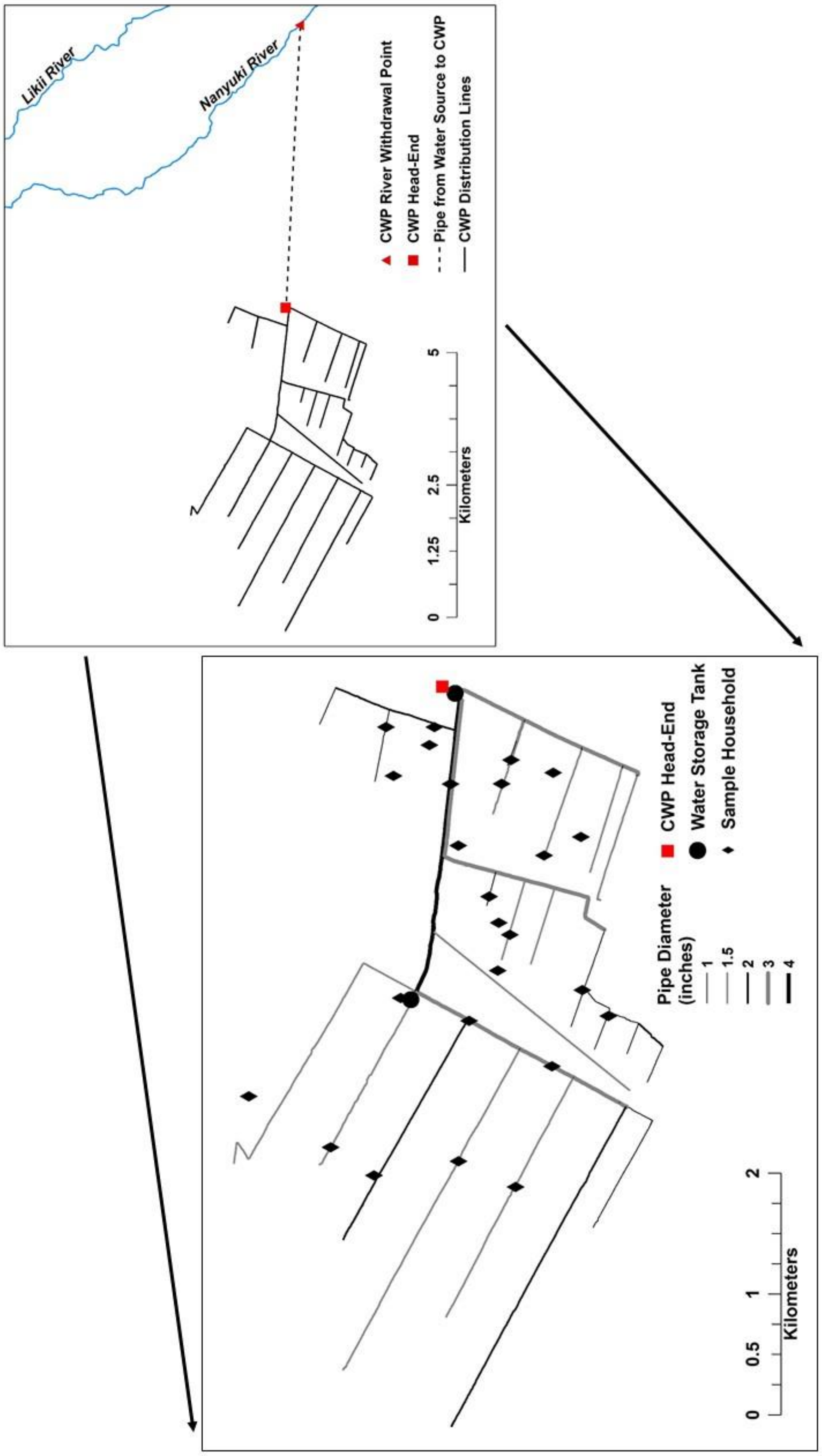


Figure 4.2. The layout of a CWP showing both the position along a river (right) and the configuration of distribution lines (left).

Table 4.1. Select physical infrastructure attributes of CWPs

CWP name[†]	WRUA name	Age of CWP	Number of lines	Total length of CWP distribution lines (m)	Areal extent of CWP (km2)	Presence of at least one water storage tank
L-CWP-1	Likii	16	4	2043.1	0.4	Yes
L-CWP-2	Likii	31	2	4735.5	1.5	No
L-CWP-3	Likii	12	3	9698.5	5.5	No
L-CWP-4	Likii	11	7	6545.0	1.8	Yes
L-CWP-5	Likii	10	8	9467.3	5.3	Yes
Nan-CWP-1	Nanyuki	26	14	22,078.4	9.1	Yes
Nan-CWP-2	Nanyuki	18	20	37,375.0	15.9	Yes
Nan-CWP-3	Nanyuki	19	25	36,119.2	17.7	Yes
Nan-CWP-4	Nanyuki	24	27	15,807.8	3.6	Yes
Nan-CWP-5	Nanyuki	9	20	17,611.6	7.1	No
Ngu-CWP-1	Ngusishi	15	3	2576.4	0.2	No
Ngu-CWP-2	Ngusishi	14	8	22,157.2	24.9	Yes
Ngu-CWP-3	Ngusishi	7	5	834.5	0.1	Yes
Ngu-CWP-4	Ngusishi	14	6	2836.3	0.4	No
Ngu-CWP-5	Ngusishi	5	8	10,074.3	4.1	Yes
NN-CWP-1	Ngare Nything	14	15	8214.7	1.2	Yes
NN-CWP-2	Ngare Nything	12	11	6661.7	1.3	No
NN-CWP-3	Ngare Nything	15	1	983.3	0.1	Yes
NN-CWP-4	Ngare Nything	27	7	2210.4	0.1	No
NN-CWP-5	Ngare Nything	41	24	59,396.7	57.6	Yes
T-CWP-1	Timau	14	4	2399.3	0.4	No
T-CWP-2	Timau	31	3	1755.6	0.1	No
T-CWP-3	Timau	27	2	3947.6	0.5	No
T-CWP-4	Timau	30	11	10,670.8	5.2	Yes
T-CWP-5	Timau	29	12	5599.8	1.2	Yes

Notes: [†]*Pseudonym used for CWP name.*

where individual decisions to excessively use water reduces availability to all other users, or provision dilemmas, where individuals may choose to free-ride rather than provide labor input to maintain the system's physical infrastructure. Rules crafted to overcome the appropriation dilemma include those specifying the actions that are and are not permissible when using water as well as those that specify the penalty for violating an agreed upon water use rule. The provision dilemma is addressed with rules specifying the regularity with which labor must be committed for infrastructure repairs as well as the penalty for failure to contribute labor. Several of these institutions are listed in Table 4.2. Collective action may also be challenged by certain features of an irrigation system's membership, such as a large, heterogeneous membership that is particularly unengaged with water issues. We include several variables in our statistical analysis, described below, to account for these obstacles.

A final notable rule crafted by the management committee explains the process by which water is rationed amongst the CWP members when it is in short supply. This typically involves a rotation schedule where water may only pass through a particular line once or twice a week. For example, a CWP with three major lines, A, B, and C, may only allow water to pass to the members of line A on Monday and Thursday, to the members of line B on Tuesday and Friday, to the members of line C on Wednesday and Saturday, and to no members on Sunday by closing all lines. The caretaker of the CWP is often responsible for opening and closing lines during the rotation process. In CWPs with smaller memberships, such rotation programs only occur during the driest months, while CWPs with larger memberships enforce rotations year-round.

4.3. Data and methods

4.3.1. Data collection

The data to evaluate household-level water delivery were collected during an eight month period from the end of May 2013 to the end of January 2014. These data group into four categories: household survey, manager survey, CWP mapping, and household water flow data.

4.3.1.1. Household survey data

Household surveys were administered to 750 smallholder farmers across the twenty-five CWPs from the end of May 2013 to the beginning of September 2013. Kenyan enumerator teams administered the surveys and were accompanied by American research assistants and graduate students. In CWPs with large memberships, surveys were conducted with at least thirty households when possible, while in CWPs with smaller memberships (i.e., less than sixty members), at least fifty percent of the member households were sampled. Surveys had a duration of approximately forty-five minutes and included questions concerning water use activities, agricultural practices, and household and community attributes (Table 4.3). In an effort to obtain a representative sample of households, survey teams visited households along all major distribution lines within each CWP. Thus, if a CWP had three major lines, enumerators would split themselves among these three lines. While sampling along each distribution line, enumerators visited every third household in order to avoid clustering the sampled households. At the conclusion of each survey, a GPS point was recorded to geo-locate responses.

The household survey data are the primary data source we used to construct household level variables for a multilevel regression model, which is described below.

4.3.1.2. Manager survey data

The chairperson, or in some cases another member of the management committee, of each CWP was surveyed to gain an understanding of the community’s rules-in-use as well as community

Table 4.2. Select institutional infrastructure attributes of CWPs.

CWP name[†]	WRUA abbreviation[‡]	CWP allows new members	Person must be member of particular village to join CWP	Caretaker must monitor water use	Water cut off for tampering with pipes	Monetary fine if no labor provided for CWP maintenance	Wet season water rotation strategy [§]
L-CWP-1	L	No	No	No	Yes	Yes	NR
L-CWP-2	L	Yes	No	No	Yes	Yes	NR
L-CWP-3	L	Yes	No	Yes	Yes	Yes	WSWR
L-CWP-4	L	Yes	No	No	Yes	No	NR
L-CWP-5	L	Yes	No	No	No	Yes	WSWR
Nan-CWP-1	Nan	Yes	Yes	Yes	Yes	Yes	WSWR
Nan-CWP-2	Nan	Yes	Yes	No	No	Yes	WSWR
Nan-CWP-3	Nan	Yes	No	Yes	Yes	No	WSWR
Nan-CWP-4	Nan	Yes	Yes	Yes	No	No	NR
Nan-CWP-5	Nan	Yes	No	Yes	No	Yes	NR
Ngu-CWP-1	Ngu	Yes	No	Yes	No	Yes	NR
Ngu-CWP-2	Ngu	Yes	Yes	No	Yes	No	WSWR
Ngu-CWP-3	Ngu	No	No	No	No	Yes	NR
Ngu-CWP-4	Ngu	No	No	Yes	No	No	WSWR
Ngu-CWP-5	Ngu	Yes	No	No	No	Yes	WSWR
NN-CWP-1	NN	Yes	Yes	Yes	Yes	Yes	WSWR
NN-CWP-2	NN	No	No	Yes	Yes	Yes	WSWR
NN-CWP-3	NN	Yes	No	Yes	Yes	Yes	WSWR
NN-CWP-4	NN	Yes	No	No	No	Yes	NR
NN-CWP-5	NN	Yes	No	Yes	No	Yes	WSWR
T-CWP-1	T	No	No	Yes	No	No	WSWR
T-CWP-2	T	Yes	Yes	No	No	Yes	WSWR
T-CWP-3	T	No	No	No	No	Yes	WSWR
T-CWP-4	T	No	No	No	Yes	No	WSWR
T-CWP-5	T	No	No	Yes	No	Yes	WSWR

Notes: [†]*Pseudonym used for CWP name.* [‡]*WRUA abbreviation – L=Likii, Nan=Nanyuki, Ngu=Ngusishi, NN=Ngare Nything, T=Timau.* [§]*Wet season water rotation strategy – NR=No rotation (CWP does not enforce water rotation at any point in the year), WSWR = CWP enforces a wet season water rotation strategy (and likely enforces a dry season rotation as well).*

assets (e.g., water storage tanks and reservoirs) and threats facing the CWP, such as droughts (Table 4.3). Additionally, these surveys provided information concerning the CWP's physical infrastructural make-up, such as the size and age of distribution lines. Surveys were administered from the beginning of June 2013 to beginning of September 2013.

Table 4.3. Data collection summary

Data category	Period of collection	Total observations	Select information provided
Household surveys	May 2013 – Sept. 2013	750	-Number of years in current location -Water storage assets -Agricultural practices -Household geographic location
Manager surveys	June 2013 – Sept. 2013	25	-Rules-in-use, including water rotation strategies, penalties for rule violation, monitoring obligations, and constraints on membership -Community level water storage assets
CWP mapping	June 2013 – Sept. 2013	25	-Geospatial dataset of pipe locations -Total number and diameter of CWP distribution lines -Total length of CWP distribution lines -Areal coverage of CWP -CWP intake location
Household water flow	July 2013 – Jan. 2014	A total of 370 households were sampled, but the spread across CWPs and the total number of weekly measurements varies. Ten households were sampled in small CWPs, while 20 were sampled in larger CWPs. The fewest number of weekly measurements for a sampled household was 21, while the largest number of weekly measurements was 28.	-Average flow rate (L/min) for all sampled households -Coefficient of variation of flow rate for all sampled households

The data derived from the manager surveys are used to determine the age of CWPs and, most significantly, to inform our construction of institutional variables that are used in a multilevel model.

4.3.1.3. CWP mapping

The distribution lines of each CWP were mapped over a two month period, from June to August 2013. A high-precision GPS unit was used to record pipe locations. Mapping was aided by the CWP's caretaker who guided the process and provided details concerning pipe diameter.

From this exercise we have information on the number of distribution lines, total pipe length, pipe diameter, and areal coverage of the CWP, which account for the physical human-made infrastructure variables in the multilevel regression model described below. Further, the mapping effort provided geospatial information that were used to calculate the elevation gradient over which water traversed.

4.3.1.4. Household water flow data

To gauge water delivery at individual households, flow measurements were taken at a subset of homes within each CWP from July 2013 to the end of January 2014. In smaller CWPs, ten households were measured, while in larger CWPs, flow was measured at twenty households. Homes that took part in the water flow measurements had also taken part in the household survey. When identifying candidates for the water flow sample, we ensured that we selected households at the head-end, middle, and tail-end of the CWP.

Initial efforts to measure water delivery relied on flow sensors affixed to individual household lines; however, the large amount of sediment in the pipes resulted in water flow becoming obstructed by the sensors. As a result, discrete flow measurements were instead taken once a week by recording the time needed to fill an 18L bucket. To ensure comparability across weeks, measurements were made from the same line after all other household lines and taps had been turned off. In total, water flow was measured at 370 households (Table 4.3); however, we were compelled to stagger the starting date of each CWP's flow measurement campaign due to logistical challenges. This resulted in a greater number of household measurements within some CWPs than others. For example, in the CWP that was last to begin flow measurements, each of the twenty sampled households were visited a total of twenty-one times from September 9, 2013 to January 24, 2014, while in the CWP that was first to begin flow measurements, each of the twenty sampled households were visited a total of twenty-eight times from July 9, 2013 to January 29, 2014.

These flow measurements are used to construct the dependent variables for the multilevel regression model. Further, they inform our investigation of water asymmetries both within and across CWPs, which we address in the Results section.

4.3.2. Multilevel regression model

Data at both the community and household level were included in a multilevel regression. We did not include WRUA level variables in the analysis for reasons specified below. This section summarizes the variables at the community and household level believed to influence water delivery and then describes the multilevel model itself.

4.3.2.1. Dependent variables: Average water flow and water flow variability

Two household level dependent variables were constructed: average water flow and water flow variability. Both of these variables will help to understand the contextual drivers of water delivery (research question 1) and household water asymmetries (research question 2) within a CWP. Flow variability relates to the *dependability* performance measure, which Molden and

Gates (1990) described as the temporal uniformity of the delivered amount of water. Average flow rate is loosely related to the measure of *adequacy* from the same study, but we do not incorporate crop water demand into this measurement as Molden and Gates propose.

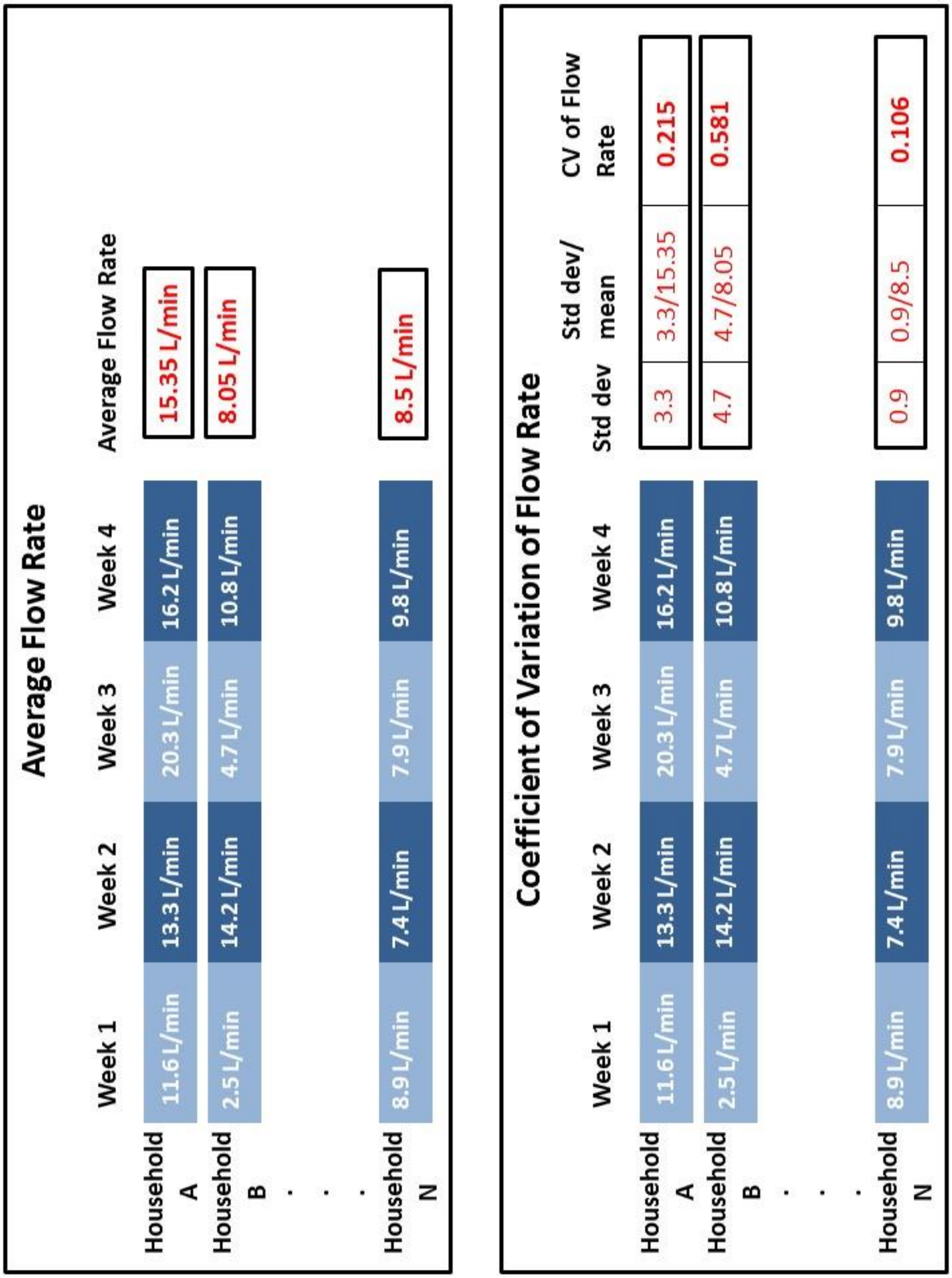
We calculated average flow rate simply by finding the average flow (measured in L/min) for each of the sampled households across the total number of weeks in which measurements were taken (example given in Figure 4.3). We assessed flow variability by calculating the coefficient of variation (CV) of water flow for each of the sampled households. This was done by calculating the standard deviation of flow for each household across the total number of measurement weeks. Standard deviation of flow was then divided by average flow for each household, which provided the household CV of water flow (Figure 4.3). Descriptive statistics of both of these performance measures are found in Table 4.4.

4.3.2.2. Independent variables: Multilevel CIS drivers of water delivery outcomes

We have split the CIS explanatory variables into four categories for clarity purposes: physical human-made infrastructure; institutional infrastructure; biophysical traits; and other pathways, including collective action obstacles (Table 4.4). Within each category, we have indicated whether or not the driver is a community level variable (level 2) or household level variable (level 1). Several of the variables within the *Institutional infrastructure* category represent a summation of total conditions, total sanctions, or total number of monitoring entities. For example, water use may be monitored by WRUA personnel, the CWP caretaker, and representatives of each distribution line in one CWP (three monitoring entities), while another CWP may only monitor water use through the caretaker (one monitoring entity). Lam (1998) employed this summation approach in his study of resource outcomes as well. Some of the more commonly occurring penalties or membership criteria are listed in the notes portion of Table 4.4 for these summation variables. All explanatory variables listed in Table 4.4 were included in the multilevel models, described below, except *Total pipe length (m)*. This variable was eliminated because it was highly correlated with *Areal coverage (km2)*, *Total members*, and *Number of distribution lines*.

The hypothesized relationships between the independent variables and the water flow outcomes are specified in Table 4.5. Looking first at the variables in the *Physical human-made infrastructure* category, our expectations were influenced by studies such as Makurira et al. (2007), which found that larger, more complex distribution networks within their study had higher incidences of water conveyance loss. Therefore, variables that indicated that water would be traveling extended distances to reach households (e.g., *Areal coverage* or *Distance intake to household*) or that water would traverse a complex network of pipes (e.g., *Number of distribution lines*) were expected to slow average water flow and increase water flow variability. The age of the CWP also was anticipated to influence water flow outcomes, with older pipe networks expected to have higher incidences of leakage leading to slower average water flow and increased variability.

Rules that are well-crafted to fit local conditions and agreed upon by resource users are anticipated to facilitate collective-action and effective stewardship (Lam 1998). Because each of the analyzed CWPs has been given autonomy to devise its own rules, we hypothesized that governance regimes imposing more water use restrictions would associate with stronger water delivery outcomes (i.e., higher average water flow and lower flow variability), while fewer restrictions would represent a missed opportunity to organize water management responsibilities and would therefore detract from household level water delivery (Table 4.5). This hypothesis



Average Flow Rate

	Week 1	Week 2	Week 3	Week 4	Average Flow Rate
Household A	11.6 L/min	13.3 L/min	20.3 L/min	16.2 L/min	15.35 L/min
Household B	2.5 L/min	14.2 L/min	4.7 L/min	10.8 L/min	8.05 L/min
. . .					
Household N	8.9 L/min	7.4 L/min	7.9 L/min	9.8 L/min	8.5 L/min

Coefficient of Variation of Flow Rate

	Week 1	Week 2	Week 3	Week 4	Std dev	Std dev/ mean	CV of Flow Rate
Household A	11.6 L/min	13.3 L/min	20.3 L/min	16.2 L/min	3.3	3.3/15.35	0.215
Household B	2.5 L/min	14.2 L/min	4.7 L/min	10.8 L/min	4.7	4.7/8.05	0.581
. . .							
Household N	8.9 L/min	7.4 L/min	7.9 L/min	9.8 L/min	0.9	0.9/8.5	0.106

Figure 4.3. Representation of steps to calculate average household flow rate (top schematic) and the coefficient of variation of household flow rate (bottom schematic).

Table 4.4. Summary statistics

Variable name	Variable description	Mean	SD	Min	Max
Dependent variables					
Average flow rate (L/min)^{HH}	Refer to section 4.2.1.	17.8510	14.451	3.8081	161.51
CV of water flow^{HH}	Refer to section 4.2.1.	0.2816	0.1782	0.0460	1.6034
Independent variables: Physical human-made infrastructure					
Areal coverage (km2)^{CWP}	Total area occupied by the CWP in km^2	6.612	12.121	0.0352	57.612
Number of distribution lines^{CWP}	Total number of CWP distribution lines	10.00	7.632	1.00	27.00
Pipe size at wtr source abs. point (inches)^{CWP}	Diameter of pipe where water is abstracted from river/spring	5.854	1.592	2.00	8.00
Total pipe length (m)^{CWP}	Sum of all distribution lines in meters	12,072.0	13,830	834.53	59,396
Distance wtr source to head-end (m)^{CWP}	Distance from river or spring to CWP head-end (m)	3277.702	3,064.5	1.00	11,928
Age of CWP^{CWP}	Age of water project	18.84	8.987	5.00	41.00
Distance head-end to household (m)^{HH}	Distance from CWP head-end to household (m)	2194.12	1,382.9	49.552	6870.2
Independent variables: Institutional infrastructure					
Membership change^{CWP}	Does the CWP allow new members to join?	0.6800	0.4665	0.00 (No)	1.00 (Yes)
Wet season rotation^{CWP}	Does the CWP rotate water during the wet season?	0.6800	0.4665	0.00 (No)	1.00 (Yes)
Membership criteria – Total conditions^{CWP}	Count of conditions to be met in order to join CWP [†]	2.5189	0.5741	2.00	4.00
Pipe damaging – Total sanctions^{CWP}	Count of sanctions imposed for damaging pipes[‡]	1.3919	0.800	1.00	4.00
Failure to pay fee – Total sanctions^{CWP}	Count of sanctions imposed for failing to pay monthly fee[§]	0.9459	0.6882	0.00	2.00
Failure to work – Total sanctions ^{CWP}	Count of sanctions imposed for failing to provide labor[ǀ]	1.2270	0.513	0.00	2.00
Wtr use monitoring – Total entities^{CWP}	Count of different groups responsible for monitoring illegal water use[¶]	2.2405	1.2650	0.00	5.00
Independent variables: Biophysical traits					
Elev. gradient wtr source to intake^{CWP}	Elevation gradient from water source to CWP intake	0.0332	0.0299	0.00	0.1100
Elev. gradient	Elevation gradient from CWP	0.0347	0.0228	-0.0432	0.1081

intake to household^{HH}	intake to household				
Independent variables: Other pathways (including collective-action obstacles)					
Total members^{CWP}	Total CWP membership	272.6838	237.84	10.00	928.00
Count of tribes^{CWP}	Count of CWP's tribal groups	2.1378	0.9928	1.00	5.00
Count of water storage devices^{HH}	Count of HH storage devices (large tanks and reservoirs)	0.5973	0.6388	0.00	2.00
Years at residence^{HH}	Number of years at residence	19.9270	11.208	2.00	60.00
Meeting attendance^{HH}	Num. of wtr meetings attended in last year (categorical)	2-5 (most common group)		Never	6+

Notes: $^{CWP/HH}$*Indicates whether the variable is at the community or household level.*

[†] *Most frequently reported conditions: Must own land (24 CWPs), must pay membership fee (24).*

[‡] *Most frequently reported pipe damaging sanctions: Water is disconnected (11).*

[§] *Most frequently reported sanctions for failing to pay monthly fee: Water is disconnected (17).*

[|] *Most frequently reported sanctions for failing to contribute labor: Monetary sanctions are imposed (18), water is disconnected (9).*

[¶] *Entities most often involved in monitoring: Management committee members (21), caretaker (13), neighbors (9).*

was dependent on the assumption that resource managers within the study area are well-informed and willing to make decisions in the best interests of their constituents; we attempted to capture resource manager knowledge of member concerns with the variable *Meeting attendance*. The decision of a water manager to curb a CWP's membership growth (i.e., a 'No' response to *Membership change*) was believed to be the product of a well-calculated weighing of information concerning water supply against an understanding of CWP water demand. Better access and utilization of information by CWP decision makers to make difficult decisions with respect to membership growth was anticipated to result in strong resource allocation outcomes (e.g., Agrawal and Gupta 2005). A CWP employing a wet season water rotation schedule was expected to lower average household water flow and increase household flow variability since, in

Table 4.5. Hypothesized relationships

Category[†]	Parameter	Hypothesized relationship with average household flow rate	Hypothesized relationship with household CV of water flow
PHMI	Areal coverage of CWP	Negative	Positive
	Num. of distribution lines	Negative	Positive
	Pipe size at wtr source abstraction point	Positive	Negative
	Distance wtr source to head-end	Negative	Positive
	Age of CWP	Negative	Positive
	Distance head-end to household	Negative	Positive
II	Membership change (allows mem. growth)	Negative	Positive
	Wet season rotation (rotates during WS)	Negative	Positive
	Membership criteria – Total conditions	Positive	Negative
	Pipe damaging – Total sanctions	Positive	Negative
	Failure to pay fee – Total sanctions	Positive	Negative
	Failure to work – Total sanctions	Positive	Negative
	Water use monitoring – Total entities	Positive	Negative
BT	Elev. gradient wtr source to intake	Positive	Negative
	Elev. gradient intake to household	Positive	Negative
CA/OP	Total members	Negative	Positive
	Count of tribes	Negative	Positive
	Count of water storage devices	Negative	Positive
	Years at residence	Positive	Negative
	Meeting attendance (more frequent attendance)	Positive	Negative

Notes: [†]*Category abbreviations – PHMI=Physical human-made infrastructure, II=Institutional infrastructure, BT=Biophysical traits, CA/OP=Obstacles to collective action/other pathways.*

some CWPs, the need to rotate water during the wet season represents membership growth beyond an optimal level.

It should be noted here that all of the independent variables in the institutional infrastructure category were reported to us by the CWP managers as “rules-in-use.” In other words, these are rules that, according to the managers, are truly employed on-the-ground. The reason we make this distinction here is to separate these rules from formal practices that may exist on paper but are not enforced in practice.

The anticipated relationships between the biophysical drivers and the water flow outcomes simply reflect the expectation that resource delivery would improve in the presence of a steeper elevation gradient (Table 4.5).

Finally, we offer hypothesized relationships for the variables within the *Other pathways* category (Table 4.5). Larger memberships were expected to hinder water delivery due to its association with increasing coordination and organizational challenges (R. Hardin 1982), more heterogeneous groups were also expected to hinder water delivery due to challenges posed to trust and cooperation (Ostrom 2005), and an increasing number of water storage devices was expected to lead a household to devalue their user group as water could be provided through multiple sources. In this category, we have also included *Years at residence* and *Meeting attendance*, which were both intended to capture individual engagement in CWP responsibilities. A long-standing member who frequently participates in community meetings was expected to be more engaged in repairing physical infrastructure and reporting flow problems, and would therefore be expected to have higher household flow rates and lower flow variabilities (Kopelman et al. 2002, Lockwood et al. 2010). Additionally, an engaged member who attends multiple meetings is able to transfer valuable CWP branch or zonal information to those at the management level who are responsible for making upkeep and repair decisions (Ostrom and Gardner 1993).

4.3.2.3. Multilevel model description

Multilevel regression models were developed due to the hierarchy of predictor variables. These models are a complex class of ordinary least squares (OLS) regression, but unlike OLS analysis, multilevel regressions allow for relationships both within and between multiple levels of grouped data to be inspected (Woltman et al. 2012). In the present analysis, two hierarchical levels exist: households (level 1) and CWPs (level 2). We did not include the WRUAs as a third level in our model for two reasons. First, the twenty-five CWPs from which we surveyed households are located in five WRUAs; thus, the number of groups within a third level would have been only five, potentially biasing the results due to the low count (Kreft and de Leeuw 1998, Maas and Hox 2007). Second, while the WRUA structures water sharing schedules during the dry season, its role ostensibly ceases once water is withdrawn from the river by the CWP. And because WRUA water sharing schedules are inflexible (personal correspondence) – that is, they do not change during the year – the WRUAs ultimate influence on household level water delivery is likely minimal in comparison to the role of the CWP. Both of the level 1 dependent variables in the model, average water flow and CV of water flow, were logged to create normal distributions.

To demonstrate the model, consider Eq. (1):

$$Y_{ij} = \beta_0 X_0 + \sum_{p=1}^{P} \beta_p X_{ijp} + \sum_{q=1}^{Q} \gamma_q Z_{jq} + \sum_{j=1}^{J} (u_{j0} Z_{j0} + u_{j1} Z_{j1}) + e_{ij} \quad \text{(equation 1)}$$

Where:

Y_{ij} = dependent variable measured for the *i*th household nested within the *j*th CWP;

β_0 = intercept parameter;

X_0 = indicator for the intercept parameter;

β_p = household level parameter capturing the model's fixed effects;

γ_q = CWP level parameter capturing the model's fixed effects;

X_{ijp} = the *p*th predictor depicting the household characteristics;

Z_{jq} = the *q*th predictor depicting the CWP characteristics;

u_{j0} = random effects of the *j*th CWP on the intercept;

u_{j1} = random effects of the *j*th CWP on the slope;

Z_{j0} = indicators for the *j*th CWP's random intercept;

Z_{j1} = indicators for the *j*th CWP's random slope;

e_{ij} = random error term associated with the *i*th household nested within the *j*th CWP.

Fixed effects, or values that do not vary across groups, were captured at the household level with β_p and at the CWP level with $\gamma_{q.}$ The X_{ijp} and Z_{jq} terms represented the household level and CWP level predictors, respectively. Random effects, or values that are allowed to vary across groups, were captured at the household level by e_{ij} and at the CWP level with u_{j0} and u_{j1}.

We used SAS' MIXED procedure to perform the analysis and restricted maximum likelihood (REML) to estimate the parameters. The REML method has been shown to produce more accurate estimates of random effects (Twisk 2006). A covariance structure was specified given the presence of random effects. We experimented with several covariance structures and settled on the *variance components* structure. In building the multilevel model, we followed the suggestion of Raudenbush and Bryk (2002): we initially defined all variables as fixed and then incrementally added them to the random statement until we found the best fit model. We tested for multicollinearity with these configurations of independent variables using the VIF option in SAS. All VIF values were below 10 suggesting that multicollinearity was not an issue.

4.4. Results

All CWPs strive for equitable water distribution to members. For many CWPs, this is a core objective explicitly stated in their constitution and it is presumed that every connection should receive the same amount of water. However, Table 4.6 illustrates the asymmetries that exist within the CWPs and the clear reality that achieving equitable distribution is exceedingly difficult. These results help to satisfy our second research question, which sought to understand disparities of water delivery within and between communities. All CWPs had at least one household with a flow variability (i.e., CV of water flow) that was at least one standard deviation greater than the CWP's mean variability (represented in Table 4.6 as the percentage of all surveyed households in a particular CWP with mean variability greater than one standard deviation of the CWP's mean variability). In other words, if one standard deviation is taken as the cutoff between acceptable and inadequate dependability of water delivery, then no CWP appears to be delivering water at a consistency that is acceptable to all members. There also does not appear to be a clear trend in terms of dependability of flow for CWPs of the same WRUA. For instance, the Nanyuki WRUA includes Nan-CWP-3, which had the smallest percentage of sampled households with inadequate dependability; however, it also includes Nan-CWP-5, which had the largest percentage of households with inadequate dependability. We acknowledge that water asymmetries could be further investigated by comparing household water supply to household water demand, since some households, such as those that are heavy irrigators, will demand more water than others. This was not analyzed in the current article since we were primarily interested in understanding the *supply* of water within CWPs, i.e., the drivers of water delivery and inequities in water delivery. We anticipate investigating water supply asymmetries alongside water demand in future analyses.

In terms of average flow rate, households also experience a range of outcomes (Table 4.6). For instance, the average household flow rate in NN-CWP-5, a CWP covering an area of 57.6 km^2, was 8 liters per minute, while Ngu-CWP-1, which occupies only 0.2 km^2, had an average flow rate of 44 liters per minute. As was true with flow variability, asymmetries of flow rate were present not only between CWPs, but also within them. Of the twenty-five CWPs, only six were able to deliver water to all households at a rate that was within one standard deviation of the CWP mean flow rate. In two CWPs, nearly a third of surveyed households were receiving water at a rate one standard deviation below the CWP mean flow rate, and in an additional eleven CWPs, water flow rate was below the one standard deviation benchmark for at least fifteen percent of households.

With evidence clearly suggesting that CWP water distribution is heterogeneous both within and between CWPs, the multilevel regression models were used to understand the contextual elements that drive these water delivery outcomes. Further, with the regression models accounting for the broader CIS, rather than predominately focusing on the institutional structure, and with performance assessed using household level water delivery data, rather than relying on a proxy for performance, the results are intended to offer explanations for resource delivery that have yet to be provided in the common-pool resource literature. These multilevel regression results help to satisfy our first research question, which sought to understand how elements of the CIS influence water delivery. Examining first the model with the log of average household flow rate as the dependent variable (Table 4.7), the challenge of delivering an adequate amount of water to households to meet their farming needs is significantly associated with several traits from the *Physical human-made infrastructure* category. Households that are within older CWPs possessing more distribution lines appear to have higher average household water flow rates. This contradicts two of our proposed hypotheses from Table 4.5 and suggests that a CWP such as NN-CWP-5 (established in 1972 with twenty-four distribution lines) may provide a superior rate of flow to its households compared to households within a CWP such as Ngu-CWP-5 (established in 2008 with eight distribution lines). Consistent with our hypothesized relationships, household flow rates were higher when water traverses a shorter distance and a steeper elevation gradient, both from the river to the CWP intake and from the CWP head-end to the homestead (from the *Biophysical traits* category, though only significant at the 0.10 level). Thus, a household positioned at the tail-end of the system infrastructure in Ngu-CWP-2 (total length of distribution lines: 22,157 m) on average experiences lower flow rates than a household at the tail-end of the Ngu-CWP-3 system (total length: 834 m).

Within the *Institutional infrastructure* category, the significant relationships suggest that household water flow rates are higher within CWPs that allow membership to grow and enforce a smaller set of sanctions for pipe damaging. These two associations counter hypotheses from Table 4.5, which anticipated that CWP performance would be improved if there were fewer households to distribute water to (i.e., capping membership) and managers were willing to craft a range of sanctioning strategies to counter illegal activities. Finally, within the *Collective action / other pathways* category, total membership is negatively associated with household flow rate. This relationship is consistent with our hypothesis that collective action may be challenged by a larger membership group, resulting in poorer water delivery.

Examining the second multilevel regression model (Table 4.8), which used the log of household CV of water flow as the dependent variable, only one variable within the *Physical human-made infrastructure* category was found to be significant: the number of distribution lines. This association suggests that households within a CWP with more distribution lines will have less dependable water flow, which is consistent with our hypothesis from Table 4.5. Therefore, despite households within numerous-lined CWPs such as NN-CWP-5 having higher flow rates on average, as suggested by the previous regression model, the reliability of water delivery to these same households may be poorer.

Within the *Institutional infrastructure* category, households belonging to CWPs imposing wet season water rotations and a smaller set of sanctions for failing to pay the CWP's monthly maintenance fee were found to have more reliable household water flow. These relationships challenge our proposed hypotheses and suggest that a household within a CWP such as L-CWP-3, which rotates water between members during the wet season, may have more reliable water delivery than a household within a CWP that never rotates water. Additionally, a larger set of conditions needed to be filled to join a CWP appears to associate with more reliable flow, which, in this case, is consistent with our proposed hypotheses (although this variable is only significant at the 0.10 level).

Finally, with respect to the *Collective action / other pathways* category, more heterogeneous memberships associate with more reliable water delivery. This relationship again challenges one of our proposed hypotheses, which anticipated that the more dissimilar a group, the more difficult it would be for individuals to collectively solve appropriation and provision dilemmas, thus resulting in less reliable water delivery. In the next section we provide additional perspective to these results by discussing potential causality concerns, which may offer explanations for some of the confounding relationships.

In terms of the practical significance of the predictor variables from Tables 4.7 and 4.8, we have calculated each variable's marginal effect to estimate the effect of a one standard deviation increase in the predicator variables (Table 4.9). We produced these estimates in a

Table 4.6. CWP water asymmetries

CWP name[†]	WRUA abbreviation[‡]	Avg flow rate (L/min) (Percentage of sampled households with average flow rate 1 standard deviation below CWP mean flow rate)	Avg CV of water flow (Percentage of sampled households with average CV of water flow 1 standard deviation above CWP mean variability of flow)
L-CWP-1	L	13.0866 (0%)	0.3960 (25%)
L-CWP-2	L	12.7313 (18%)	0.1667 (18%)
L-CWP-3	L	11.5201 (7%)	0.2589 (7%)
L-CWP-4	L	8.7187 (17%)	0.3040 (17%)
L-CWP-5	L	10.0539 (18%)	0.2001 (18%)
Nan-CWP-1	Nan	7.5175 (10%)	0.3506 (10%)
Nan-CWP-2	Nan	16.7484 (0%)	0.3951 (20%)
Nan-CWP-3	Nan	13.7884 (24%)	0.2323 (6%)
Nan-CWP-4	Nan	43.4037 (0%)	0.2736 (22%)
Nan-CWP-5	Nan	17.0160 (17%)	0.4679 (25%)
Ngu-CWP-1	Ngu	44.0366 (0%)	0.2277 (22%)
Ngu-CWP-2	Ngu	14.7535 (0%)	0.2612 (11%)
Ngu-CWP-3	Ngu	15.2452 (29%)	0.2134 (14%)
Ngu-CWP-4	Ngu	24.1239 (20%)	0.2576 (15%)
Ngu-CWP-5	Ngu	11.5243 (16%)	0.2595 (11%)
NN-CWP-1	NN	41.4151 (0%)	0.1913 (16%)
NN-CWP-2	NN	11.7590 (16%)	0.2865 (21%)
NN-CWP-3	NN	15.8447 (6%)	0.1700 (6%)
NN-CWP-4	NN	25.5290 (30%)	0.4806 (10%)
NN-CWP-5	NN	8.0075 (18%)	0.4012 (18%)
T-CWP-1	T	11.3636 (5%)	0.3221 (11%)
T-CWP-2	T	20.8532 (22%)	0.1630 (17%)
T-CWP-3	T	22.2708 (12%)	0.3011 (18%)
T-CWP-4	T	17.8944 (19%)	0.3147 (19%)
T-CWP-5	T	22.8324 (8%)	0.2640 (17%)

Notes: [†]Pseudonym used for CWP name.
[‡] WRUA abbreviation – L=Likii, Nan=Nanyuki, Ngu=Ngusishi, NN=Ngare Nything, T=Timau.

similar fashion as Cox and Ross (2011): the standard deviation of each predictor variable from Table 4.4 was multiplied by the coefficients derived from the multilevel regressions (Tables 4.7 and 4.8) to estimate the marginal effect. These values were then divided by the standard deviation of the outcome variables to calculate the percentage of the outcome variables' standard deviation accounted for within the marginal effect. For instance, the marginal effect of the

Table 4.7. Multilevel model results: Average household flow rate

Category†	Parameter	Estimate	Std Err	p	95% CI	
	Intercept	2.421	0.465	<0.001	1.4595	3.381
PHMI	Areal coverage of CWP^{CWP}	-0.014	0.009	0.110	-0.0310	0.003
	Num. of distribution lines^{CWP}	0.025	0.010	0.015	0.0049	0.044
	Pipe size at wtr source abstraction point^{CWP}	0.013	0.049	0.794	-0.0832	0.108
	Distance wtr source to head-end^{CWP}	0.000	0.000	0.386	-0.0000	0.000
	Age of CWP^{CWP}	0.023	0.009	0.010	0.0055	0.039
	Distance head-end to household^{HH}	-0.000	0.000	0.034	-0.0001	-0.00
II	Membership change^{CWP}	0.255	0.126	0.043	0.0076	0.503
	Wet season rotation^{CWP}	0.091	0.131	0.484	-0.1654	0.348
	Membership criteria – Total conditions^{CWP}	0.022	0.130	0.867	-0.2329	0.276
	Pipe damaging – Total sanctions^{CWP}	-0.158	0.080	0.048	-0.3157	-0.01
	Failure to pay fee – Total sanctions^{CWP}	-0.169	0.151	0.264	-0.4655	0.128
	Failure to work – Total sanctions^{CWP}	-0.198	0.130	0.130	-0.4547	0.058
	Water use monitoring – Total entities^{CWP}	-0.072	0.068	0.286	-0.2067	0.061
BT	Elev. gradient wtr source to intake^{CWP}	3.516	2.011	0.080	-0.4234	7.455
	Elev. gradient intake to household^{HH}	2.867	1.516	0.060	-0.1174	5.851
CA/OP	Total members^{CWP}	-0.001	0.000	0.015	-0.0017	-0.00
	Count of tribes^{CWP}	0.085	0.053	0.110	-0.0194	0.189
	Count of water storage devices^{HH}	0.004	0.035	0.915	-0.0642	0.071
	Years at residence^{HH}	-0.000	0.002	0.863	-0.0037	0.003
	Meeting attendance$^{HH, \ddagger}$					
	-Never	-0.101	0.199	0.615	-0.5120	0.309
	-Once	-0.212	0.131	0.119	-0.4820	0.058
	-6+ times	-0.041	0.097	0.673	-0.2420	0.159
	Sample size	370				

Notes:$^{CWP/HH}$*Indicates whether the variable is at the community or household level.*
†*Category abbreviations – PHMI=Physical human-made infrastructure, II=Institutional infrastructure, BT=Biophysical traits, CA/OP=Obstacles to collective action/other pathways.*
‡*Meeting attendance: the reference variable is attendance of 2-5 meetings on water issues in the last year.*

Table 4.8. Multilevel model results: CV of water flow

Category[†]	Parameter	Estimate	Std Err	p	95% CI	
	Intercept	-0.164	0.456	0.721	-1.0823	0.754
PHMI	Areal coverage of CWP^{CWP}	0.012	0.008	0.169	-0.0050	0.006
	Num. of distribution lines^{CWP}	0.021	0.010	0.029	0.0022	0.040
	Pipe size at wtr source abstraction point^{CWP}	-0.060	0.046	0.197	-0.1495	0.030
	Distance wtr source to head-end^{CWP}	-0.000	0.000	0.970	-0.0001	0.000
	Age of CWP^{CWP}	-0.009	0.008	0.253	-0.0249	0.006
	Distance head-end to household^{HH}	0.000	0.000	0.410	-0.0000	0.000
II	Membership change^{CWP}	-0.139	0.119	0.246	-0.3730	0.096
	Wet season rotation^{CWP}	-0.339	0.127	0.008	-0.5889	-0.08
	Membership criteria – Total conditions^{CWP}	-0.228	0.123	0.065	-0.4694	0.014
	Pipe damaging – Total sanctions^{CWP}	0.038	0.074	0.603	-0.1065	0.183
	Failure to pay fee – Total sanctions^{CWP}	0.297	0.138	0.032	0.0257	0.568
	Failure to work – Total sanctions^{CWP}	-0.016	0.120	0.895	-0.2520	0.220
	Water use monitoring – Total entities^{CWP}	-0.084	0.066	0.203	-0.2138	0.045
BT	Elev. gradient wtr source to intake^{CWP}	-1.641	1.898	0.388	-5.3758	2.094
	Elev. gradient intake to household^{HH}	0.489	1.877	0.795	-3.2039	4.182
CA/OP	Total members^{CWP}	0.000	0.000	0.390	-0.0004	0.001
	Count of tribes^{CWP}	-0.110	0.051	0.033	-0.2103	-0.01
	Count of water storage devices^{HH}	-0.074	0.047	0.113	-0.1654	0.017
	Years at residence^{HH}	-0.000	0.002	0.890	-0.0049	0.004
	Meeting attendance^{HH,}[‡]					
	-Never	-0.081	0.192	0.672	-0.4588	0.296
	-Once	-0.025	0.113	0.822	-0.2475	0.196
	-6+ times	-0.099	0.089	0.264	-0.2735	0.075
	Sample size	370				

Notes:$^{CWP/HH}$*Indicates whether the variable is at the community or household level.*

[†] *Category abbreviations – PHMI=Physical human-made infrastructure, II=Institutional infrastructure, BT=Biophysical traits, CA/OP=Obstacles to collective action/other pathways.*

‡*Meeting attendance: the reference variable is attendance of 2-5 meetings on water issues in the last year.*

Table 4.9. Marginal effects

		Average flow rate (L/min)		CV of water flow	
Category†	Parameter	Marginal Effect	% of DV's std. dev.	Marginal Effect	% DV's std. dev.
PHMI	Areal coverage of CWP^{CWP}	-0.170	-1.17%	0.145	81.62%
	Num. of distribution lines^{CWP}	0.191	1.32%	0.160	89.94%
	Pipe size at wtr source abstraction point^{CWP}	0.021	0.14%	-0.096	-53.60%
	Distance wtr source to head-end^{CWP}	0.104	0.72%	-0.004	-2.34%
	Age of CWP^{CWP}	0.207	1.43%	-0.081	-45.39%
	Distance head-end to household^{HH}	-0.069	-0.48%	0.032	17.85%
II	Membership change^{CWP}	0.119	0.82%	-0.065	-36.39%
	Wet season rotation^{CWP}	0.042	0.29%	-0.158	-88.75%
	Membership criteria – Total conditions^{CWP}	0.013	0.09%	-0.131	-73.45%
	Pipe damaging – Total sanctions^{CWP}	-0.126	-0.87%	0.031	17.06%
	Failure to pay fee – Total sanctions^{CWP}	-0.116	-0.80%	0.204	114.70%
	Failure to work – Total sanctions^{CWP}	-0.102	-0.70%	-0.008	-4.61%
	Water use monitoring – Total entities^{CWP}	-0.091	-0.63%	-0.106	-59.63%
BT	Elev. gradient wtr source to intake^{CWP}	0.105	0.73%	-0.049	-27.53%
	Elev. gradient intake to household^{HH}	0.065	0.45%	0.011	6.26%
CA/OP	Total members^{CWP}	-0.238	-1.65%	0.078	43.64%
	Count of tribes^{CWP}	0.084	0.58%	-0.109	-61.28%
	Count of water storage devices^{HH}	0.003	0.02%	-0.047	-26.53%
	Years at residence^{HH}	-0.003	-0.02%	-0.004	-2.01%

Notes:$^{CWP/HH}$*Indicates whether the variable is at the community or household level.*
†*Category abbreviations – PHMI=Physical human-made infrastructure, II=Institutional infrastructure, BT=Biophysical traits, CA/OP=Obstacles to collective action/other pathways.*

number of distribution lines in the model explaining CV of water flow is 0.160 (0.021 * 7.632), which represents 90% of the standard deviation of CV of water flow (0.160 / 0.1782). Table 4.9

indicates that the marginal effects of the predictor variables in the average flow rate model are quite small given the wide range in household flow rates. In terms of the CV of water flow, the percentage of the dependent variable's standard deviation is much larger. This results from a narrower range between households with particularly reliable flow and households with particularly unreliable flow. While both models are valuable in understanding the contextual elements driving water delivery outcomes, Table 4.9 suggests the predictor variables to be more effective in explaining changes in the CV of water flow than average household water flow rate.

4.5. Discussion

4.5.1. Causality within a CIS

In this study we queried elements from the CIS's institutional, physical human-made, and biophysical infrastructures to evaluate resource provisioning by way of two multilevel models, which helped to satisfy our first research question. By including institutional, technological, and biophysical traits, a challenge emerged in interpreting our results related to the issue of causality. In explaining the issue of causality in CPR studies, Anderies et al. (2016) return to the idea that institutional arrangements have been favored in explanations of resource outcomes, and they go on to state that in some cases the assemblage of these institutional traits may actually be the product of dynamics within the CIS, not the treatment prescribed to remedy an unwanted resource outcome. In other words, the institutional infrastructure in some cases needs to be viewed as "emerging from" rather than being "assigned to" a particular situation (Anderies et al. 2016: 508). To demonstrate this further, we draw on one of the confounding relationships returned from the regression models.

Earlier, we hypothesized that household water flow rates would be lower within CWPs that enforced fewer sanctions for damaging CWP pipes. Our reasoning for this was as follows: more sanctions would lead to a more compliant CWP membership which would ensure the integrity of pipes and result in superior performance outcomes, such as higher household flow rates. Yet, our regression model returned the opposite result, suggesting that fewer sanctions for damaging pipes associates with higher flow rates. We speculate, however, that this is an instance of reverse causality where the decision of the CWP management committee to impose fewer sanctions reflects the committee's understanding that, for example, the physical human-made infrastructure is well-cared for and elements of the biophysical context will not impede delivery of water. In other words, the limited number of sanctions does not result in higher flow rates; rather, the causal pathway is reversed: superior flow rates achieved by, potentially, fitness of the physical human-made and biophysical infrastructures have allowed the management committee to impose fewer sanctions without detracting from water delivery outcomes. Agrawal (2001) similarly recognized that researchers needed to be cognizant of reverse causality in CPR-based case studies that predominately focused on institutional arrangements. In expanding our focus beyond the institutional infrastructure, our analysis provides new understandings of the causality issues raised both by Agrawal and Anderies et al. Furthermore, inclusion of elements from a broader CIS helps to avoid the spurious correlation fallacy: erroneously linking a particular outcome to a variable under study when the true relationship is with an omitted variable. Such is the risk of analyses that focus on the institutional infrastructure while overlooking other elements of the CIS.

4.5.2. Information exchange to improve outcomes

For the management committee of a CWP – or any of the various CPR user groups around the globe – to understand which households are receiving poor water delivery and the contributing forces of the CIS leading to this outcome, household level information is needed. We indicated earlier that financial and technological issues impede the use of flow sensors on household water distribution lines. In the absence of these measurement devices, branch or zonal representatives are responsible for reporting flow obstruction issues to their CWP management committee. This acts as an important information transfer intended to improve household water delivery. In the regression models, we included a variable for the number of times in a year that a household attended a meeting on water-related issues. In the absence of comprehensive data concerning the branch representatives and their duties, we believed that this variable would be an adequate alternative: an individual who is particularly concerned with water-related issues would be more likely to report such concerns to the management committee and, therefore, more likely to have better flow outcomes. We were surprised that this variable was insignificant in both of the regression models given the importance of knowledge transfers as it was explained to us during fieldwork. In fact, when a subset of the management committees were asked about the proceedings of their general meetings, fifteen of eighteen committees stated that complaints of low water flow were regularly voiced by branch representatives during these meetings. A subsequent review of the bylaws and constitutions that could be obtained from the CWP committees revealed that eleven of fourteen CWPs had positions on their committees specifically devoted to branch representatives charged with relaying constituent concerns.

It is possible that a variable better targeted at the relationship between branch representatives and management committees may have identified an information exchange signal. It may also be the case that this signal is captured in the significant relationship found between total membership size and household flow rate, which associates households within larger membership CWPs with lower flow rates (see Table 4.7). Studies such as Agrawal and Goyal (2001) have demonstrated that collective action can be challenged by group size. In our analysis, larger memberships may make coordination more difficult and obstruct formation of trust amongst membership. Information exchange between branch representatives and the CWP management committee may be one of the areas in which coordination difficulties result in water asymmetries. In this vein, we could expect communication within a CWP such as NN-CWP-4, which has twenty-five members, to be more fluid than within a CWP such as Nan-CWP-2, which has over 800 members. If this is true, then the information exchange signal may be captured within the relationship between membership size and water delivery.

The inability of CWP management committees to possess household level water delivery data, as well as the limited information concerning associations between CIS elements and water delivery, suggests that consistent meetings of membership and strong communication with the management committee may constitute the most effective strategies for resolving poor water delivery outcomes. The broad range of elements making up the CIS do seem to be common topics discussed during CWP meetings. Eight CWP management committees indicated that the condition of the physical human-made infrastructure is frequently discussed with their memberships and that assessments of the fitness of distribution lines are carried out whenever decisions to add new members are made. Topics discussed during these meetings include the age of the physical infrastructure and the number of distribution lines already existing on a particular branch. The institutional infrastructure also receives attention during these meetings. For example, evaluations of when to begin rotating water between distribution lines during the dry season critically impacts farmer planting and harvesting decisions. As the rainy season wanes, meetings are commonly held with CWP memberships to assess climate information provided by higher levels of governance (such as the catchment level WRUA) in order to evaluate the water rotation rule set. Finally, communication both among user group members as well as between these members and the management committee appears to be a priority of these meetings. Aside from individuals reporting water flow concerns at these general meetings, users will also address their concerns about the actions of other CWP members. In thirteen of eighteen interviews within management committees, grievances about the actions of another member, such as an individual's excessive water use or failure to keep a particular distribution line in good repair, were stated to be a common item at their general meetings. These channels for communication help to address collective action dilemmas when they arise and offer means by which water delivery concerns are addressed.

4.6. Conclusion

Managing a complex resource system relies on a wide swath of information about the CIS. This study demonstrated relationships between water delivery and a range of elements constituting the physical human-made, institutional, and biophysical infrastructures of twenty-five CWPs in the Mount Kenya region. In describing these relationships, we addressed causality issues as well as the role of information sharing in ensuring the success of a user group. As it relates to sharing of information, the importance of this action can be summarized as follows: due to the absence of real-time household level data to assess CWP performance, information sharing offers opportunities for members to relay concerns of poor flow and address issues they may have with the state of physical and institutional infrastructure.

We believe that this study makes several important contributions to the CPR literature, as well as the broader social-ecological systems (SES) literature, which we have repositioned around CISs. First, we have conducted an assessment of user group performance by employing household level data that avoids the use of a proxy variable. In estimating user group performance, we feel this is important in order to avoid complications introduced by intervening variables. Second, we address two commonly-stated concerns within the SES literature: that biophysical elements are underrepresented and that the significance assigned to institutional attributes when evaluating system outcomes is regularly overstated. Finally, we speak to the importance of communication and information sharing in the absence of sophisticated technologies geared toward evaluating resource provisioning. As it relates to research evaluating the successes and failures of CPR user groups, each of these contributions are ripe for further research and inquiry.

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Chapter 5: Conclusions

While Chapters 2-4 each ended with a summary of their primary findings, in this chapter I connect these findings by linking them to the major themes introduced in Chapter 1. After summarizing the findings, I close by highlighting future directions for this research.

5.1. Vulnerability and smallholder adaptation

Semi-arid systems pose many challenges to smallholder farmers. Earlier, increasingly variable precipitation events were listed as the primary challenge exacerbated by a warming climate within the Mount Kenya region. Taken together, Chapters 2-4 each describe a tenuous situation in which smallholders need to be aware of the vulnerabilities that they face. Chapter 2 focuses on crop diversification, a strategy that some farmers may employ to reduce their sensitivity to external shocks. This chapter advanced the notion that accessibility and socioeconomic standing may influence smallholder ability to adapt. In particular, this chapter revealed that households with higher incomes and more frequent exposure to extension agents were more likely to grow a diverse array of crops. Importantly, the biophysical environment was also found to play a role in cultivation strategies as smallholders in areas with greater average rainfall grew a wider range of crops.

This finding is consistent with studies such as Deressa et al. (2009), which demonstrate that the biophysical environment limits the range of adaptation measures available to smallholders. However, it also suggests a role for water governance in reducing smallholder sensitivity to water shortages. Crop diversity was highest within the communities belonging to the Likii WRUA (Figure 5.1). Well-developed water management rules exist within these communities, including rules for the upkeep of irrigation infrastructure. While these communities receive, on average, more rainfall each year than those communities shown in Figure 5.1 as outside of the Likii WRUA, the finding does suggest that irrigation infrastructure and the presence of well-crafted institutions to maintain this infrastructure may play an important role in reducing smallholder vulnerability to external shocks.

In Chapter 4, this irrigation infrastructure and the rules devised to manage water use and pipe upkeep were explanatory variables in a model seeking to understand water provisioning. Irrigation has been described as a significant adaptation mechanism for smallholder farmers (Morton, 2007; Bryan et al., 2009), and by identifying key institutional and pipe network variables related to water delivery, Chapter 4 offered insight concerning households that are particularly affected during dry periods. Notably, the results from Chapter 4 did not reveal clear trends related to the influence of institutional and infrastructural characteristics on household water availability. Unexpected associations, such as households within older water projects enjoying higher average flow rates, and seemingly conflicting findings between the outcome variable in one model, average household flow rate, and the outcome variable in another model, coefficient of variation of household water delivery, hampered interpretation of the results. However, the results clearly reveal that water delivery within smallholder operated irrigation systems is a complex process influenced by an array of forces and that all irrigation systems in the study were unsuccessful in equitably delivering water to their members.

As it relates to smallholder vulnerability and adaptation, these results give way to some skepticism concerning the effectiveness of irrigation systems in reducing vulnerability to dry spells. If a smallholder household is one of the many households with water delivery that is less reliable than the irrigation system’s mean variability of flow (see Table 4.6), then it may be foolish to believe that enough irrigation water will be provided to bridge an unexpected dry spell.

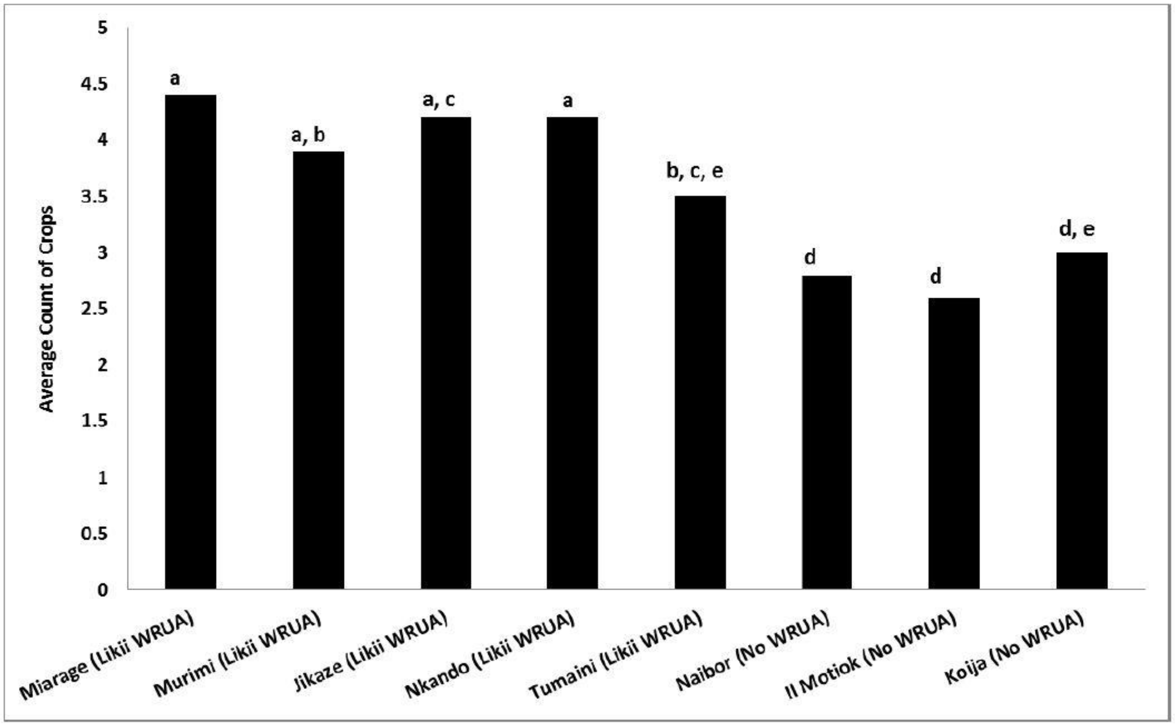

Figure 5.1. Average crop diversity by community. *Note: Letters on top of the bars indicate community water project that do not differ significantly in their levels of crop diversification.*

To this end, the mere presence of an irrigation system is not enough to ensure adaptation during an unexpected dry period; the irrigation system must also be well-managed and well-maintained to deliver equal benefits to all members.

5.2. Common-pool resource governance

Common-pool resource governance was an inherent theme in each of the three preceding chapters, though it was only dealt with explicitly in Chapters 3 and 4. By detailing a national effort to restructure water governance and tracing the effects of this restructuring to outcomes within community level water management, Chapter 3 offered a unique contribution to the field of institutional analysis since very few studies have detailed a country's transition from a centralized to a polycentric approach to resource governance (Andersson and Ostrom, 2008).

In addition to describing such a transition, Chapter 3 also revealed how actor roles have changed following the polycentric transition, as well as some of the potentially unexpected water access adjustments that were made since governance reform. In terms of changing actor roles, the 2002 transformation created the WRUAs and WRMA, which provided new opportunities for communication between water managers within the same catchment. These water managers were now expected to coordinate, through the WRUA, the timing of their dry season water extractions in order to improve downstream availability. Another example of shifting actor roles came in the form of a "scout" employed by one WRUA to serve as a common caretaker for the catchment's irrigation systems. This serves the purpose of not only providing a savings to communities that no longer need to employ a caretaker, but it also creates redundancies in maintenance and monitoring roles since these same communities have their own representatives in place to watch over individual distribution lines. Thus, if one actor fails to fulfill their monitoring and maintenance responsibilities, a backup is in place to perform these duties.

In spite of some of the benefits created by these new roles, the 2002 water reform appears to have made some smallholders worse off. Upstream users have complained that they had more water before the WRUA ordered a percentage of water to reach downstream users. According to some, this has reduced the amount of irrigation that they are now able to apply to their fields. Irrigation system members also complained that the costs of membership are now higher than they were before the 2002 reform, partly due to new fees for purchasing equipment designed to ensure that water extraction is equitable across all irrigation systems (e.g., flow meters). Identification of these water reform consequences was a significant contribution of Chapter 3, especially since studies of polycentric reform rarely employ empirical evidence of local level "winners" and "losers."

In Chapter 4 significant attention was given to the importance of communication between irrigation system managers and their members. By relying on information exchanged between these parties and encouraging membership participation, irrigation systems exhibit several of the adaptive co-management traits identified by Huitema et al. (2009). Further, effective communication and participation by the membership is critical given the absence of household flow meters and other useful data that would help managers identify problematic distribution lines. Representatives for each of the major distribution lines essentially perform the crucial role of reporting water flow "data" to the management committee. However, despite the importance of information exchange, the multilevel model developed in Chapter 4 did not reveal a significant relationship between a household's attendance at irrigation system meetings and their rate of water delivery, perhaps suggesting that information exchange related to water flow is more informal and occurs outside of these official monthly and bimonthly meetings.

Chapters 3 and 4 also highlighted the importance of collective action. In establishing the WRUAs, the 2002 water reform sought a solution to conflicts that had arisen between upstream and downstream communities due to excessive water withdrawals by upstream users. Collective action therefore was needed between user groups to ensure that a percentage of water was allowed to flow downstream, and the WRUAs were devised as the facilitator of this cooperation. The interview responses reported in Chapter 3 reveal that the WRUAs have been effective in terms of improving downstream water availability; however, this cooperation has not been entirely organic and some irrigation systems begrudge the efforts to achieve collective action stating that their inability to take more water from the rivers disfavors their memberships. This suggests that the collective action witnessed between upstream and downstream users in Chapter

3 may not be the traditional form that institutional scholars often cite when discussing commons dilemmas.

In Chapter 4 the multilevel regression model included several variables that the CPR literature has listed as affecting collective action efforts, including membership size and group heterogeneity. These were included due to free-rider risks associated with infrastructure maintenance and the inherent challenges in achieving equitable water delivery in irrigation systems with poor cooperation amongst the membership. The results of the model were mixed: smallholders located within irrigation systems with more members correlate with higher average household flow rates, and individuals within irrigation systems with a wider ethnic diversity associate with less reliable water delivery. The collective action literature supports the latter but not the former relationship. These conflicting results again speak to the challenges of grasping the drivers of smallholder irrigation water delivery.

5.3. Social-ecological systems

The concept of SESs was dealt with most explicitly in Chapters 3 and 4. To my knowledge, Chapter 3, which was published in Spring 2016 in the *Policy Studies Journal*, is the first application of the combined IAD-SES framework that has appeared in a scholarly journal. In using this framework, the social, institutional, and biophysical components of the system were identified and, perhaps more noteworthy, the changes to these components were evaluated over the time period spanning the pre- and post-2002 water reform. This allowed for a comprehensive analysis of changes to the resource system, actor roles, and the governance arrangements over time and helped to identify the post-reform features that overlap with elements of adaptive co-management.

From a more practical standpoint, applying the combined IAD-SES framework to the Kenya case contributes to ongoing scholarly efforts seeking to refine the SES Framework since its publication in Ostrom (2007). For example, a recently cited shortcoming of Ostrom's SES Framework is its limited focus on biophysical elements. To remedy this, Epstein et al. (2013) suggested adding a new variable – ecological rules – to the framework to account for this general absence of ecological elements and processes. Others, such as Vogt et al. (2015), have suggested further elaborations to the framework by providing added detail to the highest-tier "resource system" and "resource unit" variables. Cole et al. (2014) devised the combined IAD-SES framework to correct an often expressed limitation that the SES Framework lacks dynamism. By using empirical data in my application of this framework in Chapter 3, I have highlighted some of the benefits of the framework, including its focus on system outcomes, as well as some of its challenges, such as obstacles of data availability and the often subjective process of choosing distinct time periods for inspection.

Chapter 4 elaborates on the criticism that studies of social-ecological systems often neglect the "ecological" element. In that chapter I cited a recent study by Rissman and Gillon (2016: 7), which stated that "better integration of ecology is needed in SES research." Further, Rissman and Gillon found that SES studies with an independent variable-dependent variable linkage were more apt to have a social indicator as the dependent variable. In response to this imbalance, the multilevel model in Chapter 4 included a biophysical outcome variable and inspected a range of institutional, infrastructural, and biophysical explanatory variables in endeavoring to understand the drivers of household water delivery. Additionally, Chapter 4 used the term coupled-infrastructure system (CIS) rather than social-ecological system in response to a study by Anderies et al. (2016), which claimed that SES studies have focused on institutional arrangements disproportionately and that the role of technology and the environment needs to be better articulated. Given the array of elements that influence water delivery, “CIS” was used in recognition of the balance needed between all elements within complex systems.

5.4. Food production and smallholder livelihoods

The cropping strategies of farmers that were investigated in Chapter 2 provided a glimpse into food security challenges. While the focus of this chapter was on crop diversification, the results can be extended to identify households that may be at a greater risk of becoming food insecure. For example, households positioned downstream in areas of lower rainfall and with less access to extension agents were found to be growing a less diverse array of crops. Not only are these households poorly protected from an unexpected shock, but they may also lack other risk-reducing skills that would have been provided to them in a farmer outreach program, such as cover-cropping practices and income diversification strategies (e.g., bee keeping for honey production). As a result, identification of households growing fewer crops, as well as the covariates associating with this cultivation decision, may provide a useful idea of which smallholders are at risk of becoming food insecure and why they may be at risk.

While not included in Chapters 2-4, ongoing research is using Landsat and ASTER satellite imagery to understand temporal dimensions of food security within a collection of the study area’s irrigation systems. Figure 5.2 provides a snapshot of “greenness” calculated using the Normalized Difference Vegetation Index (NDVI), and Figure 5.3 demonstrates the temporal and spatial variability of this metric within a particular irrigation system. In pursuing this endeavor, I am attempting to build off from a finding from Chapter 4. In that chapter, the point was made that if water is not delivered in a reliable fashion, then membership within an

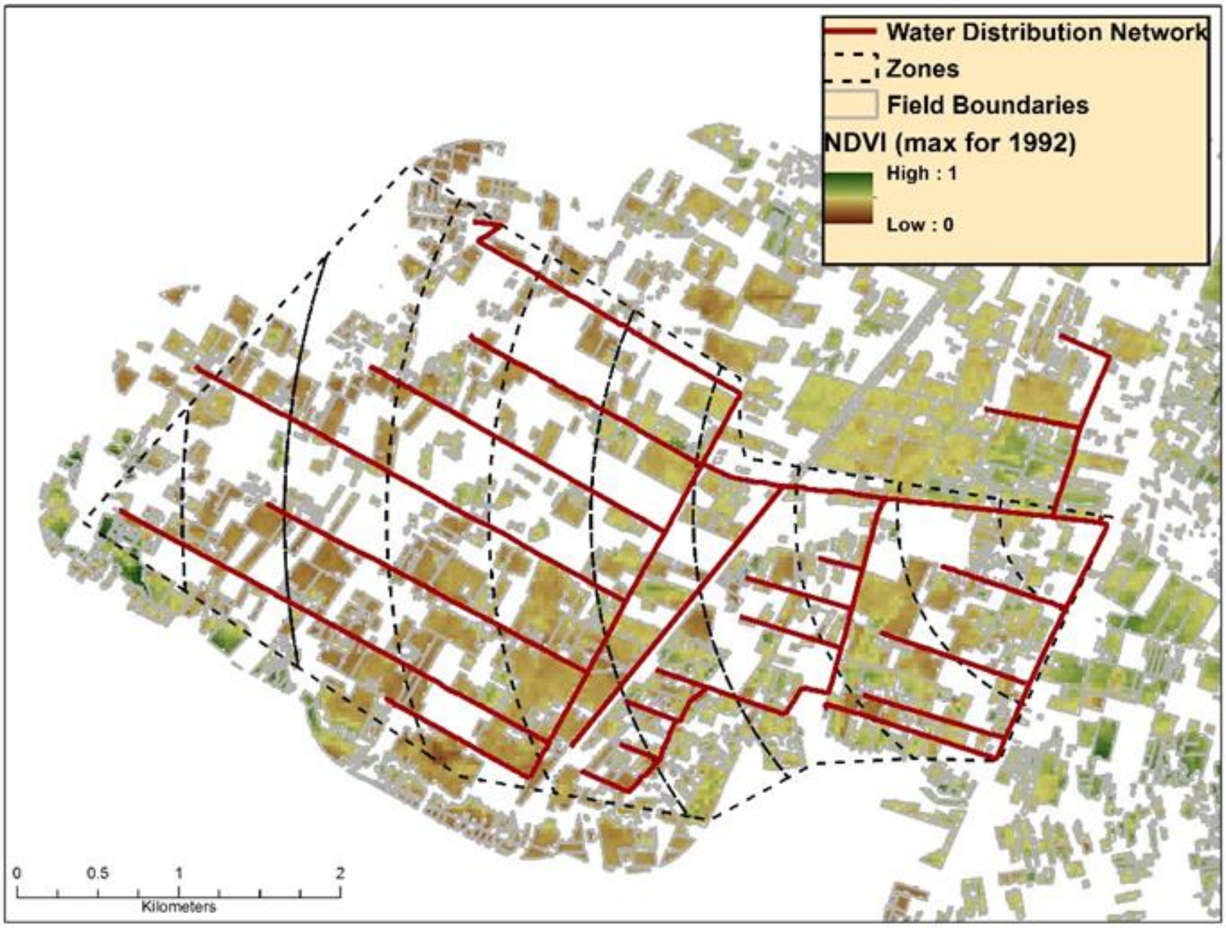

Figure 5.2. Normalized Difference Vegetation Index at farm plots within an irrigation system.

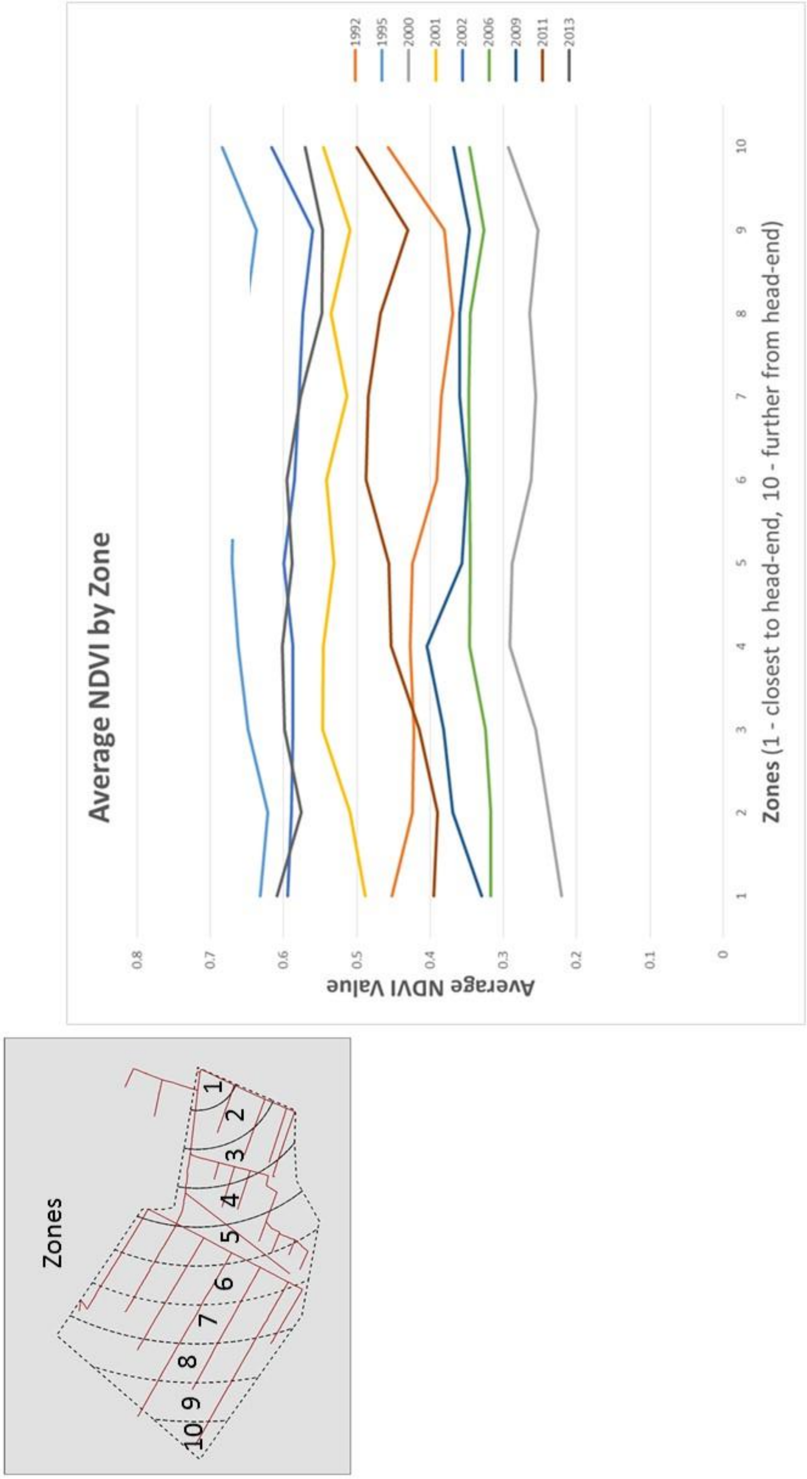

Figure 5.3. Temporal and spatial variability of NDVI within an irrigation system. *Note: Zones are numbered from closest to the irrigation system head-end to furthest away. Each zone is the same width.*

irrigation system may make little difference in protecting a harvest against an unexpected dry spell. By interrogating the vigor of crops more directly through satellite imagery, I hope to clearly demonstrate a link, or lack thereof, between irrigation system membership and household food security.

5.5. Future directions

Having positioned the results of the empirical chapters into several thematic areas, directions for future research to build off from the existing findings are discussed. Several significant findings, particularly from Chapters 3 and 4, indicated that: **1)** in shifting from a monocentric to polycentric resource management regime, “winners” as well as “losers” are created; **2)** coordination roles within polycentric systems are important, particularly when data concerning the performance of user groups is absent; **3)** the mere membership within an irrigation system may not be enough to guarantee a successful harvest if water is not delivered to households in a reliable fashion; **4)** inequalities in terms of water availability as well as other social dimensions can lead to varying livelihood outcomes; and **5)** when investigating the performance of user groups, including irrigation systems, high resolution information is needed to identify inequalities that may exist.

I intend to build off from the first point by more closely inspecting the role of collective action in guaranteeing access to all water users within the confines of a catchment. To what degree will individuals voluntarily cooperate to ensure that other users have equal access to water? Does a large-scale catchment-wide effort to improve downstream water availability necessitate top-down intervention? Where is the tipping point between upstream farmer willingness to reduce on-farm irrigation and guaranteed downstream water access? In acknowledging that “winners” and “losers” are created when a resource system is expected to be shared amongst all users, questions concerning cooperation and resource sustainability quickly come to the fore.

The polycentricity literature details the importance of coordination between different levels of management. However, scholars rarely address this point using empirical information derived from technology-poor settings. Information sharing between, for example, the WRUAs and the irrigation systems relies on a significant amount of trust: the trust that irrigation systems will accurately report their water use activities to the WRUAs and the trust that WRUAs will “hear” the concerns of irrigation systems if they believe that water rotation schedules disfavor them. The mechanism by which information flows is clearly an important one, and, as a result, I hope to explore topics related to: procedures for choosing representatives responsible for communicating local level information to irrigation system managers, procedures for choosing representatives responsible for communicating community level information to WRUA managers, and the disparities in resource delivery that would exist in the absence of these communication networks.

As I mentioned when describing the ongoing analysis of NDVI within the study area, membership within an irrigation system may not guarantee high yields. In fact, because water provided to households is primarily to be used for domestic purposes, it remains to be seen if membership within the Mount Kenya irrigation systems improves yields over households outside of these irrigation systems. As a result, a future research endeavor will seek both to better understand spatial and temporal dynamics of crop vitality within irrigation systems and inspect potential “yield gaps” between individuals within and outside of the irrigation systems.

In Chapter 3 and 4 I found evidence that strong water asymmetries exist within and across irrigation systems in terms of piped water availability. Also, Chapter 2 found evidence that rainfall disparities may lead to different on-farm practices. These disparities need to be investigated in greater detail to understand their influence on food security and smallholder coping strategies. Additionally, attention should be given to other dimensions of inequality. Kenya features many ethnic groups that practice different, and sometimes competing, livelihood strategies. Potential exclusion from an irrigation system or delegation to more marginal areas are not unreasonable concerns. The colonial era featured evictions of Maasai from the Mount Kenya region, and present day evictions or exclusions from water access are worth exploring.

Finally, Chapter 4 revealed disparities in household water delivery. In CPR studies, the robustness of resource management regimes is often measured according to the possession of specific institutional traits. However, resource inequalities within user groups could portend future collapse. Many of the irrigation systems in the Mount Kenya region have existed since the 1970s and 1980s. Thus, they have endured for a significant period of time; yet, resource inequalities exist amongst the memberships. Within this vein, I would like to investigate why these user groups persist in the presence of inequality. Is it simply an absence of awareness (i.e., not understanding how much water one’s own neighbor has)? I also plan to investigate other user groups outside of the Mount Kenya region to get a sense for the institutional traits consistent with equitable and inequitable household level resource distribution. Because these studies rarely use household level empirical evidence, this would be a significant contribution to CPR studies.

In pursuing these research trajectories, I would be able to build off the results presented herein. More importantly, such research would make significant contributions to literatures related to common-pool resource governance, food security, and vulnerability studies.

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Manuscripts under review

McCord, P.F., K.B. Waldman, E. Baldwin, J. Dell'Angelo, and T.P. Evans. *In Review*. Multilevel adaptation to climate variability and water security in smallholder agricultural systems. Under review at *World Development* (Submitted September 2016).

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McCord, P.F. *, S. Sweeney, and T.P. Evans. (2017). Exploring irrigated agricultural production in the context of water distribution networks. Presented at the 2017 Annual Meeting of the American Association of Geographers, Boston, MA.

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Messina, J.P.*, **P.F. McCord**, and M.H. DeVisser. (2012). Modeling ecosystem services over space and time: The case of African trypanosomiasis in Kenya. Presented at the Ecosystems Services Partnership Conference 2012, Portland, OR.

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