A multilevel inspection of water delivery and well-being within smallholder-operated irrigation systems in the Mount Kenya region

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Abstract:
Within the last several decades, common-pool resource (CPR) management has attracted the attention of researchers and practitioners interested in the success of local-level users collectively managing their resource system. Studies of these CPR regimes have often been at the community-level and primarily focused on the regime's management structure, leaving uncertainties with regards to resource provisioning at the household-level and the corresponding connection to livelihood outcomes. We address these often overlooked aspects through a study of households nested within twenty-five user-operated irrigation systems, known as community water projects (CWPs), in the Mount Kenya region. Specifically, we examine household-level water outcomes (i.e., average flow rate and reliability of water provisioning) and the community-level and household-level institutional, infrastructural, and biophysical drivers that effect household water outcomes. We attempt to connect water outcomes to household livelihoods by constructing a well-being index based on smallholder assets within the study area. A multilevel regression is used to identify drivers of household-level water provisioning. Our study finds that many of the infrastructural and biophysical parameters significantly influence average household-level flow rate, while fewer institutional parameters were found to significantly influence average flow rate. Fewer parameters were significantly associated with the reliability of water provisioning, although several noteworthy institutional relationships were identified. Our findings with respect to the connection to farmer livelihoods were inconclusive and need further attention. By focusing on household-level outcomes, our study expands on the growing body of knowledge surrounding CPR management. This includes moving beyond an inspection of the governance traits of a CPR regime to assess resource inequalities and the forces behind these inequalities. These results are informative for researchers and practitioners studying both user-operated irrigation systems and semi-arid agricultural systems.

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; 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 bleak 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). Ostrom (2007) further integrated diagnostic analyses of institutional arrangements and biophysical characteristics of natural resources by unveiling the Social-Ecological Systems framework (SES framework). Utilization of this framework has allowed researchers to investigate, on one hand, the rules-in-use for resource management and, on the other, the biophysical setting. Studies such as Ostrom (2007), Basurto and Ostrom (2009), Ostrom and Cox (2010), and Poteete et al. (2010) have used the SES framework to diagnose the specific institutional and biophysical traits leading to sustainable management and effective self-organization of resource users in their respective settings.

While diagnostic analyses of institutional arrangements tell us much about the governance structure and institutional regimes of CPRs, it does not necessarily inform us of the regime's performance in terms of resource provisioning (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)). In other words, a common-property system may be considered robust in that it exhibits all eight of Ostrom's design principles; however, in terms of resource provisioning, elements such as infrastructural and biophysical traits may affect outcomes as much as the governance characteristics. Inequalities in resource outcomes at the household-level may further translate to livelihood security dissimilarities across households. This is particularly true in the case of user-operated irrigation systems where institutional arrangements (e.g., water rotation strategies and penalties for tampering with pipes) merge with infrastructural traits (e.g., age of irrigation system and total number of distribution lines) and biophysical elements (e.g., elevation gradient) to effect household-level water delivery. While CPR sustainability is of critical importance for all common-property systems, we focus solely on irrigation systems throughout the remainder of this article due to the compelling assemblage of traits influencing household outcomes.

Several institutional analyses have assessed irrigation system outcomes in terms of resource provisioning. For example, Cox and Ross (2011) used remotely sensed data to estimate the crop production of fifty-one acequia-irrigated areas in New Mexico's Taos Valley. In their study, higher levels of production were linked to better water provisioning as actors were able to overcome collective-action problems. The collective-action problem exists when individual decisions, such as the choice to withdraw more than one's allotted share of water, influence group outcomes. Lam (1996, 1998) assessed, among other things, factors contributing to differences in self-reported water availability among head-end and tail-end members of irrigation systems within Nepal. Lam went to great effort to include variables consistent with the institutional, infrastructural, and biophysical environment, thereby recognizing the synergistic influences on irrigation system outcomes. However, as is often true with institutional analyses of common property regimes, these studies were conducted either at the irrigation system-level or within different regions of the irrigation system and, therefore, tell us little about performance outcomes at the household-level and the relationship with household well-being. As Chambers (1988) puts it, an understanding of the total amount of water available within an irrigation system does not translate to an understanding of overall well-being at the individual-level.

Recognizing the need for a more localized inspection of outcomes, this study examines institutional, infrastructural, and biophysical drivers of household water delivery at both the community and individual level within twenty-five community water projects (CWPs) in the Mount Kenya region. Biophysical and "sociotechnical" drivers were present in the analysis conducted by Lam (1996, 1998), and given their synergistic influences on irrigation system performance, they feature prominently in our analysis as well. A multilevel statistical model is employed to assess these drivers. Additionally, we endeavor to connect water delivery to a well-being index tailored to the Mount Kenya agricultural landscape in an effort to interrogate the role of irrigation system performance in guaranteeing livelihoods. Building from the existing institutional analysis literature, the objective of this study is three-fold: (1) to assess irrigation system performance outcomes at the household-level, (2) to investigate drivers of water supply at various levels within nested systems of management, and (3) to explore the linkages between household water availability and smallholder livelihoods. The remainder of the paper is structured as follows: first, we provide contextual information related to irrigation system performance measures and drivers; second, a description of the study area is given; we then describe the data and methods used; next, the results are presented; finally, we provide a discussion concerning the statistical results and how the results relate to smallholder well-being in the Mount Kenya region.

2. BACKGROUND

2.1. Irrigation systems and irrigation performance measurements

Irrigation systems are defined as the physical and institutional components that allow for both the capture of water from natural sources and the conveyance to land used for agricultural activities (Small and Svendsen 1990). *Institutions* are meant as the rules-in-use, norms, and strategies that govern and structure interactions among actors within an irrigation system. An irrigation system may range from a large, government-operated distribution network with lined canals and permanent headworks to small, user-operated networks of partially lined canals and temporary headworks. In other water distribution networks, a system of gravity-fed pipes may be used instead of canals. The reliance on agriculture by much of the world's smallholder farmers, and the use of irrigation by these smallholders, highlights the importance of irrigation systems in maintaining livelihoods across countless settings (Anderies and Janssen 2011).

Performance of irrigation systems has been a critical issue in research on rural development. Civil engineering studies have paid extensive attention to issues of water delivery within a range of systems. Molden and Gates (1990) provided definitions for several measures of performance, while at the same time accounting for structural and management contributors to water delivery. 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 and then applied these measures to systems in Sri Lanka and Egypt. Molden and Gates relied on temporal field measurements of water flow at delivery points to estimate these indicators. Others have used remotely sensed images to estimate irrigation system performance. Bastiaanssen and Bos (1999) conducted a review of studies applying this technique and detailed strategies for calculating measures of adequacy, equity, reliability, and productivity (i.e., a comparison between water consumed by crop evapo-transpiration to the amount of irrigation water supplied) by way of remotely sensed data. The authors listed data standardization among the advantages of using remotely sensed images as opposed to more traditional canal measurements of water flow. Research has also focused on linking measures of irrigation system performance to critical questions concerning poverty alleviation (Molden et al. 2007); equitable water distribution between different groups, including gender inequality (van Koppen 2002); and perception differences of "good" performance held by various groups within a system (Svendsen and Small 1990).

Studies of irrigation system performance within the domain of institutional analysis highlight the role of governance traits and rule changes in bringing about water delivery outcomes. Lam (1998, 1) described the difference between institutional and "traditional" analyses of performance as one where traditional assessments emphasize engineering and economic elements of irrigation infrastructure but often overlook institutional arrangements, while institutional analyses recognize both human interactions and physical infrastructure in creating a "sociotechnical" system that drives outcomes. Despite this understanding, few institutional analyses have investigated the influence of sociotechnical drivers on water delivery, and fewer still have done so at the household-level.

2.1.1. Drivers of irrigation system performance

Given the interdependence of infrastructural, institutional, and biophysical traits, it is best to consider drivers of irrigation system performance as part of an entwined SES instead of distinct, individual constituent parts. For example, water delivery is clearly influenced by the conduit through which it is transported. Giustolisi et al. (2008) studied the contributors to leakage within a water distribution network and explained that aging and deteriorating pipes are often responsible for water losses. Apart from these infrastructural elements, different types and configurations of rules affect management outcomes (see Ostrom et al. 1994). For example, position rules within an irrigation system may create the role of a caretaker who is responsible for the upkeep of aging pipes. The position rules that create the caretaker role, the boundary rules used to determine how an individual is assigned to this role, and the choice rules describing the obligations of the caretaker help guard against major water leakages and demonstrate the importance of institutions in driving water delivery outcomes (Ostrom 2005). The irrigation system's size of service area may also influence performance as some studies have showed that larger systems experience greater water loss through leakage and seepage (e.g., Makurira et al. 2007). However, this infrastructural driver again does not stand alone: management decisions to increase membership may be the force expanding the overall size of the irrigation system, which would suggest that both the sheer size of the system (i.e., the infrastructural driver) as well as the less restrictive membership rules imposed by the managing committee (i.e., the institutional driver) work in tandem to create water delivery outcomes. Finally, the terrain plays a role in the rate at which water is provided as a sufficient hydraulic gradient must exist in order to get water from the irrigation system's point of entry to individual households. Also in this case, like the above narratives, the biophysical element is not isolated. A water rotation scheme may be devised by the governing body of an irrigation system where entire canals or pipe lines are closed in an effort to improve water flow within those lines remaining open (Ostrom and Gardner 1993). This institutional arrangement may result in households going days or in some cases weeks without water delivery, but acceptable flow rates are generated within those lines that are open.

2.2. Collective action within irrigation systems

The institutional arrangements of an irrigation system seek to overcome collective-action problems, which are those dilemmas created when individual incentives differ from the incentives of the group. Cox and Ross (2011) described two types of collective-action problems confronted by irrigation system members: resource appropriation and provision. Appropriation collective-action problems relate to individual excessive water consumption, which reduces available water to other users. This is a common problem within upstream-downstream environments since those with first access may be indifferent to, or unaware of, downstream water demand. Provision problems relate to efforts to establish and maintain irrigation infrastructure as individuals have an incentive to free-ride and thereby benefit from the labor of others while providing no inputs themselves.

The existence of certain conditions pose substantial challenges to the prospect of irrigation system members acting collectively. For example, group size impinges upon collective efforts since transaction costs associated with organization and coordination increase with additional members (Hardin 1982). A group of heterogeneous rather than homogenous water users may also struggle to maintain collective-action if distrust, which is expected to be higher within a heterogeneous group, interferes with ability to establish and abide by agreements (Walker and Ostrom 2009). Additionally, the presence of more than one water source may reduce incentives to act collectively since a user's well-being is not solely dependent on a single water supply source (Lam 1998). Origin of the user group and income disparities have also been shown to influence collective-action, with members of older user groups showing more cooperation (Fujiie et al. 2005) and user groups with greater income disparity showing less cooperation (Ternstrom 2003). Whatever the conditions of the user group may be, institutional arrangements that are commonly understood amongst members and viewed as well-enforced, legitimate, and responsive to changing conditions are more likely to foster collective-action and achieve desired, sustainable outcomes (Ostrom 1990).

2.3. Smallholder well-being within irrigation systems

Smallholder farmers face multiple sociopolitical and environmental challenges in securing their livelihoods. In semi-arid regions, a common environmental obstacle to smallholder agricultural production is between and within season rainfall variability (Cooper et al. 2008). This is precisely where irrigation systems offer the potential to extend a growing season or bridge a dry spell to avoid a failed harvest. Such reliance upon irrigation systems for improved production exists across the globe as smallholders utilize irrigation water to supplement water received via rainfall (Anderies and Janssen 2011).

A household with better overall water delivery from an irrigation system may be better positioned for higher yields, opportunities to cultivate more land, abilities to grow a wider array of crops, and the potential to receive higher returns at market. As a result, smallholder well-being is contingent to a certain extent on water provisioning. Well-being in this study is measured not through the use of purely monetary terms, but instead in accordance with context-specific assets that lend support to poverty reduction (Carter and Barrett 2006). While the supply of water from an irrigation system is itself an asset, we view it as a preceding resource that influences further asset accumulation. Put another way, more reliable water delivery may put a smallholder in a position where they are able to assemble an asset portfolio that offers a higher level of well-being. A context-specific measure of well-being, which will be discussed below, is constructed for the Mount Kenya region using an index provided by Ulrich et al. (2012) to determine if households with better average flow and more reliable water delivery also experience higher levels of well-being.

3. STUDY AREA

The twenty-five community water projects (CWPs) under study are found on the northern and northwestern slopes of Mount Kenya in the Upper Ewaso Ng'iro basin (Figure 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 in cultivating crops, but utilize irrigation water provided by their CWP to extend growing seasons and span dry spells. The basin's population has grown from 50,000 in 1960 to 500,000 in 2000 (Ngigi et al. 2007), which has in turn reduced streamflow in some of the basin's major rivers (Liniger et al. 2005).

3.1. Infrastructural features 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 intake. 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 community water project (Figure 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 2. The distribution lines of the CWP are buried and range in diameter in order to maintain pressure. Water held in the community'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.

Infrastructural characteristics vary greatly across the CWPs (Table 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 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 ranges from a complex configuration of twenty-five lines (this is the CWP shown in Figure 2) to a single, straight conduit with households affixed at various points. Larger, more complex distribution networks may have a higher incidence of water conveyance loss (Makurira et al. 2007), which we will have the opportunity to test in this study given the variety of CWP configurations.

3.2. Institutional features 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 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 also play a critical 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 June to September. In many 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 looks only at water management at the community level and saves a more detailed inspection of the WRUA rules-in-use for future work.

The management committee of a CWP, typically consisting of a chairperson, vice-chairperson, secretary, treasurer, and other representatives from the community, is responsible for designing procedures that ensure household water availability both during the wet and dry seasons. To ensure water availability, institutions are crafted explaining, among other things, whether an upper bound on membership exists at which point water supply becomes strained (position rule), how one may gain membership to a CWP (boundary rule), what actions a member must and must not perform (choice rule), and what the penalty might be if an individual's actions violate an agreed upon rule (payoff rule). Several of the rules-in-use are listed in Table 2. A notable choice rule that individuals in the management position must consider is the process by which water is rationed amongst the CWP members. 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 community water project, typically a paid employee, is often responsible for opening and closing lines during the rotation process. In CWPs with smaller memberships, such rotation programs may only occur during the driest months, while user groups with larger memberships enforce rotations year-round.

4. DATA AND METHODS

4.1. Data collection

All data 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.

4.1.1. Household survey data

Household surveys were administered to 750 smallholder farmers across the twenty-five CWPs, with more surveys administered in those CWPs with larger memberships. Surveying took place from the end of May 2013 to beginning of September 2013. Smallholders were queried about their water use activities, agricultural practices, and household and community attributes (Table 3). At the conclusion of each survey, a GPS point was taken to geo-locate responses.

4.1.2. 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 assets (e.g., water storage tanks and reservoirs) and threats facing the CWP (Table 3). Surveys were administered from the beginning of June 2013 to beginning of September 2013. These surveys also provided information concerning the CWP's infrastructural make-up, such as the size and age of distribution lines.

4.1.3. CWP mapping

The distribution lines of each CWP were mapped out 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.

4.1.4. 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 community water projects, ten households were measured, while in larger CWPs, flow was measured at a total of twenty households. 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 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.

4.2. Multilevel regression model

Data at both the community and household level were considered given the multi-scalar drivers of water delivery outcomes. This section summarizes the variables at both levels believed to influence water delivery and then describes the multilevel model itself.

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

Two dependent variables were constructed: average water flow and water flow variability. 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 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 3). Descriptive statistics of both of these performance measures are found in Table 4.

4.2.2. Independent variables: Multilevel drivers of water delivery outcomes

Infrastructural and biophysical drivers of household level water delivery existed at both the community and household level, while the rules-in-use were consistent throughout a CWP; therefore, all of these variables differ only at the CWP level (Table 4). From an institutional perspective, we were interested in the effect of a management committee's decision to cap membership as this may limit infrastructural growth of the CWP and improve water delivery. Water delivery outcomes may also improve if a CWP does not rotate water amongst its users throughout the year as this may signal a water project that has responsibly expanded within its means. In cases of rule infractions, CWPs may choose to punish their members through multiple sanctions. For example, if an individual tampers with a CWP distribution line, they may have a fine imposed upon them and additionally have their water disconnected. In cases such as these, we have summed up the number of penalties enforced or criteria that must be met for each rule grouping, an approach also used in Lam (1998). Some of the more commonly occurring penalties or membership criteria are listed in the notes portion of Table 4.

Finally, we were interested in community and household level variables that may influence water delivery outcomes either by challenging collective action or simply by acting through other pathways. As a result, drivers such as ethnic diversity (often taking the form of members from different tribes) within a CWP, membership size, and the total number of large water storage devices for each household were taken into consideration (Table 4).

All explanatory variables listed in Table 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*.

4.2.3. Multilevel model description

A multilevel regression model was developed given 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). The dependent variable within a multilevel model must be a level 1 variable, which is true in our analysis: average water flow and CV of water flow are both household level outcomes. These variables were both logged to create normal distributions.

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

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

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 γ_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.

4.3. Well-being analysis

A well-being index using data entirely from the 2013 household survey was constructed to analyze potential relationships between water delivery and overall household welfare. The well-being index used context-specific assets associated with poverty reduction. This was chosen over a purely monetary measure of well-being since asset-based measures offer a more comprehensive and reliable means of representing those elements critical to poverty alleviation (Carter and Barrett 2006). Construction of our well-being index was guided by Ulrich et al. (2012), an analysis of smallholder livelihoods within Laikipia County, Kenya. The spatial extent and composition of smallholders within our study is similar to that of Ulrich et al. Assets included in the present well-being index that were also found in Ulrich et al. include: land size, number of livestock, and on-farm income. We also included crop diversity given its regional importance in balancing diets and reducing vulnerability to climatic disturbances (McCord et al. 2015). Crop diversity was calculated in the same fashion as McCord et al.: maize, mixed beans, and Irish potatoes were given a value of "1" regardless of whether the smallholder was growing one, two, or all three of these crops; additional crops were each counted as "1." Therefore, a smallholder growing maize, mixed beans, kales, and tomatoes would have a crop diversity score of "3." The number of livestock were measured in standard livestock units.[1]

Each of the assets making up the well-being index were classified from one to five, with five being the highest score. In some cases we have classified the assets in the same fashion as Ulrich et al.; in other cases, when the majority of observations fell into either one or two groups, we have adjusted the classification procedure. The assets and classification scheme are shown in Table 5.

Bivariate correlations were performed to examine the relationship between the outcome variables of interest (i.e., average flow rate and CV of water flow) and the well-being index. We also inspected the relationship between the outcome variables of interest and each asset of the well-being index individually (e.g., CV of water flow and land size, CV of water flow and livestock, CV of water flow and farm income, and so on).

5. RESULTS

5.1. Multilevel drivers of water delivery outcomes

The results of the multilevel regression models for both average flow rate and the CV of water flow are presented in Table 6. Examining first the model with the log of average flow rate as the dependent variable, several explanatory terms appear to significantly influence average household water flow. In particular, a large number of the variables classified in the *infrastructure and biophysical traits* category were found to be significant. Somewhat unexpectedly, households within older water projects with more distribution lines appear to have higher average household water flow rates. Additionally, household flow appears to be higher when water traverses a shorter distance and a steeper elevation gradient, both from the river to the CWP intake and from the CWP intake to the homestead. Within the *rules-in-use* category, the significant relationships suggest that household water flow rates are higher within water projects that allow membership to grow and enforce a smaller set of sanctions for pipe damaging. This will be discussed in more detail below. Finally, water projects with larger memberships had lower household flow rates, which may suggest an obstacle to collective action.

Fewer significant relationships were found with the log of household variability of water flow as the dependent variable. Again, the number of distribution lines was significant, but this time the relationship was in the expected direction as it suggests that CWPs with more distribution lines result in higher (i.e., less predictable) variability of flow at the household level. The *rules-in-use* category again yielded several significant associations. Water projects

[1] Factors for standard livestock units: 1 cow; 0.5 donkey; 0.1 goat; 0.1 sheep; 0.02 chicken.

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. Additionally, a larger set of membership conditions appears to associate with more reliable flow. Finally, with respect to membership heterogeneity, the hypothesized relationship stemming from the collective action literature appears to be contested as more heterogeneous memberships associate with more reliable household water flow.

5.2. Connecting household well-being and water delivery outcomes

In addition to inspecting the drivers of household level water delivery, the paper sought to connect household well-being with the delivery outcomes discussed above (i.e., average household flow rate and variability of household water flow). It was anticipated that the performance of a water project would directly relate to a context-specific metric of well-being where better flow rates and more reliable water delivery would positively associate with well-being. A total of 346 households were scored according to a well-being index with zero and twenty as the lowest and highest potential values, respectively. On average, households were found to have a well-being score of 9.03. Four was the lowest recorded score (comparatively worse off) and seventeen the highest (comparatively better off). Table 7 arrays the mean well-being score across quintiles of the water delivery outcomes. Average household water flow and CV of water flow were broken into quintiles for clarity purposes.

The results presented in Table 7 show no discernable difference in well-being in response to water delivery. Had the hypothesized relationship between well-being and water delivery existed, higher average well-being scores would have been found in quintiles 4 and 5 of average flow rate (i.e., higher water flow rate and higher level of well-being) and quintiles 1 and 2 of CV of water flow (i.e., lower variability of water flow and higher level of well-being). To ensure that these results were not an artifact of the quintile approach, we correlated well-being scores against raw water delivery values and again found no significant relationship. Further, we correlated water delivery values against the individual components making up the well-being index (i.e., land size, total livestock, on-farm income, and crop diversity) to ensure that the results were not an artifact of the index itself, and were again unable to return a significant association in any of these analyses.

6. DISCUSSION AND CONCLUSION

In the semi-arid tropics, the difference between a successful and failed harvest may be the availability and reliability of irrigation water. Our research has presented community and household level variables that assist with or detract from adequate and reliable water delivery. However, despite the importance of irrigation within semi-arid farming systems, we were unable to correlate superior levels of water delivery with higher levels of well-being. We discuss first some of the relationships discovered through the multilevel statistical analysis and then review the results of the well-being assessment.

We had anticipated explanatory variables associated with CWP growth to negatively influence water delivery outcomes. This stems from studies such as Makurira et al. (2007), which have shown that conveyance losses occur within systems where water traverses long distances and complex ditch or pipe configurations. However, CWPs that continue to allow new members surprisingly had higher average household flow rates, and if we draw the connection to more distribution lines within those CWPs that allow new members, we again find average household flow rates to be unexpectedly higher with *more* distribution lines. This is counterintuitive to the hypothesis that water conveyance losses occur over longer, more complicated distribution networks. On the other hand, we do find a negative relationship between the distance from the CWP intake to the household and average household flow rate, and a positive relationship between the number of distribution lines and the CV of water flow. Both of these relationships support the idea that poorer delivery outcomes occur in larger, more complicated distribution networks. We hypothesize that the unexpected relationships regarding CWP growth and water delivery outcomes result from a careful calculation performed by CWP management committees. If it is deemed that the water project will be able to maintain its performance level with the addition of new members, then membership and infrastructure may be allowed to grow. This agrees with conversations held with CWP care takers who stated that assessments are often performed before adding new distribution lines. Thus, it is entirely possible that, rather than anticipating performance to be better in CWPs that have capped membership, we should expect higher performance in those CWPs that believe they can take on new membership. From this perspective, it is worthwhile to consider the directionality of the relationship, since the presence of strong water outcomes may be driving the decision to expand membership, rather than the reverse.

In an ideal governance arrangement, management occurs on multiple levels and, where possible, the rules-in-use are crafted by local actors with an understanding of the SES (Ostrom 1990). It may be expected that if the rules-in-use are crafted within this context, and members view the rules to be legitimate, the sheer number of penalties in place will deter illegal activity, and therefore improve overall CWP performance. This was indeed a focal point of investigation from Lam (1996). However, in our analysis we found several instances of *fewer* sanctions leading to better performance. In particular, fewer sanctions for damaging CWP infrastructure led to higher average household flow rates, and fewer sanctions for failing to pay the monthly maintenance fee led to lower variability of flow rates. We hypothesize that this may be due to the fact that many of the CWPs within the study have been operating for a number of years (on average, 19 years) and that trust has been built up amongst members. If members do in fact trust each other, fewer sanctions may be needed to obtain ideal outcomes. Additionally, although we have mostly overlooked the higher levels of management within this study, conflict resolution and sanctioning procedures at the level of the WRUA (i.e., the sub-catchment level), within which CWPs are nested, may limit the number of penalties necessary at the CWP level. In this respect, the arrangement of management institutions within the Mount Kenya context and the trust built up amongst long-standing user groups may have reduced the need for extensive sanctioning in order to obtain ideal outcomes. Unrelated to the sanctioning process, we also found CWPs enforcing a wet season rotation schedule to have more reliable water delivery. In many cases, it is the larger CWPs that rotate water among members during the wet season. Because a low CV says nothing about the rate of water delivery it is entirely possible that while delivery is reliable, household flow rates are lower when rotation takes place. Alternatively, as discussed above, water management boards that have determined their CWPs to be capable of taking on more members, and therefore needing a wet season rotation procedure, may be those CWPs that are better maintained and managed, and consequently better positioned for optimal household water delivery outcomes. This again questions the directionality of this relationship as strong water outcomes may be driving the decision to expand and employ the wet season rotation.

CPR regimes must overcome collective-action challenges if cooperative resource management is to be sustainable. Early scholarship predicted resource destruction if property rights systems took the shape of anything aside from a public or private arrangement. Subsequent scholarship demonstrated the ability of users to collectively manage their resource (e.g., Ostrom 1990; Agrawal 2003), and attention was then directed toward determining those factors that facilitated or detracted from collective-action. Several of these factors were tested by the multilevel regression, including membership size, user homogeneity, and the presence of alternative water sources. In the case of membership size, it indeed appears that more desirable outcomes are achieved if user groups are smaller, lending credibility to the hypothesized difficulty of obtaining sustainable outcomes within larger user groups. However, with respect to reliability of water delivery, more desirable outcomes were achieved in water projects with a more heterogeneous member make-up. The reasoning for this result is not entirely clear, but a potential explanation is that trust amongst users has been built up in the face of adverse conditions. In other words, rather than allowing their CWPs to collapse, users posed with challenging conditions have created a more effective arrangement of institutions in order to gain trust in one another and work around their demanding circumstances.

Given the importance of irrigation water in ensuring the success of semi-arid farming, we were surprised that no significant association existed between water delivery and the context-specific measurement of well-being. Water delivery was viewed as a pre-condition for well-being outcomes, thereby setting up different levels of well-being depending on the effectiveness of the irrigation system. Viewing water delivery in this way is related to Sen (1981), since water provisioning from the irrigation system is part of the ownership bundle commanded by the smallholder which exposes them to different entitlement sets. Our inability to discover a significant association between water delivery and well-being may stem from our framing of water availability as the sole pre-condition for different well-being outcomes, as well as the variables included in the well-being index. Without a doubt, the ability to irrigate is of paramount importance in semi-arid agriculture; however, Barron (2004) and Rockstrom et al. (2010) both demonstrate that without proper management of crops and soils, no discernable agricultural benefits will be realized from access to irrigation water alone. Therefore, rather than considering solely water delivery as a pre-condition for higher levels of well-being, soil properties and on-farm management practices likely need to be included in the framing of ownership bundles and entitlement sets. Additionally, while the components making up the well-being index are relevant to the Mount Kenya agricultural landscape, a different bundle of assets may have been more appropriate for an analysis of irrigation water availability and reliability. Well-being index variables that may be more appropriate in a revised analysis include maize and potato harvest and dry season crop failure.

This study set out to address three objectives: (1) to assess irrigation system performance outcomes at the household-level, (2) to investigate drivers of water supply at various levels within nested systems of management, and (3) to explore the linkages between household water availability and smallholder livelihoods. It deliberately viewed water delivery outcomes as the product of sociotechnical and biophysical drivers, which often is not a point of focus in "traditional" inspections of irrigation system performance. The performed study is also one of the first to inspect *household* level water delivery outcomes within the institutional analysis literature. We have unveiled hierarchical drivers of household level water outcomes, some of which were unexpected given the literature on CPR management and collective action. We have further demonstrated that in connecting water delivery to well-being, water provisioning by the

CWP is not the sole condition influencing livelihood outcomes, and factors such as soil condition and on-farm management practices should also be considered. Future work will further investigate the well-being of smallholder farmers as it relates not just to water delivery, but also to those conditions that influence crop production.

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8. TABLES and FIGURES

Table 1. *Select infrastructural 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
Jikaze	Likii	16	4	2043.1	0.4	Yes
Miarage	Likii	31	2	4735.5	1.5	No
Murimi	Likii	12	3	9698.5	5.5	No
Nkando	Likii	11	7	6545.0	1.8	Yes
Tumaini	Likii	10	8	9467.3	5.3	Yes
Huku	Nanyuki	26	14	22,078.4	9.1	Yes
Kaga	Nanyuki	18	20	37,375.0	15.9	Yes
Maka	Nanyuki	19	25	36,119.2	17.7	Yes
Mwea B	Nanyuki	24	27	15,807.8	3.6	Yes
Ruai	Nanyuki	9	20	17,611.6	7.1	No
Batian	Ngusishi	15	3	2576.4	0.2	No
Chumvi	Ngusishi	14	8	22,157.2	24.9	Yes
Kabubungi A	Ngusishi	7	5	834.5	0.1	Yes
Kongoni	Ngusishi	14	6	2836.3	0.4	No
Wiumiririe	Ngusishi	5	8	10,074.3	4.1	Yes
Mayangalo	Ngare Nything	14	15	8214.7	1.2	Yes
Mugokongo	Ngare Nything	12	11	6661.7	1.3	No
Mwimenyi A	Ngare Nything	15	1	983.3	0.1	Yes
Nasakuja	Ngare Nything	27	7	2210.4	0.1	No
Ntumburi	Ngare Nything	41	24	59,396.7	57.6	Yes
Karukunku	Timau	14	4	2399.3	0.4	No
Kiguru	Timau	31	3	1755.6	0.1	No
Kithima-Kiamunyi	Timau	27	2	3947.6	0.5	No
Milimani B	Timau	30	11	10,670.8	5.2	Yes
Muguna	Timau	29	12	5599.8	1.2	Yes

Table 2. *Select institutional attributes of CWPs*

CWP name	WRUA abbreviation[1]	CWP allows new members (Position)	Person must be member of particular village to join CWP (Boundary)	Caretaker must monitor water use (Choice)	Water cut off for tampering with pipes (Payoff)	Monetary fine if no labor provided for CWP maintenance (Payoff)	Wet season water rotation strategy (Choice)[2]
Jikaze	L	No	No	No	Yes	Yes	NR
Miarage	L	Yes	No	No	Yes	Yes	NR
Murimi	L	Yes	No	Yes	Yes	Yes	WSWR
Nkando	L	Yes	No	No	Yes	No	NR
Tumaini	L	Yes	No	No	No	Yes	WSWR
Huku	Nan	Yes	Yes	Yes	Yes	Yes	WSWR
Kaga	Nan	Yes	Yes	No	No	Yes	WSWR
Maka	Nan	Yes	No	Yes	Yes	No	WSWR
Mwea B	Nan	Yes	Yes	Yes	No	No	NR
Ruai	Nan	Yes	No	Yes	No	Yes	NR
Batian	Ngu	Yes	No	Yes	No	Yes	NR
Chumvi	Ngu	Yes	Yes	No	Yes	No	WSWR
Kabubungi A	Ngu	No	No	No	No	Yes	NR
Kongoni	Ngu	No	No	Yes	No	No	WSWR
Wiumiririe	Ngu	Yes	No	No	No	Yes	WSWR
Mayangalo	NN	Yes	Yes	Yes	Yes	Yes	WSWR
Mugokongo	NN	No	No	Yes	Yes	Yes	WSWR
Mwimenyi A	NN	Yes	No	Yes	Yes	Yes	WSWR
Nasakuja	NN	Yes	No	No	No	Yes	NR
Ntumburi	NN	Yes	No	Yes	No	Yes	WSWR
Karukunku	T	No	No	Yes	No	No	WSWR
Kiguru	T	Yes	Yes	No	No	Yes	WSWR
Kithima-Kiamunyi	T	No	No	No	No	Yes	WSWR
Milimani B	T	No	No	No	Yes	No	WSWR
Muguna	T	No	No	Yes	No	Yes	WSWR

Notes: [1]WRUA abbreviation – L=Likii, Nan=Nanyuki, Ngu=Ngusishi, NN=Ngare Nything, T=Timau.

[2]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).

Table 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

Table 4. *Summary statistics*

Variable name	Variable description	Mean	Min	Max
Dependent variables				
Average flow rate (L/min)[HH]	Refer to section 4.2.1.	17.8510	3.8081	161.5179
CV of water flow[HH]	Refer to section 4.2.1.	0.2816	0.0460	1.6034
Independent variables: Infrastructure and biophysical traits				
Areal coverage (km2)[CWP]	Total area occupied by the CWP in km^2	6.612	0.0352	57.6127
Number of distribution lines[CWP]	Total number of CWP distribution lines	10.00	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	2.00	8.00
Total pipe length (m)[CWP]	Sum of all distribution lines in meters	12,072.00	834.5308	59,396.74
Distance wtr source to intake (m)[CWP]	Distance from river or spring to CWP intake (m)	3277.702	1.00	11,928.13
Elev. gradient wtr source to intake[CWP]	Elevation gradient from water source to CWP intake	0.0332	0.00	0.1100
Age of CWP[CWP]	Age of water project	18.84	5.00	41.00
Distance intake to household (m)[HH]	Distance from CWP intake to household (m)	2194.12	49.5528	6870.22
Elev. gradient intake to household[HH]	Elevation gradient from CWP intake to household	0.0347	-0.0432	0.1081
Independent variables: Rules-in-use				
Membership change[CWP]	Does the CWP allows new members to join?	0.68	0.00 (No)	1.00 (Yes)
Wet season rotation[CWP]	Does the CWP rotate water during the wet season?	0.68	0.00 (No)	1.00 (Yes)
Membership criteria – Total conditions[CWP]	Count of conditions to be met in order to join CWP [1]	2.5189	2.00	4.00
Pipe damaging – Total sanctions[CWP]	Count of sanctions imposed for damaging pipes[2]	1.3919	1.00	4.00
Failure to pay fee – Total sanctions[CWP]	Count of sanctions imposed for failing to pay monthly fee[3]	0.9459	0.00	2.00
Failure to work – Total sanctions [CWP]	Count of sanctions imposed for failing to provide labor[4]	1.2270	0.00	2.00
Wtr use monitoring – Total entities[CWP]	Count of entities monitoring illegal water use[5]	2.2405	0.00	5.00
Independent variables: Other pathways (including collective action obstacles)				
Total members[CWP]	Total CWP membership	272.6838	10.00	928.00
Count of tribes[CWP]	Count of CWP's tribal groups	2.1378	1.00	5.00
Count of water storage devices[HH]	Count of HH storage devices (large tanks and reservoirs)	0.5973	0.00	2.00
Years at residence[HH]	Number of years at residence	19.9270	2.00	60.00

Meeting attendance[HH]	Num. of wtr meetings attended in last year (categorical)	2-5	Never	6+

Notes: [CWP/HH]Indicates whether the variable is at the community or household level.
[1]Most frequently reported conditions: Must own land (24 CWPs), must pay membership fee (24).
[2]Most frequently reported pipe damaging sanctions: Water is disconnected (11).
[3]Most frequently reported sanctions for failing to pay monthly fee: Water is disconnected (17).
[4]Most frequently reported sanctions for failing to contribute labor: Monetary sanctions are imposed (18), water is disconnected (9).
[5]Entities most often involved in monitoring: Management committee members (21), caretaker (13), neighbors (9).

Table 5. *Well-being indicators*

Asset	Comparably worse off ←			→ Comparably better off	
	1 point	2 points	3 points	4 points	5 points
Land size (acres)	<2	2-3	3-6	6-10	>10
Livestock (LSU)[1]	<2	2-3	3-5	5-10	>10
Farm income (Kenyan shillings)	<20,000	20,000-32,000	32,000-85,000	85,000-170,000	>170,000
Crop diversity (count)	1	2	3	4	>5

[1]Factors for livestock unit: 1 cow; 0.5 donkey; 0.1 goat; 0.1 sheep; 0.02 chicken.

Table 6. *Multilevel model results*

Category	Parameter	Log average household flow rate	Log household CV of water flow
	Intercept	2.421 (0.465)***	-0.164 (0.456)
Infrastructure and biophysical traits	Areal coverage of CWP^{CWP}	-0.014 (0.009)	0.012 (0.008)
	Num. of distribution lines^{CWP}	0.025 (0.010)**	0.021 (0.010)*
	Pipe size at wtr source abstraction point^{CWP}	0.013 (0.049)	-0.060 (0.046)
	Distance wtr source to intake^{CWP}	0.000 (0.000)	-0.000 (0.000)
	Elev. gradient wtr source to intake^{CWP}	3.516 (2.011)*	-1.641 (1.898)
	Age of CWP^{CWP}	0.023 (0.009)***	-0.009 (0.008)
	Distance intake to household^{HH}	-0.000 (0.000)**	0.000 (0.000)
	Elev. gradient intake to household^{HH}	2.867 (1.516)*	0.489 (1.877)
Rules-in-use	Membership change^{CWP}	0.255 (0.126)**	-0.139 (0.119)
	Wet season rotation^{CWP}	0.091 (0.131)	-0.339 (0.127)***
	Membership criteria – Total conditions^{CWP}	0.022 (0.130)	-0.228 (0.123)*
	Pipe damaging – Total sanctions^{CWP}	-0.158 (0.080)**	0.038 (0.074)
	Failure to pay fee – Total sanctions^{CWP}	-0.169 (0.151)	0.297 (0.138)**
	Failure to work – Total sanctions^{CWP}	-0.198 (0.130)	-0.016 (0.120)
	Water use monitoring – Total entities^{CWP}	-0.072 (0.068)	-0.084 (0.066)
Collective action / Other pathways	Total members^{CWP}	-0.001 (0.000)**	0.000 (0.000)
	Count of tribes^{CWP}	0.085 (0.053)	-0.110 (0.051)**
	Count of water storage devices^{HH}	0.004 (0.035)	-0.074 (0.047)
	Years at residence^{HH}	-0.000 (0.002)	-0.000 (0.002)
	Meeting attendance$^{HH, 1}$		
	Never	-0.101 (0.199)	-0.081 (0.192)
	Once	-0.212 (0.131)	-0.025 (0.113)
	6+ times	-0.041 (0.097)	-0.099 (0.089)
	Sample size	370	370

Notes:$^{CWP/HH}$Indicates whether the variable is a the community or household level.
[1]Meeting attendance: the reference variable is attendance of 2-5 meetings on water issues in the last year.
***Statistical significance indicated at the 0.01 level.
**Statistical significance indicated at the 0.05 level.
*Statistical significance indicated at the 0.10 level.

Table 7. *Average well-being score within each water delivery quintile*

Average household flow rate		CV of household water flow	
Quintile	Average well-being score	Quintile	Average well-being score
1 (lower average flow rate)	8.87	1 (lower flow variability)	9.07
2	9.65	2	9.21
3	9.00	3	8.93
4	8.96	4	8.65
5 (higher average flow rate)	8.59	5 (higher flow variability)	9.22

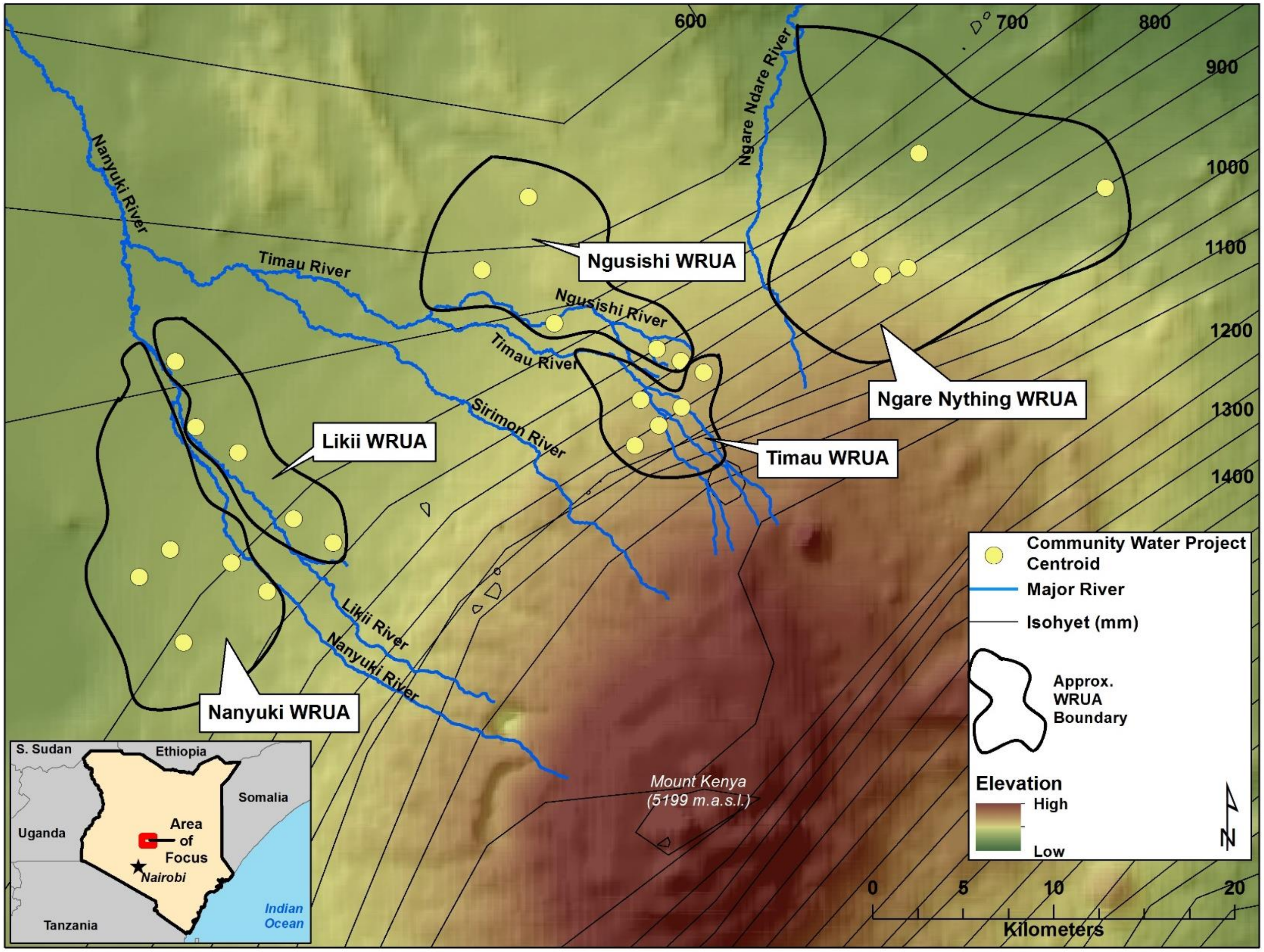

Figure 1. Study Area. *Note*: WRUA boundaries have been approximated. CWP locations are presented with their centroids. Isohyets represent average yearly precipitation in millimeters.

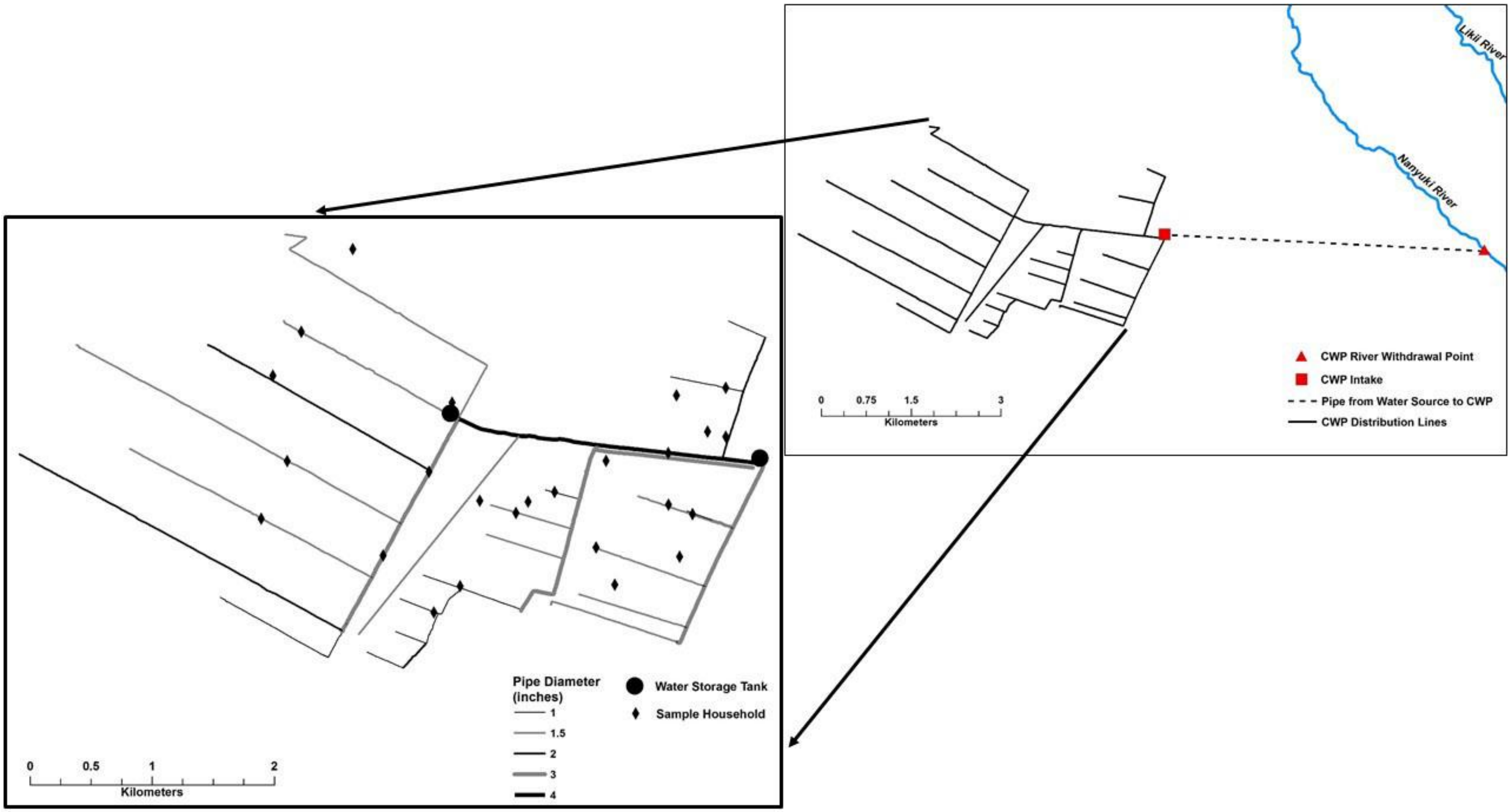

Figure 2. The layout of a CWP showing both the position along a river (right) and the configuration of distribution lines (left).

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