

Research Paper

What factors determine the technical performance of community-managed rural water systems in the middle hills of Nepal?

Raj K. GC, Shyam Ranganathan, A. L. (Tom) Hammett and Ralph P. Hall

ABSTRACT

Gravity-fed water systems are widely used in the rural hills of Nepal. This study identifies the systematic factors that contribute to rural households not obtaining water due to system breakdowns. The study makes use of data from a 2017 to 2018 study of 202 households served by 10 community-based water systems from three localities within the western middle hills of Nepal. A hierarchical regression model is used to capture both household- and system-level variables. The analysis identifies three household-level and three system-level predictors of the duration of water system breakdowns. The significant household-level predictors include (1) a sense of ownership toward the water system, (2) user involvement in decision making during the planning and implementation of the water system, and (3) income earned from water-based productive activities. The significant system-level predictors include (1) distance from the village to the water source, (2) the performance of the water user committee, and (3) the water system operator's level of activity. In addition, the interactions between household- and system-level variables are captured. The empirical relationship between household productive income and the duration of breakdowns is a novel finding. These findings will be valuable to the Nepalese government and other actors working to implement sustainable water systems.

Key words | duration of water system breakdown, gravity-fed water system, hierarchical regression model, Nepal, productive income, sustainable

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HIGHLIGHTS

- Uses a hierarchical regression model to identify household- and system-level variables that contribute to rural water system breakdowns.
- Predicts technical, geographic, and socioeconomic factors contributing to system breakdowns.
- Predicts household-level water-based productive income, which is significantly related to the duration of system breakdowns.
- Offers evidence to support the sustainable planning of rural water systems.

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INTRODUCTION

A typical rural water system in the hills of Nepal is gravity-fed, where water from one or multiple spring sources is collected in a reservoir tank located above the community and conveyed through a piped water system to tap stands. Water supply practitioners often classify these systems as either single-use domestic (SUS) or multiple-use (MUS) systems. The vast majority of the systems are conventional SUS, which were planned, designed, and financed for domestic use purposes. MUS in Nepal emerged during the early 2000s to support both domestic water needs and other productive uses by adding, for example, irrigation for small vegetable plots. To develop MUS, engineers modified the technical components of traditional domestic water systems to provide water for productive uses by adding, for example, additional water irrigation tanks and off-takes to irrigate fields (Yoder *et al.* 2008).

Prior studies have shown that communities use rural water systems to meet multiple water needs, regardless of system design (Van Koppen *et al.* 2014; GC *et al.* 2019). For instance, a study of piped water systems conducted by Hall *et al.* (2014) in Senegal, Kenya, and Colombia, reported that a majority of families (71–75%) were engaged in domestic use and small-scale water-based productive activities. A study of SUS versus MUS systems in Nepal – based on the same dataset used in this paper – revealed that more than 90% of SUS and MUS users were found to use water for various productive activities (GC *et al.* 2019). These activities included growing vegetables, raising livestock, producing dairy products and biogas, and making rakshi (an alcohol drink). Interestingly, while the SUS and MUS systems supported similar levels of engagement in productive activities, the water-based income earned by MUS households was nearly double that earned by households served by SUS. These results emphasize that, in practice, rural water systems are an income-enabling productive infrastructure regardless of whether the system is designed for MUS or SUS. However, the design features can influence the level of income generated from water-based activities.

Over the past decade, studies have reported on the poor functionality of domestic water systems in rural Nepal (White *et al.* 2015). In general, the non-functionality of domestic water systems lies between 30 and 40% in developing

countries (Smets *et al.* 2017). The high frequency of breakdown is typically due to the poor condition of infrastructure, limited timely system maintenance, and a lack of an institutional arrangement that supports operation and maintenance (Marks *et al.* 2013). Other factors affecting the technical sustainability of rural water systems include the system's age, the use of poor materials and workmanship during construction, a lack of post-construction support (Marks *et al.* 2013), the convenience of water-point locations (Bhandari & Grant 2007), the willingness to pay for water (Gurmessa & Mekuriaw 2019), and the availability of funds for operation and maintenance (Budhathoki 2019). Further, the performance of water systems has been found to rely on *system-level* variables (such as improved water services, effective institutional structures, and capable water user committees and operators) (Moriarty & Butterworth 2003; Budhathoki 2019) and *household-level* variables (such as household participation in water system planning and decision making, payment for water services, and the contribution of labor to the construction of the system) (Marks & Davis 2012). A study of 1,500 households in Accra, Ghana, showed that family income, place of residence, and educational status were significant predictors of a household's access to reliable water supply (Mahama *et al.* 2014).

Several studies have examined the critical role of users throughout system planning and project development, and during its operations and management. User groups can be organized to make key decisions about a project including the selection of water sources, pipeline routes, the location of water system components (GC *et al.* 2019), the desired water service levels, and the amount of labor donated during system construction (Marks & Davis 2012). A study of 45 rural water projects in India concluded that community participation was critical to project success (Prokopy 2005). However, participation may not bring a sustained change unless the capacity of users to engage in the process is enhanced and they have an ability to influence decision making.

In general, inadequate capacity of water user committees (Budhathoki 2019) and a lack of appropriate tariffs (Tadesse *et al.* 2013) diminishes system performance and sustainability. Thus, the extent and nature of responsibilities

undertaken by water user committees is critical to the technical performance of systems (Marks *et al.* 2013; Hall *et al.* 2014) including the adoption of user fees to pay for system upgrades and maintenance.

The above discussion indicates how technical, geographical, and socioeconomic factors can affect the number and severity of system breakdowns, system performance, and the overall sustainability of the water system. However, few empirical studies explore the relationship between all these factors. Since the Nepalese government plans to improve water service levels and the sustainability of water systems from 2021 to 2025, this study aims to provide policy makers and planners with critical information on the key factors impacting water system performance and whether/how these predictors relate to the technical performance of rural water systems.

The following sections describe the study communities, the research methodology, the model used in the analysis along with the key variables, the main research findings, and concludes with a discussion of the main findings.

RESEARCH COMMUNITIES

This study was conducted in the three districts of Syangja, Kaski, and Palpa in the western middle hill region of Nepal. The region is geographically diverse with elevations in the districts ranging from 219 to 7,987 m (Figure 1). The study concentrated on three wards – Annapurna-6 of Kaski, Walling-5 of Syangja, and Bagnaskali-1 of Palpa. These wards (the lowest administrative unit of local government) are depicted in Figure 1. Agriculture remains the major economic activity in the region (Mikhail & Yoder 2008; GC & Hall 2020). Most families grow rice, maize, and wheat, typically for household consumption (GC & Hall 2020). Average per capita income in these three wards was around \$850 in 2018, which is below the national average of \$998 (GC & Hall 2020).

METHODS

The lead author of this paper conducted the research from June 2017 to July 2018 in two phases – (1) fieldwork

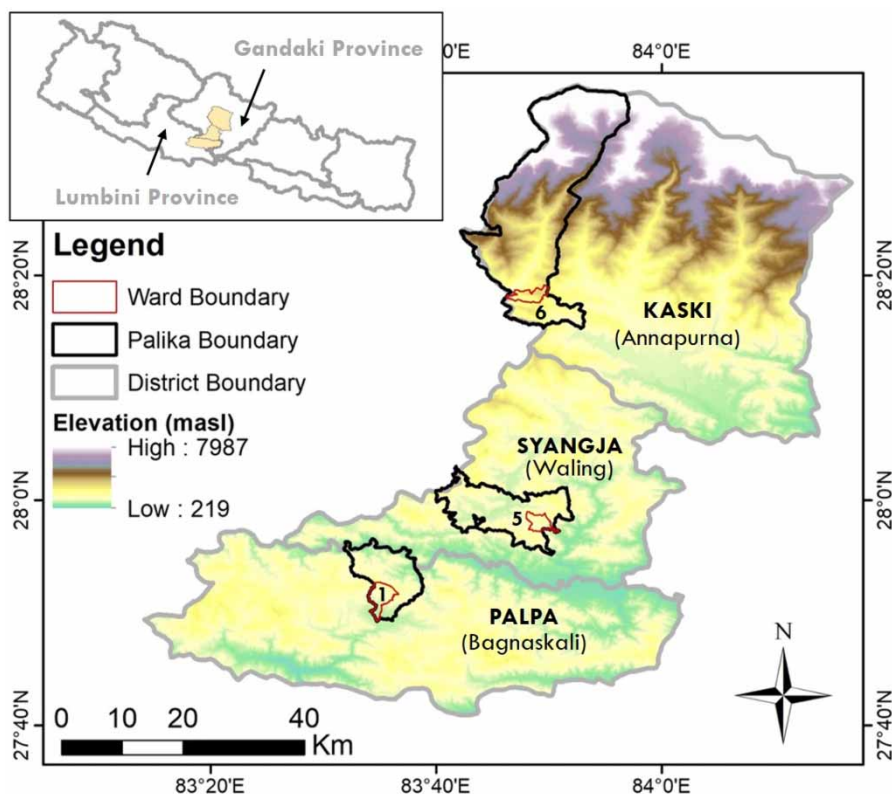


Figure 1 | Study area (Source: The authors).

preparation followed by (2) data collection in the three sample wards. The sample frame and each of the study techniques are discussed below. This study was undertaken in compliance with research protocol 17-846 approved by Virginia Tech's Institutional Review Board (IRB).

Sample frame

Using secondary data and consulting with local stakeholders, three middle hill districts were selected for this study that have a long history of domestic water systems and the greatest concentration of MUS systems nationally. Three sample wards were then selected, each having both domestic and multiple-use systems. A rapid assessment of 60 water systems was conducted across the three wards from which 10 systems (5 MUS and 5 SUS) were selected for the study. Water systems were excluded from sampling if they were: (1) serving fewer than 10 families, (2) shared by two or more neighboring communities, (3) partially functioning, and (4) operating in parallel with another system in the same community. These criteria informed the purposeful sampling of 10 water system serving 213 households for in-depth study.

Households survey

Structured interviews were conducted with 202 households out of the total 213 households that received water from the 10 water systems. The paper-based survey focused on four topics: (1) household demographic and socioeconomic characteristics; (2) domestic and productive use of water and related income; (3) the physical condition and operation/management of the water system, and the roles played by the water committee, system operators, and external support services; and (4) the household's involvement in water system planning and decision-making processes.

Engineering assessments of sample water systems

The major components (e.g., intake, tanks, pipelines, and taps) of the 10 sample systems were assessed to determine their physical condition and functional status. This examination also revealed the designed characteristics of each system and whether it was being adequately maintained. The system performance was also discussed with water

committees and system operators. This assessment helped identify the relevant system-level variables (e.g., the level of activity of the water committee and system operators) and provided background information on these variables.

THE MODEL

Figure 2 presents the conceptual framework behind the model used to assess the technical performance of the water systems. The data were coded using appropriate scales and analyzed using the R programming language. Figure 2 illustrates the nesting of system- and household-level variables and their potential relationship with the dependent variable. The relationship between these variables is further discussed in the following sections.

A hierarchical linear model (HLM) was used to identify the significant predictors of breakdown duration. HLMs are most commonly used to analyze variance in the response variables when the predictors are at varying hierarchical levels (Woltman *et al.* 2012). In other words, the HLM model is appropriate when a dataset contains nested relationships/structures as shown in Figure 2 – i.e., household-level predictors are a subset of system-level predictors. HLMs are effective in simultaneously capturing dependencies among households served by the same water system and among individual households in general. The regression model is expressed as follows:

$$\begin{aligned} y_{ij} &= \beta_0 + \beta_1 * x_{1ij} + \dots + \beta_k x_{kij} + \gamma_1 * z_{1ij} + \dots + \gamma_l * z_{lij} + \epsilon_{ij} \\ \gamma_1 &= \eta_{01} + \eta_{11} * s_{1j}^1 + \dots + s_{mj}^1 + \epsilon_j^1 \\ &\dots \\ \gamma_l &= \eta_{0l} + \eta_{1l} * s_{1j}^l + \dots + s_{mj}^l + \epsilon_j^l \end{aligned}$$

In the above series of equations, y represents the dependent variable measured in household i and system j . The x represents the fixed effects, which are household-level variables. The z represents the random effects (modeled in this article as *mixed effects* that include a fixed effect and a random effect component). The β represents the coefficients of the fixed effects, and the γ represents the coefficients corresponding to the random effects. The hierarchical structure

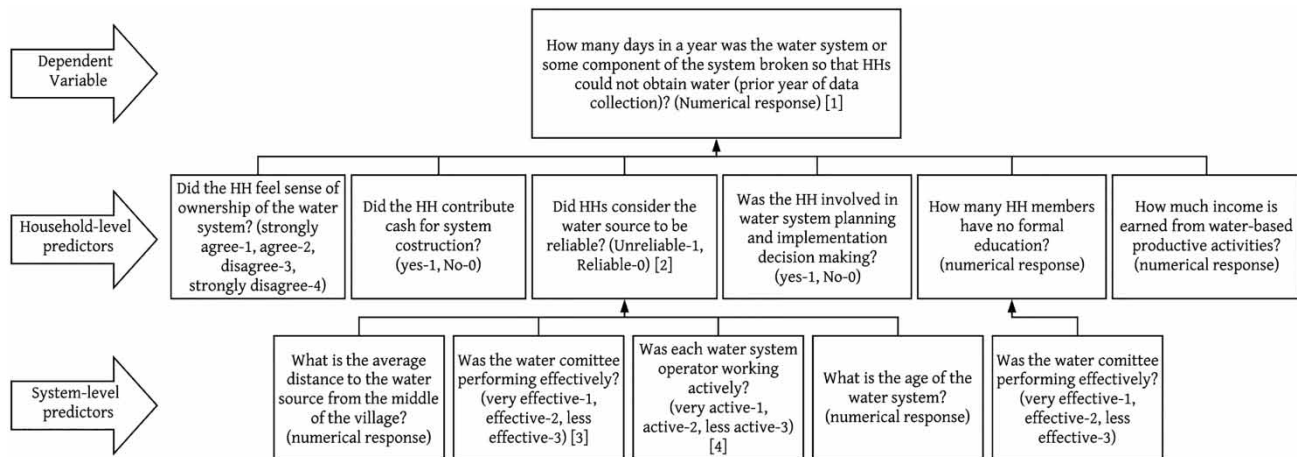


Figure 2 | Model diagram: (1) Water system breakdowns are measured in terms of the duration of a breakdown. This dependent variable of technical performance captures the functionality of infrastructure such as tanks, taps, and pipes and the impact of existing operation and maintenance practices. (2) Since water system users are typically located far from a water source (intake), they do not know the exact status of the water source at certain point of time or at different periods throughout the year. Thus, the reliability variable is based on their perceptions of the reliability of water sources and is defined as follows: (a) *Unreliable*: Users consider an unreliable water source/intake (e.g., due to flooding during the monsoon, intake blockages, lime deposits, or other reasons) to be the main cause of water supply disruptions. (b) *Reliable*: Users consider the water source/intake to be reliable and not the main cause of water supply disruptions. (3) Water committee performance is defined as follows: (a) *Very effective*: Water committee meets at least once a month to discuss operation and management problems or issues related to the water system, develop a clear schedule for system operation (e.g., the schedule for opening/closing the main gate valve) that is followed, and address/resolve major issues with the users. (b) *Effective*: Water committee meets and discusses issues when a problem arises. The committee develops system operation schedules, but does not implement them as planned, and infrequently consults with users. (c) *Less effective*: Water committee neither meets regularly nor discusses issues when they arise. The committee does not develop system operation schedules. The committee chairperson or someone from the committee makes most decisions related to system operation and management. (4) The water system operator's level of activity is defined as follows: (a) *Very active*: Operator(s) maintain/repair the water system in less than 48 h when a problem is identified by the operator(s) or water committee. They operate the system in accordance with the schedule provided by the water committee. The operator(s) are formally appointed by the committee, work in consultation with the committee, and have the required maintenance tools. (b) *Active*: Operator(s) maintain/repair the water system within 48–72 h when a problem is identified by the operator(s) or water committee. They are formally appointed by the committee and have only some of the required maintenance tools. (c) *Less active*: A water committee member or an individual (who is not officially trained) is the *de facto* operator and spends more than 72 h working to maintain/repair the system when a problem is identified. They do not have the required maintenance tools.

of the model where households (i) are nested within water systems (j) is captured by a series of equations that predict the random effect using system-level variables s_{ij}^l . Since there are l random effects in the household-level equation, there are potentially l auxiliary equations, with the system-level variables that predict each of the different random effects. For instance, in Figure 2, four system-level variables predict the perceived reliability of the water source by households, whereas only one system-level variable predicts the household-level education variable.

RESULTS

Characteristics of the water systems and households

This research considers rural water systems in the study area to be community-based public infrastructure, developed through demand-driven processes, and largely constructed

and thereafter managed by its users. Engineers from the government or another oversight agency often set design standards and provide recommendations concerning the use of specific system components. Water users are typically involved in the construction of their systems, with engineering support and oversight provided by the government or local actor/NGO.

The age of the water systems varied between 7 and 18 years with a mean of 10 years. It reportedly took 4–7 months to complete the installation of the water systems. Households participated in multiple forms of planning and management activities, and attended on average six meetings during the development of their water system. The respondents reported they contributed labor (136, $n = 193$), cash (113, $n = 193$), and local materials (86, $n = 191$) to the construction of their water system. They also provided support in terms of sharing design ideas, selecting the location of taps and the water tank, identifying pipeline routes, and making other decisions during consultative

discussions. Most of the respondents recalled the contributions made by themselves or their family members. In some cases, the water committee was able to provide a record of the contributions made by the users.

Each community created a committee of 7–11 people to oversee the major administrative duties related to the operation and management of their water system. They also elected at least one woman into one of the five leadership positions (e.g., chairperson, vice-chair, secretary, joint-secretary, and treasurer). In most cases, the committees appointed an operator for major technical duties. The organizations implementing the water systems provided communities with operation and maintenance training and provided some maintenance tools.

The average number of days each household could not obtain water was 12 per year – most often due to a complete system breakdown or a component failure where a cluster of households were unable to access water. Each family used an average of 34 liters per capita per day (lpcd) for domestic use and 179 liters per household per day for productive activities (e.g., irrigating vegetables, raising livestock, and producing alcohol and biogas) from their primary water system connection. Some households used a secondary source (e.g., streams and springs not connected to the water system) for productive activities, especially for irrigating vegetables. For those households without a secondary water source, the system breakdowns presented a major challenge to irrigating crops, etc. When a system failed to supply sufficient water, households often carried water from public springs/spouts near to their homes for domestic use.

Model results

The HLM was used to determine the significant predictors of breakdown duration. The fixed effects results are presented in Table 1 and random effects in Table 2.

Table 1 shows the relationships between the breakdown duration and the independent variables. Three household-level variables – productive income ($p < 0.001$), a household's involvement in decision-making processes ($p < 0.001$), and a household's low sense of ownership (strongly disagree, $p < 0.001$) versus high ownership (strongly agree) – significantly predicted the duration of breakdowns.

All else held constant, three system-level variables are significantly associated with the duration of a water system breakdown: a water committee's performance (less effective versus very effective, $p < 0.05$), the level of a system operator's activity (active versus very active, $p < 0.01$; and less active versus very active, $p < 0.001$), and the distance to a water source ($p < 0.01$). These findings provide evidence that the reliability of the water source is associated with the distance to a water source, the performance of the water committee, and the operator's technical activity.

Interestingly, water-based productive income is a significant determinant of the duration of a breakdown. This finding implies there is potential for increased productive income to pay for recovery costs and important maintenance services, and aligns with other research that found increased income can improve system operation and management and enhance the resilience of water systems (Renwick *et al.* 2007; Clement *et al.* 2015).

The finding that household involvement in decision making reduces the duration of breakdowns is consistent with similar research on water system sustainability (Tadesse *et al.* 2013; Marks *et al.* 2014; Domínguez *et al.* 2019). However, cash contributions toward the construction of water systems were not found to be significantly ($p = 0.549$) correlated with the duration of system breakdowns.

There is no statistical evidence ($p = 0.247 > 0.05$) that source reliability is significantly associated with the duration of breakdowns. In addition, non-educated persons in the household ($p = 0.843 > 0.05$) and system age ($0.335 > 0.05$) were not found to be significant predictors of the duration of a breakdown.

The p -values for the interaction effects output results (Table 1) suggest that interaction between system age and water source reliability ($p < 0.05$), and the level of activity of system operators and water source reliability ($p < 0.01$) are statistically significant. These findings indicate that the duration of breakdowns derived from the reliability of a water source depends on system age and the level of a water system operator's activity. The duration of a breakdown significantly increases for unreliable water sources when system operators are not performing their operation and maintenance duties effectively. Conversely, the duration of breakdowns is predicted to decrease even for unreliable sources when

Table 1 | Summary of hierarchical multiple regression (fixed effects)

Variables	Coefficients (β)	Standard error	p-value
Productive income	−0.000061	0.000067	<0.001
Cash contribution for system construction	−0.1894	0.3160	0.5490
<i>Sense of ownership of water system (strongly agree)</i>			
Ownership (agree)	0.0514	0.3420	0.8800
Ownership (disagree)	0.7308	0.4633	0.1160
Ownership (strongly disagree)	1.9580	0.5810	<0.001
Involvement in decision making relating to project planning and implementation	−1.4730	0.4271	<0.001
Non-educated persons in the household	0.0774	0.3893	0.8430
Reliability of water source	2.9420	2.3060	0.2470
System age	−0.0849	0.0860	0.3350
<i>Water committee performance (very effective)</i>			
Water committee performance (effective)	−1.0170	0.8076	0.2100
Water committee performance (less effective)	2.0630	0.9686	< 0.05
<i>Level of system operator activity (very active)</i>			
Level of system operator activity (active)	3.8960	0.6627	<0.01
Level of system operator activity (less active)	7.3550	1.5480	<0.001
Distance to water source from the community	0.0011	0.0003	<0.01
<i>Interaction effects output</i>			
Reliability of water source: System age	−0.4739	1.7110	< 0.05
Reliability of water source: Level of system operator activity (active)	3.8960	0.9635	<0.01
Reliability of water source: Level of system operator activity (less active)	7.3550	1.5480	<0.01
Reliability of water source: Distance to water source from the community	0.00009	0.0005	0.8609
Reliability of water source: Water committee performance (effective)	−1.228	1.3180	0.3552
Reliability of water source: Water committee performance (less effective)	1.1060	1.3820	0.4245
Non-educated persons in the household: Water committee performance (effective)	−0.0467	0.4466	0.9202
Non-educated persons in the household: Water committee performance (less effective)	0.0552	0.4833	0.9090

Note: β_0 (intercept) = 1.061; REML criterion at convergence: 804; Variables have different scales.

system age increases. This implies that the ability to manage/operate a water system is likely to improve over time. The interaction between non-educated persons in the household and the performance of the water committee is not statistically significant.

The random effects table (Table 2) indicates significant variation based on the reliability of a water source across localities (i.e., the three wards: Annapurna-6, Walling-5, and Bagnaskali-1). The intercept and number of non-educated persons in the household show some variation across localities, but it is not statistically significant.

DISCUSSION AND CONCLUSION

This study identifies several factors that impact the performance of rural water systems in the middle hills of Nepal. One principal finding is the identification of significant household and system variables that predict the duration of system breakdowns. This study builds on previous research by incorporating a more holistic examination of social, economic, geographic, and management factors that affect system sustainability (Prokopy 2005; Tadesse *et al.* 2013; Marks *et al.* 2014; Smets *et al.* 2017; Domínguez *et al.* 2019). The study used a hierarchical predictive regression model

Table 2 | Summary of hierarchical multiple regression (random effects)

	Variance	Standard deviation
Locality (Intercept) ^a	0.10938	0.3307
Reliability of water source	3.14175	1.7725
Non-educated persons in the household	0.01216	0.1103
Residual	3.12064	1.7665

N = 171; Groups (Locality) = 3 REML criterion at convergence: 804.

^aThe constant in the regression model is called the intercept. It represents the 'baseline' effect on the dependent variable when all the other variables are taken to have value 0. In this case, the random intercept represents the variation in the baseline effect across systems irrespective of the additional effects of other variables.

that captured both household- and system-level variables that contribute to system breakdowns.

The study establishes three primary insights. First, household-level variables nested with system-level variables (Figure 2), responded significantly to the dependent variable and produced meaningful results. In other words, the hierarchical modeling yielded a result that explains the local context. Similarly, variables with fixed effects and random effects are accounted for in the model. While the fixed effects are the only variables that individually predict the dependent variable, random variables interact with system variables to better predict the duration of breakdowns. Interactions between system- and household-level variables enable the capture of a holistic analysis that can support the development of effective system planning and implementation strategies.

Second, the empirical evidence confirms that increased household productive income leads to a significant decrease in the duration of breakdowns. This reinforces the current debate that increased productive income enhances the ability of households to support system maintenance and upgrades (Clement *et al.* 2015). As our model suggests, creating cash flow from water-based enterprises, such as vegetable production especially during the dry season when prices are higher, allows for the collection of user fees that support water system operation and maintenance while improving the livelihoods of poor and marginalized rural farmers. However, the organizational, financial, and technical skills of community leadership would need to be developed to realize this aim.

Third, in Nepal, the design and execution of participatory processes is a critical determinant for the effectiveness

and sustainability of rural water systems. It is within this process that social, economic, engineering, and management variables are assessed by system users to produce design solutions. International and local NGOs facilitated the community engagement and training of water user committees during the planning and installation of the water systems included in this study. A key outcome from this process was the formation of a water user committee constitution or norms that include the following basic elements: member composition, selection, and tenure; scope of authority; water allocation and conflict resolution; user fees; and employment and management of a system operator. The model results demonstrate that increased management capacity of water user committees is significantly related to the duration of system breakdowns. A deep level of user engagement and involvement in rural water system planning, combined with user fees and donated construction labor, creates a strong sense of system ownership among system beneficiaries (Marks & Davis 2012). These findings highlight the importance of robust community engagement and capacity building efforts during project selection, design, construction, and beyond.

RESEARCH LIMITATIONS

Data on the duration of water system breakdowns and water-based productive incomes were self-reported by the surveyed households. This may lead to some inaccuracies despite efforts to gather these data as accurately as possible. In addition, the farming communities surveyed for this research are typical of those found in the middle hills of Nepal, with each containing 10–35 households. The findings from this study may not be applicable to larger communities or those located in peri-urban settings.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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