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Review

A Life-cycle Approach to Improve the Sustainability of Rural Water Systems in Resource-Limited Countries

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Abstract: A WHO and UNICEF joint report states that in 2008, 884 million people lacked access to potable drinking water. A life-cycle approach to develop potable water systems may improve the sustainability for such systems, however, a review of the literature shows that such an approach has primarily been used for urban systems located in resourced countries. Although urbanization is increasing globally, over 40 percent of the world's population is currently rural with many considered poor. In this paper, we present a first step towards using life-cycle assessment to develop sustainable rural water systems in resource-limited countries while pointing out the needs. For example, while there are few differences in costs and environmental impacts for many improved rural water system options, a system that uses groundwater with community standpipes is substantially lower in cost that other alternatives with a somewhat lower environmental inventory. However, a LCA approach shows that from institutional as well as community and managerial perspectives, sustainability includes many other factors besides cost and environment that are a function of the interdependent decision process used across the life cycle of a water system by aid organizations, water user committees, and household users. These factors often present the biggest challenge to designing sustainable rural water systems for resource-limited countries.

Keywords: water; sustainability; life cycle; resource-limited country

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1. Introduction

Providing sustainable potable water systems for rural areas in resource-limited nations remains at the forefront of national and international agendas. WHO and UNICEF [1] reports that in 2008, approximately 884 million people around the globe lacked access to improved water sources, while 2.6 billion people lacked adequate sanitation services. Unfortunately, these figures mask the extent to which these problems affect rural communities: 84 percent of people lacking potable drinking water and 70 percent of people lacking improved sanitation services reside in rural areas [1]. According to the World Bank, the only way to overcome poverty in rural regions is by addressing the specific root causes such as water provision [2]. Unfortunately, lack of water services in many areas is not for lack of effort on the part of government agencies and aid organizations, but is the result of implementing unsustainable systems, in part because the user characteristics are not fully understood [3,4].

As described in [5] and from an infrastructure perspective, the water system life cycle has four main activities: construction, operation, maintenance and demolition of the systems. Within the operation activity, there are eight life-cycle stages. For the first stage of the life cycle, water supply systems are generally designed to extract, collect, and store water from a variety of freshwater sources including groundwater, surface water, desalinized sea-water, and rainwater harvesting, or non-freshwater sources such as wastewater recycling. The water supply is treated, often stored, and distributed to users. Distributed water is used by various sectors for potable and non-potable purposes at a charge from the water company/board that may or may not be based on usage rates. After use, the wastewater (sometimes with additional water from non-sector use such as drainage water) is collected, stored, treated, and disposed or recycled. Throughout the process, other co-products result including sludge and gaseous emissions. This wastewater management may result in a fee charged by the company/board that is often based on a percentage of the water usage. On a large scale and with centralized facilities, environmental sustainability can be difficult to achieve for these systems.

The water infrastructure sector is generally made up of either public or private companies that provide these operational services to different users [5]. In many urban communities, a single company manages the entire water system life cycle [5]. In other urban communities (often large), several companies, public and private, manage various operational stages along with the associated activities for the water life cycle, e.g. company A may handle everything before the wastewater stages including the construction, operation, maintenance, and demolition of the associated systems. On the other hand, company B handles all of these stages and activities for the wastewater portion. In contrast, for rural communities, water user committees (WUC) and/or community boards themselves manage the activities and operational stages for the water life cycle [5]. Often, this is limited to communal systems for water supply with individual users managing their own wastewater disposal stages.

Because of the use of non-governmental committees and boards staffed by community members to manage the operational aspects, the sustainability success of a rural water system in a resource-limited country is closely connected to how the individuals within that community view the water system. In addition, regardless of funding, many systems are in part constructed with “sweat-equity” by the community residents. However, even if the community was never involved with construction, the long-term operation and maintenance of the system almost always depends on user fees.

Ostrom *et al.* [3] described three characteristics of a household user's responses to (or decisions to use) water infrastructure. The first characteristic is that individuals ultimately make varied decisions depending on how they interpret the risks and benefits of the alternatives and the outcomes of these alternatives [3]. For example, one water user may choose to purchase chlorine tablets for water she intends to drink and collected from a nearby river based on her understanding of the health risk. Another user in the same community may have a different understanding of the health risk and choose not to chlorinate the water.

The second characteristic is that an individual inevitably makes mistakes when faced with decisions that have a large degree of uncertainty, but can learn from these mistakes with institutional incentives [3]. Continuing with the example, the user who chooses to drink the untreated water may do so several times and then contract a stomach illness from a water-borne disease. Note that getting ill from drinking non-potable water is not a certainty. When the user visits a local clinic, the health provider explains the risk in more detail and how she can minimize that risk, and gives her vouchers towards the purchase of the chlorine tablets. The user then makes a different decision moving forward.

The third characteristic is that the individual is "intendedly rational," (p. 45) and makes a decision after weighing the risks and benefits of that decision with its associated incomplete information [3]. Again, using the same example, the user experiences the benefits of drinking potable water by using the vouchers for chlorine tablets. Once the vouchers are used up, the user weighs the "cost" of being ill occasionally *vs.* the cost of purchasing the chlorine tablets and rationally makes a decision for herself and her family moving forward.

These three characteristics are largely affected by the user's "time and place information," as well as how he/she understands the social and environmental characteristics of the area, the production capacity, and the institutional capacity to maintain a system [3]. In other words, the relationship of the user with the life cycle of the water system affects how he/she makes decisions regarding the system and these decisions ultimately affect the overall sustainability of that system.

In their 1999 study in the Katarko village in northern Nigeria, Nyong and Kanaroglou extensively examined the "time and place" decision factors that influence a household user's selection of a particular water source over another [4]. Nyong and Kanaroglou's fieldwork revealed that 61 percent of respondents cited proximity of water source as one of the most important factors for system selection [4]. The second most important factor (cited by 17.4 percent) was the maintenance and condition of the water source [4]. And, the third ranked decision factor (cited by 11.5 percent) was the number of people utilizing the water source [4]. Interestingly, only eight percent of water users considered water quality as an important factor in choosing a water source [4].

Of these factors, the quality of a water source and its impact on the user is the most uncertain. While Katarko water users did not reference "institutional and social constraints" when asked why they *did* chose a particular water source, 23 percent identified these as reasons for why they *did not* use a particular water source [4]. Expanding on this later consideration, Ostrom *et al.* have suggested that if an individual has a personal connection with the system operator, he/she may be more inclined to select that system because the shared language, moral standards, and project expectations that exist within kin networks may significantly lower the transaction costs associated with reaching an agreement [3]. Other authors have suggested a variety of sustainability considerations that could be considered institutional and social constraints. In other words, sustainability across the life cycle of a rural water system in a resource-limited community includes many dimensions: technical, environmental, institutional, community and managerial, financial, and human health. We illustrate these dimensions with a description of various sustainability considerations and possible measures (Table 1) that are generic to some extent so that they can apply to a variety of alternatives, independent of each other if possible, limited to the most important aspects in terms of sustainable decisions, quantifiable, unambiguous, and representative [5–8].

Table 1. Sustainability factors for water system design [1,5,9–15].

	Sustainability Factors	**Unit of Measurement**
Technical Factors	How much is demanded *vs.* how much the system can supply	% of residents who are unsatisfied with present water supply
	Compatibility with existing water-supply & sanitation systems	% of components from existing system that can be incorporated into new system
	General skills available	Yes or no
	Specialized skills required	Number of external specialists needed; number of training hours required
	Extension Capacity	% of unused hydraulic capacity within the design; unused latrine pit storage within the design
	Robustness	% of the year system will be in full service Previous % breakage/leakage with proposed materials Yes or no
	Quality & durability of materials	% of system that can use local materials
	Availability of spare parts	Yes or no
	Dependence on local materials	Yes or no
Environmental Factors	Non-renewable energy use	% of total energy demand from non-renewable sources
	Pollutant loading to body of water, land, and air	Pollutant contamination *vs.* carrying capacity
	Water transfer	Withdrawal *vs.* yield capacity
	Natural resource use	Natural resource use *vs.* yield capacity
	Hazardous chemical exposure (human and ecosystem)	Level of chemical exposure *vs.* regulated standards (for human and ecosystem)
	Noise pollution	% of samples in compliance
Institutional Factors	Existence/planned WUC	Yes or no
	Support from government, NGO, community, private sector	% of capital project cost shared by each entity
	Monitoring system in place/planned	Yes or no
	Regulatory system in place/planned	Yes or no
	Planned system compatible with national strategy	Yes or no
	Operation and management system in place/planned	Yes or no
Community and Managerial Factors	Local economy	Unemployment rate *vs.* national avaerage
	Living patterns	# of people/sq mile; demographic diversity
	Population expansion	% of system capacity available for growth
	Living standards	Average annual household income *vs.* national average
	Users' system preference	% of potential users who prefer system choice

Table 1. *Cont.*

	Sustainability Factors	Unit of Measurement
Community and Managerial Factors	Historical experience collaborating with different projects	% of success for projects conducted with major stakeholders within in the past 10 years.
	Community willingness to participate in construction of system, and to own, operate, and maintain said system after the initial construction phase	Yes or no
	Community water rights	% of system owned by community
	Acceptance of external help	% of community approval
	Equity in terms of system design	% of community with better or worse results as compared to averages
	User applications of collected water	Number of purposes water users use collected water for, other than for drinking; Volume of water required per day for purposes other than drinking
	Collection time	Number of minutes it takes user to collect water (traveling to source, waiting in line, and traveling home; does not include time spent engaging in activities along the way)
Financial Factors	Financial participation of users	% of users willing to pay portion of capital costs & tariff
	Water user fees	Maximum user fees are 5% of median household income
	Cost recovery	Annual household fees = annual O&M costs
Human Health Factors	Source protection	% of water that is source-protected
	Accessibility of water	% of community that will have access to an improved water system within 1 km of home
	Reliability of water source	% of demand met in each season
	Quantity of water provided by water sources	% of minimum standard met in each season
	Water quality	% of water samples below maximum allowable levels (pathogens *et al.*); % of water users who treat collected water
	Adequate sanitation	% of community with non-public, improved sanitation system
	Adequate hygiene practices	Approximately 10% of surveyed population know the appropriate times to wash their hands
	Rates of malnutrition	% of women & children clinically underweight.
	Young children (<5) mortality rate	Children's mortality rate (attributed to poor water and sanitation) in community *vs.* national population
	Incidence rate of diarrheal disease *	% of diarrheal disease (attributed to poor water and sanitation) among given population during 5 year period *vs.* total population

* Specifically, the mathematical model introduced by Fewtrell *et al.* (2007) estimates the burden of disease directly associated with poor water, sanitation, and hygiene for national and individual community populations. We focus on diarrheal disease because WHO states that it is the condition most-attributed to poor water, sanitation, and hygiene services (Prüss-Üstün *et al.* 2006). Other water, sanitation, and hygiene diseases may be selected from the following: intestinal nematode infections (ascariasis, trichuriasis, hookworm), schistosomiasis, trachoma, malaria, lymphatic filariasis, onchocerciasis, dengue fever, Japanese encephalitis, drowning (Fewtrell *et al.* 2007). Other indicator chemicals may also be added to sustainability factors e.g., arsenic, fluoride, [nitrate] (Howard and Bartram 2003).

In summary, Nyong and Kanaroglou argue that a household user's "accumulated knowledge", gained through adapting his/her water use to variations in surroundings, should be integrated into decisions about sustainable water systems [4]. From a life-cycle perspective, this means that aid organizations must make critical up-front decisions regarding water system technology and operation and maintenance (O&M) based on *predictions* of these decision outcomes that, in turn, depend considerably on the adaptable decisions of the water users. In other words, if the science of rural water infrastructure development is to improve, the sector must advance the predictive modeling of infrastructure decisions that recognizes this interaction among stakeholders and the life-cycle aspects that affect the formal decision process.

To develop this predictive capability, a life-cycle approach is needed that is based on first having a thorough understanding of the environmental and cost impacts, and then combining this with the considerations at each life-cycle stage of the decision process using many of the factors listed in Table 1. In this paper, we demonstrate the potential of such an approach using both a hypothetical case study to illustrate the cost and environmental aspects, and three real case studies to illustrate the other aspects. We focus the demonstration on potable water systems.

To understand the life-cycle environmental and cost impacts we used a modified life-cycle assessment (LCA). A formal LCA includes a delineation of the life-cycle stages of a system, an inventory of the inputs and outputs at each stage of the life cycle, and an assessment of the impact of those inputs and outputs. We limited our approach to the life-cycle inventory stage (LCI). We developed several potable water scenarios for a hypothetical community and extrapolated the LCIs from the environmental and cost studies for other water system contexts. Part of the extrapolation is based on using unit data for inputs and outputs while adjusting for typical community sizes and water usage patterns. The potable water scenarios depend on the water source, extraction method, type of connection to the water system, and treatment methods for the water supply. Table 2 describes these potable water scenarios and categorizes them.

Table 2. Water system scenarios for rural communities in resource-limited countries.

Scenario	Water Source	Extraction	Distribution	Water Treatment
A	Groundwater	Borehole with pump & above-ground storage	Centralized/Yard Taps	–
B	Groundwater	Boreholes with pump	Community Standpipes	–
C	Surface Water	Pump with above-ground storage	Centralized/Yard Taps	Drip Chlorination
D	Surface Water	Pump with above-ground storage	Centralized/Yard Taps	Slow Sand Filter
E	Surface Water	Pump with above-ground storage	Community Standpipes	Drip Chlorination
F	Surface Water	Pump with above-ground storage	Community Standpipes	Slow Sand Filter
G	Surface Water	Manual collection	–	Point-of-Use Bio-sand Filter
H	Spring Water	Spring-box/above-ground storage	Centralized/Yard Taps	Drip Chlorination
I	Spring Water	Spring-box/above-ground storage	Centralized/Yard Taps	Slow Sand Filter
J	Spring Water	Spring-box	Centralized/Yard Taps	Point-of-Use Bio-sand Filter
K	Spring Water	Spring-box/above-ground storage	Community Standpipes	Drip Chlorination
L	Spring Water	Spring-box/above-ground storage	Community Standpipes	Slow Sand Filter
M	Spring Water	Spring-box	Community Standpipes	Point-of-Use Bio-sand Filter
N	Rainwater	Harvesting system	Yard Taps	Point-of-Use Bio-sand Filter

To think about a rural water system from the remaining sustainability factors, we used the decision frameworks for WHO, a large-scale development organization, and WaterAid Nepal, a non-governmental organization (NGO), along with three projects from the Asian Development Bank (ADB).

There are two primary limitations to the work presented. The first is that most of the LCI data for water systems focuses on the urban, resourced country context which can be quite different from that for rural water systems in resource-limited countries. The second is that rural water system design most often exists in a local context since the choices depend in large part on the available assets. Since we rely on combining published literature (environmental, cost, *etc.*) from a variety of case studies, our results are not specific and cannot be used for any one community. Instead, the results are intended to help the reader understand the challenges and benefits of using a life-cycle approach to examine a context that has yet to benefit from such a tool.

2. Scenarios

2.1. Hypothetical Community for Cost and Environmental Assessment

There are many definitions about what is rural *vs.* urban, with population being only one factor. The US Bureau of Census defines an urbanized area as a central city and surrounding areas where the population is greater than 50,000. The US Census Bureau also considers towns outside of an urbanized area with a population greater than 2500 as urban. In the US, any community that does not meet these definitions is considered rural. On the other hand, the Organization for Economic Co-operation and Development (OECD) defines rural as an area with no more than 150 inhabitants per square kilometer. A working paper by the Eurostat defines a similar threshold level for rural communities as 200 people per square kilometer [16]. This is in contrast to statistical data from The World Bank that states the "rural" population density worldwide is 492 people per square kilometer [17]. Household size also varies significantly from country to country.

Based on the literature, we define a hypothetical rural community in a resource-limited country as one with the following characteristics: 256 inhabitants, 64 homes (4 inhabitants per home), one square kilometer community area. We assume that once a community identifies the need, the aid organization uses a bottom-up approach to design the system, the community organizes itself with a WUC that coordinates O&M of the water system and collects tariffs, and the users act in a homogeneous way based on their response to this system [18].

For most LCIs, one determines a functional unit that is kept the same for all alternatives so that the inputs and outputs can be directly compared. For water systems, such a functional unit might be the annual water usage for a community, or the daily water usage per capita. However, the water usage for rural alternatives in resource-limited communities is dictated in large part by the available infrastructure and the location of the access point. As such, while we use daily community water usage as the functional unit for this study, the amount of that water usage varies by scenario.

There are various published estimates for daily water needs for typical rural communities in resource-limited countries that depend on the topography and the availability of water resources, e.g., in some locations where water is scarce, fetching water takes more time, is regarded as a task for women and children, and consequently results in less water usage [19]. As shown in Table 3, approximately 80 L/capita-d is recommended for the various household uses for potable and non-potable water without considering agricultural and other external demands. However, Table 4 shows that this water demand varies from 5 to 80 L/capita-d depending on how the water is accessed by the user. An additional consideration comes from South Africa where the 1998 National Water Act mandates that every citizen is entitled to at least 25 L/d of potable water within 0.2 km walk from the home. Water usage with a rainwater system depends less on user accessibility, and more on weather patterns and varies quite a bit from case to case. For the scenarios we describe in this paper, we assume the following:

- 50 L/capita-d for the following scenarios:
    - centralized community standpipe at no greater than a 0.25 km walk
    - decentralized manual collection from surface water at no greater than a 0.25 km walk
    - decentralized rainwater system with yard tap
- 80 L/capita-d for centralized systems with yard taps

Table 3. Usage data from Southern Asia [20].

Use	Quantity (L/capita-d)
Drinking	5
Cooking	3
Sanitary purposes	18
Bathing	20
Washing utilities	15
Clothes washing	20

Table 4. Data for typical rural community in a resource-limited country [20].

Water supply	Quantity (L/capita-d)	Quantity range (L/capita-d)
Community Standpipe at >1 km	7	5–10
Community Standpipe at 0.5–1 km	12	10–15
Community Standpipe at <0.25 km	30	20–50
Yard Tap	40	20–80

2.2. Infrastructure Estimates for the Scenarios

For the scenarios we describe in this paper, we had to estimate the infrastructure needs. These estimates are discussed below with results summarized in Table 5.

Groundwater: Groundwater is a suitable source of water if extraction methods are practical and economical. Wells are hand dug, driven, or drilled to access the water in underground aquifers, and often equipped with pumps. For smaller, rural communities, typically a drilled well with a narrow diameter (2 to 3 cm with a depth of no more than 100 m) is used that is referred to as a borehole. Aquifers are natural storage for groundwater, and usually groundwater is free of pathogenic bacteria, however, groundwater may have high mineral content.

Table 5. Infrastructure assumptions for water system scenarios (taps, wash basins, valves, spring boxes, and other appurtenances are not included).

Scenario	Usage (L/d)	Borehole (#) (3 cm, 50 m, 100 mm PVC casing)	Pump (#, type)	Tank (m^3 & #)	Treatment System (# & type)	Transmission + Distribution Piping (km) (2 cm diameter)
A	21	1	1 diesel (3.73 kW)	1 elevated (21 m^3)	–	10
B	13	12	12 hand pumps	–	–	–
C	21	–	1 diesel (3.73 kW)	1 elevated (21 m^3)	1 (drip chlorination)	10
D	21	–	1 diesel (3.73 kW)	1 elevated (21 m^3)	1 (slow sand filter)	10
E	13	–	1 diesel (3.73 kW)	1 elevated (13 m^3)	1 (drip chlorination)	9
F	13	–	1 diesel (3.73 kW)	1 elevated (13 m^3)	1 (slow sand filter)	9
G	13	–	–	–	64 (point-of-use)	–
H	21	–	–	1 (21 m^3)	1 (drip chlorination)	12
I	21	–	–	1 (21 m^3)	1 (slow sand filter)	12
J	21	–	–	–	64 (point of use)	12
K	13	–	–	1 (13 m^3)	1 (drip chlorination)	11
L	13	–	–	1 (13 m^3)	1 (slow sand filter)	11
M	13	–	–	–	64 (point of use)	11
N	13	–	–	64 (0.2 m^3)	64 (point of use)	–

For a reliable groundwater supply, a reasonable assumption is that 3 cm diameter, 50 m deep boreholes are used in aquifers with sufficient yield capacity. These boreholes are completed using cable tool percussion drilling with a 100 mm PVC vertical pipe (serves as the casing) and well screen to keep the borehole from caving, prevent surface contaminants from entering the borehole, and protect the installed pump from drawing in sand and sediment. Cable tool percussion drilling as opposed to rotary drilling is a simple and cost-effective method for drilling boreholes in small rural communities [21]. Based on case studies in rural Africa [22], drilling each borehole with a small diesel engine and 6 to 8 laborers results in depths of 15 to 20 m per day for a maximum of five days and 15 to 20 L of diesel fuel per day [21]. Water is drawn out of each borehole using either a 3.73 kW capacity diesel powered pump for the centralized system, *vs.* hand pumps for the community standpipes. And, no treatment is needed because the soil acts as a filter for the water that seeps into the aquifer (this assumes adequate location design for wastewater disposal). The characteristics for the various scenarios are as follows:

- Community distribution system with yard taps—One borehole and one water-storage tank is needed to provide a pressure head and prevent the pump from operating continuously. According to data on specifications for the pump, the water is raised to a total head of just less than 10 m at 3.93 L/s [23]. Such a pump operates for 1.5 h daily to fill a 21 m^3 HDPE storage tank. A 10 km grid of

3 cm PVC pipes distributes the water to each household from the tank. At each house there is a tap, faucet, and basin.

- Community standpipe option—A report by the World Health Organization (WHO) recommends that if groundwater is the primary water source, there should be access to at least one well for every 200 inhabitants in a rural community, and no user should have to carry water over a distance greater than 100 m [19]. As such, water is drawn out of 12 boreholes at 12 locations within the community such that every member has access to water within 250 m of their residence. There is no need for storage tanks since water is pumped by hand at each of the standpipes. Hand pumps do not require external sources of energy to be operated other than manual labor.

Surface Water (fresh): Surface water includes rivers, lakes, ponds, streams, and wetlands. Water must be collected from the source, and needs to be treated primarily for microbial contaminants. Collection is manual, or for centralized systems, via various types of pumps. These sources may also include the construction of reservoirs to store water. Storage tanks that provide a pressure head (to prevent continuous pump operation) are also common for gravity-based distribution systems.

For reliable surface water options, we assume there is a water body running along one side of the community. A simple intake structure is used to extract water and the water is collected through 3 cm PVC pipes extending out into the river from a well sump built on the bank about five m away from the river [20]. A 3.73 kW submersible diesel pump transports the water through the pipes out of the well sump into a raised 21 m^3 HDPE storage tank. All surface water supply options need treatment, however we assume that the river water is below the maximum permissible turbidity of 50 ppm [19]. The characteristics for the various scenarios are as follows:

- Community distribution system with yard taps: Slow sand filtration and drip chlorination are the two most common centralized treatment options in rural communities. After treatment, the water is gravity-fed to the households via a 10 km grid of 3 cm PVC piping. The treatment options are as follows:
  - Drip Chlorination—Water is disinfected within the tank with drip chlorination using the assumption that 60 mL of sodium hypochlorite can disinfect 400 L of water [24]. Chlorination is a common method of disinfecting and several forms of chlorine may be used, including, elemental chlorine gas, calcium hypochlorite and sodium hypochlorite. Sodium hypochlorite is most suitable for these scenarios because it is cheaper than using calcium hypochlorite, but safer than handling chlorine gas in remote and rural areas [24]. The recommended level of residual chlorine concentration for disinfecting drinking water supplies is 0.5 to 1 mg/L to prevent toxic effects that can result in substantial disruption of aquatic life [25]. The toxicity of chlorine in wastewater does not depend on the amount of chlorine added, but rather on the concentration of the chlorine residual.
  - Slow Sand Filtration—Slow sand filtration is one of the oldest methods of water purification. The filter is composed of a column of sand supported by a gravel under-drain. A biologically active layer (schmutzdecke) forms on the top surface of the sand layer and removes organic particulates and microbial contaminants in the inlet water [26]. A slow sand filter requires minimal operation and maintenance, and virtually no external energy.

The rate of infiltration for a slow sand filter is usually low and on the order of 2.8 m^3/m^2/day [24]. Maintenance procedures include scraping four to 6 cm of sand off the top of the filter and washing it to remove contamination, for reuse. This requires no equipment other than light rakes. It takes the schmutzdecke a few days to grow before the filter can become fully functional again [26]. The use of a slow-sand filter requires a second pump to lift the treated water to a storage tank.

- Community standpipe option: Instead of delivering to each household, the treated water is delivered via a 9 km 3 cm piping grid to 12 standpipe locations within the community such that every member has access to water within 250 m of their residence. Most other characteristics regarding treatment for the yard taps scenarios apply. A smaller 13 m^3 storage tank is used since the demand is lower for the community standpipe option. As a result, the amount of sodium chloride required is less and the pumps operate less.

- Manual water collection: This scenario is based on having accessible surface water within a 0.25 km walk for each home. No infrastructure is needed other than point-of-use treatment and we base the design on using bio-sand filtration. Bio-sand filtration is an established method used in rural areas of many resource-limited countries [27]. It operates using the same principles as slow sand filtration, but on a smaller scale suitable for daily household use. Concrete is a commonly used material for the filter container because it is waterproof, rustproof and non-toxic [27].

Spring Water: Springs are outcrops of ground water, typically at higher elevation than the community served, and often at a distance from that community so it precludes manual collection. Digging out the area around a spring without disrupting the underground formation can increase the quantity of water flow. Spring water requires treatment since there is typically little leachate and runoff control around the watershed. However, a spring source does not require a storage tank (or pumps) for a gravity-based distribution system, though it may still require storage for treatment and/or diurnal flow management.

For the spring water option we assume pumping is not needed for a reliable supply, there is a spring about two km away from the community and the flow is such that diurnal storage is not required. Spring water is collected through a pervious-bottomed spring box with typical dimensions (1 m × 1 m × 1 m) [28]. Once collected, the water flows by the force of gravity through two km of 3 cm PVC piping. The characteristics for the various scenarios are as follows:

- Community distribution system with yard taps with centralized treatment—Either slow sand filtration or drip chlorination is used for treatment as described previously, with the treated water distributed via a 10 km 3 cm PVC piping grid to each household. Because of the treatment needs, a 21 m^3 HDPE tank is needed.

- Community standpipe option with centralized treatment—Either slow sand filtration or drip chlorination is used for treatment as described previously, with the treated water distributed via a 9 km 3 cm PVC piping grid to each of 12 standpipes. Because of the treatment needs (not storage needs), a 13 m^3 HDPE tank is needed.

- Community distribution system with yard taps and point-of-use treatment—The water is distributed via a 9 km 3 cm PVC piping grid to each household tap where users rely on bio-sand filtration for treatment.

- Community standpipe option with point-of-use treatment—The water is distributed via a 9 km 3 cm PVC piping grid to each of 12 standpipes where users rely on bio-sand filtration for treatment.

Rainwater: Rooftop rainwater harvesting depends on the climate and weather characteristics of a rural settlement. Simple catchment systems with filters are built to collect and store water at the point of use. Rainwater can act as a supporting source to a regular water supply, or as the supply itself depending on seasonal precipitation in terms of both flow and frequency. Rainwater must also be treated since pathogenic bacteria from birds, *etc.*, along with other air-borne pollutants may be washed off rooftops. Rainwater harvesting is considered a decentralized option with water accessible at individual yard taps.

We assume that each household will have a system to collect enough rainwater and store it to serve all its needs on a daily basis. As such the required storage for each home is a 0.2 m^3 HDPE tank. The collection system has to include a gutter and downpipe where the gutters are fitted to the roofs of the houses on all four sides to channel the run-off into a collecting vessel (the tank) through the downpipe [29]. The water collected in the storage tank is treated with bio-sand filtration when used.

2.3. Case Studies for Social Assessment

For the analysis of the social aspects, we used three actual case studies that were available and cover various success levels in terms of sustainability. The three case studies are from ADB's "Water for All" initiative in Nepal. The communities include Jhumka, Indrapur, and Panchakanya.

Panchakanya is a village development community located within the Sunsari District of Nepal. This ADB subproject specifically refers to the ethnically-diverse village of Devigaon, which is located in Panchakanya's fifth ward [30]. This "Gravity Flow" subproject was implemented under ADB's third RWSSP and was completed in 1999. The project included 14 new community water taps in the village [30]. Prior to ADB involvement in Panchakanya's water and sanitation sector, locals experienced significant water hardship because the community's nine existing community taps could not supply adequate water quantity to meet user needs [30]. As a result, users, especially women, were forced to walk uphill for more than two hours to obtain water from a spring and worse during the rainy season [30].

Jhumka is a rural, but rapidly expanding village development community (VDC) in the Sunsari District of Nepal. ADB classifies the subproject as a "Pumped Water" project under the fourth Rural Water Supply and Sanitation Sector Project (RWSSSP) [30]. The RWSSSP consists primarily of gravity-fed piped systems and groundwater pumped systems to provide reliable water services for approximately 1500 rural communities in the far-western, mid-western, and eastern development regions of Nepal [31]. ADB completed the fourth RWSSSP in 1997 [30]. Under the Jhumka subproject, ADB provided users in wards two, five, six, and nine with household connections. In addition, the VDC received 14 community water taps.

The water system in Indrapur had been in operation for approximately 10 years when WaterAid deemed the sustainability of the system to be doubtful [30]. The Indrapur project was part of the third RWSSSP (1992–1999) that resulted in the ADB-installation of 220 community tube-wells and five "deep-set tube-wells" (p. 37) in five of the community's nine wards [30]. Previously, a river 20 to 30 min away from the households served as the village's primary water source [30].

3. Results and Discussion

3.1. Life-Cycle Cost Perspective

As described in Table 1, the aspect of financial sustainability is in large part determined by the capital costs and the recurring operation and maintenance costs. These dimensions can be captured with the-time value of money using a discount rate and an assumed design life to determine present worth costs. Cost data is sourced from published non-governmental (NGO) and inter-governmental (IGO) organizational reports and publications available online. The cost data is adjusted for inflation to 2005 levels using the Consumer Price Index (CPI) and then converted to US dollars to allow for comparison. Various other assumptions underlie the calculation for each scenario as follows:

- The lifespan of the infrastructure systems in each scenario is 20 years. One exception is the point-of-use bio-sand filter treatment systems with a design life of 30 years [27].
- Costs are incurred at the beginning of each year.
- O&M costs are annualized.
- Where O&M data is not available, a percentage of capital cost is used as an estimate. Higher energy (mechanical) components have an annual O&M cost of 15% of capital costs. Other low energy components have an annual O&M cost of 5% of capital costs. Pipelines have an annual O&M cost of 2% of capital costs.
- A uniform discount rate of 10% is used which is standard practice among multi-lateral development banks and institutions when evaluating projects.
- Inflation is not accounted for.
- Where scenarios require elevated storage, 15% of the cost of the tank is added to account for the costs associated with the construction of the supporting structures.

Table 6 summarizes the cost LCI for the various rural water system alternatives. Given that aid organizations often sponsor much of the capital costs, the O&M costs may be more important for a life-cycle sustainability approach. One conclusion we can draw from the results is that the O&M costs mirror the capital costs and can be used as a proxy for total life-cycle costs. Another conclusion is that if a community has a full suite of choices for a water system, a groundwater system with community standpipes is one of the lower total cost options for an improved system. In general and as expected, community standpipe systems for all water sources are less costly over the life cycle than individual household taps. In terms of treatment alone, a point-of-use system is slightly less expensive than a drip chlorination system while a slow sand filter system is the most expensive.

Table 6. Summary of community life cycle costs for rural water systems.

Scenario	Scenario–Brief Description	Life Cycle Costs $1000 (2005)	Capital Costs $1000 (2005)	Annual O&M $1000 (2005)
A	Groundwater, yard taps, no treatment	88–160	71–135	2.0–2.9
B	Groundwater, community standpipes, no treatment	59–138	49–127	1.1–1.2
C	Surface water, yard taps, drip chlorination	73–130	56–105	2.0–2.9
D	Surface water, yard taps, slow sand filter	87–158	60–110	2.9–5.1
E	Surface water, community standpipe, drip chlorination	52–89	34–67	1.4–2.0
F	Surface water, community standpipes, slow sand filter	61–112	39–72	2.3–4.2
G	Surface water, manual collection, point of use	0.8–2	0.8–2	–
H	Spring water, yard taps, drip chlorination	74–140	60–116	1.6–3.1
I	Spring water, yard taps, slow sand filter	82–161	65–123	2.0–4.7
J	Spring water, yard taps, point of use	71–136	59–115	1.4–2.8
K	Spring water, community standpipes, drip chlorination	48–96	40–84	1.1–2.2
L	Spring box, community standpipes, slow sand filter	55–115	43–85	1.4–3.8
M	Spring box, community standpipes, point of use	45–92	38–82	0.8–1.8
N	Rainwater, yard taps, point of use	31–72	31–72	–

Of course, the manual collection systems are the lowest in terms of tangible life-cycle costs, but there are certainly intangible costs in terms of the collection time for women and children who are often the ones primarily responsible. Note that these intangible costs are not captured by the financial factors in Table 1. Instead, other sustainability factors have to be considered. To complete the sustainability analysis from a life-cycle cost perspective, the next step is to determine if users in a particular community are capable of *and* willing to provide these capital and annual costs over the design life for the system. See Table 1 under financial factors. Unfortunately, this is beyond the scope of this paper.

3.2. Life-Cycle Environmental Perspective

Table 1 illustrates the various sustainability factors to assess from the environmental perspective. As stated, most of the available, published environmental LCI data are for large-scale urban systems. Much of this data is aggregated for several activity phases including construction, operation, maintenance and demolition. However, a few published LCI studies present disaggregated data for various activity phases, as well as for specific operation activity stages in terms of extraction, transport, storage, treatment, distribution, and use. This data is primarily related to energy demand and is summarized in Table 7. Other assumptions underlie the calculation for each scenario's LCI as follows:

- Based on a review of LCIs for different categories of water system infrastructure, energy usage in the raw materials activity phase is determined for the piping and the point-of-use treatment systems as described below. We assume that energy demand for the raw materials activity phase for other materials such as tanks, valves, gutters, well casing, *etc.*, is similar across the scenarios, negligible compared to the piping, and in place for long time periods. We also do not include energy demand for installing the wells, tanks, and other infrastructure.

Table 7. Water system energy consumption for various life-cycle stages.

Water System Life Cycle Stages		**Energy consumption Minimum**	**Energy consumption Maximum**	**Reference**
Intake pumping (surface)		0.05 kWh/m^3	1 kWh/m^3	[32]
Intake pumping (ground)		–	0.18 kWh/m^3	[33]
Point-of-use Bio-sand Filter (concrete container manufacture)		–	0.0001/64 GJ	[34]
Rainwater (container manufacture)		–	0.005/64 GJ	[35]
Piping (Fabrication)				
Internal Diameter (m)	Thickness (mm)			
0.1	–	–	2 GJ/m	Extrapolated
1.52	14.5	–	9.8 GJ/m	[36]
1.83	17.3	–	14.0 GJ/m	[36]
3.35	31.8	–	47.2 GJ/m	[36]
4.57	43.4	–	87.8 GJ/m	[36]
5.18	49.1	–	112.8 GJ/m	[36]

- The available published energy data for piping materials (water lines and borehole casing) includes pipe diameters much larger in those studies than what is typical for the scenarios we are looking at. We extrapolated to estimate the energy data for 6 inch (0.1 m) piping. The references are included in Table 7.
- Energy usage for the materials in point-of-use treatment systems is only directly available for clay filters. The amount of cement used in the concrete needed for the filter body of a typical household bio-sand filter unit is given in a set of specifications produced by Center for Affordable Water and Sanitation Technology [27]. Using the energy content of Portland cement [34] we calculated the energy expended in building the bio-sand filter.

• No published data is available for habitat impacts during the construction activity phase. Given its importance as noted in Table 1, we represent these impacts in terms of linear distance of disturbed land.

• We used LCIs for the pumping and treatment stages for water system infrastructure to estimate the energy usage during the operation activity phase.

• No published data is available for the expendable materials usage and disposal during the operation activity phase. Given it's importance as noted in Table 1, we estimate this output based on the volume of materials consumed over a design life. We include point-of-use systems, and the sand used in centralized systems. Maintenance of the bio-sand filter includes scraping the top few inches of sand. Thus through the life span of a concrete bio-sand filter, which is assumed to be 30 years [27] the only material disposed of or reused is the sand in the filter. The spring box construction requires four 50 kg bags of cement [28].

• We do not include habitat and other resource impacts during the operation activity phase because our analysis is based on using only sustainable water sources where the quantity of water redistributed does not affect the natural habitat, and is replenished completely.

- We do not include the infrastructure demolition phase since we assume the systems are in place for significant time periods for each scenario. However, there may be eventual burdens here that should be considered as part of a LCA conducted over an extended time period. This type of analysis can be more reasonably performed for a specific case study with a smaller number of potential alternatives for water system development.

Table 8 summarizes the environmental LCI for the various rural water system alternatives according to the environmental sustainability factors listed in Table 1.

Table 8. Summary of life-cycle inventory for rural water systems.

Scenario	Scenario-Brief Description	Energy-Material Production million MJ	Habitat Impacts-Construction 1000 yd^2	Energy-Operation million MJ/lifetime	Disposed Materials-Operation m^3/lifetime
A	Groundwater, yard taps, no treatment	3.4–5.0	8.0	0.4	–
B	Groundwater, community standpipes, no treatment	0.1	0.2	–	–
C	Surface water, yard taps, drip chlorination	3.4–5.0	8.0	0.4	–
D	Surface water, yard taps, slow sand filter	3.4–5.0	8.0	0.8	24
E	Surface water, community standpipe, drip chlorination	3.0–4.5	7.2	0.4	–
F	Surface water, community standpipes, slow sand filter	3.0–4.5	7.2	0.8	16
G	Surface water, manual collection, point of use	0.0001	–	–	minimal
H	Spring water, yard taps, drip chlorination	4.0–6.0	9.6	–	–
I	Spring water, yard taps, slow sand filter	4.0–6.0	9.6	–	24
J	Spring water, yard taps, point of use	4.0–6.0	9.6	–	minimal
K	Spring water, community standpipes, drip chlorination	3.7	8.8	–	–
L	Spring water, community standpipes, slow sand filter	3.7	8.8	–	16
M	Spring water, community standpipes, point of use	3.7	8.8	–	minimal
N	Rainwater, yard taps, point of use	0.005	0.05	–	minimal

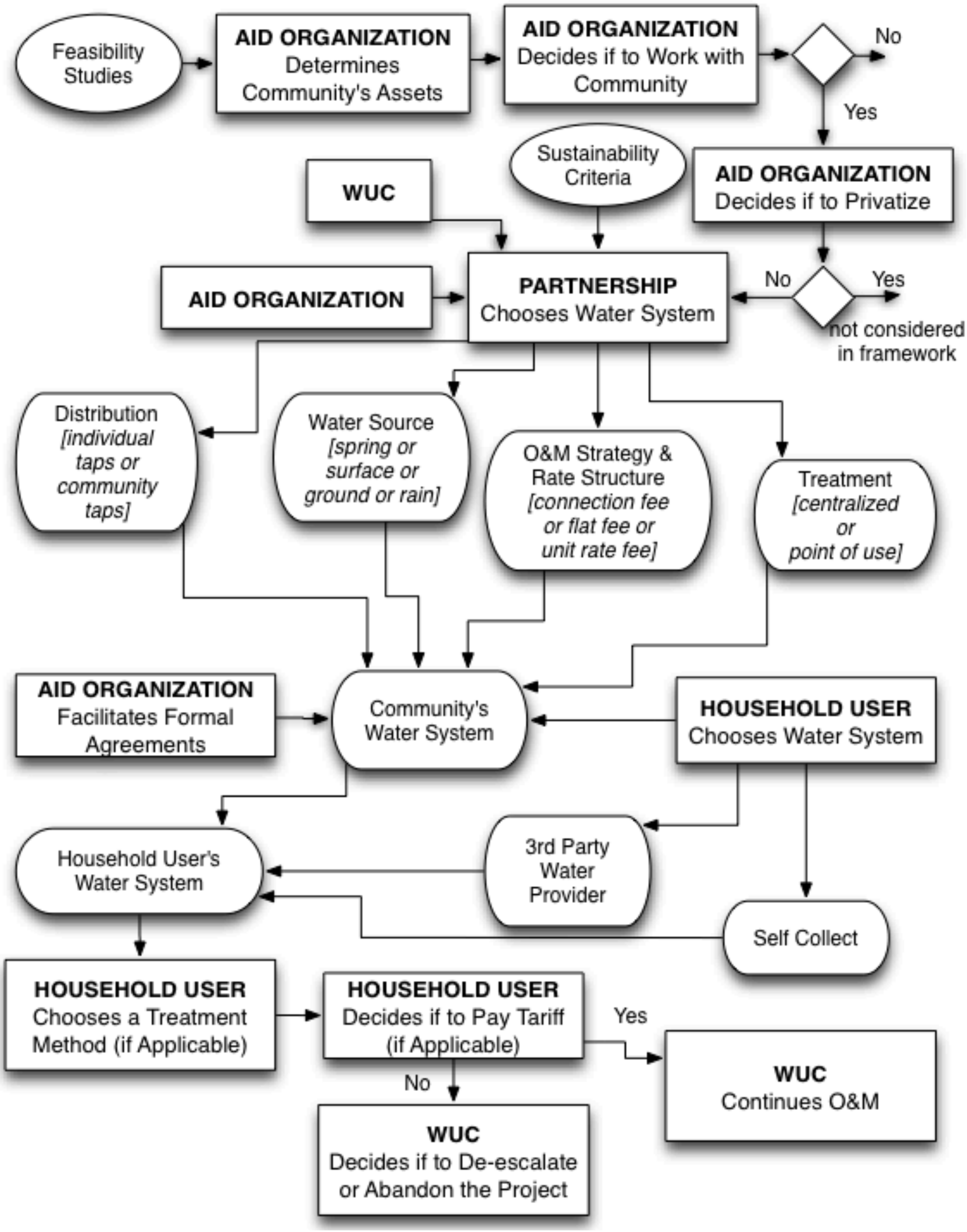
In general, the data gathered from published environmental LCIs indicate that regardless of the context for a water system, the operational activity phase is responsible for the most energy input, and energy is the most significant environmental issue given current energy sources [37]. In general, the construction and demolition activity phases for water-wastewater systems are not important in terms of the life-cycle environmental inventory since infrastructure systems typically have long lifetimes. However, these activity phases (particularly construction) vary inversely with system capacity, therefore for smaller, rural water-wastewater systems such as the ones we consider in this study, construction activity may be a more important consideration for sustainable development. Also, the sustainability of rural water systems that do not rely on externally-supplied energy sources is likely determined by the size of the environmental inputs and outputs due to the construction activity phase in terms of materials usage (primarily for the distribution system) and habitat effects.

The extraction, transport, and treatment life-cycle stages (all part of the operational activity phase) for a water-wastewater system contribute to energy consumption, however the fraction for each, and the overall energy consumption depends significantly on the source for the water. Efficient energy usage is also a concern for rural water systems, particularly if water for potable uses must be boiled, or purchased due to safety concerns. Other important variables that affect the energy inventory (and in some cases the materials inventory) include technology choices, water quality at the source and at the disposal location, as well as the relative location of the water source, treatment plant, usage points, and disposal options. There are also concerns from chemical disposal and its effects on wastewater quality, sludge quality, and air emissions.

3.3. Life-Cycle Social Perspective

The LCI results for environment and cost (or financial) factors agree for the most part in terms of how to prioritize water system alternatives in terms of sustainability. However, these are only two of the categories of factors that affect the sustainability of a rural water system as described in Table 1. The remaining categories are technical, human health, institutional, and community and managerial factors. When one examines the measures for the technical and human health factors, it is clear that there is a high degree of cause and effect between environmental and financial sustainability as it affects the technical and human health sustainability of a system. For example, a community water system that is financially sustainable means that there are adequate finances available to size the system appropriately and maintain reliable operation that results in users having adequate quantities and quality of water for their various needs. Similarly, we suggest that there is a high degree of cause and effect with the institutional and community and managerial aspects of sustainable water systems and this is where the socio-economic perspective matters. We examine these socio-economic sustainability factors of the water system by looking at the various decisions made across that life cycle, as well as the characteristics of those making the decisions. Below, we describe the main stages for each main decision maker with an overview in Figure 1.

Figure 1. Overview of the decision process for the life cycle of a rural water system in a resource-limited country.



The Aid Organization. Typically the capital funding is provided in whole, or in part by an aid organization. The more common types of aid organizations are the large multilateral agencies and the international NGOs. Despite differences in organizational characteristics, the decision process for these organizational types has evolved to include many similarities as illustrated by WHO and WaterAid Nepal. WHO is a large multilateral agency while WaterAid Nepal is an international NGO.

Descriptions of their decision processes are similar except that WaterAid emphasizes the importance of the initial decision to enter a community and the need for ongoing O&M and monitoring while WHO [38] emphasizes the need for a contextual set of sustainability considerations for both system design and formal agreements. We use the combination to describe the typical four-step decision framework for an aid organization that occurs up front in the life cycle of a water system. The process is described below.

Step 1: <u>Determine the community's assets</u> based on a data-gathering stage known as the feasibility study. The feasibility study allows the aid organization and the community to determine viable technology options, to assess existing assets including the community's capacity, and to establish the potential scope of the proposed project [18]. A well-designed feasibility study includes appropriate design and wording of the questions, a thorough interviewer, and an adequate data pool across a variety of water users (household, community, and public institutions), the WUC, and the water sellers. Each of these entities is invested in a different aspect of the water sector and therefore perceives the life-cycle needs of the system differently [18].

Step 2: <u>Decide whether or not to work with the community</u> based on the data collected during the feasibility study. The key determination is whether the proposed community demonstrates the capacity necessary for effective project implementation and long-term system sustainability (WaterAid Nepal 2006a). WaterAid Nepal suggests that the decision to work with a community depends on whether the system is demand driven, if water users have a sense of system ownership, if there is an active WUC, and if it is likely that spare parts will be available over time. All of these considerations are life-cycle oriented [18].

Step 3: <u>Use sustainability factors to choose the water system.</u> This step involves four sub-decisions made in partnership with the WUC regarding the (a) distribution system; (b) water source; (c) treatment method; and (d) O&M strategy and rate structure. These selections should be made based on sustainability factors, and should also consider the community's assets, with the ultimate goal of producing a life-cycle system design [38].

Step 4: <u>Facilitate the formal agreements</u> necessary for system implementation. The roles and responsibilities of involved stakeholders must be clearly defined to avoid confusion about which groups are responsible for performing particular services over the life cycle of the system [38]. These stakeholders include the WUC, the users of the system, and any external groups, such as regional entities and/or private sector providers.

The Water User Committee (WUC). The outcomes of the aid organization's decisions then depend on the decisions by the WUC and the households respectively. The community WUC is typically responsible for the daily management of the water system over its life cycle that includes setting and collecting water user tariffs, mobilizing local labor and materials for routine system repairs, and maintaining strong communication networks with water users [31]. The process is described below.

Step 1: <u>Use sustainability factors to choose & design the alternative(s).</u> In a bottom-up approach, the WUC selects the water system design in partnership with the aid organization. Using feasibility data along with identified sustainability criteria, the WUC partnership then selects the (a) distribution system; (b) water source; (c) treatment method; and (d) system O&M strategy and rate structure. Collectively, these four sub-decisions result in the design of the overall water system.

Step 2: De-escalate or abandon the project. Based on the success of system implementation in terms of the household users' response over the life cycle, the WUC periodically decides whether to continue providing water system services. Unfortunately, little literature is available regarding such project de-escalation and abandonment for water systems though it happens repeatedly as evidenced by failed systems throughout the resource-limited world. Poor response from the household user in the form of non-payment and/or not fulfilling responsibilities for the O&M of the system is one of the factors contributing to de-escalation and project abandonment for water system projects.

The Household User. The household users' decisions represent the responses to the decisions previously made by the WUC and the aid organization in terms of the choices for a water system. The general process is described below.

Step 1: Which system to collect water from. The household users' selection of a water system directly impacts his/her subsequent choice of treatment and payment because these two decisions depend on the logistics and design of the water system. However, as noted by [4], the choice as to which system the user prefers is complex and depends on the technologies provided as well as household characteristics such as financial capability and demographics, plus community characteristics including topography and site layout.

Step 2: Using a water treatment method (if applicable). In terms of treatment, a household user does not need to select a water treatment method if he/she previously chose a WUC-operated system with centralized treatment, or a third-party provider (we assume third party providers employ centralized treatment) e.g. bottled water. However, if the user self-collects from an unimproved source, or selects a WUC-operated system designed for point-of-use treatment, water treatment becomes a household responsibility and is subsequently included as part of the decision process.

Step 3: Paying the tariff (if applicable). As with Step 2, payment, whether it is a connection fee, a flat fee, or a unit rate fee, is required if a third-party water provider or WUC-operator is selected by the homeowner. However, payment is typically not required if the household users choose to self-collect.

The Panchakanya Case Study: The feasibility study data used by ADB showed that community members, particularly women, walked uphill in excess of two hours to collect water from a spring because the community's existing taps could not provide sufficient water quantity [30]. As such, ADB wanted to ensure that the final system would prevent that hardship [30]. The design alternative selected was a WUC-operated system consisting of 14 community water points and several private household taps. The Panchakanya's water users complained that they did not have a large role in the decision-making stages and the WUC members claimed that they did not receive sufficient financial and construction information [30]. However, WaterAid Nepal reports the presence of significant community influence that allowed designers to consider community-specific characteristics in the project design [30]. There are several examples of this cooperative decision process as discussed below.

The project designers originally planned to install 13 community water taps. However, they ultimately decided to add a fourteenth tap at the request of the water users who informed officials about five or six houses in a region of the village where no other water taps existed [30]. All 14 ADB community taps were located a convenient distance from the household with a short wait time and short collection time [30]. Additionally, the system provided water from the community taps throughout the day because the designers constructed reservoir tanks to ensure an adequate water supply at peak times. Furthermore, during the rainy season, the water provided by the taps could become muddy at the intake point, however the design included stored water that minimized this negative effect on users [30]. The presence of these tanks also allowed water users to utilize the taps during the afternoon and at night thus providing the opportunity to partake in household gardening to supplement their diets [30]. Finally, the WUC initially called for a monthly tariff of NPR 25, but lowered it to NPR 20 after water users, who were accustomed to paying only NPR 10 per month for an alternate system (or the free spring), bitterly complained [30].

The Jhumka Case Study: Based on the feasibility study, ADB determined that while the Jhumka community obtained the majority of its water from private tube-wells financed either through a UNICEF revolving fund, or personal funds, rapid population expansion had placed significant strain on the existing infrastructure [30]. As such, ADB selected a system that included 135 private household piped connections and 14 community taps [30]. ADB required the creation of a WUC prior to project implementation [30]. In terms of O&M, ADB (1996) used a "two-tier[ed]" approach made up of WUCs and the respective District Water Supply Office (DWSO). The regional DWSO played a "hands-on" role within communities by explaining O&M costs and responsibilities. DWSO also monitored and supported WUCs until they could independently manage the systems [31]. The WUC employed a plumber, a meter reader, and a pump operator for the multiple tasks related to system O&M [30].

In terms of formal agreements, ADB outlined three major issues that affected the Jhumka community: land rights, water rights, and government assurances to the ADB. Regardless of location, ADB (1996) dictated that communities must assume full responsibility for acquiring the land necessary for storage reservoirs, pipelines, and public tap stands. These acquisitions, per ADB decree, could not displace households or rural settlements [31]. Once the government obtained the land, they were required by ADB to enforce holds on the land for all purposes other than DWSO office construction [31]. A last factor that ADB addressed is that Nepal's two primary laws governing water resources that only addressed domestic water rights. To remedy this situation, ADB mandated that the Nepalese government draft and enact the Drinking Water Supply Regulations by May 1997 [31]. These regulations were required to include provisions on: WUC establishment and responsibilities, uniform registering and licensing procedures for "*de jure* legal status," and legal authorities including mitigating water dispute resolution [31]. Finally, the Nepalese government was required to make specific "assurances" to ADB regarding the project, all of which were incorporated into legal documents containing standard agreements.

The above factors align with a life-cycle approach to water system design despite the fact that the WUC could not play an active part since it did not exist prior to the project. However, ADB made some decisions that could be seen as limiting successful sustainability. First, the Jhumka community did not rank highly in terms of all of ADB's three selection criteria for project aid including hardship, per capita cost, and community participation. In particular, since the majority of the community water users already had private tube-wells and while water demand was increasing, the village was not experiencing a full-scale water crisis [30]. Second, ADB limited the design alternatives that were considered to pre-selected technologies even though such a limitation does not consider the local context for a community [30].

So how did the Jhumka community fare in the long term based on these decisions? Jhumka's newly created WUC actively engaged in its required O&M responsibilities and WUC members regularly conducted community campaigns to encourage the installation of piped connections in an attempt to improve the financial sustainability of the system [30]. In terms of daily maintenance and management, the Jhumka water system functioned at full capacity, and pipes and most spare parts for the individual household connections were readily available [30]. The WUC set the initial connection fee at NPR2305 with a minimum monthly tariff at NPR30 and the majority of users reported to WaterAid Nepal that they could afford the fees [30]. These are all signs of long-term sustainability of the water system across the life cycle.

However, at the time of the assessment report, only two of the 14 community taps (not household taps) that were designed to provide water to areas where the population lacked access to alternative sources were functioning [30]. And, financial constraints led to the loss of two of the five original WUC employees [30]. In addition, while 300 household connections were needed to make the project financially sustainable, only 135 were connected since some water users refused to pay for the installation costs because of poor water quality (allegedly due to a high iron content) [30]. The WUC also concluded that the water system needed a treatment component, however it claimed that the regional administration disregarded the request [30].

WaterAid ultimately concluded that the long-term sustainability of the Jhumka project was doubtful [30]. The first reason relates to the lack of thoroughness in terms of considering alternative water resources that brings that adequacy of the feasibility study into question [30]. The second reason is the WUC's reluctance to take responsibility for the system when users complained bitterly about poor water quality indicating a lack of ownership [30]. This result may be due in part to the lack of a WUC during the initial decisions. The third reason appears to be the lack of communication between stakeholders at several points in the process [30].

The Indrapur Case Study: This case study demonstrates how poor technical, institutional, and managerial decisions along the life-cycle affect long-term sustainability.

The design of the water system included a majority of areas where one tube-well served between three and four households, however, in the community's poorer areas, 20 to 25 households were forced to share one well [30]. The distribution of the tube-wells were determined by the WUC and the Water Supply and Sanitation Division Office (WSSDO) [30]. WaterAid Nepal's review found that while the WUC was made up of nine members from each of Indrapur's nine wards, when it came time to actually distribute the tube-wells, the ward chairs decided how many wells should be distributed and where they should go [30]. In other words, the shift of "real" power to the chairpersons had major ramifications in terms of the decisions made.

Another poor design/construction decision occurred in one of these poorer areas where citizens had to filter the water with muslin cloths because of insects [30]. The project developers blamed poor hygiene habits and the settlement's low elevation for the poor water quality, however the reports show that the problem actually arose from carelessness during construction along with the insufficient training of the well managers [30]. The water system design also resulted in annual water shortages below minimum ADB levels [30]. In some instances, the shortages were seasonal while in other cases the wells were completely broken only a few years after construction. WaterAid Nepal reported that these shortages also resulted from poor construction decision since the wells were dug during the rainy season when the groundwater levels were high so workers stopped digging when they hit water [30].

Besides design problems, other issues arose due to a lack of system ownership along with the community's crumbling institutional organization ([30]. The user's sole contribution to the project was a flat installation fee that resulted in users assigning O&M duties to the household closest to the infrastructure, rather than utilizing the three-member subcommittees assigned to handle O&M [30]. In addition, the majority of the institutional structures created to support the community and the WUC failed to provide necessary assistance e.g., DWSO failed to provide the community with the necessary tool sets to perform system maintenance and repairs; when tool sets were provided, the wrenches often did not fit the screws [30,31]. Additionally, WaterAid Nepal reports that spare parts were not locally available, forcing system repair workers to improvise with materials found in the community markets [30]. Finally, the community's maintenance fund was poorly understood and managed by the WUC and members did not know how much money was available, nor what the funds should be used for [30].

What the Case Studies Show: While we do not have complete information regarding the aid organization's decision process for the Panchakanya case study, the resulting water system design and the user response to the system suggest that the institutional as well as community and managerial sustainability factors described in Table 1 were taken into account throughout the process. The Juhmka case study is more complicated. While technical decisions by the aid organization regarding the design of the Jhunka water system appeared to result in a successful system design based on short-term results, there were some indicators of problems for long-term sustainability due to failure to fully partner with the WUC and community. These results illustrate that many community and managerial factors can affect the success of an aid organization's decisions, even when the majority of best practices are followed for institutional and financial sustainability. With the Indrapur case study, the project was headed towards possible de-escalation and failure in large part because many community and managerial sustainability factors were not included throughout the decision life cycle. The root cause of these problems appears to be changes in project management that led to local political leaders using the promise of tube-well installation as a way to appeal to their constituencies [39]. Project managers also attempted to make these negative outcomes appear less threatening to the public in the face of unambiguously negative feedback and contradictions to the minimum service level targets, however this minimization only made the problem worse [39].

While it is clear that if best practices for certain aspects of technical, financial, and environmental sustainability are not followed, a system is likely to fail, following those best practices does not ensure that the resulting water system will be sustainable. This result is in large part due to the responses from the households along the life cycle of the water system as they have to make decisions regarding what source to use, what treatment to use, and if to pay user fees. In particular, the prioritization among the sustainability factors listed in Table 1 varies across decision makers and over time and space thus complicating the problem.

4. Conclusions

Our objective in this paper is to demonstrate how using a life-cycle approach can improve the sustainability of rural water system design in resource-limited countries. We suggest that the reason for the many failures of such systems is that the outcome of the design decision depends in large part on the response of the system's users and other stakeholders over the life cycle of the system. However, we also show that there are many sustainability factors that affect one's ability to effectively apply such a life-cycle approach to develop a water system infrastructure solution for these contexts. We use several hypothetical and real case studies to draw our conclusions.

Assuming that a community has a full suite of choices for a water system, a life-cycle approach shows that a groundwater system with community standpipes is the most environmentally sustainable improved option, as well as one of the most financially sustainable options. All other improved options are similar in terms of environmental inputs and outputs. In general and as expected, community standpipe systems for all water sources are less costly over the life cycle than individual household taps. However, while standpipe systems are somewhat more environmentally sustainable than household yard taps, the differences are small if the systems are designed to provide for WHO specifications (with the exception of groundwater sources as already mentioned). In terms of treatment alone, the various options have similar life-cycle inputs and outputs, however a point-of-use system is less expensive than a drip chlorination system while a slow sand filter system is the most expensive.

As expected, the manual collection option (as opposed to improved options) in conjunction with point-of-use treatment is by far the lowest cost alternative with less environmental inputs and outputs than the improved systems described above. We obtained a similar result for a rainwater system in conjunction with point-of-use treatment, however this system design requires sufficient rainfall. Given that this assumption often does not exist, particularly over time and across seasons, we do not consider this option reliable. In addition, these non-improved options typically result in lower per diem water quantities with associated negative social impacts. However, a community member's choice of where to get water for daily needs in terms of convenience and other attributes may result in choosing these lower cost options and this choice can significantly affect the sustainability of the improved system that may have been installed by an aid organization.

Given the limited financial resources of community members in these rural settings who have to maintain the systems over time combined with the relatively similar environmental LCI, the life-cycle cost is the higher priority as compared to environmental factors when choosing among available water sources and treatment options. The only exception to this conclusion is the situation where groundwater with community standpipes is a viable option. These results need to be modified if situations are significantly different from the assumptions we used in this study e.g., much farther distance to the spring or depth to groundwater, significantly worse water quality, much larger and/or less dense community population, *etc.* In general, the farther a water source is from the community, the higher the cost and environmental LCI relative to the other options due to the piping involved. Similarly, the larger the community is, the less the difference is in terms of the cost and environmental LCI for the community standpipe *vs.* the yard tap options.

Besides the life-cycle cost, the case studies demonstrate that there are many institutional and community and managerial factors (described in Table 1) that affect the sustainability of rural water system design for resource-limited countries. The three case studies illustrate that while not thinking up front about how the sustainability characteristics important to the key decision makers can doom a project, it can be very difficult to adequately address these characteristics despite the best intentions. In large part, this is because the aid organization that is making the decision about the water system design, including life-cycle aspects, has to accurately predict how the household users and the WUC will react to that design from a variety of perspectives. Even when working closely with the WUC and the households, such prediction is very difficult because the decision process is dynamic and interactive. An outcome at one stage of the decision process can change the available alternatives and thus the outcome at the next stage, and so on. The case studies further illustrate that while there is an overlap in the sustainability considerations, each stakeholder applies a different priority weighting as he/she makes decisions. Knowing this prioritization is a critical component of reliably predicting the outcome of rural water infrastructure decisions.

Our study shows that using a life-cycle approach to determine the cost and environmental LCI for the alternatives is difficult because there is limited data available for such systems and water system design is very dependent on the local context. That said, the results can help a decision maker prioritize the feasible alternatives that are most sustainable from an environmental and cost perspective. However, this prioritization is often useless from a holistic sustainability perspective if they are abandoned because users will no longer pay to maintain them and/or WUCs do not support such maintenance. The aid organization needs to also consider the likely reaction of the WUC and users to the various options before making a final decision. Unfortunately this approach is difficult to do with current tools.

What is needed is a predictive decision tool that captures the interaction of the key stakeholders: the aid organization, the WUC, and the household user. The tool must also capture how this broad array of sustainability considerations affects the risk of project failure *vs.* success. The key to successfully developing such a predictive tool is recognizing the main considerations used by the three stakeholders as they formulate the individual decisions that, in concert, impact the overall outcome of the decision process. Identifying these main considerations and how they change under dynamic conditions is not included in this paper and is a work in progress. In particular, the rich literature regarding the role of gender and culture needs to be incorporated into these considerations and into any predictive tool. Besides being useful for aid organizations, such a tool will allow further research on how to prioritize the relative impact of the various sustainability considerations. Ultimately, this tool can lead to real change in addressing the significant potable water and public health needs across the globe.

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