Micro Water Distribution Networks: A Participatory Method of Sustainable Water Distribution in Rural Communities

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***Abstract*—Water scarcity has been a major thrusting issue in rural India, warrantinga high demand to design and implement different water distribution networks for easy and efficient use of existing water sources. Both macro and micro level systems exist of which, macro level water distribution networks have higher capital and maintenance costs. This is due to its size and the remote beneficiaries to which it caters. This paper describes the design of one such water distribution system in two rural villages in India whose design considerations includes the local community needs, availability of labor, local resources, climate, cost, and time for implementation. This paper also compares the micro and macro water distribution network's impact on sustainability. Sustainability is defined in terms of water wastage, usage rate, source capacity, total network length, cost of deployment, source recharge, and the network leakage rate. The paper discusses the water distribution projectscompletedin a village in Orissa and in a village in Rajasthan (two states in India) where all households were given 24/7 access to clean and safe drinking water for more than a year. The paper also draws insights on the socio-economic impact of the project carried out in these two states.**

Keywords—water distribution; system sustainability; sustainable development;

I. Introduction

The rural population in India is comprised of more than 1 billion people residing in about 1.42 million habitations spread over diverse ecological regions [1]. Along with the issues of poverty, education, socioeconomic development, diverse practices and rituals, addressing the pressing need of water management is a herculean task for state administrators. According to Indira Khurana, et al, poor water quality has its impact on the socioeconomic horizon of India where one hundred million Indians are affected by water borne diseases, three million children die due to diarrhea, and seventy-three million working days are lost due to water borne diseases which results in an estimated total economic burden of one billion dollars per year[2].

Most parts of India are blessed with rivers, long, Himalayan tributaries, large forest covers and surplus monsoon seasons. However, the impact of the pressing population explosion on the environment is tremendous. As more and more, swampy areas are converted into agricultural lands and inhabitant areas, forest cover in all corners of India have started to deplete and have a huge impact on the water table. Varying demands, leakage losses, low water quality, day to day operational, and maintenance costs makes rational water distribution a complex process. The difficulty in planning the water distribution system for a small community is discussed in Wagner and Lanoix [3]. In addition, changing consumption patterns add to the complexity of the system [4].

The Government of India's Ministry of Drinking Water and Sanitation has a National Rural Drinking Water Program(NRDWP) which envisions providing safe and adequate drinking water for all and at all times in rural India. The key timelines presentedare :

> "To ensure that at least 50% of rural households are provided with a piped water supply; at least 35% of rural households have a piped water supply with a household connection; less than 20% have to use public taps and less than 45% have to use hand pumps or other safe and adequate private water sources by the year 2017. All services meet set standards in terms of quality and number of hours of supply every day. Also ensure that all households, schools and anganwadis(courtyard shelters) in rural India have access to and use an adequate quantity of safe drinking water. They also will try enabling support for local government institutions and local communities to manage at least 60% of rural drinking water sources and systems[5]."

Although the Government has put allocations for participatory implementation of water distribution through other methods, most of them have failed. Wells are polluted, hand pumps are dried out, and villagers have to walk miles to fetch water for their daily needs. There are many reasons for this failure and crisis in water distribution. The Ministry of Rural Development, Government of India points out that the usage of the same ground water source for domestic consumption and irrigation is a prime reason. Eighty percent of the water resources in India have been utilized for irrigation [6].

Considering the above challenges gives insight into the importance of sustainable water distribution systems. Rural water distribution systems have been traditionally categorized into Small Village Scheme (SVS) and Multi Village Scheme (MVS) [5]. Analysis on these two schemes suggests that the categorization on which systems have to be designed, implemented, and operated has to be on the target number of villages under the scheme and not on its impact. As the system is neither demand driven nor supply driven, defining a system based on demand/supply alone is extremely challenging. Therefore, a new categorization for water distribution systems based on the number of households is offered.The categorization of the water distribution systems based on supply and demand driven models is shown in Table I. Keeping this analysis as a baseline, this paper discusses how we developed a framework for a sustainable water distribution system which is based on target beneficiaries in villages in Rajasthan and Orissa.

Table I. Categorization of Water Distribution Systems

Sl No	**Categorization**		
	Number of house holds	***Demand and supply driven***	***Demand/ supply driven***
1	<50	Nano	SVS
2	>50	Micro	SVS
3	>300	Mini	SVS
4	>1000	Macro	MVS

Water related issues have been one of the most critical issues within most of the villages adopted under the Amrita SeRVe[1] project. Researchers under the project,who form a part of the Live-in-Labs™ [2]program,determined that water related issues affect the overall goal of the project, i.e. transforming these villages into self-reliant ones. Access to clean water will catalyze the efforts in health, income generation, and education. Evaluation of the causal impact of the improved access to water for domestic consumption is beyond the scope of this paper. Different existing sustainability frameworks were evaluated to model the implementation of a water distribution system in these villages. The paper is divided into different sections: Section II presents related work on sustainable water distribution systems, Section III describes our methodology to develop a framework for micro water distribution systems, Section IV delineates our system design, Section V presents our case study on the implementation of the systems in the villages and design of a frame work for determining sustainability coefficients and adaptability indices.

[1]Amrita self reliant villages (AmritaSeRVe) is a village adoption program managed and funded byM.A. (Mata Amritanandamayi) Math

[2]Experiential learning program under Amrita University.Weblink:- https://www.amrita.edu/international/live-in-labs

[3]SVS - Single Village Scheme and MVS - Multi Village Scheme

II. Related Work on Sustainable Water Distribution System

There are different advantages of the MVS and SVS3 in regard to the rural communities[7]. The WHO report addresses the inefficient approaches practiced in the SVS and MVS. It also evaluates the performance of the different water distribution schemes which are implemented by the government or government appointed agencies [7]. But most of the supply driven schemes are underperforming and dilapidated.

The report makes an attempt to model the performance on the basics of (a) adequacy and reliability, (b) affordability, (c) environmental sustainability, and (d) financial sustainability indices [7]. It also discuss the failure of framework in evaluating the causal variables such asskill/expertise of the design engineer, participation of the community, etc. [7]. The key findings are (1) poor performance of the schemes in enabling availability of good quality and quantity of water for the community,(2) huge copying cost borneby the communities,(4) higher cost of service provision,(5) excessive capital cost of service delivery, (6) poor maintenance optimization and efficiency, (7) over provisioning of schemes or existence of multiple schemes in the villages, (8) economics of scale not being realized, and (9) an inefficient service delivery model.

III. Methodology

A diffused bottom up methodology is used to develop a generalized framework for design, development and implementation of micro water distribution system. The methodological flow of the process is represented in Figure 1.

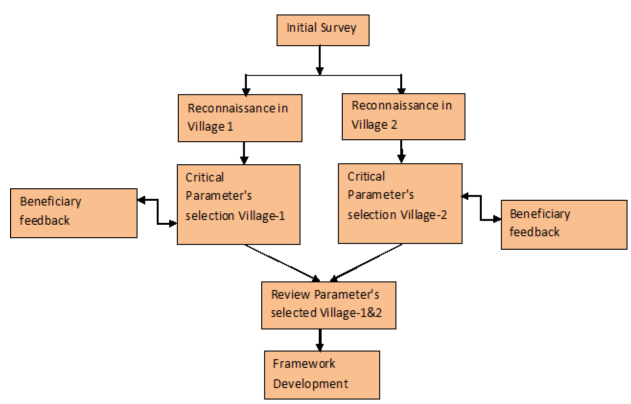


Fig.1: Methodology: Process Flow diagram

To know the demand and supply side requirements, the implementation team performed phased reconnaissance in both of the villages. Critical parameters for the design werethen

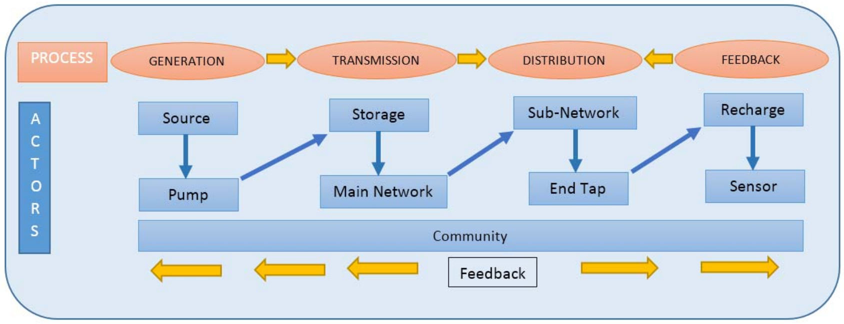


Fig. 2: Water Distribution Scheme as a System

identified from these surveys. The parameters identified weresubjected to constant review from the community and input from the other village, and these parameters weredefined with field conditions and community needs in mind. The prioritization is based on a participatory approach from the community it benefitted. Community feedback is provided back into the flow while reviewing each parameter. The identified parameters are then used to design the system.

IV. SYSTEM DESIGN

A system is said to be sustainable only if it persists or survives over time [8]. But the additional imperative queries are (1) how long it should persist and (2) how we can define it. Related works on sustainability suggest that choosing a proper physical scale of a system is imperative to define sustainability [9]. The impact of a proper scale and comprehensiveness of the framework determines the performance of sustainability indicators [10]. Keeping these factors as a reference,the goal was to design a sustainable system for villages in Rajasthan and Orissa that would be sustainable and replicable in all rural communities.

The system consists of two main entities, i.e. actors and process. The various actors in the system are (1) Source (2) Pump (3) Storage (4) Main Network (5) Sub network (6) End taps (7) Recharge (8) Sensors, and (9) Community. The functional categorization of these actors makes up the various processes in the systems such as (1) Generation, (2) Transmission, (3) Distribution, and (4) Feedback. The system is shown in Figure 2.

The system becomes active with the pumping of water from the source (GENERATION). The pumped water is stored in a central storage and transmitted through the main network (TRANSMISSION). This water is distributed to the end user using sub networks and finally consumed through end taps (DISTRIBUTION). The community is a common actor in all steps including feedback, defined next. The system gets closed through the flow of water and information via recharge, sensor and community actors respectively (FEEDBACK). The actor recharge encompasses local surface water bodies, rainfall precipitation, and drainage pattern of the system.

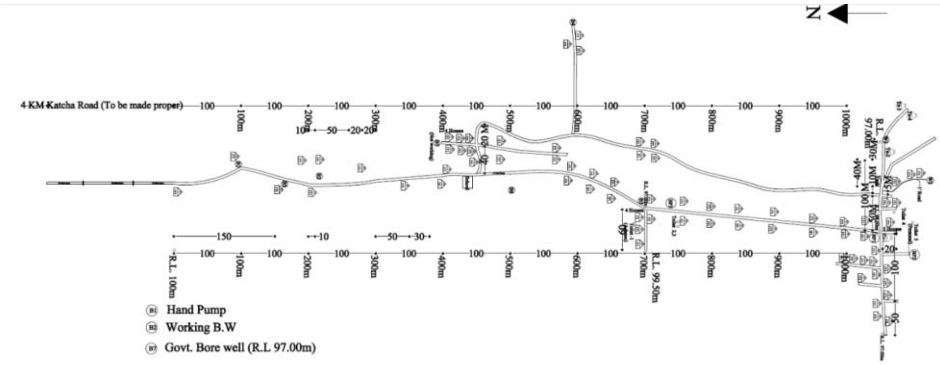
Design of the system took into account the geographic and demographic lay out of the two villages as well as the micro water distribution system implemented in these two villages

V. CASE STUDY: ORISSA AND RAJASTHAN

Guptapada is a small village in the Khurda district of Orissa, which lies in the outskirts of the capital city Bhubaneswar. The relative level of the village is 25.1m above MSL (Mean Sea Level) along 20°16'55.9"N and 85°40'2.5"E. The overall population of the village is 300, distributed among62 houses with the majority in the age group of 15-35 years, as shown in Fig. 5. The main source of income for the people in the village is firewood collection, which earns them hardly 1 US Dollar per day/family. Migration to a nearby city is the biggest threat in achieving self-reliance of the village. Fig. 3 shows the daily plight of women to carry water from a far off land.

Fig. 3: Lack of easy access to water at Guptapada village

Harirampur is a small village in SawaiMadhopur district of Rajasthan. The nearest highway to this village is about 36 km away. The water source in this village includes a small stream, open wells and bore wells. The main occupation is agriculture and cattle rearing, which also serves the needs for basic nutrition. The crops cultivated are primarily wheat, bajra and mustard. Even though there is a primary school inside the village, children tend to drop out when they barely start to read and write. The population of the village is about 500 people distributed in 65 houses as given in Figure 4.



SI.NO	SYMBOL	DESCRIPTION	NOS	ANY EXPLANATION
1		HOUSE	55	500 Poulation
2		BOREWELL PERSONAL	3	Mainly for agriculture
3		BOREWELL (Govt)	7	B7- Not working
4		TEMPLE	4	3,4 - Kulla deivam
5		TOILET	5	1to 3 - Ashram + Personal 4,5 - Personal
6		WELL	2	Drinking water
7		R.L		

Fig. 4: As Is Map of Harirampur

The geographical area covers 3.8 Sq Kilometers; domestic settlement forms 0.4 sq kilometers, and the rest is used as agricultural land.

Both villages face common community challenges. These include: physical and cultural isolation from the rest of the world; inadequate access to safe drinking water; poor health and hygiene practices; extremely high rate of illiteracy and dropout among school children; lack of proper medical care.

The initial survey in each of the villages helped in identifying the following values for the following processes. The *As Is Map*that was prepared to map Harirampur village is shown in Figure 4.

The copying cost in accessing water and opportunity cost of poor sanitation practices are two costs of the poor waterdistribution model available in the village.

Generation: A single phase 1.5 Hp pump for the village in Rajasthan, where electricity is scarce and a 15 Hp pump for the village in the Orissa.

Transmission: 30,000 liters capacity tank with a minimum head of 20m in Rajasthan and a 25,000 liters capacity tank with a minimum height of 5 m.

Distribution: 2,000 m GI pipe of 120mm diameter and 240 m of 25 mm diameter pipe is suggested for Rajasthan. In Orissa it is divided in three sections as shown in Figure 5. Section A consists of a 4 inch main distribution and 1 inch domestic distribution lines with desired lengths running to 720m and 320m. Section B and section C have 2 inch and 1 inch Distribution Lines as main and sub. The respective lengths for Section B are 324 m and 40 m, and for Section C are 210m and 56 m.

Taking into account the opinion of the target beneficiaries, key factors for design consideration were localization efforts, i.e.geographic boundary where the community assumes voluntary ownership of installations, cost of maintenance; optimal design which aligns the future expenses with the community expectations, their usage rates; s highly routine and predictable life style which helps to identify the peak hours and whether the system is able to meet that demand and if they are equipped to cater to acceptable risk mitigations.

A. Design Modification

The entire system design is modified to accommodate the factors discussed above to make it reliable and to minimize operations and maintenance costs. Both systems are similar, but the final design was optimized to suit the needs of the individual community.

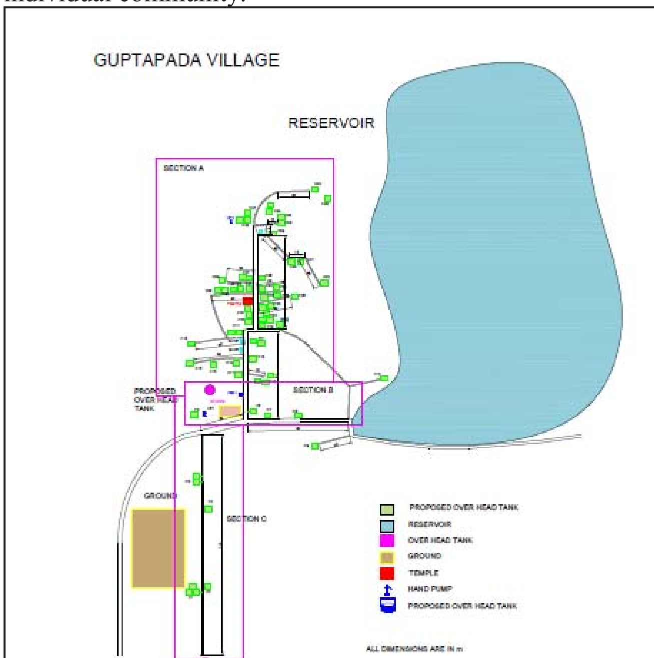


Fig. 5: Proposed design for water distribution system in Guptapada

- *Use of Storage Tank*: The factors considered for optimizing the supporting structure of the central tank are ease of availability of raw materials, labor cost, duration of actual deployment and ease of maintenance. The storage tank in the Harirampur village is elevated on a hybrid structure whereas in Guptapada. a steel structure has been used. The better community participation in design ensured a low cost structure and reduced capacity for the storage unit without compromising on demand requirements. Thus. the demand patterns and supply potentials were matched to scale down to capacity to more than 25% of the conventional design. Figure 6 shows the storage structure and tank in Harirampur.

Fig.6: Storage Tank and Structure in Harirampur

- *Network:* Although the network is designed to deliver water at 40 lpcd, the peak time delivery rate is optimized in consensus with community. Thus, the network design and complexity werereduced to contain the cost of installation and maintenance. Sub network length is higher in Harirampur because of the community request for an individual pipe at a low flow rate. The number of taps in Orissa was based on the demand pattern as determined through community participation, and has reduced the cost of pipes and associated labor by 30 %.
- *Village Participation:* The level of community participation during these implementations are much higher compared to the alternate model discussed [7]. Figure 7 and Figure 8 shows the community participation in trench digging and routine meetings for the design of the network.

Fig.7. Discussion session

The villagers participate in the reconnaissance, design, implementation, and maintenance. Considering these factors, the initial parameters were customized to a new set of process values, which is shown in Table II.

Fig.8: Community participation in trench digging

Table II. Comparison of Schemes in Orissa and Rajasthan

Village	Orissa	Rajasthan
Mainline Length (4 inch pipe)	1200 meters	650 meters
Branchline Length (2 inch pipe)	100 meters	450 meters
Tapping Points	37	70
Central tank Capacity	5000 liters	10000 liters
Support structure	Steel Structure	Steel-Concrete Hybrid Structure
Pumping Station	0.75 hp	10 hp
Groundwater levels*	80 feet	300 feet
Annual Precipitation[1]	1427 mm	156 mm

[1]India Meteorological Department (average precipitation for the period 2006-2010)

B. Challenges

The key challenges in implementation were to design aparticipatory-based system and a phased implementation approach. Keeping the agility to include the recommendations and community interest during implementation was very challenging. In Orissa, road expansion plans forced a change in the network design. Remoteness of the village was the other key challenge in implementation, which directly affected the procurement of raw materials and local expertise required for the project. Another challenge involved the accommodation and food for the implementation team and their adaptation to the culture of the villages.

C. Socioeconomic Impact

The copying cost in accessing water for domestic consumption has been significantly reduced. The associated socio benefits outweigh the economic benefits with the women and children being relived ofthe burden of carrying water for long distances. The project's psychological impact on well-being of the community is beyond the scope of this paper. However,one must point out the reception (shown in Figure 9), that the team received during their post implementation visit, which depicts the joy of the community.Access to water has changed the social profile of both of the villages.

AMMACHI Labs[1] has reported significant improvement in the usage of toilets in the last six months after implementing the water distribution system.

After implementing the water distribution system, health workers from AmritaSeRVe also reported a significant reduction in health care spending. Figure 10 shows school children accessing safe piped water supplied through the scheme. Now the school children can use toilets whichwere otherwiseabandoned, due to inaccessibility of water. Figure 11 shows the construction of a soakage pit for water recharge. Several soakage pits were constructed in and around the village. Concrete rings were pushed into the pits to ensure the longevity of the pits. The concrete rings were made by the women masons trained under AMMACHI Labs' sanitation program. With an estimated life of a minimum of 10 years, the cost of installation will be approximately $15 per household per year, which is only 5 % of the annual income. This 50 % reduction in the per capital cost of installation compared to normalized SVS schemes ensures the financial sustainability of the projects.

Fig. 9: Reception Received

VI. MEASURE OF SUSTAINABILITY

A generalized framework on sustainability is proposed based on the water distribution systems implemented in the two villages. Sustainability coefficients are defined from the observation factors identified throughout the process, factors that we took time and effort to assess with the input of the villagers. The measure of sustainability would be erroneous if we did not take into account the performance of the system.

Fig. 10: School Children Enjoying Access to Piped Water

Fig.11: Soak Pit

So a formula was devised called the Measure of Sustainability of the System, or SM. SM is defined as a function of Sustainability Coefficient and Adapted Indices of Effectiveness.

SM= fn (Sustainability Coefficient, Adapted Indices of Effectiveness)

The Sustainability Coefficients taken into consideration were (1) Localization Coefficient (2) Cost Point Coefficient (3) Overlap Coefficient (4) Endurance Coefficient (5) Loop Coefficient and (6) Interaction Coefficient. The general assumption in defining thisframework is that theduration of the system under study is infinite. This assumption of infinite duration of the system has given the measurement framework validity at any point in time and is not dependent upon the nature of the actors.

*Localization Coefficient:*The Localization coefficient explains the topographical area covered by the system and its interaction with the density of users. The Function can be defined by the equationbelow.

$$Lc = f(Nl) + \sum_{i=a}^{z} f(Di) \quad (1)$$

[1]AMMACHI Labs is an academic and research center at Amrita University that brings an interdisciplinary approach to addressing societal challenges by creating innovative educational tools and skill development solutions to help uplift entire communities.

where L_c is the Localization coefficient, *Nl* is the total Network Length function and*Di* is the distance between various actors a, b...z.

Cost point coefficient. The cost point coefficient represents the system process sustainability

$$Cc = f(Gc,t) + f(Tc,t) + f(Dc,t) + f(Fc,t) \quad (2)$$

where $t_x<t<t_y$is the Cost point coefficient, $f(Gc,t), f(Tc,t), f(Dc,t), f(Fc,t)$ are the functions of generation cost, transmission cost, distribution cost and feedback cost in the time interval between t_a and t_b.

Overlap Coefficient: Overlap coefficient matches the demand and supply driven models. The advantages and disadvantages of supply-driven and demand-driven modelshave already been discussed, and this coefficient attempts to match them. The coefficient is defined as a function of the Number of Users(U_t), the Water table level in normal (H_n)and summer(Hs) season, the Consumption rate(R_t), and availability of energy source(Et).

$$Oc = f(Ut, Hn, Hs, Rt, Et, t) \quad (3)$$

Table III. Adapted Indices of Effectiveness Indicators(1)

Indices of Effectiveness	**Indices of Effectiveness Indicators**	**Adapted Indices of Effectiveness Indicators**
Reliability and Adequacy	Percent schemes supplying water as per design norms (design norm of 40 lpcd or more than 40 lpcd)	Percent number of households receiving water as per design norms[7]
	Percent schemes supplying daily (at least four hours of regular daily supply)	Percent number of households receiving water at least 12 hours per day
	Percent schemes with households spending less than 30 minutes per day in collecting water	Percent number of households spending less than 30 minutes per day in collecting water
	Percent schemes with no major breakdown in the past six months (a major breakdown defined as 'more than two days of disruption in water supply')	Percent number of pack with no major breakdown in the past six months
	Percent schemes with good water quality: (i) no bacteriological contamination; (ii) no chemical problems of arsenic, fluoride, salinity	Percent number of households with good water quality: (i) no bacteriological contamination; (ii) no chemical problems of arsenic, fluoride, salinity

*Endurance Coefficient:*The sustainable systems will undergo many devaluation processes due to aging of actors. Endurance coefficient defines how the system reacts with various devaluation processes. It is defined as a function of average demand, complexity of the network, and the area covered by surface water bodies[11].

*Loop Coefficient:*This will quantify the continuous flow of water and information in the system, so loop coefficient can be defined as a function of feedback actors and the community actor.

*Interaction Coefficient:*This is a function of participation of community members in the design, operation and maintenance, number of activities performed and copying cost of water conservation.Adapted Indices of Effectiveness is used to denote the performance of a system. This is shown in TablesIII and IV.

Since the indices of effectiveness indicators are not representative of the Micro water distribution network, we adopted new indicators using the same analogy, which we used for categorization.

The Sustainability Coefficient is normalized relative to the Adapted Indices of effectiveness. Symmetry of this normalized value, the SM, is considered as the measure of sustainability.

Indices of Effectiveness	**Indices of Effectiveness Indicators**	**Adapted Indices of Effectiveness Indicators**
Financial Sustainability	Percent schemes with more than 80 percent O&M cost recovery	Percent monthly collection with more than 60% cost O&M cost Recovery
	Percent schemes with more than 80 percent collection efficiency	Percentage Households with more than 80 percent collection efficiency
Affordability	Water tariff for household connections as a ratio of rural per capita income	Percentage number of houses with more than 80 percent contribution efficiency
	Water tariff for stand post users (shared connections) as a ratio of rural per capita income	Household Water tariff as a ratio of per household income
	Percent schemes with more than 50 percent household connections	Percentage number of water taps utilized for more than 6 hours a day
Environmental Sustainability	Percent schemes with source providing more than 80 percent yield (as per design norms)	Percentage number of months the Energy Tariffs is more than design norms
		Percentage number of toilets using the water supplied under the scheme

Table IV. Adapted Indices of Effectiveness Indicators(2)

Future interventions are being planned in other villages where we can use this innovative framework to designand implement a sustainable water distribution system.

VII. Conclusion and discussion

The micro water distribution system has proven to be an effective tool to meet the water requirements of developing Indian villages. The participatory model has proven to be both unique and effective for successful micro schemes with the minimum per capita cost of installation and maintenance. However, the success of the two projects does not guarantee the same results unless done in a systematic way.

The sustainability framework has been developed to model similar interventions with assured success. Normally participatory models pose high risks due to the dynamic nature of the actors in the system. This measurement framework helps design a system that allows for risk assessment during the design phases, thereby increasing a successful outcome. Since the key focus is in realizing the best participatory implementation, this framework is less likely to succeedwith non-participatory interventions.

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