FROM LAB AND SOCENT STARTUP TO IMPACT ON 200,000 LIVES: A SUSTAINABLE MICROENTERPRISE MODEL FOR VILLAGE-SCALE ARSENIC REMOVAL FROM DRINKING WATER

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Abstract

Hundreds of millions of people worldwide are at risk of debilitation or death from natural arsenic and fluoride poisoning their drinking water. Unfortunately, economically sustainable remediation has remained elusive. Village-scale arsenic and fluoride treatment technologies, and an accompanying microenterprise business model, have been developed at Lehigh University and evolved with support from VentureWell. Local communities and local entrepreneurs are now successfully–and self-sustainably–operating and maintaining village-scale arsenic and fluoride systems, benefiting more than 200,000 individuals in India, Nepal, Cambodia, and Bangladesh. Students, faculty, research labs, international partners, and a social business startup have all played important roles. Key economic and groundwater conditions for self-sustainable microenterprise operations have been identified across multiple contexts. Well run local microenterprise operations at scale can generate income significantly above the poverty line, while simultaneously reducing arsenic contamination well below world health standards.

Introduction

The quality, quantity and ease of access vary greatly across regions, but water access is a necessity. In locations without adequate infrastructure, groundwater is a preferred source because it tastes good and is biologically-safe, except for human contamination, and has local ownership and control. Compared to microbiologically unsafe surface water (e.g., ponds, rivers), groundwater improves public health metrics through reduced waterborne illnesses. Increased groundwater use in the Indian subcontinent began in the 1960s as part of intensive irrigation programs with the Green Revolution. In the 1970s, large social engineering efforts pushed mass installations of tube wells as “safe” potable water sources, especially for rural communities. Since then, tube well installation has increased dramatically due to their convenience and symbol of status. Bangladesh has more than 10 million hand pump wells (Kinniburgh and Smedley, 2001; Cheng, et al., 2005). Unfortunately, many groundwater locations in the Indian subcontinent have geogenic arsenic, fluoride, hardness, and/or iron, making the water either undesirable or unsafe for long-term use.

Arsenic

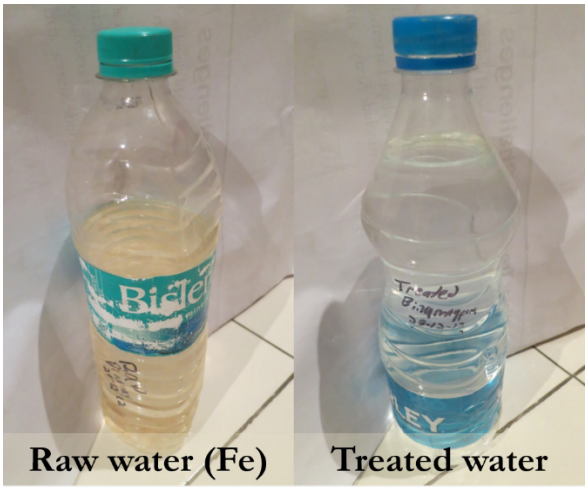
Natural arsenic contamination was first recognized in 1982 in India and 1984 in Bangladesh as arsenicosis (Saha 2003), and in 1999 in Cambodia (Tseng 2005; Bagla and Kaiser 1996; Bundschuh, et al. 2009; Ravenscroft, et al. 2005). Arsenicosis initially causes gruesome physical effects for hands and feet, and then various cancers and early death. Over twenty years of increased scientific and humanitarian effort, thousands of papers have been published. Yet today millions of people remain at risk of drinking water well above the WHO recommended limit (0.010 mg/L or ppm As). Thousands of broken "arsenic filters" exist across India, Bangladesh, Nepal, Burma, Vietnam, Cambodia, Laos, and China. (Berg, et al. 2007; Hossain, et al. 2005; Rodriguez-Lado, et al. 2013; Stanger, et al. 2005; Sun 2004). Finding economically sustainable approaches to remediation has proven a major challenge.

Fluoride

Although not as lethal as arsenic, the chronic consumption of fluoride can cause debilitating aesthetic issues and functional deformities to teeth and bones. Dental fluorosis was first attributed to geogenic fluoride in 1931 in the US and France (Churchill 1931; Smith, Lantz, and Smith 1931; Velu 1931). Over 100 million people are at risk of high fluoride consumption (1.5 ppm, WHO limit) throughout East Africa and the Indian subcontinent, where fluoride-contaminated groundwater is the most viable water resource (Ayoob and Gupta 2006; Susheela, et al. 1999). Work to address fluoride in India has been ongoing since 1975 with the "Nalgonda technique," a labor-intensive, sludge producing process, which was considered the status quo until the last decade (Nawlakhe, et al. 1975).

Other Water Quality Concerns

Iron, hardness, and alkalinity are common constituents of groundwater that cause aesthetic concerns and scaling risk more than health problems. Iron gives water a metallic taste and forms brown suspended solids. Hardness and alkalinity form scale inside plumbing and along heating surfaces (e.g., cooking pots, boilers). As such, these water constituents don't receive much attention during groundwater treatment by NGOs or government public health initiatives in remote, developing communities. However, for economic sustainability and social acceptance of long-term water consumption, water aesthetics are equally, if not more, important than trace contaminant removal (Boisson, et al. 2013). Figure 1 pictures untreated and treated water at two different locations in rural West Bengal, India where iron and hardness (i.e., calcium) removal are key to sustainable business operations. Like anyone drinking water, people impacted by arsenic want clean, clear water.



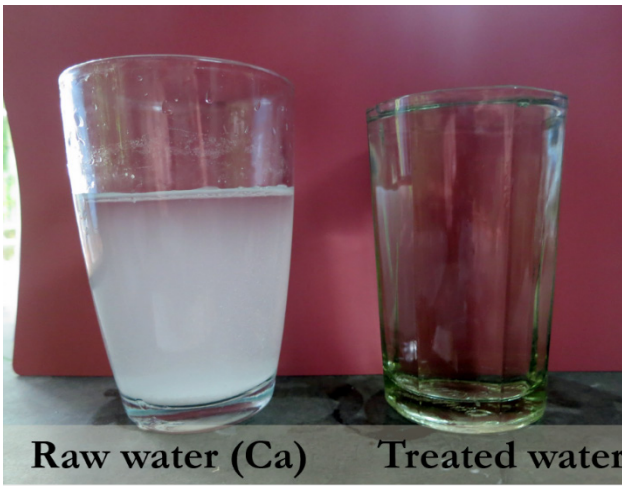


Figure 1. (Left pair) Results of iron removal (Binimaypara, N. 24 Parganas, West Bengal); (Right pair) Hardness removal at Simurali, Nadia, West Bengal.

Water Treatment Ecosystem

Technology-based development initiatives must be grounded in robust and effective science and engineering. Over the last fifteen years, Dr. Arup K. SenGupta has been a leading expert on selective trace contaminant removal, especially for arsenic and fluoride. He pioneered the subfield of hybrid ion exchange (HIX) materials where polymeric ion exchange resin supports and metal oxide nanoparticles create a synergy of high capacity and highly reusable trace contaminant sorbent (Sarkar 2005; Sarkar 2007; Sarkar 2010). In 2004, initial research developed and patented the HIX-NanoFe materials based on iron oxide nanoparticles for high efficiency arsenic, fluoride, and phosphate removal (Cumbal, et al. 2003; Cumbal and SenGupta 2005). In 2013, Dr. SenGupta and Dr. Surapol Padungthon patented HIX-NanoZr materials that use zirconium oxide nanoparticles to achieve high capacity fluoride removal (SenGupta 2013; Padungthon, et al. 2014; Padungthon, et al. 2015). Research on waste sludge byproducts generated during water treatment has created a passive and robust waste management process for community and environmental protection (Blaney and SenGupta 2006; Ghosh, et al. 2014).

User-Centered Design

Aside from focusing on end-user consumption, it is also critical to consider desirability-of-use for the system. It is often assumed that end-user labor in developing countries is essentially free, and thus the value of human resources is not properly considered in capital expenses (CapEx) or operating expenses (OpEx). If disregarding wages, affordable processes will be designed to be labor intensive. To produce safe water for a community of 100 households, for example, a decentralized model using household-based filters appears more economical if end-user labor is free, e.g., a "Brita filter" model. If 100 households diligently pay for materials and fees, and do maintenance properly, then a "Brita filter" company could be quite profitable. However, remembering to perform preventative maintenance on systems that don't clearly show evidence of failure is a challenge.

In rural regions of the Indian subcontinent without water delivery infrastructure, water must still be transported to the house. In such locations, a centralized water treatment system could be created with dedicated employees: say, one trained operator and two delivery personnel. The operator would be intimately familiar with the system's operation to ensure water treatment effectiveness and water filter uptime. The delivery personnel could be paid employees who eliminate the burden of water transportation for the general

population. A centralized system could significantly reduce labor hours per day for the community and generate employment, as seen in a rudimentary overview in Figure 2.

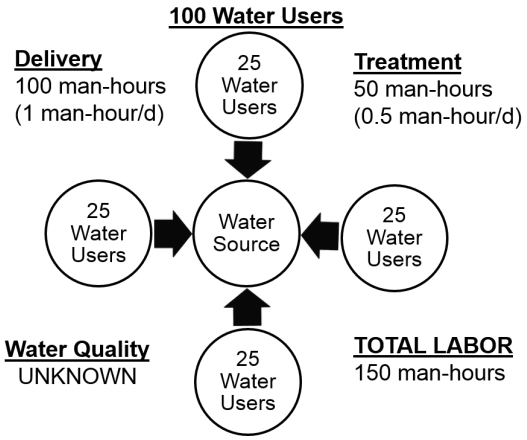


Figure 2. (Left) Decentralized, home-based water treatment for 100 households in rural India/Bangladesh might require 150 man-hours/day and produce water of unknown quality. (Right) Centralized water treatment for 100 water users operated by one operator (8 man-hours/day) and two delivery personnel (6 man-hours/person) can save a community 130 man-hours/day, generate three jobs, and ensure high quality water.

Knowledge Transfer from US-India

The large-scale field implementation work discussed here, based out of Kolkata, would not have been possible without the lifelong ties of Dr. SenGupta to West Bengal and his local colleagues, friends, and family. He first became aware of the arsenic crisis through his past Kolkata-based professors and colleagues, with whom he later worked to develop solutions. His lengthy biannual personal-professional trips to Kolkata have been dominated by arsenic work for the last fifteen years. His ability to work through local organizations, bureaucracy, cultural nuances, etc. in Bengali and English while having world-class research facilities and support at Lehigh University has enabled greater local impact than if he were solely based in one location. The sincerity of someone who equally values the time and input of less-educated people living in arsenic-impacted areas, combined with prestigious academic bona fides gives him the gravitas and breadth to investigate not only the science but also the social and economic structures that may lead to scalable solutions that are sustainable and profitable.

US-originated research at Lehigh has been replicated in India and brought to the field through in-country collaborations with the Indian Institute of Engineering Science and Technology, Shibpur (IIEST-Shibpur, formerly Bengal Engineering & Science University), Society for Technology with a Human Face (STHF, an NGO), Tagore-SenGupta Foundation (TSF), Ramkrishna Water Enterprise (Durgapur, West Bengal), and Drinkwell (WIST, Inc.). STHF, TSF, and Drinkwell have been critical for expansion of HIX-based systems from India to Nepal and Bangladesh. Drinkwell, a private venture-capital-raising startup co-founded by two of the authors, aims to address scale-up problems to produce safe water for >1 million people in five years, leveraging the foundational work of Dr. SenGupta.

Financing Options

Community-based water treatment systems have significant upfront capital expenses and logistical challenges for rural communities. The main options for funding capital expenses are individual investment, private or NGO donation/purchase, public contracts, or financial services. Each option presents challenges. Wealthy individuals or community organizations with philanthropic or entrepreneurial mindsets are uncommon in impacted areas. Many NGOs actively support water and sanitation, and many have supported groundwater treatment. However, long-tem sustainability of those well-meaning efforts has been problematic at best. NGOs must be more entrepreneurially minded and focused on long-term results. A challenge with public contracts is that in India they must go to the lowest bidder who meets specifications. Collusion between bidders is

common, as is graft in government decisions. Implementation often minimizes material costs and decreases system performance. Contract payment can take a year or more after completion, complicating cash flow planning. As for financial services, private investment of $5,000-$10,000 can be supported by a competitive marketplace of microfinance institutions throughout the Indian subcontinent at higher interest rates (20-40%), but access to bank funding at lower commercial business interest rates (~12%) requires proof of decreased risk via successful business track record and demonstrated ability of payback.

Drinkwell has raised $515,000 of grant funding since 2013 to establish filter production, implement HIX-based systems in the field, and de-risk operating economics to facilitate access to more favorable financing. As discussed in the results sections below, the upfront capital expenses remain a significant hurdle in many field settings, but field evidence also suggests it can be overcome with well-managed operations at village scale. By contrast, operating expenses have been readily covered across a majority of situations.

Methods

Partners for Growth

Every new community installation was a learning exercise between all parties: US researchers, local scientists, NGOs, and communities. Through the iterations, best practices were developed for sustainable local operation. Through international arsenic conferences, connections have been established to institutions in areas with endemic arsenic crises. The Institute of Technology of Cambodia (ITC) and the Resource Development International-Cambodia (RDIC), an NGO in Phnom Penh, Cambodia, have overseen installation and operation of numerous HIX-NanoFe arsenic treatment systems through the support of a 2008 VentureWell Sustainable Vision Grant. A handful of partners in Laos and Vietnam installed systems, and the Tagore-SenGupta Foundation (501(c)(3) USA), along with Ramkrishna Enterprise, installed an HIX-NanoFe system in Western Nepal in May 2013. Through the work of STHF and Drinkwell, HIX-NanoFe treatment expanded to Bangladesh in Feb 2015. RiteWater Solutions (I) Pvt. Ltd. is now the commercialization partner for HIX-Nano in large-scale systems (>50m^3/hr) in India.

HIX-NanoZr Commercialization

A locally producible, high capacity arsenic and fluoride sorbent was necessary for scale-up in the Indian subcontinent and Southeast Asia. In 2007, Surapol Padungthon began developing a new sorbent to use low-cost, waste zirconium oxide for significant arsenic and fluoride sorption capacity (SenGupta 2013; Padungthon, et al. 2014; Padungthon, et al. 2015). Refinements to the process by Jinze Li have led to the current form of hybrid ion exchange resin with nanoparticles of zirconium oxide (HIX-NanoZr). Mike German was in Kolkata for two years (2012-2014) as part of his Fulbright-Nehru Fellowship, where he helped STHF prepare for HIX-NanoZr production. Starting in December 2014, HIX-NanoZr began production by STHF and Drinkwell for arsenic and fluoride treatment in Kolkata, West Bengal. Multiple sites across India and Kenya are using HIX-NanoZr today for pilot-scale testing and community-scale operations (see Figure 3).

HIX-NanoZr

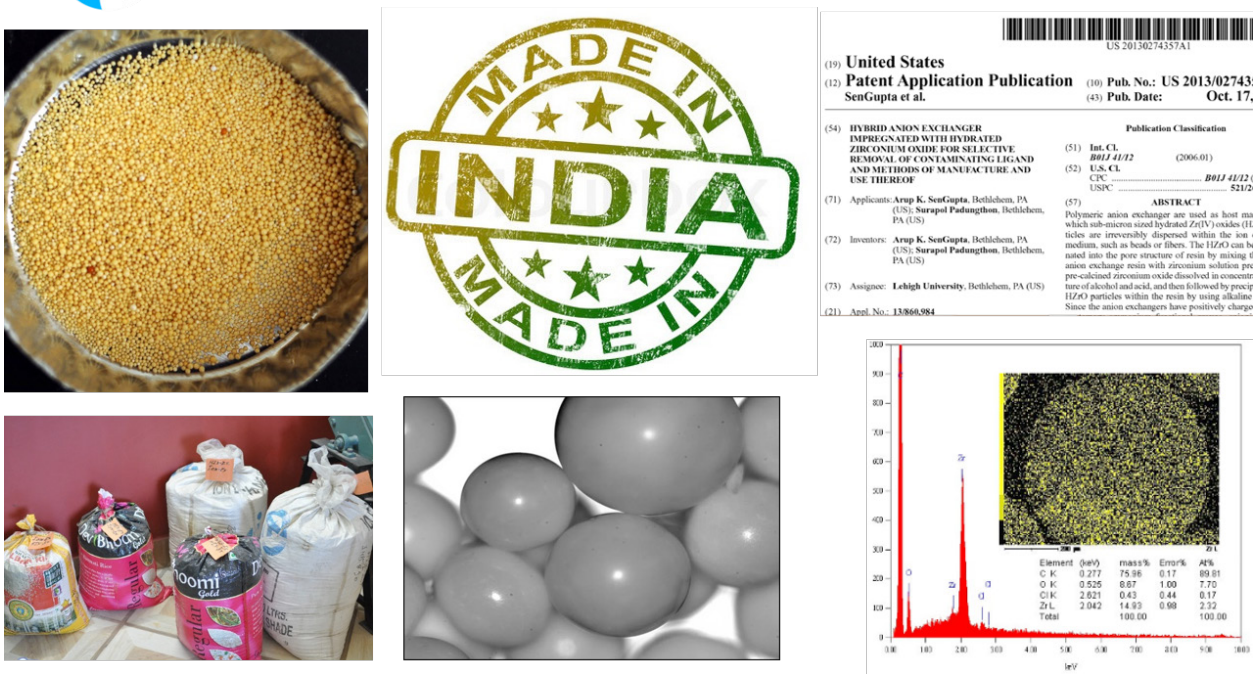


Figure 3. HIX-NanoZr produced by Drinkwell in Kolkata, India.

Cash Flow Model

Trisha Chakraborty developed a cash flow model for unit economics for up to twelve years of operations. The model attempts to account for all process economics on a month-by-month basis to track cash flows: capital expenses (e.g., site preparation, HIX-Nano resin, process equipment, construction), operating expenses (e.g., wages, electricity, operation and maintenance, delivery, marketing, overhead), financing (e.g., loan interest rate and amortization schedule), and business operations (e.g., price of water, population, willingness to purchase, customer growth rate).

To explore conditions for self-sustaining operations, Monte Carlo simulations (using Palisade's @Risk 7 in Excel 2016, 2000 iterations) were used to determine the likelihood of HIX-Nano being profitable under various scenarios. Probability distributions for variable input parameters in the cash flow simulations were best fit distributions from data collected from actual system implementations in the field and from national survey sources. The major outputs under observation were monthly operational profitability, time till breakeven for cumulative cash flow, and internal rate of return (IRR). Given the input distributions, possible scenarios were considered when: 1) the initial cost was/was not borne by the owner and/or was loan financed; and, 2) the caretaker did/did not take a salary. These scenarios represent the potential (or not) of full capital infusion or subsidization by outside groups; and whether or not operations can create opportunities for wage employment.

Field Results

Over the past fifteen years, over 200,000 people have been served across the Indian subcontinent by arsenic treatment systems designed by Dr. SenGupta. HIX-Nano arsenic treatment systems have been successfully installed and operated in rural

communities of developing countries for up to ten years. The first use of HIX-Nano to produce potable water from naturally arsenic-contaminated water occurred near Nabarun Sangha Community Club, Ashok Nagar, N. 24 Parganas, West Bengal, India in 2004. Today, people drink arsenic-safe and iron-free water at Nabarun Sangha from multiple treatment columns, profits are returned back to the community, and the caretakers/water distributors have permanent employment. The local caretakers often discuss aspirations of expansion and greater sales. Such longevity is possible because of a focus on a holistic water treatment ecosystem, overviewed in Figure 4.

eliminated or greatly reduced. If the purchaser does not want digital payment tracking, "Water ATM," "Solar Panel," and "Reporting System" can be removed. The needs to supply a local delivery van or import materials through customs are also location dependent.

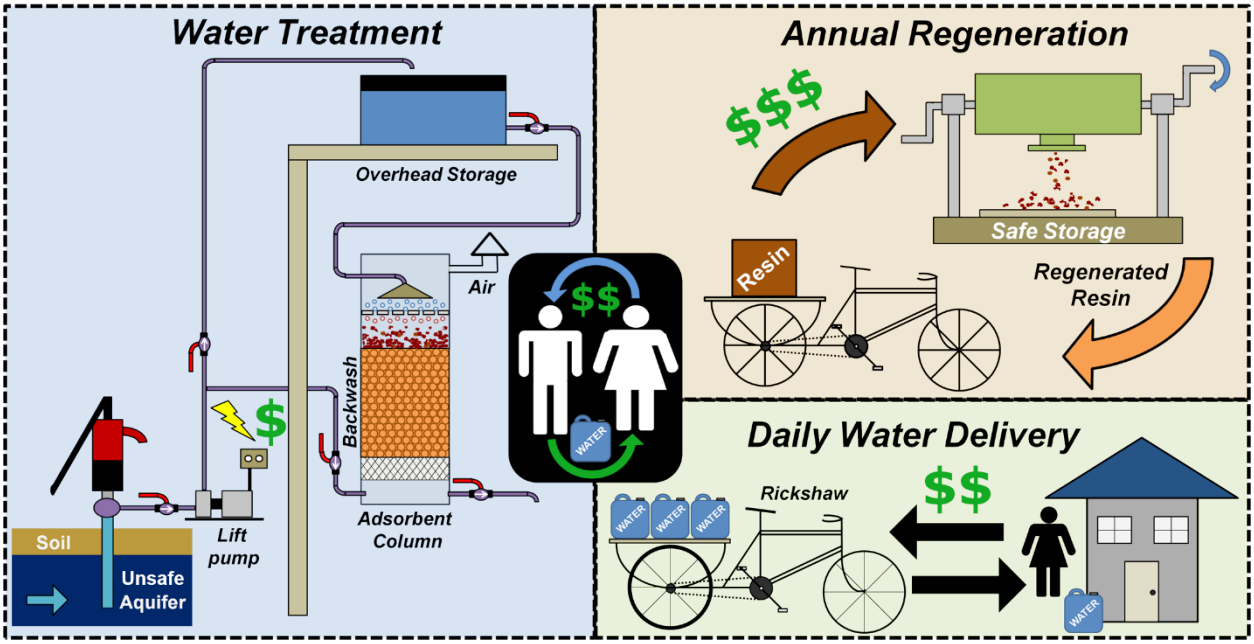


Figure 4. A general overview of a sustainable, interconnected water ecosystem to produce safe water and sustain good-paying local jobs.

HIX-Nano systems can have different configurations depending on the budget and requirements of the customer. Table 1 lists approximate costs of the major capital expense (CapEx) components for different system requirements. Depending on the system purchaser, several of the large costs may or may not be included. If the purchaser owns land with a tube well and a nearby concrete structure, "Land," "Building Construction," and "Tube well" can be

Table 1. Overview of CapEx components for an HIX-Nano system.

EXAMPLE INITIAL CAPITAL EXPENSE COMPONENTS	NEW SITE, FULL W/ATM PAY SYSTEM (INR)	EXISTING WELL & STRUCTURE	BAREBONES
HIX-Nano Media & Commodity Chemicals	102,750	102,750	102,750
Land	250,000		
Tube well Drilling	48,000		
Overhead Tank	15,000	15,000	15,000
Resin Reactors	50,000	50,000	50,000
Storage Tank	15,000	15,000	15,000
Water Jugs	36,750	36,750	
Solar Panel	23,850	23,850	
Water ATM	85,000	85,000	
Building Construction	140,000		
Sales Tracking & Reporting System	6,400	6,400	
System Installation	32,000	32,000	32,000
Delivery Vehicle	44,800	44,800	
Launch Festival	15,750	15,750	
Total INR	865,300	427,300	214,750
Total USD (@ 68 INR/$, Jan. 2016)	$12,754	$6,298	$3,165

Competitive Benchmarks

Many companies are installing community water kiosks to be operated by local entrepreneurs in rural India. The majority of these systems use reverse osmosis (RO), which produces less water than it wastes, is prone to mechanical failure, and can only operate with consistent electricity. By using a selective adsorbent, STHF/Drinkwell systems operators can charge much lower monthly fees versus other organizations (see Table 2). The standard fee generally provides each customer household 20L/day.

Table 2. Comparison of monthly subscription prices for community water kiosks.

MONTHLY SUBSCRIPTION PRICE (INR) FOR 20L/DAY	DESCRIPTION
35	STHF (N. 24 Parganas, West Bengal) *
100	STHF (Ballia, UP) *
100	Drinkwell (Bangladesh); SHRI (India) *
120	Safe Water Network
150	E-Health Point/Naandi Foundation
180	Waterhealth International
200	Waterlife
240	Sarvajal
270	Springhealth

* HIX-Nano installations

Example of Indian Operations: Ballia, Uttar Pradesh

In mid-2013, Mr. Ashok Singh approached STHF to install an arsenic treatment system in his rural village in Ballia, UP (see Figure 5A). Mr. Singh showed great passion for his vision of a permanent safe water treatment system being operated in his community. STHF felt confident that Mr. Singh would oversee activities in a sustainable fashion based on several qualitative factors: his persistence in approaching STHF, their detailed correspondences, and his commitment of financial support for preparations (e.g., site preparation, water analysis). Different qualitative descriptors and decision matrices can be used to evaluate new partnerships, but the value of intuition about a person or organization based on field experiences and cultural understanding cannot be understated when operations are beyond structured governance. Mr. Singh took a twelve-hour overnight train to meet STHF in-person in Kolkata, where the relationship was formalized. System capital expenses were borne by Rite Water Solutions (I) Pvt. Ltd. (Nagpur, Maharashtra, India), construction was completed by Ramkrishna Water Enterprise (Durgapur, West Bengal), and the system was operational by November 2013 (see Figure 5B). Mr. Singh's facility has been well-managed by paid caretakers since day one, as is evidenced by his consistent profit-generation from happy, paying households (Figure 6). Mr. Singh has tested and reported the water quality every month as per the agreement with STHF (Figure 7). Monthly fees are INR 100/household for 20L/day.

Figure 5A (top). A resident of Ballia, UP suffering from arsenicosis lesions on his hands before the installation of the arsenic treatment system; Figure 5B (bottom). The installed, simple HIX-Nano system, which has produced over 1 million liters of arsenic-safe water since opening.

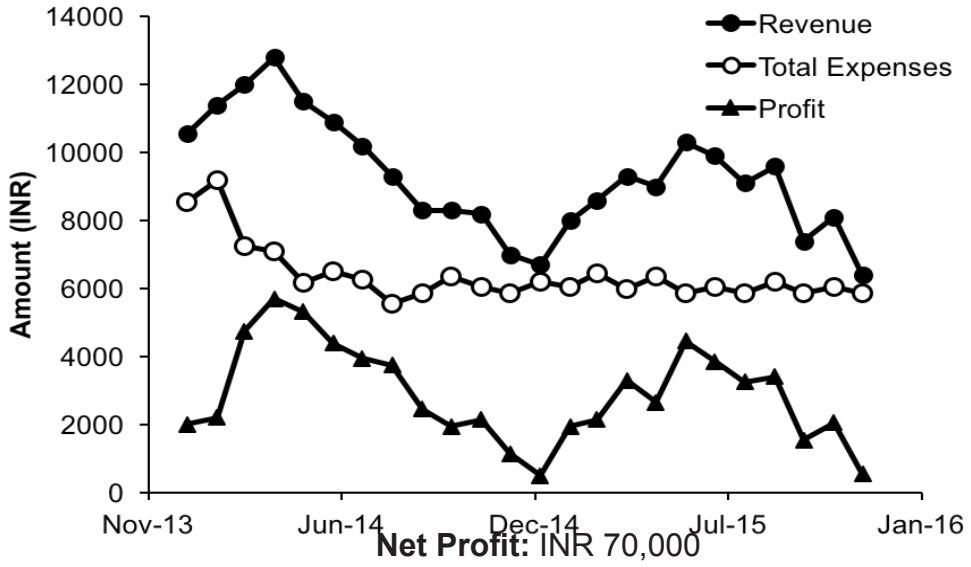


Figure 6. Monthly operating revenue, expense, and profit records from operation of a HIX-NanoFe system by Mr. Singh in Ballia, UP.

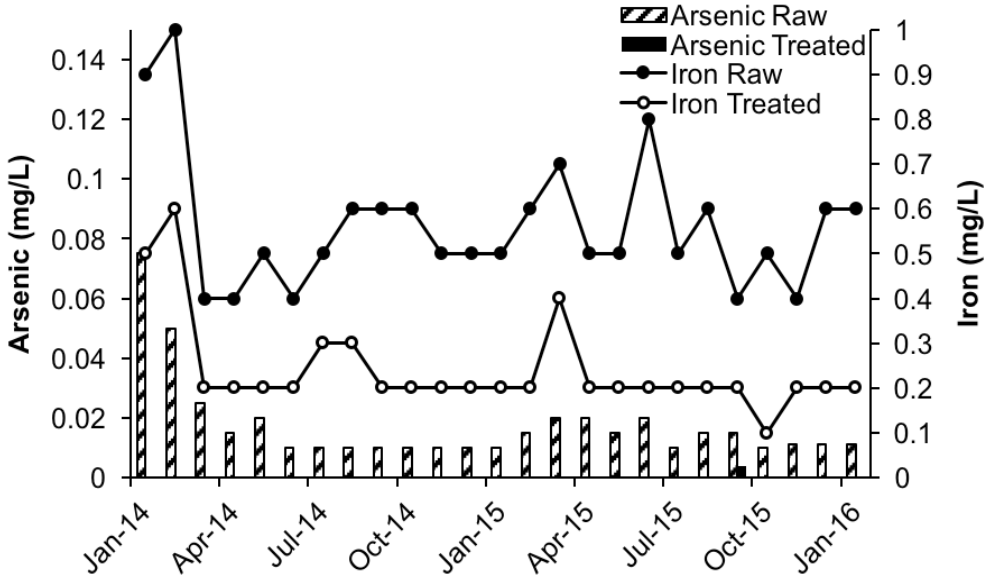


Figure 7. Water chemistry analysis throughout operations in Ballia, UP. Note that the treated arsenic levels are always below 0.01 mg/L and iron is consistently below 0.3 mg/L.

After installation, Mr. Singh faced some local water sales competition from other NGO/ government offerings, which impacted his peak sales and revenue. After several months, he also expressed concern about light hardness precipitation issues, but he made his community patient for changes, which were

addressed with a post-treatment system in July 2015. As a small community operation, Mr. Singh opted for a basic system and utilized existing resources, reducing his total system CapEx to approximately INR 325,000 (~$5,000). Without automated RFID water purchases and data collection/transmission, CapEx are lower, but monthly accounting and water chemistry information has still been submitted in a timely fashion through the diligence of Mr. Singh and his caretakers.

The CapEx at Ballia was fully subsidized and the system at current operations could not pay back the CapEx with or without interest costs because of the low population density and number of paying customers. However, operations pay caretaker employee wages are self-sustaining and profit-generating after the CapEx subsidy. The system has been cash-flow positive, operating marginally profitably each month for two years. Earnings beyond expenses and wages amount to a few dollars daily, on average, with clear seasonal swings. As seen in the Monte Carlo simulations below (Figures 13-15), results like these—operating costs that can be covered, but capital investments that might take long periods to pay back—appear likely to be typical.

N. 24 Parganas, West Bengal

The oldest installations of HIX-Nano systems are located in the N. 24 Parganas District of West Bengal and are upward of ten years old in Binimaypara and Nabarun Sangha (Figure 8). In 2012, another local community organization, Sakthi Sadhana, demanded STHF install a system and today 700 families collect safe water at this new site (Figure 9). At both Nabarun Sangha and Sakthi Sadhana, high profits from water sales have been reinvested in community construction and local events.

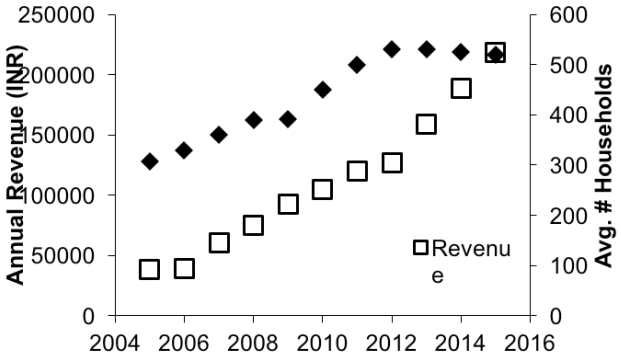


Figure 8. Water revenue records over 10 years at Nabarun Sangha, N. 24 Parganas, W. Bengal.

Figure 9. HIX-NanoFe customers at Sakthi Sadhana Community Club.

Drinkwell Installations

Supaul, Bihar, India

A social entrepreneurial commercial startup established in 2013 as part of WIST Inc., Drinkwell has begun selling and servicing HIX-Nano systems and services. Sanitation and Health Rights in India (SHRI, an NGO) has a community toilet block of 16 stalls (8 male, 8 female) that serves 800 daily users in rural Supaul, Bihar at no cost to users. In order to subsidize toilet expenses and to create a holistic water and sanitation hub, SHRI purchased a community water treatment system through WIST, Inc. and STHF in March 2015. The influent water has unacceptable levels of arsenic, iron, and total coliforms. Thus, the treatment system installed has iron removal media,

HIX-Nano resin, and UV treatment, so that treated water meets WHO standards.

From March 2015-December 2015, water quality has remained consistently within WHO regulations, but sales have fluctuated. Initial sales increased through excitement over the novelty and word-of-mouth communication about the water quality, affordable price, and ease of delivery. Sales stagnated and decreased in May 2015-June 2015 when the temperature of the water in the black overhead storage tanks reached >55°C due to high summer solar radiation. The high temperature made people not want to purchase the treated water. Instead, people opted for water directly from the lower temperature underground aquifers, despite the undesirable taste and color and the potential for arsenic or coliform contamination. To meet the new aesthetic water demands of the local consumers, SHRI purchased a water chiller (INR 60,000) to cool water to 15 degrees Celsius. Sales were stable after chiller purchase, decreased during Ramadan (June 2015), and returned to Pre-Ramadan levels. The overview of monthly water sold, revenue, expenses, and profit are shown in Figure 10.

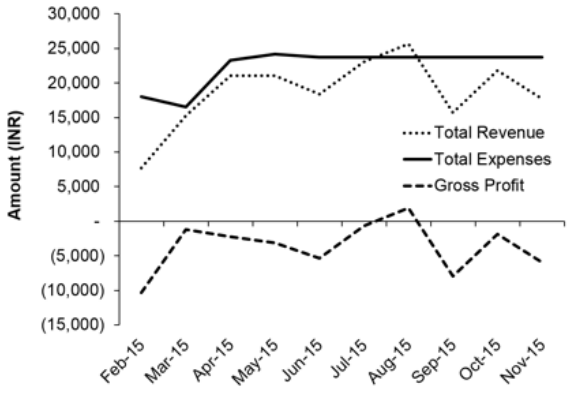


Figure 10. Revenue, expenses, and gross profit at SHRI's HIX-Nano installation in Supaul, Bihar.

Betila, Manikganj, Bangladesh

Another Drinkwell/WIST Inc. system, the first HIX-Nano system installed in Bangladesh, was imported in early 2014 from Kolkata, but was only installed in early 2015 because of passport issues for the Indian installation team and water ATM import delays. Two more systems have been installed in Bangladesh since then using local materials and contractors to avoid cross-border issues. In March 2015, the HIX-Nano arsenic treatment system was finalized in Manikganj, Bangladesh in a collaboration between Grameen Seba Songstha, STHF, and WIST, Inc. Water testing was initially done at one tube well the system was designed for and first connected to (February 2015-April 2015), but it was found that the water flow rate was too slow because the tube well was too shallow. The system was reconnected to a nearby deep tube well, where the water quality was not tested prior to installation and was later found to have significantly higher iron concentrations. In August 2015, after the monsoon period ended, black precipitate was noticed in the treated water. Additional oxidative media was installed as pretreatment and black precipitate has no longer been a concern. However, this period of poor water quality led tens of households to revert to other water options (treated and untreated) in the region. After the problem was corrected, the majority of the households who had left did not return, while new customers were acquired via new sales efforts. The history of monthly water sold, revenue, expenses, and profit are in Figure 11.

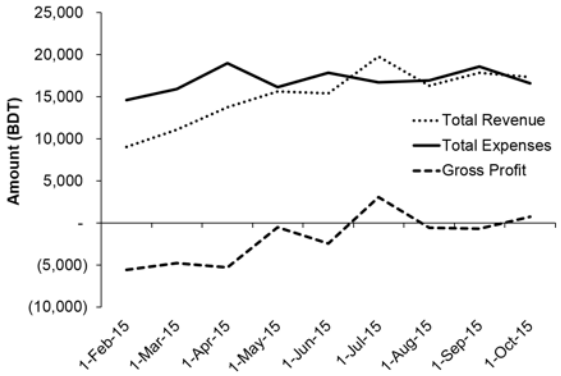


Figure 11. Manikganj monthly trends for revenue, expenses, and gross profit.

Lessons Learned from Ballia, Supaul, and Manikganj

Qualitative observations can be made from these several locations. Major influences on water sales were water quality (e.g., undesirable precipitation), water aesthetics (e.g., temperature), and seasonality (e.g., seasonal temperature changes, Ramadan fasting). Note that none of these factors relate to the primary concern for water treatment: arsenic. Hardness and iron content must be appropriately managed to ensure the final water quality meets user aesthetic expectations and to maintain their business. Expectations of summer conditions and the uses of water--as a refreshing beverage--should influence system design to minimize solar radiation and water temperature increase. Religious celebrations are known in advance and sales strategies and water delivery planning should be designed to minimize decreases in water sales as community actions and behaviors change temporarily, e.g., how to minimize the burden of water access during fasting, how to maximize water desirability through price variations, discounts, etc.

Neither Supaul nor Manikganj have been cash flow positive for more than two months consecutively in the first year, but monthly sales and revenue have increased. As the cash flow Monte Carlo modeling below (Figures 13-15) suggests, depending on local conditions, an average of 150 paying households per month is necessary to make operations cash flow positive without HIX-Nano system provider Drinkwell earning a servicing fee (e.g., for system maintenance and HIX-Nano media regeneration). With a scaled servicing fee to Drinkwell, 225 households are required. Ballia has been cash flow positive for the entirety of its operation, although having similar numbers of customers and prices (INR 100/month) as Supaul and Manikganj, because their standard monthly fee does not include delivery labor or vehicle.

Cash Flow Modeling

Based on data collected from these and other field implementations of the HIX-Nano systems and business model, it is possible to explore economic conditions required for self-sustainable microenterprise operations. Key input and output parameters in the cash flow model were varied in Monte Carlo simulations.

Input Parameter Distributions

Summary input parameter distributions are found in Table 3**,** with the actual relative frequency distributions from field data and the best-fit distributions (from @Risk) used in modeling illustrated (in thumbnail) in Figure 12. Initial capital expenses were varied based on the system options presented in Table 1 (above) and installation costs encountered in the field. Revenue per customer, or water price, has three main modes (INR 30, 100, 150 per month for 20L/day) depending on availability of delivery and historical pricing--initial low NGO-subsidized prices have been slower to be increased. For operational scale in customers per month, newer (< 3 years) and more remote field installations typically had smaller scale operations with 50-200 households. Upper end observations above 500 are from long-established, well managed operations at Sakthi Sadhana and Nabarun Shangha. Monthly operating costs exclude wages. Rural wage distributions were drawn from 2014 surveys by the Labour Bureau, Government of India. Microfinance interest rate data was sourced from MFTransparency.org and represents 94 different microfinance institutions (MFIs) in India, offering hundreds of different loan products; microcredit interest rates in India hover near 30% APR, and depend marginally on the loan term.

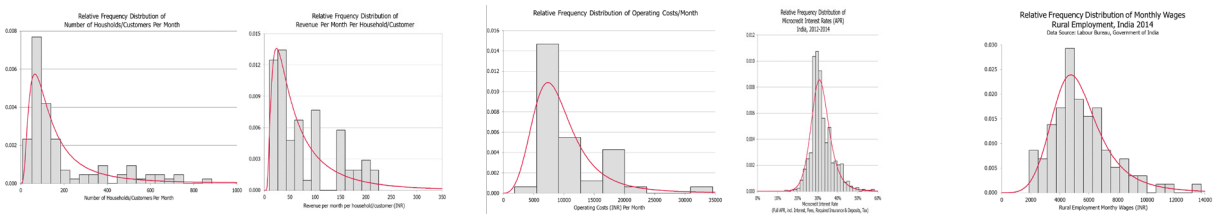
Table 3. Field experience data and national data used in modeling, summary statistics.

		MEAN	ST. DEV.	MIN	MAX	SKEWNESS	KURTOSIS	BEST FIT DISTRIBUTION
Field Data	Initial Capital Expense, INR	359,272	249,267	155,000	718,387	0.895	2.547	LogNorm
	Revenue Per Customer Per Month, INR	79	63	10	225	0.886	-0.431	InvGauss
	Customers per Month	194	195	8	884	1.669	1.941	Pearson6
	Operating Costs per Month (not incl. wages), INR	1,951	2,520	15	11,250	2.218	5.346	LogLogist
National Data	Rural Wages/Month, INR *	5,532	2,105	1,887	13,744	1.070	2.051	LogLogist
	MicroLoan Interest Rate **	32.1%	5.7%	13.4%	58.3%	0.973	1.835	LogLogist

** Data source: MFTransparency.org, 2012-2014*

*** Data source: Labour Bureau, Government of India, 2014.*

CUSTOMERS/ MONTH | **REVENUE PER CUSTOMER/ MONTH** | **OPERATING COSTS PER MONTH** | **MICROCREDIT INTEREST RATE *** | **RURAL WAGES * PER MONTH**



** Data source: MFTransparency.org, 2012-2014*

*** Data source: Labour Bureau, Government of India, 2014.*

Figure 12. Thumbnails of relative frequency distributions from field data & best-fit distributions.

Outputs

Under the most expensive operating conditions, i.e., financing the upfront capital expenses with a microfinance rate loan and paying market rate rural wages to a caretaker to operate the system, fully 90 percent of scenarios that became cash flow positive did so between 40 and 468 households monthly, as shown in Figure 13. Most of the actual field experience data lies in this range of customers, suggesting that the operational scale needed for self-sustainable operations with operators earning above average wages is readily achievable.

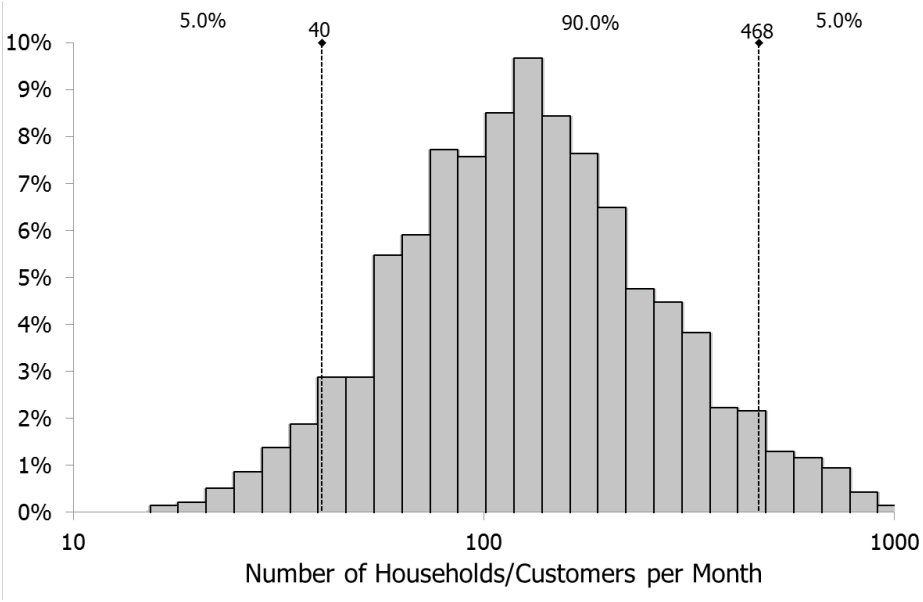


Figure 13. Monte Carlo outcome relative frequency distribution for the number of households per month at which monthly net operating profit becomes positive, in models with a microfinance loan and market-rate wages.

Similar evidence comes from simulation results on monthly gross operating profits, the monthly take home for any owner. Two-thirds or more of scenarios, in models either employing a salaried caretaker or not, are cash-flow positive by end of ramp up year 1 (illustrated for models without salaries in Figure 14). In fact, about one-third of scenarios enable earning more than India's average per capita income of roughly INR 5,500. In Figure 14, we also see another condition of operationally sustainable operations. If monthly fees per household (for 20L/day access) are INR 30 or more, after one year operations are five times more likely to be cash flow positive than to operate at a loss. Below 30 INR/month, nearly half the scenarios show monthly losses. In equivalent purchasing power terms, 30 rupees per month amounts to less than a US penny a day.

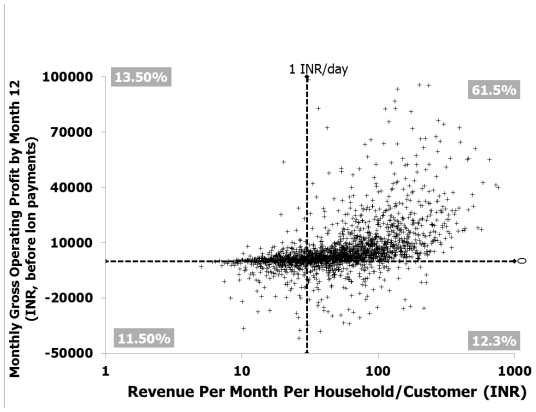


Figure 14. Monte Carlo outcome cumulative probability distribution for monthly gross operating profit per month, without a salaried caretaker and no loan financing.

In short, self-sustaining ongoing operations appear relatively achievable under a wide range of field settings. What is problematic, however, is that in scenarios, particularly those with wages paid to system caretakers, thin operating margins tend to mean long time periods (>5 years) are required for paying off capital expenses. Long expected payback times will make capital investments difficult for private owners to justify without subsidy. Even in models with no caretaker wages, as in Figure 15, more than 40% of breakeven scenarios take longer than five years to pay back. Fewer than one in five

reach breakeven before two years. Only locations that can accurately foresee several hundred paying households will be amenable to financing the majority of capital expenses through a standard 3- or even 5-year loan. However, the odds of positive returns on the upfront investment are more than doubled if capital expenses (not including filter materials) are kept below the expected average of about 250,000 INR (Figure 16).

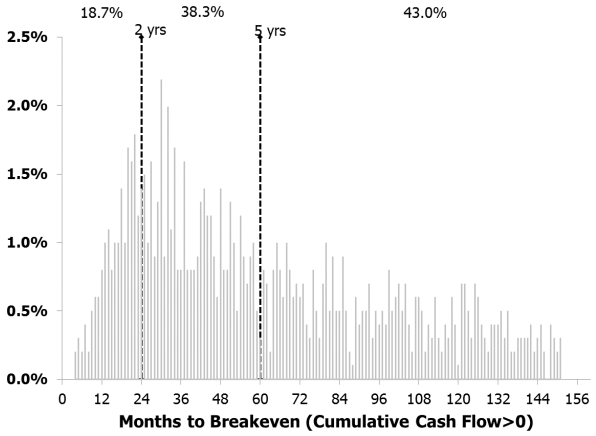


Figure 15. Monte Carlo outcome frequency distribution of time in months until cumulative cash flow is positive, if ever, including CapEx. (This particular model does not take a loan or pay a caretaker).

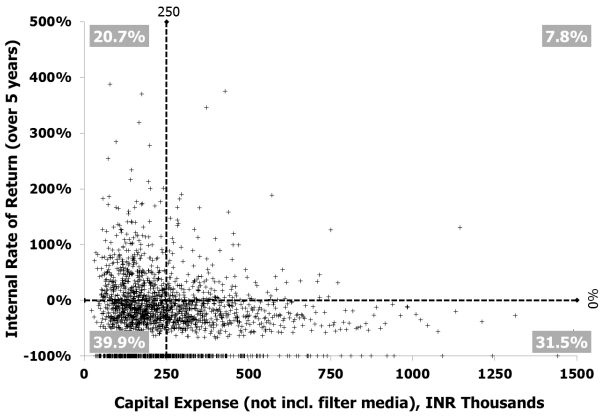


Figure 16. Internal rate of return (over 5 years) vs. CapEx. Model without loan or wages.

Finally, exploring the relative importance of key economic variables (Figure 17) overall, the main drivers of self-sustainability of operations lie in achieving scale in numbers of customers served and setting adequate fees charged for water—i.e., what matters most for sustainable operations is the price and quantity, like in the Economics 101 total revenue equation TR=PxQ, Simulation results are not very sensitive to the initial cost of HIX-Nano filter materials, compared to existing alternatives. However, the high quality HIX-Nano is key to significantly lowering ongoing operating costs and long-term profitability.

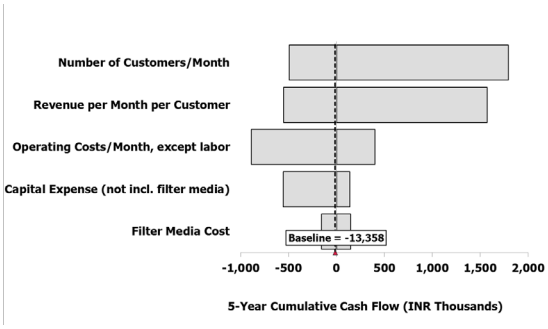


Figure 17. Sensitivity analysis of multiple input parameters on the cumulative cash flow over 5 years without a loan or wages.

Conclusion

Over the past fifteen years, Dr. SenGupta has created arsenic and fluoride treatment ecosystems that can effectively provide safe water for rural communities over long-term operation. Success has been seen in multiple countries in South/Southeast Asia and new efforts will bring fluoride treatment to East Africa shortly. Using a detailed cash flow model and distributions drawn from field experience, Monte Carlo simulation analysis found total number of households served, water prices, and recurring expenses to be the most significant factors to reach self-sustainability, in agreement with experience.

The main other takeaways from the Monte Carlo simulations are: 1) once capitalized, self-sustaining operations are relatively achievable under a wide range of scenarios; and 2) can generate monthly income for an owner-caretaker, or a wage employee, near or above average rural income in India (~INR 4500-5500), and well above the average in

Bangladesh; 3) covering capital costs is likely going to remain a problem for all but the best managed operations at scale; 4) either subsidies to cover the upfront expenses or payback times longer than five years appear to be necessary if average systems continue to have operating characteristics like those seen to date, meaning 3- or 5-year loans periods are unlikely to be attractive options; 5) filter media cost is of less importance as a driver of overall cash flows. As Drinkwell expands, rapid user acquisition should be emphasized for maximum impact and growth.

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Note: Dr. Arup K. SenGupta, Michael German, and Minhaj Chowdhury are co-founders of WIST, Inc.

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