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TECHNOLOGICAL INNOVATIONS

FOR RURAL WATER SUPPLY IN LOW-RESOURCE SETTINGS

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ACRONYMS AND ABBREVIATIONS

AI	Artificial intelligence
AMI	Advanced meter infrastructure
AMR	Automatic meter reading
AOR	Activity Officer Representative
ATM	Automated teller machine
ATREE	Ashoka Trust for Research in Ecology and the Environment
GIS	Geographic information systems
GSM	Global System for Mobile Communications
GWCL	Ghana Water Company Ltd.
IoT	Internet of things
JMP	Joint Monitoring Programme for Water Supply, Sanitation and Hygiene
KNUST	Kwame Nkrumah University of Science and Technology
qPCR	Quantitative polymerase chain reaction
REAL-Water	Rural Evidence and Learning for Water
RO	Reverse osmosis
RWSN	Rural Water Supply Network
SCADA	Supervisory control and data acquisition
STREAM	An onsite electrochemical chlorine generator
SWN	Safe Water Network
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
USSD	Unstructured Supplementary Service Data codes, also called "quick codes," for phone-based services
WASH	Water, Sanitation, and Hygiene
WHO	World Health Organization

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EXECUTIVE SUMMARY

CHALLENGE

Globally, the Sustainable Development Goals (2015–2030) are driving efforts to increase water service levels, while ensuring that services are affordable and no vulnerable population is left behind (United Nations 2018). In concert with global development goals, the United States Agency for International Development (USAID) Rural Evidence and Learning for Water (REAL-Water; 2021–2026) program focuses on identifying ways to expand water access and safety in rural areas of low- and middle-income countries. Rural areas pose special challenges for water supply, as homes may be too few or too dispersed to justify the cost of installing underground pipes from a high-quality water supply source or a centralized drinking water treatment facility. As of 2020, the majority of people lacking even basic water services (i.e., water from a protected source requiring no more than 30 minutes to collect) lived in rural areas (WHO UNICEF Joint Monitoring Programme (JMP) 2021).

REPORT OBJECTIVES

This report provides an overview of water supply technologies that are innovative in either design or application (i.e., not yet commonplace) and promising (i.e., show potential for advantages exceeding the status quo) in rural areas such as small villages and dispersed settlements. It highlights categories of high-technology concepts (i.e., advanced electronic devices, materials, and designs) that offer a greater range of options to decision-makers, donors, practitioners, and consumers who manage rural water supplies. The concepts may have sufficient merit to warrant further exploration and testing within later stages of REAL-Water or other implementation research programs; however, the REAL-Water consortium does not endorse or relatively rank specific providers of these technologies[1]. Specific technology choices should be weighed relative to one's local setting and context. Information is summarized to evaluate conditions and trends in rural water innovation, leading to overarching recommendations.

TECHNOLOGY SYNOPSES

1. SOLAR PUMPS

Rural communities in Africa, Southeast Asia, and parts of Latin America and the Caribbean may not be connected to an electrical grid; however, most of these locations receive abundant solar irradiation. Solar-powered water supply solutions offer vast (and underappreciated) potential for replacing grid electricity or diesel generators. Advantages include energy independence, sufficient water quantity, fewer queues, minimal maintenance, and the ability to raise water into elevated tanks to support gravity-fed distribution. Thus, solar pumps provide off-grid communities with a fairly reliable and climate-friendly means of producing high-quality water with few interruptions (e.g., extended cloudy periods, vandalism or theft). Adequate technical capacity to operate and maintain these systems is critical. Financing upfront, maintenance, and eventual replacement costs can be justified by long-term cost-effectiveness relative to alternatives. Solar pumps are **commercially available** and used for rural water supply applications on several continents.

1 The authors have not independently reviewed the validity or performance of specific technologies or manufacturer claims described in this report; information is provided solely for reference. The examples provided are not exhaustive. Businesses enter and exit the market regularly and mergers occur, while technology developers and distributors continually upgrade their product and service offerings.

2. COMMUNITY-SCALE DISINFECTION

Water disinfection represents a low-cost, effective means of inactivating disease-causing microorganisms, with substantial public health returns. Among disinfection methods, chlorination has been implemented at points of water storage and collection (e.g., tanks, standpipes, handpumps) in small rural systems across many different geographies. Drawbacks include that chlorine is not effective against resistant pathogens (e.g., protozoan cysts), disinfection does not address chemical contamination, and higher-turbidity (cloudier) source water requires pretreatment. Research finds that centralizing water disinfection at the community scale reduces the labor burden on individual consumers. Other dosing, acceptability, and recontamination challenges might be best addressed through automated technologies. Onsite production of disinfectants such as sodium hypochlorite and ozone has undergone extensive technological development over the past decade, enhancing performance and convenience. Solar energy can power these approaches, along with UV light disinfection systems that leave no chemical residues. Newer disinfection technologies perform well in ideal settings, but they remain **under testing** to properly address challenges posed by real-world rural, low-income contexts.

3. MEMBRANE FILTRATION

Physically separating impurities from water via membrane filtration is among the most active areas of water treatment research and development. Membranes have pore diameters optimized to consistently capture different contaminant sizes across several orders of magnitude, ranging from large, visible suspended particles to tiny salts, metal ions, and viruses. Depending on initial water quality, water may require pretreatment to prevent fouling (from microorganisms) and scaling (from hard water deposits) of the costly membranes. Energy is sometimes needed to create a pressure gradient, and regular backwashing generates a wastewater concentrate for disposal. Widely employed in high-income contexts for some time, membrane filtration is finding new commercial applications in low- and middle-income contexts, whether in single-step or multi-stage decentralized community water treatment systems.

4. REVERSE OSMOSIS

Water scarcity and natural or human-driven water contamination affect many geographies around the world. The type of membrane filtration (Innovation 3) capable of separating the smallest contaminant sizes is termed "reverse osmosis," wherein water is pressure-forced through a membrane with very small pores. This achieves near-complete removal of all categories of contaminants, but it normally requires some pretreatment steps and incurs higher energy costs. While reverse osmosis represents one of the most effective forms of water treatment (even for purifying seawater and recycled wastewater), the membranes remain relatively pricy and the process produces large volumes of concentrated "reject" water, up to 80% of the inflow. In areas where salinity or dissolved metals pose the dominant water quality challenge, reverse osmosis is becoming an **increasingly efficient treatment solution**, as technological advances and greater market penetration bring down costs.

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5. SMART METERS

Information and communication technology advances have enabled widespread upgrading of electronic devices in recent decades, including community and household water meters. "Smart" meters (with automated self-monitoring and remote communication) offer a wide range of potential benefits to both water suppliers and consumers, aiding cost recovery, water conservation, and service delivery. These increase accountability by efficiently tracking and transmitting water usage data throughout service areas, wherein telecommunication networks, energy supplies, and equipment must be maintained. Device availability is expanding, and replacing or retrofitting meters has become more affordable. The transition to smart meters has occurred primarily in wealthier countries, with **some entry points** into rural areas of low-to-middle income countries.

6. DIGITAL PAYMENTS

Traditional cash payments for water are cumbersome to convey and susceptible to poor accountability. Digital payments represent a rapidly evolving innovation with implications for both the financial and operational sustainability of water service providers. Digital payments reduce operational costs associated with deploying or stationing employees at the point of sale. They facilitate reductions in burdensome queueing and create more flexible work opportunities. Technologies may be set up for prepayment or post-payment, and can occur via existing mobile money (electronic wallet), digital banking transactions, or self-service payment kiosks. Importantly, these systems should be tailored to offer flexible payment options or subsidies for vulnerable populations. Rural consumers may assume understanding of water supply as a paid service, although acceptability varies. While the technology is **readily available** and growing quickly in urban settings, digital payment for water use in rural areas remains less widespread.

7. DECENTRALIZED WATER QUALITY TESTING

To verify drinking water safety, water quality testing is commonly performed for urban water systems throughout the world, either in the field (in situ with sensors or onsite with portable equipment) or in a laboratory (samples collected and transported offsite for analysis). Standard field tests are available for a suite of physicochemical parameters, such as temperature, pH, electrical conductivity (to determine salinity), turbidity (suspended particulate matter), and chlorine. Measuring microbiological parameters generally requires laboratory equipment for incubation or DNA amplification, although several field kits for indicator bacteria (a proxy for pathogen presence) have been developed and tested for drinking water monitoring. Remote and field-based monitoring approaches with low costs and high replicability **need to be disseminated more consistently** to rural, low-resource areas, and will require shifts in public accountability, technological and managerial design, incentivization, and local capacity building.

8. SENSORS

Water supply infrastructure in low-resource settings has historically been plagued by a lack of ongoing oversight and maintenance. Sensors for monitoring piped water system performance (e.g., functionality, flow rate, basic water quality) are widely deployed by urban utilities in high-income countries, many of which remotely transmit data to a central management dashboard. Critically, monitoring systems must incentivize and enable responsible institutions to act upon the data produced by cost-effective sensor networks. Candidate devices and systems designed or customized for rural water settings would benefit from larger-scale markets to continue reducing costs and refining stability and reliability. **Piloting and scale-up are underway** in many countries, often involving iterative technology development.

9. DIGITAL MANAHMENT APPLICATIONS

Compared to urban water utilities, rural water supplies often lack sufficient personnel, monitoring schemes, and record-keeping systems. This leads to challenges addressing routine issues, allocating resources for system management, understanding spatial and temporal resolution of data (e.g., to enable alerts), and preparing for long-term risks. Three primary technologies have potential to ease data collection, monitoring, and management activities. First, cloud-based "supervisory control and data acquisition" software systems allow two-way remote water supply system monitoring and management. Second, "Internet of Things" systems consist of physical objects (e.g., sensors) that connect and exchange data with other devices and systems over communications networks. Third, "digital twins" offer virtual replicas of the physical water supply system with real-time updates. These automated tools reduce labor and time collecting and processing data, even facilitating machine learning and prediction. Still, they come with many common drawbacks of non-human intelligence: upfront investment, increased energy use, possible data loss or malfunction, and potential ethics concerns. Digital management applications are steeply on the rise among high-income, urban water suppliers, with fewer specialized products **under development** for remote, rural, and low-resource settings.

UPTAKE CONSIDERATIONS

Diffusion of Innovation theory explains that most people look to their social peers before adopting new ideas, and therefore spread circulates outward into larger social circles until reaching critical mass (Rogers 2003). Later technology acceptance theories acknowledge the influence of multiple dimensions (e.g., context, psychosocial factors, and the technology itself) affecting innovation uptake decisions on multiple levels (e.g., larger governance structure, community, household, and individual; Dreibelbis et al. 2013). Implementation science offers a pathway from passive "diffusion" to more active "dissemination," by identifying barriers to scale-up of evidence-informed practices and matching them to strategies likely to bring about performance improvement (Haque and Freeman 2021; Setty et al. 2019). Example factors supporting innovation uptake include regulatory oversight, active coalitions, cost-recovery accounting, and performance monitoring (Rouillard et al. 2016; Machado et al. 2019; Smits and Lockwood 2015).

The risks and potential impacts of various technologies differ among rural settings. Since incentives for technological innovation differ in a global development context, where access to safe water represents a human right, both the public and private sectors play critical roles in scale-up (Wehn and Montalvo 2018). Commercialization efforts must include underrepresented parties, such as minority voices and local consumers. The rapid evolution of information and communications technology introduces further complexity into commercialization processes, but in most cases facilitates expediency and cooperation. Technological commercialization has also shifted (in large part due to consumer demand and recognition of past failures) to require a concerted emphasis on social and environmental responsibility. These foci are critical to tackling key issues, such as climate change.

RECOMMENDATIONS

All innovation categories described herein hold promise for advancing rural water supply efforts in low-resource settings. At the same time, technological innovation benefits from continued research and development, marketing, and supplier competition to address drawbacks and awaken new possibilities. Low-risk, high-impact innovations such as community-scale disinfection can be promoted in many settings, while other innovations such as reverse osmosis may render benefits under certain conditions. Critically, partnerships coupling implementation efforts with research efforts can help to clarify the most favorable conditions for each technology.

The financial, technical, and social aspects of rural water supply interact in complex ways, and different bottlenecks may apply to different scenarios over time (Walters and Javernick-Will 2015; Carter 2019; REACH 2017). To better facilitate technological innovation serving rural water consumers in low- and middle-income countries, this report reached the following overarching recommendations:

- **Water supply managers** should incrementally adopt more advanced technologies, where justified by projected long-term cost-savings, improved verification of safe water delivery, and/or reduction of negative externalities.
- **Public sector investors** play a key role in developing business models and demonstrating the viability of serving peri-urban, rural, and remote areas. Water service implementers should set affordable price points from the outset to encourage consumer buy-in and ownership. (Learn more in the companion report: *Financial Innovations for Rural Water Supply in Low-Resource Settings*.)
- **Researchers and technology suppliers** should adopt user-centered, community-involved, and ecologically minded approaches (emphasizing care, interconnectedness, and integrity) to designing and testing next-generation technologies.
- **Technology suppliers** should couple new water supply infrastructure with "smart" (preferably automated or semi-automated) monitoring feedback to increase long-term accountability among technology purveyors, such as donors, governments, and service providers.
- **All parties**, in the face of climate change, should combine energy-consuming rural water supply technologies with sustainable, renewable energy sources where possible.
- **Donors, implementers, and researchers** should pair technology trials with social ("soft") science approaches, such as improvement cycles or implementation support follow-up, to periodically consider remaining barriers to change and address them with evidence-informed strategies.
- **Donors, researchers, and water supply managers** should holistically assess and prioritize risks threatening the resilience of existing rural water infrastructure.

INTRODUCTION

WHAT IS REAL-WATER?

REAL-Water (2021–2026) is an initiative of the United States Agency for International Development (USAID). The Aquaya Institute leads a seven-member consortium that aims to help policy makers, development partners, and service providers make strategic decisions and implement best practices for rural water management through evidence and learning. REAL-Water also supports coordination with other USAID programs contributing to the USAID Water for the World Implementation Research Agenda, to bolster global efforts to achieve the United Nations' (UN) Sustainable Development Goal 6 on "water and sanitation for all."

The three main components of REAL-Water are:

1. Implementation research that applies scientific methods, international collaboration, and rigorous analyses. Focal countries for field research include Ghana, India, Kenya, Tanzania, and Uganda. Three focal topics are:
    a. Professionalizing rural water service delivery
    b. Strengthening water quality monitoring
    c. Improving planning for water resources
2. Use of evidence to support decision-making by national policymakers and government officials, development partners, and public and private sector service providers.
3. Coordination and collaboration with related programs cotributing to the WASH knowledge base.

"Innovation" is one cross-cutting theme that spans all aspects of the REAL-Water program. This report and the companion report on financial innovations set a stage for identifying and integrating innovative approaches into rural water supply implementation research.

WHAT IS RURAL WATER SUPPLY?

The specific water sources, treatment and distribution processes, and cultural habits around storage, transport, or home treatment vary widely among geographic settings. Figure 1 illustrates several common water supply methods that may be found in low-income, rural areas, while Figure 2 expands on the many variable characteristics of rural water supplies. In general, rural water collection methods (e.g., handpumps, gravity-driven channels, manual retrieval using containers) are much simplified compared to urban settings, which often have large, semi-automated central treatment plants and extensive, pressurized distribution systems to serve tap stands or households. Rural positioning far from urban energy grids may limit options for extracting and treating water onsite.

In theory, a "safe" drinking water supply **should not pose any significant health risk over a lifetime of consumption, due to either quantity or quality** (WHO 2017b)**.** Contaminants may include infectious microorganisms, metals, organic chemicals, or other harmful substances. **"Safely managed" means the water supply** is always accessible at a person's residence, available when needed, and free from contamination (WHO UNICEF Joint Monitoring Programme (JMP) 2017). As of 2020, the majority of people lacking even basic water services (i.e., water from a protected source requiring no more than 30 minutes to collect) lived in rural areas (WHO UNICEF Joint Monitoring Programme (JMP) 2021).

Figure 1. Simplified diagram depicting several common rural water supply methods in low-income settings, including (a) piped household connections, (b) public tap stands, (c) household rainwater harvesting, (d) community groundwater boreholes with handpumps, and (e) surface water collection (Source: Vanessa Guenther, Aquaya Institute)

Characteristics of Rural Water Supplies

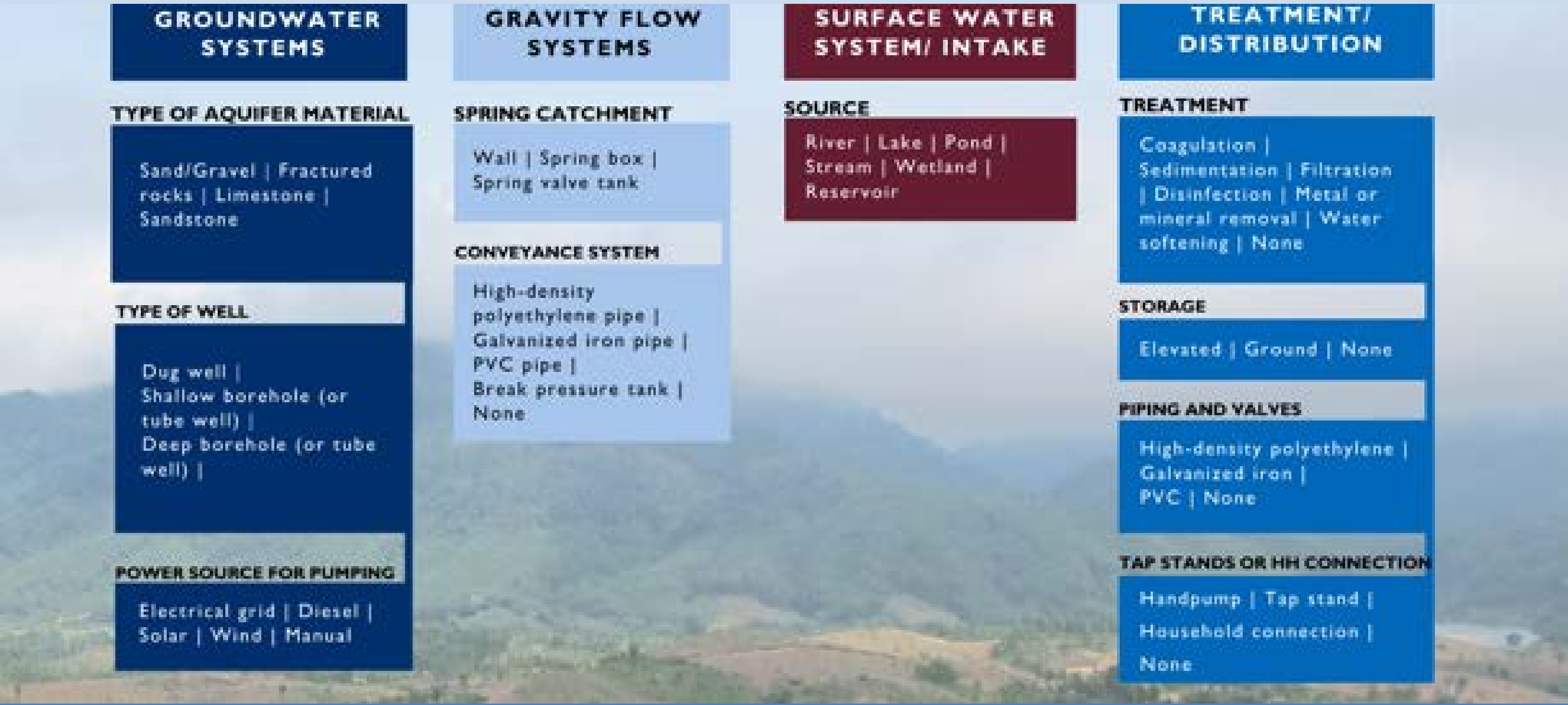

Figure 2. Varied characteristics of rural water supplies in low- and middle-income countries (Source: Vanessa Guenther, Aquaya Institute). These aspects may be used separately or in combination, typically with an emphasis on simplified engineering to fit local conditions.

- **Aquifer** = belowground layer of water formed amid rock or unconsolidated material
- **Borehole** = a narrow shaft drilled into the ground vertically or horizontally, in this case to extract water from an underground aquifer
- **Break pressure tank** = a chamber engineered to reduce pressure, prevent backflow, and mediate water flow coming from an uphill source
- **Coagulation** = mixing powdered substances such as iron or aluminum salts into water to neutralize the negative charges of dissolved and suspended particles and cause them to clump together
- **Deep borehole** = a hole drilled to access deep aquifers that are less likely to be influenced by surface contamination (usually >20 meters)
- **Handpump** = manually powered pumps, usually with a lever or wheel, that bring water from belowground to the surface
- **Sedimentation** = allowing water to settle so particles fall to the bottom
- **Tap stand** = an outlet connected by pipes to a pressurized water source, such as an aboveground storage tank, that dispenses water on opening
- **Tube well** = a type of well where a long tube or pipe is placed in the borehole to convey water
- **Water softening** = removing minerals such as calcium, magnesium, and iron, which leave undesirable deposits and waste soap

Continuous, piped household connections to safely managed water represents a gold standard for water service delivery. Untreated surface waters (e.g., lakes, ponds, rivers) are unfit for human consumption, as they lack protection from contamination. Thus, rural water suppliers often need to decide between treating potentially contaminated water onsite in a compact, inexpensive way or investing in expensive startup drilling to reach deep, protected groundwater. Container water (e.g., bottles, jugs, or tankers) treated elsewhere is inefficient to transport and often unaffordable. Good practices for rainwater harvesting make it a promising local source; however, rainwater availability changes seasonally, appropriate roofing material requires a (potentially prohibitive) startup investment, and users require some training for safe collection, storage, and use.

WHY IS RURAL WATER SUPPLY CHALLENGING?

Rural areas pose distinct challenges for water suppliers, as homes may be too few or too dispersed to justify the cost of laying pipes from a high-quality water supply source or centralized water treatment facility. Rural residents of high-income countries are often served by on-plot groundwater wells, along with septic tanks or other onsite wastewater containment and treatment systems. Optimally, onsite sanitation systems are engineered to maintain adequate separation from the drinking water source. In rural areas of low-income countries, self-supply may be outside of residents' financial and technical reach. Further, government institutions frequently lack the budgets, technical capacity, and professional management capabilities to provide basic services to everyone. Bolstering both dispersed and centralized solutions may enhance service for diverse rural populations.

Another primary challenge comes not from the infrastructure itself, but from a lack of post-implementation support, as charitable actors may enter and leave communities in quick succession. These startup investments go to waste when installation projects are succeeded by poor maintenance, loss of functionality, and eventually regression of safe water service coverage. For innovations to be successful, they must be technically feasible, affordable, and well-matched to the geographical setting and capacity of local operators. Even when shown efficacious in theory, a water supply solution's effectiveness and (both positive and negative) consequences must be evaluated in a field setting to understand whether it is appropriate.

HOW HAS RURAL WATER SUPPLY CONTEXT CHANGED OVER TIME?

In the 1970s, more than 70% of the world's rural populations lacked safe and adequate drinking water supplies, leading to high mortality (Carter 2021). At the 1972 UN Conference on the Environment, participants issued a global call (the Stockholm Declaration and Action Plan for the Human Environment) for water supply, sewerage, and waste disposal systems adapted for local conditions. The UN Conference on Human Settlements in 1976 called for an "International Drinking Water Supply and Sanitation Decade," along with national action plans for drinking water supply and sanitation. These were included in the "Mar Del Plata Action Plan," which emerged from the first UN International Water Summit held in Argentina in 1977. Around the same time, the UN Children's Fund (UNICEF) identified widespread issues with handpump functionality in rural India and undertook rehabilitation efforts (Baumann and Furey 2013). Thus, the 1980s ushered in an increased global focus on water supply issues. Handpump production also scaled up (Box 1; Figure 3).

By 1990, the UN Convention on the Rights of the Child had materialized from the Declaration and Plan of Action established during the World Summit for Children. It called for universal access to safe drinking water and systems for sanitary excreta disposal by 2000. The international community first recognized a specific human right to water in 2002 through the UN Committee on Economic, Social and Cultural rights. Human rights to both water and sanitation were established in 2010 through UN General Assembly and UN Human Rights Council resolutions. The Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) also formed in 1990 when the World Health Organization (WHO) and UNICEF decided to coordinate monitoring of global water and sanitation conditions. A professional network of rural water suppliers, initially the "Handpump Technology Network" and later the "Rural Water Supply Network," was born in 1992.

The UN Millennium Development Goals were released in 2001, after the Millennium Declaration was ratified in 2000. JMP reports were recognized as UN-wide monitoring outputs after the formation of the interagency coordinating group, UN-Water, in 2003. Target 7c, finalized in 2006, aimed to "reduce the proportion of the population without sustainable access to safe drinking water and basic sanitation by half between 1990 and 2015." The Sustainable Development Goals were activated in succession by the UN's 2030 Agenda for Sustainable Development and unanimously adopted by UN Member States in 2015. Goal 6 aims to "ensure availability and sustainable management of water and sanitation for all" by 2030.

BOX 1. BIRTH OF HANDPUMPS

Handpumps in principle use simple machines and physics to draw high-quality groundwater to the surface with a minimal amount of human labor. Many designs have been developed and trialed over time in different parts of the world, for both household and community use. The basic piston and rope pump designs were invented prior to the Common Era in Egypt and China, respectively. Use of a pitcher handpump in 1854 was famously linked to a cholera outbreak in London, England, sparking awareness of the potential for shallow groundwater contamination. Gas-powered pumps became common in high-income settings by 1910, vastly improving yield. Submersible pumps arose in Russia in 1916. In 1933, a government water supply officer designed the Zimbabwe Bush Pump for low-resource rural areas, which was next improved in the 1960s and renamed the Bush Pump (Baumann and Furey 2013). During the 1980s and 1990s, extensive research and development work went into scaling up and making handpumps, including the India Mark II/III and Afridev styles, more resilient and user friendly. By 2020, installation of handpumps such as UNICEF's "Number 6" had shifted more from the public to the private sector (Robinson and Paul 2000). Handpump research continues through the present day, not only on resilient designs, but also community-appropriate management and maintenance programs that ensure safe water service.

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KEY EVENTS

In Rural Water Supply Development

POLITICAL EVENTS | HANDPUMP EVENTS

1972
Stockholm Declaration and Action Plan for the Human Environment was issued, calling among other items for water supplies adapted to local conditions.

1974
UNICEF carried out a survey of handpumps fitted on bore-wells in India, and found about 75% of the cast-iron handpumps were inoperative.

1975
UNICEF purchased 6,500 Sholapur 'conversion heads' to help governments replace the cast-iron handpumps' pump heads, leading to successful hybridization.

1976
United Nations Conference on Human Settlements called for urgent action to improve both urban and rural water supplies

1976 - 1977
Field testing of the India Mark II handpump was carried out by the Tamil Nadu Water Supply and Drainage Board and UNICEF.

1981-1990
The UN International Drinking Water Supply and Sanitation Decade ushered in substantial attention on global water supply development.

1984
Thirty-six companies had licenses from UNICEF to manufacture India Mark II handpumps, with annual production at more than 200,000 units.

1989
The Skat Foundation issued the first international standard specification for the Afridev handpump, conceived as a deep well pump that was easy to maintain, could be manufactured in low-resource countries, and minimized corrosion.

1990
The UN Convention on the Rights of the Child treaty defined civil, social, health, and other rights for children.

The WHO/UNICEF Joint Monitoring Programme (JMP) was created.

1992
The global "Handpump Technology Network" was formed at the International Handpump Workshop in Kakamega, Kenya.

1993
Growing awareness of arsenic-contaminated groundwater led the World Health Organization to revise its global drinking water quality guidelines.

1999
Public domain specifications for the improved Zimbabwe Bush Pump became available.

2000 - 2015
United Nations Millennium Development Goals aim to reduce the number of people without access to safe drinking water by half, relative to 1990.

2004
The Handpump Technology Network officially changed its name (and scope) to the Rural Water Supply Network.

2010
United Nations General Assembly recognized the human right to water and sanitation through Resolution 64/292.

2011
Delegates from 240 organizations and 54 countries gather at the Rural Water Supply Network Forum in Kampala, Uganda.

2012
Millennium Development Goal target was met!

2015
United Nations Sustainable Development Goals target safely managed water access for all by 2030.

2020
WHO/UNICEF Joint Monitoring Programme maintains that 1.6 billion rural inhabitants still lack safely managed drinking water sources.

Figure 3. Timeline of key events in rural water supply development (Source: The Aquaya Institute; Baumann and Furey 2013; Danert 2022; Bartram et al. 2014; WHO/UNICEF Joint Monitoring Programme 2021)

WHAT IS THE STATUS OF RURAL WATER SUPPLY?

As of 2022, the Sustainable Development Goals continue to drive global efforts to increase water service levels, while ensuring that services are affordable and no vulnerable population is left behind (United Nations 2018). Achievement of these goals by 2030 remains extremely ambitious. While the percentage of rural populations with safely managed drinking water services rose from 42% in 2000 to 60% in 2020, two billion people still lacked safely managed drinking water services in 2020, 80% of whom lived in rural areas (WHO/UNICEF 2021).

A safe water supply is essential for healthy communities and improved living standards. Worldwide, water consumption for municipal, industrial, and agricultural uses is expected to increase substantially, and solutions are needed to ensure water security for all. Rural populations have risen by 26% globally from 1980 to 2020, although the continued trend toward urbanization is expected to reduce rural dwellers in most world regions (Carter 2021). In contrast, Africa's rural populations are expected to continue rising over the next several decades.

WHAT DOES THIS REPORT COVER?

This compendium compiles highlighted high-technology concepts for quick comparison and reference by research planners, donors, and decision-makers involved in rural water development for low- and middle-income countries. It focuses on addressing basic needs as specified in global WASH agendas, particularly water access and microbiological safety, notwithstanding the importance of customizing incremental service or water quality improvements to local settings. The information and examples provided are not systematic or exhaustive. A multitude of additional water supply technological innovations and nature-based solutions exist, as described in more comprehensive catalogs (Deal, Furey, and Naughton 2021); in-depth resources such as research articles and technical guides are referenced and available elsewhere.

Reflecting the cross-cutting aims of the REAL-Water program, the report selected concepts that could feasibly expand safe water access in rural areas of low- and middle-income countries and accelerate progress toward global goals. Regarding scale, household-level safe water storage and treatment technologies used at the point of consumption were not featured in this report. In several parts of the world, these have been limited by persistent behavior change challenges (Brown and Clasen 2012; Rosa, Kelly, and Clasen 2016), although individually boiling water or other forms of treatment are more common in the Asia-Pacific region (Rosa and Clasen 2010) and emergency settings. Likewise, large- and full-scale treatment facilities that replicate the common approach to municipal water treatment in urban areas are not discussed, due to the inherent financial and technical capacity limitations of replicating these for the smaller population sizes of rural communities.

We defined "rural" as locations outside of urban centers, including small (often agrarian) villages and low-density communities but excluding mid-sized or large towns. "Innovation" broadly refers to a new idea, method, or device. **The report focuses on high-technology innovations (sophisticated electronic devices or scientific, analytical, and engineering methods), with a recognition that their uptake strongly depends on other factors, such as user acceptability, supply chains, performance under real-world conditions, and affordability.** The innovations featured should on balance remain practical for use at larger scales, offering some advantages over typical approaches.

The report covers nine modules with information on technological innovations for safe rural water supplies, arranged roughly in order of the cycle from the water source to point of consumption:

Extraction/Collection	**Storage/Distribution**
Treatment	**Monitoring/Management**

Each technological innovation section discusses the background (need for the technology), solutions (technical offerings), and examples in practice. "Pros" summarize the innovation's advantages relative to other options (the status quo), while "cons" summarize the relative disadvantages. We also comment on the stage of development, marketing considerations (including whether the innovation's appeal or applicability is limited to specific contexts), and scale of dissemination globally. Although more detailed classification schemes exist, the stage of development was simplified to:

Conceptual	**Under pilot evaluation**
Limited production	**Commercially available**

Commentary on rural water history, context, comparison of innovations, and models for uptake are included, with practical examples and references to specific technology providers for more information. Because technological innovation information is often proprietary and not formally documented in academic literature, the authors' direct knowledge, presentations, and media coverage with varied reliability and timeliness offered key sources of information. The report primarily draws from resources published in English and focused on Africa, Asia, and Latin America.

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INNOVATION 1: SOLAR PUMPS

CATEGORY

Extraction/Collection

STATUS

Commercially available

BACKGROUND

Remote communities around the world require lasting, resilient solutions to the water-energy-food nexus, wherein energy supplies are needed to develop water and food supplies and vice-versa (Mabhaudhi et al. 2019). In the absence of a natural gravity gradient (e.g., from a mountain spring), pumping, treating, and moving groundwater or surface water from the source to the consumer requires substantial amounts of energy. The ability to pump water into elevated tanks creates a gravity-driven pressure gradient that supports reserve storage and piped water distribution. Other needs in the community, such as lighting, food production, and powered communications, likewise stand to benefit from a larger supply of energy and water.

Centrally accessible water supply locations also require less travel time, pose fewer dangers than surface water collection, and may reduce the carriage burden that can lead to musculoskeletal disorders (Geere et al. 2018). Manual groundwater pumping can take tens to hundreds of strokes per user per day, leading to extensive queues, handpump overcrowding, excessive wait times, and interpersonal conflicts (Kumasi 2020). Women and children typically tasked with collecting water may lose an entire half-day or day that could otherwise be spent on income-generating labor or education.

SOLUTIONS

Solar-powered water supply solutions (Figure 4) are likely to play a critical role in making progress toward universal water access goals (Bamford and Zadi 2019). National rural water supply strategies have begun driving the use of solar-powered water systems for developing new water infrastructure, replacing diesel generator systems, upgrading from unreliable grid power, responding to droughts, and building resiliency for climate change. With high flow and pressure capacity, solar pumping can easily serve larger communities and reduce issues associated with the excessive queuing times at community water points during high-demand periods.

Offering key advantages over traditional power options in remote areas, solar pumping is becoming a more common solution for powering delivery of both ground and surface water sources. Solar-powered water supply systems are largely operationally and environmentally sustainable once installed. The pumps commonly used for these systems are directly solar-driven and do not require the use of batteries or charge controllers. They accept a wide range of electrical inputs and have robust built-in protection systems. This allows for minimal maintenance and long-term reliability. Solar may offer key advantages in post-disaster situations, when other power options have been disrupted or destroyed (International Organization for Migration (IOM) 2017).

When designed, installed, and maintained correctly, solar-powered water systems can be very durable. Lifespans of individual components can range from 7 up to 20 years. Clear and professional mechanisms for operation, maintenance, and cost recovery through user fees must be in place to achieve such performance and longevity. Like all mechanical systems, solar pumps are susceptible to breaking down. An evaluation in Kenya suggested steps can be taken to ensure the procurement of adequately designed and good quality equipment and to minimize risks associated with vandalism, theft, and premature electromechanical failure (IOM 2018). Countermeasures include raising the solar panels, fencing, security lights, guarding the system, locating equipment within a private home, and tight welding.

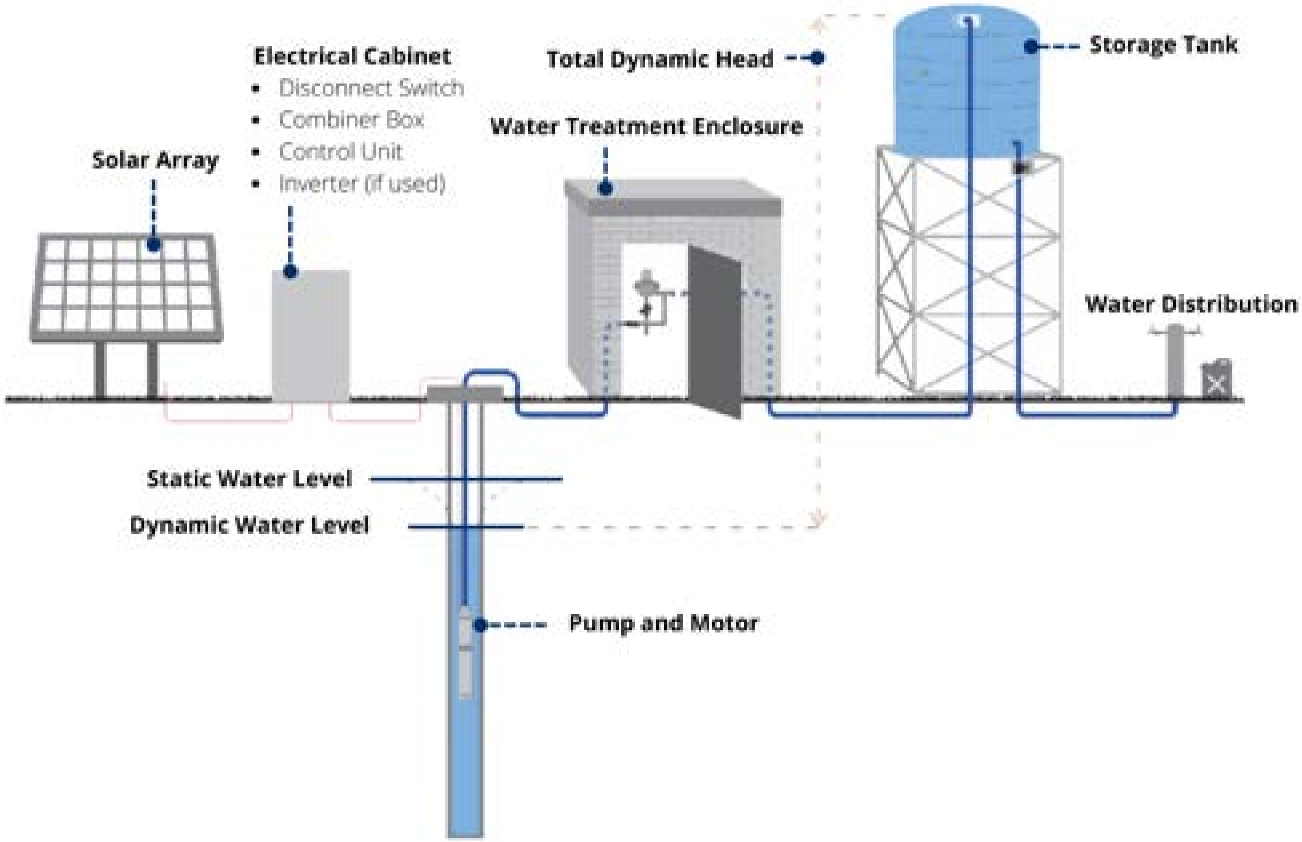

Figure 4. Diagram of a solar-powered rural water system (Source: Water Mission)

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PROS

- Solar-powered water systems can **serve more people** compared to manual handpumps, where populations are more concentrated.

- Solar power (like diesel or on-grid power) can facilitate pumping, as well as **water treatment and storage** in elevated tanks. When combined with gravity-driven distribution systems, this means that safe water can be delivered to tap stands where end users most need them (e.g., near homes, schools, and offices), reducing the labor burden on traditional water gatherers.

- Solar arrays may offer an **energy supply** for other uses.

- Solar-powered water systems provide high levels of service in **remote areas,** reaching those who have traditionally been left behind by water service development.

- Solar power is a **clean, renewable energy** source that does not require cooling water or result in local noise and chemical pollution.

- Solar pumps **reduce reliance on grid power and costly generators,** potentially reducing carbon emissions that contribute to global climate change.

- Solar-powered water systems **minimize operation and maintenance costs** and supply interruptions. They require very little capital maintenance while continuing to function reliably for decades.

CONS

- Despite increasing awareness of the opportunities associated with solar-powered water systems, **misconceptions and capacity gaps** persist (Armstrong, Mahan, and Zapor 2017). Decision-makers in several African countries, for instance, lacked accurate and transparent information on solar pumping performance and cost-effectiveness in specific contexts (Goodier 2019). As a result, national trade and water supply policies often fail to recognize its feasibility and create a healthy enabling environment for the technology. To ensure solar pumping can be used to its full potential, key bottlenecks must be identified and addressed, and scale-up opportunities must be identified and invested in.

- **Proper guidance and training are required** to address gaps in knowledge, resources, and practice. Existing international standards and reference materials are underused, leading to inadequate dimensioning, installation, and operation and maintenance. For solar pumping systems to remain sustainable, they must be properly designed, sited, operated, and maintained by trained professionals.

- **Supply chain challenges** remain for non-standard pump parts and solar panels, with few local manufacturers in low-income countries.

- Sufficient solar irradiation is available to provide power in **many world regions,** including Africa, South America, and South Asia.

Figure 5. Community-scale solar-powered water pumping system in Tanzania (Source: Water Mission)

EXAMPLES

Solar pumping systems are used in many applications. Commonly, they have been used for potable water supply to institutions (e.g., health care facilities and schools), community-based water supply systems (e.g., Figure 5), irrigation systems, and livestock watering.

Solar-powered water systems present a viable solution in humanitarian disaster response projects for refugee and internally displaced persons camps (Figure 6). Procuring fuel is often difficult in these situations, and solar pumping reduces or removes the dependence on fuel and oil common to generator-driven pumping or tanker water delivery.

- The most **common malfunctions** experienced by solar-powered water systems are electrical and wiring failures as well as complications arising from insufficient borehole yield, particularly during dry months. These issues are closely linked with inadequate groundwater assessment, borehole siting, system dimensioning, and installation and can be addressed by following internationally recognized design and installation specifications.

- Realistic financing mechanisms are needed to serve low-income countries, as upfront installation and eventual replacement **costs pose a barrier.** This raises the risks of inadvertent consumer exclusion or amplification of existing barriers to water service inclusion. For instance, a 2016 evaluation of UNICEF's solar-powered water system programming found that in nearly half of the study sites, the poorest populations chose to use alternative unimproved water sources because they considered the tariff unaffordable (Bamford and Zadi 2019). As the first step in any solar-powered water system program, marginalized populations and **barriers to inclusion need to be identified.** Then, the influence of solar-powered water systems on service levels should be carefully evaluated considering these barriers.

- Solar pumping systems may **stop working** during periods of heavy cloud coverage or downtime for repairs, requiring backup water storage or alternative sources.

- Solar pumping systems **require greater security** against theft or vandalism (IOM 2018).

Figure 6. Solar pumping system installed in a refugee camp in Tanzania (Source: Water Mission)

STAGE OF DEVELOPMENT

Many global WASH actors have supported installation of solar pumping systems. The International Electrotechnical Commission hosts an international standard (Standard 62253: Photovoltaic Pumping Systems) that outlines a comprehensive methodology for designing small- to medium-sized solar-powered water systems. Several additional manuals and tools enhance the technical design and support the proper dimensioning of solar pumping systems (UNICEF 2020; Kiprono and Llario 2020; EWB 2020). As with all civil works, regulatory codes and supervision of construction and installation are critical. Adequate opportunities for training and capacity development specifically tailored to the technical skills required to support these systems must be established. In addition, solar pumping schemes benefit from groundwater governance schemes, to avoid exacerbating environmental, technical, and social issues.

STATUS

Solar pumps are commercially available from reputable international manufacturing networks (e.g., Grundfos, Lorentz).

MARKETABILITY

A common barrier to adoption is the difficulty of drawing comparisons across the range of solar-powered water supply products and materials available. Products should be selected for long-term quality and reliability rather than upfront cost, convenience, or brand-name recognition. All equipment and materials used in solar pumping systems should adhere to internationally recognized certifications and testing standards as defined by the International Electrotechnical Commission, and equipment should be covered by manufacturer warranties over the initial period during which failures due to defects are likely to occur. Socially responsible manufacturer practices also come into play; many solar panels are manufactured using the forced labor of China's Uyghur Muslims (Murphy and Elima 2021).

Furthermore, the lifetime sum of all costs and benefits associated with various products ("lifecycle costs") should be considered when evaluating alternative options. Guidance and examples inform the development of bidding documents that incorporate these principles (Armstrong 2019; Kiprono and Llario 2020). The feasibility, scalability, and long-term viability of solar-powered water systems in any context depends on the interrelated functions that enable governments and public and private partners to engage in effective water service delivery. For instance, national monetary and trade policies can either support or hinder development of local markets for solar pumping products; thus, they influence the availability of quality equipment and spare parts. One evaluation placed solar pumping in a low range of capital and operational expenditures per person, among water supply alternatives, on the order of $1.51[2] per person per year for a "typical" medium-sized scheme (Armstrong, Mahan, and Zapor 2017).

2 All values are given in U.S. Dollars.

SCALE OF DISSEMINATION

Solar pumping is used in rural water supply systems on several continents. A 2017 compilation traced solar water pumping applications developed by relief organizations in 24 countries in Africa, 8 in the Middle East, 5 in Asia, and 1 in South America (International Organization for Migration (IOM) 2017).

INNOVATION 2: COMMUNITY-SCALE DISINFECTION

CATEGORY

Treatment

STATUS

Traditional

Commercially available

Advanced

Under pilot evaluation

BACKGROUND

Rural water sources in low- and middle-income settings are inconsistently disinfected before consumption; according to the WHO-UNICEF JMP Progress Report, 45% of rural dwellers have contaminated drinking water supplies (WHO UNICEF Joint Monitoring Programme (JMP) 2021). This takes a heavy toll on health. Nearly 500,000 children under 5 years of age die from diarrheal diseases every year, making it the third leading cause of death for this age group. South Asia and Sub-Saharan Africa are most affected (Dadonaite, Ritchie, and Roser 2022).

In high-income countries, childhood mortality due to unsafe drinking water has been virtually eliminated. When first introduced in the United States in the early 1900s, public drinking water chlorination and related safety measures led to a significant decline in overall mortality and child mortality (Symons 2006). One study estimates that between 1900 and 1936, the rollout of water filtration and chlorination in major cities contributed to nearly half of the reduction in overall mortality, two-thirds of the reduction in childhood mortality, and three-quarters of the reduction in infant mortality (Cutler and Miller 2005). Efforts that leave water treatment (including disinfection) up to household consumers, in contrast, have shown less consistent adherence and health benefits (Brown and Clasen 2012; Rosa, Kelly, and Clasen 2016; Rosa and Clasen 2010).

SOLUTIONS

Water treatment strategies in rural communities physically remove (e.g., through filtration; see Innovations 3 and 4) and/or inactivate pathogenic microorganisms. Exposing drinking water to chlorine is a well-established, inexpensive, and effective method for inactivating many diarrhea-causing pathogens (CDC 2014). Chlorination is more effective with relatively pure water (e.g., groundwater) or following a pretreatment step (e.g., coagulation, filtration). Otherwise, it will be rapidly consumed in reactions with naturally occurring substances in raw water (e.g., organic matter, iron, manganese), leaving less available to inactivate pathogens. Advanced treatment systems may use ozone, which is unstable and usually produced onsite, or UV light for disinfection. Disinfection can be used as a single treatment step for high-quality groundwater.

Disinfection strategies require consistent supply chains and educational messaging to address misconceptions and promote correct and sustained use. Strategies that rely on household users adding chlorine to drinking water were once widely promoted; however, they failed to achieve high rates of sustained adoption in many contexts (Luby et al. 2008; Rosa and Clasen 2010; Luoto et al. 2011; Null et al. 2018). Placing the burden of water treatment on the household consumer requires consistent, sustained behavior change to realize the potential health benefits, and even slight declines in compliance bring significantly increased health risks (Enger et al. 2013; Brown and Clasen 2012). Disinfection prior to the point of water distribution reduces the burden on users and therefore holds more promise. Still, it relies on water supply operators to comply with treatment procedures and on consumers to continue using that water source, to safely transport the water, and not to store it for too long.

UV disinfection does not leave chemical residues, but chlorine or ozone addition may lead to formation of disinfection byproducts (trace harmful chemicals formed after oxidation of naturally occurring substances present in the water). This issue mainly affects chlorinated surface water sources enriched with organic matter, although ozonation of surface or groundwater can form byproducts from dissolved bromide or iodide. The WHO affirms that microbial risks outweigh disinfection byproduct risks, and measures can be taken to monitor disinfection byproduct levels and reduce exposure (Amy and International Programme on Chemical Safety 2000). In high quantities, these byproducts are linked to long-term negative health effects, such as bladder cancer (Amy et al. 2000).

IN-LINE CHLORINATORS

Most community-scale chlorination in low-income rural settings has been performed at or near reservoir tanks. Along with manual addition of chlorine liquid, tablets, or powder products, mechanical chlorine dispensing devices (e.g., dripline, piped tablet feeders, mixing chambers, floating dispensers) have been designed over the years to use natural gravity and water flow to maintain more consistent dosing at community supplies. Such systems can be purchased at low cost or constructed using locally available materials. None of these systems work without an operator who continuously replenishes the chlorine supply. Drip chlorinators with smaller holes are considered less robust in terms of ease of dosing adjustment, maintenance needs, and resilience (Orner et al. 2017).

Automated or passive methods generally offer advantages in terms of more consistent performance and ease of use. In-line chlorinators are typically flow-driven, chlorination systems installed along a piped water system (either before or after water storage tanks) or attached to handpumps or taps (Lindmark et al. 2022). They do not require electricity but allow slow-dissolving chlorine tablets or a concentrated chlorine solution to mix with flowing water, achieving chlorination at a target concentration (Pickering et al. 2019; Amin et al. 2016; Powers et al. 2021). The dosing adjustment process remains critical, as switching to chlorinated water often brings up taste and odor concerns that consumers may or may not habituate to over time (Jhuang, Lee, and Chan 2020; Piriou et al. 2015; Smith, Islam, et al. 2021).

Among chlorination chemicals, sodium hypochlorite is commonly used in community-scale water treatment (Geremew et al. 2018). Alternative forms such as chloramines and cyanurates might have advantages, such as less perceptible chlorine taste and smell, or disadvantages, such as lower efficacy against viruses (Clasen and Edmondson 2006; Gallandat et al. 2019). Calcium hypochlorite tablets have been gaining popularity for rural community systems (e.g., for Safe Water Network in Ghana). These products can generally be stored for up to a few years, but will lose potency over time depending on their chemical makeup and storage conditions.

One randomized evaluation of in-line chlorinators in Dhaka, Bangladesh revealed decreases in childhood morbidity from diarrhea relative to control households who did not receive water treatment (Pickering et al. 2019). The authors hypothesized that these results were attributed to centralized chlorination, bypassing the burden on consumers to treat water individually. While chlorination encouraged by outside parties can help reduce disease incidence in the short term, long-term effectiveness requires expanded investment in implementation and built-in accountability mechanisms (Kaplan 2022).

Examples

Chlorine brands such as WaterGuard, Aquatabs, and P&G Purifier of Water (formerly PUR) have been widely marketed for community or household-level chlorination, including small-scale school, hospital, orphanage, or emergency applications. In Ghana, Saha Global encourages female entrepreneurs to treat water from local sources (coagulation followed by chlorine disinfection in a central supply tank) and resell it at an affordable price. Dispensers for Safe Water, implemented by Evidence Action and its partners, dispense chlorine at the point of collection, which then disinfects water while it is carried to the household (Yates et al. 2015; Millennium Water Alliance 2019). Examples of in-line chlorinator technologies are highlighted in Table 1, Figure 7, and Figure 8. In addition, Lindmark et al. (2022) reviewed an extensive array of passive in-line chlorinators, recommending greater focus on developing handpump-compatible chlorinators.

TABLE 1. IN-LINE CHLORINATORS

DEVICE	WATER SYSTEM TYPE	WATER TREATMENT CAPACITY / REFILL	ESTIMATED DEVICE COST (U.S. DOLLARS)	STAGE OF DEVELOPMENT	FIELD TESTING EXAMPLES
Water4 NuPump	Handpumps	N/A	N/A	Prototype	Ghana (The Aquaya Institute 2021)
EaSol PurAll	Handpumps, Piped systems	Varies	Varies	Commercially available	Bangladesh (Sikder et al., 2020); Nepal (Crider 2021)
Medentech Aquatabs Flo	Piped systems (storage tanks)	180,000 L @ 1 ppm (advertised); 308,000 L (measured)	$87	Commercially available	Bangladesh (Pickering et al. 2019; Smith, Sultana, et al. 2021); Nepal (Crider 2021)
Medentech Aquatabs Inline	Piped systems	360,000 L @ 2 ppm	$150	Commercially available	N/A
Water Mission Erosion chlorinator	Piped systems	900,000 L @ 1 ppm	$700	Commercially available (to non-profits)	Tanzania (Check, Abdiel, and Mbwille 2017)
Compatible Technology International (now Bountifield International) CTI-8 Chlorinator	Piped systems (gravity flow systems)	N/A	N/A	Open-source instructions for construction from common materials	Nicaragua and Guatemala (Jacob and Taflin, n.d.); Honduras (Henderson, Sack, and Toledo 2005); Panama (Orner et al. 2017)
Zimba	Handpumps	10,000–20,000 L Varies with strength of hypochlorite solution	$240	Commercially available	Bangladesh (Amin et al. 2016; 2021)
Mountain Safety Research MSR/Stanford Venturi Doser	Piped systems (kiosks), predecessor for handpumps discontinued	N/A (compatible with flow rate 6–60L/min	$34 (Venturi only, excludes: chlorine storage tank, valves, cover)	Prototype	Bangladesh (Pickering et al. 2015); Kenya (Powers et al. 2021)

N/A = information not available

Figure 7. Erosion chlorinator (Source: Water Mission)

Figure 8. PurAll Handpump chlorinator (Source: EaSol Private Limited)

DOSING PUMPS

Liquid chlorine dosing pumps are most effective in drinking water supplies where water flows continuously and energy is readily available. This is by far the most widely employed mechanism of post-filtration disinfection of treated water in urban water treatment plants, which automatically add chlorine solution to treated water at a flow-dependent rate before it enters the distribution system. The dosing rate is set to achieve the desired chlorine residual concentration (amount of free chlorine remaining after oxidation reactions). More advanced dosing systems are feedback-oriented, with sensor-based measurement of chlorine levels in the treated water. Where dosing pumps are used by larger utilities, skilled operators or technicians may be available to support training, installation, and/or maintenance in rural water systems.

Examples

Commercial providers of chlorine dosing pumps for small water treatment systems include Grundfos, Dosatron, LMI, Pentair, and Milton Roy.

ONSITE DISINFECTANT GENERATION

Recent technological advances have made onsite generation an attractive and cost-effective option for community-scale drinking water disinfection. As an alternative to purchasing chlorine, electrolytic chlorine generators use a relatively simple technology that passes electrical current through a concentrated salt solution to produce liquid chlorine (sodium hypochlorite). Ozone for drinking water disinfection can likewise be created onsite by converting oxygen from the atmosphere using microplasma technology (Dorevitch et al. 2020). Generators may be powered by solar energy. Onsite production replaces dependence on purchasing and storing tablets, powder, liquid, or gas disinfectants. Chlorine gas is highly corrosive and toxic, and the large pressurized cylinders require careful handling and storage to mitigate safety and security risks (Rivera and Matousek 2015).

Examples

The MSR SE200 Community Chlorine Maker (Figure 9), SafiStation Chlorine Generator (Figure 10), WATATM Technology (four devices: Mini WATA, WATA Standard, WATA Plus, MaxiWATA) (Figure 11), and STREAM Disinfectant Generator (Figure 12) are described in Table 2. Most chlorine generation applications in low- and middle-income rural areas have produced liquid bleach for sanitizing surfaces in healthcare facilities. More research is needed to understand the conditions in which onsite generators can be successfully paired with rural water systems.

TABLE 2. ONSITE CHLORINE GENERATORS

DEVICE	WATER TREATMENT CAPACITY	POWER REQUIREMENT	DEVICE LIFETIME	ESTIMATED COST (U.S. DOLLARS)	SCALE OF DISSEMINATION
Mountain Safety Research and PATH MSR SE200	200 L/batch	12 V DC, 110–220 V AC	5+ years	$160	Devices used in field trials by World Vision in Mali and Kenya.
Mountain Safety Research and PATH SafiStation™	Up to 15,000 L/hour @2 ppm	12 V DC, 110–220 V AC	5 years at 8 hours/day	$1,500–2,000	40 devices were pilot-tested in healthcare facilities in Ghana and Uganda (Drolet and Kallen 2019).
Antenna Foundation WATA-Standard™	8,000 L	12 V DC, 100–240 V AC	10,000 operating hours, or 5+ years	$417	Devices have been installed in Donbass, Ukraine, by the Swiss Humanitarian Aid Unit; schools in Madagascar; and in Kivu region of the Democratic Republic of Congo to combat cholera outbreaks.
Aqua Research STREAM Disinfectant Generator	Up to 230,000 L/day	12 V DC, 110–220 V AC	10 years	$3,500	USAID has conducted an Environmental Assessment of the STREAM system for a health care facility in Haiti. Testing has also been performed in many countries in Africa, with over 400 devices operating around the world.

N/A = Information not available

Figure 9. MSR SE200 community chlorine maker (Source: PATH)

Figure 10. SafiStation™ Chlorine Generator (Source: SafiStation)

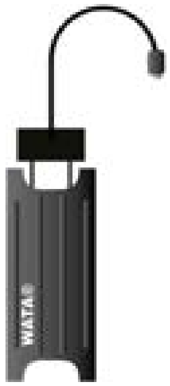


Figure 11. WATA-Standard™ (Source: Swiss Bluetec Bridge)

Figure 12. STREAM Disinfectant Generator (Source: Aqua Research)

One example of an onsite ozone generation system comes from a startup, EP Purification, supported by innovation incubation programs at the University of Illinois Urbana-Champaign, the United States Environmental Protection Agency's Small Business Innovation Research program, and a Wells Fargo entrepreneurship award (UIUC 2022). Household piloting by 10 families in a Kenyan village found the solar-powered technology to be effective and favorably perceived by end users (Dorevitch et al. 2020).

CUTTING EDGE: "Electrochemical" remediation techniques remove dissolved substances in water using reactions on the surface of an electrode (Hand and Cusick 2021). It has attracted increased attention as a scalable, decentralized water disinfection approach, and has also been used to remove arsenic and lead. This approach requires energy and additional study under field conditions.

ULTRAVIOLET (UV) LIGHT

Often used in urban water or wastewater treatment plants with sufficient electrical supplies, UV light disinfection is also beginning to play a role in water treatment in low- and middle-income countries. Light in this wavelength is a powerful disinfectant, inactivating bacteria, viruses, and even protozoan cysts by altering their DNA or impeding reproduction. UV irradiation is less effective in turbid (cloudy) waters, because less light passes through. Pre-filtration is recommended in these cases. UV lamps can be scaled from large community systems to handheld devices, but centralized treatment involves fewer behavior change barriers (Gruber et al. 2013). It involves greater operating costs and equipment relative to chlorination, but does not leave any residual taste or odor. Unlike chlorination, however, no residual disinfectant remains to address water recontamination during storage or use. To work effectively, the water must have an adequate exposure time to the light source (usually on the order of seconds), algae and biofilms must be cleaned off the lamps, and lamps must be replaced periodically (about once a year, depending on usage) as they lose gradually effectiveness. Microbes can escape harm or repair themselves and reactivate if the exposure is inadequate.

Examples

The Mesita Azul® (translation: little blue table) uses a UV lamp mounted inside a horizontal cylindrical tube to disinfect water at a rate of 5 liters/minute (Reygadas 2022). It was designed and developed by Cantaro Azul in collaboration with the University of California, Berkeley and participants from marginalized communities, particularly women. It has been deployed in households, schools, and community kiosks in rural Mexico (Reygadas et al. 2015). Another technology, the Dayliff UV Purifier from Davis & Shirtliff has been used in school, trading center, and community settings in a number of East African locations (Lubango 2022). The social enterprise 1001fontaines arranges franchised water kiosks offering UV-treated local water in Cambodia, Madagascar, Vietnam, and Myanmar.

PROS

- Disinfection leads to a well-characterized reduction of most bacterial and viral pathogens in water as well as a **reduction in diarrheal disease incidence.**
- Centralized community-scale chlorination **reduces the requirement of consumer behavior change.**
- Proper chlorine dosing offers **residual protection** against bacterial recontamination when water is transported or stored.

CONS

- Chlorine offers relatively low protection against **resistant pathogens** such as protozoan cysts and does not treat inorganic contaminants such as arsenic.
- Chlorine and UV disinfection are **less effective in highly turbid water** sources, such as surface water.
- Many users object to chlorine **taste and odor**, and habituation varies.
- Some disinfection setups **require water pre-treatment**, consistent electricity, and specialized equipment and maintenance.

- Among disinfection methods, in-line chlorination carries the **lowest cost and fewest barriers** to entry. Chlorine supply chains are fairly well-developed in many countries, and chlorine dispensing devices can be constructed with inexpensive, locally available materials.
- For onsite chlorine and ozone generation, **local production** avoids dependence on disinfectant suppliers and challenges with transport and prolonged storage.
- Dosing pumps help to **automatically regulate** chlorine dosing, maintaining adequate amounts while avoiding high-concentration spikes.
- UV light disinfection offers a **chemical-free alternative** with no offending taste, odor, or residues.
- Solar power can facilitate **off-grid** use of disinfection systems that require electricity.

- Ongoing **quality control** (e.g., for dose concentration, contact time, residual concentration) is essential to maintain effective disinfection dosing. Good disinfection performance requires trained and motivated water supply operators as well as regular oversight.
- **Disinfection performance varies widely** under field conditions, depending on initial water quality, operation and maintenance, and water transport and storage. Despite demonstated efficacy in ideal conditions, research into disinfection effectiveness in rural, low-income settings is ongoing.
- **Safety requirements** (e.g., gloves, ventilation, spill cleanup supplies, leak prevention) apply to handling and storing disinfection chemicals.
- While chlorine products are relatively stable and can be stored safely in ideal (cool, dark, dry) conditions for a year or more, like most chemicals, they **lose potency** and expire. Operators should track manufacture dates and order in usable quantities.
- In-line chlorinators designed for relatively small systems **may require multiple installations** in parallel for larger supplies or re-dosing at different locations for longer distribution systems.
- Some onsite disinfectant generators and dosing pumps **require softened water, salt, acid** (e.g., vinegar), and/or electricity for operation and cleaning, which may be difficult to obtain in rural areas.

- Chlorine and ozone disinfection introduce the potential for long-term health effects of **disinfection byproducts**, which should be monitored and managed where possible.

STAGE OF DEVELOPMENT

Mechanical chlorine dispensers have been in widespread use for some time, although addition of chlorine products still poses some operational consistency and consumer acceptability challenges. Onsite chlorine generation has achieved small-scale commercialization for hospital use but is seldom paired with drinking water supplies. In-line chlorinators also have limited commercial availability (in some cases, coming from different applications such as swimming pool or pond maintenance) and continue to undergo field trials for drinking water applications. Dosing pumps and UV lamps are widely used in urban settings, but have seen fewer applications in rural settings with less water treatment infrastructure.

STATUS

Commercially available

MARKETABILITY

Chlorine dispensers are equally adaptable to large- or small-scale water supplies in rural areas, but require operational changes and sensitization efforts to promote acceptance. Newer technologies that use onsite chlorine generation, in-line chlorinators, and UV light have generally been promoted to date at a limited scale by non-profit organizations and development agencies. In-line chlorinators remain under testing at the point of supply for piped systems and at community water collection points (handpumps).

SCALE OF DISSEMINATION

Examples of rural community-scale drinking water disinfection applications are widespread across several world regions, including Latin America, Asia, and Africa.

INNOVATION 3: MEMBRANE FILTRATION

CATEGORY

Treatment

STATUS

Traditional

Commercially available

Advanced

Under pilot evaluation

BACKGROUND

Water quality challenges vary across different geographies, ranging from fecal pollution to metals to emerging contaminants. Thus, techniques that can consistently separate many or all classes of contaminants from water have the potential to benefit public health. A "membrane" is a permeable or semi-permeable barrier that selectively allows the passage of certain substances dissolved or suspended in a solution, while restricting others. Separation of substances from the solution depends on the contaminants' size and electrostatic charge (aka static electricity). Advances in materials technology over the past several decades have brought membranes to the forefront as an increasingly viable method for water treatment, ranging from small to large volumes.

SOLUTIONS

Like filtration through larger porous media (e.g., sand), membrane filtration physically removes impurities from water without adding any chemicals. Various membrane types offer a range of filtration capabilities and operational requirements. Moving water through a membrane with tiny pores requires sufficient energy to produce a pressure gradient, dependent on the membrane pore size, surface area, and initial water quality. Membranes with smaller pores and surface areas require higher applied pressure. To avoid clogging membrane pores prematurely, turbid source water (containing suspended matter) may require pretreatment steps.

Descriptions are grouped below by relative pore size of the membrane. Low-pressure membrane technologies include microfiltration (MF) or ultrafiltration (UF), while nanofiltration (NF) and reverse osmosis (RO) involve higher-pressure processes. Figure 13 shows the filtration spectrum for the different types of membranes. Due to its inherently different requirements and appropriate applications, reverse osmosis is described in a separate section (see Innovation 4).

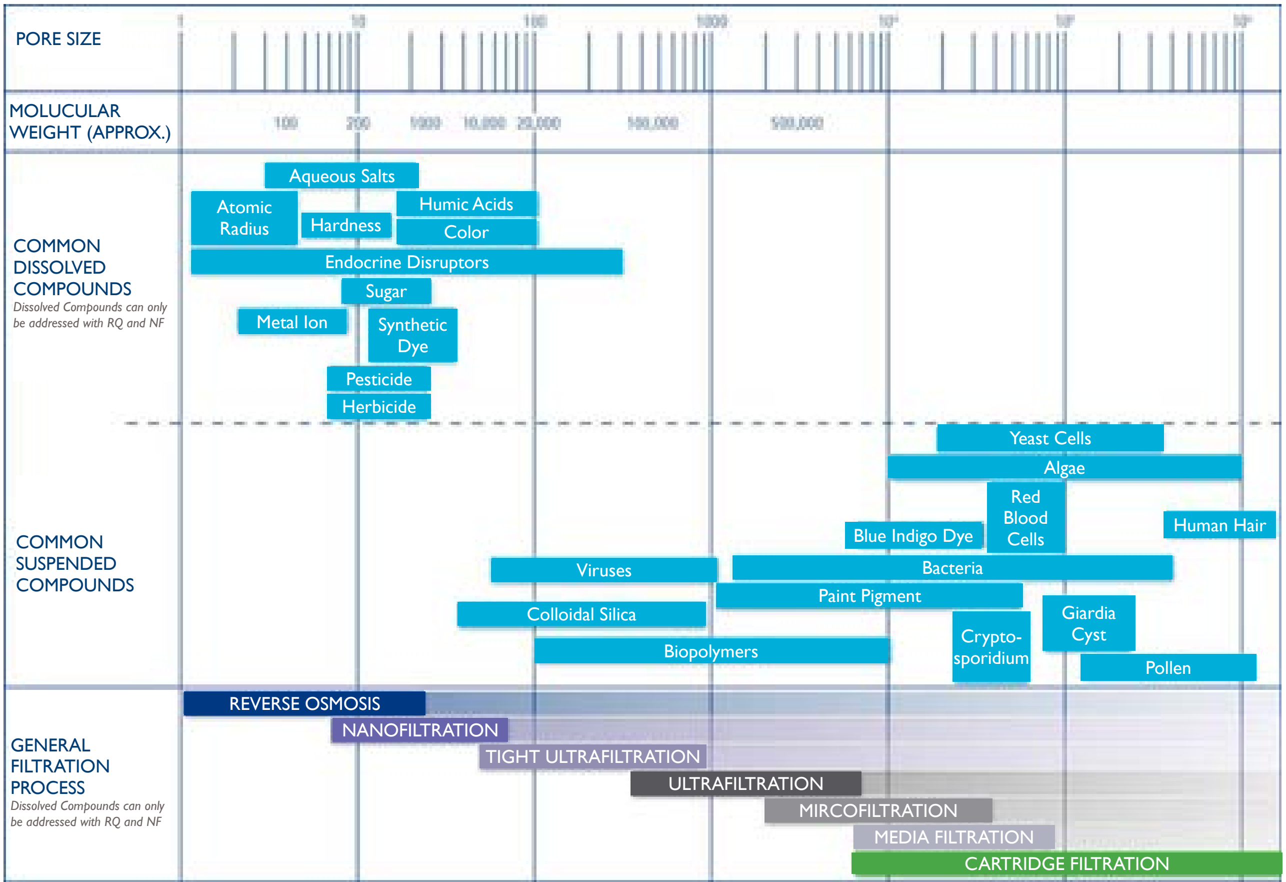


Figure 13. Filtration spectrum showing the removal of substances under different filtration methods, with pore size in angstrom units and molecular weight cut-offs in daltons (Source: Pentair)

MICROFILTRATION

Microfiltration (MF), with pore sizes in the range of 0.1–5 μm, is one of the oldest pressure-driven membrane filtration techniques. It was first used in the 1980s in municipal water treatment to remove particulate matter and bacterial and protozoan pathogens from water (Sillanpää, Metsämuuronen, and Mänttäri 2015). It can remove particles larger than 100 nm, including suspended particles, bacteria, yeast cells, and some proteins on the basis of size exclusion. An operating pressure of less than 2 bars is required to drive microfiltration (Pal 2017). Membranes are usually made from synthetic materials, such as nylon or polytetrafluoroethylene polymers (Frenkel 2015). Depending on initial water quality, pretreatment steps can help prevent clogging (aka fouling) the membranes. Alternatively, microfiltration can pretreat water to preventing fouling of smaller-pore ultrafiltration, nanofiltration, or reverse osmosis membranes.

ULTRAFILTRATION

Ultrafiltration (UF) membranes have pore sizes in the 2–100 nm range and work at an applied pressure of 2–5 bar. They retain bacteria, viruses and protozoans as well as large organic molecules such as proteins. Ultrafiltration membranes are made from a variety of chemically and thermally stable polymers, including polyacrylonitrile, polyvinyl chloride, and polycarbonate. These are perhaps the most common type of membrane filters deployed in rural areas of low- and middle-income countries to treat surface water for drinking purposes.

NANOFILTRATION

Nanofiltration (NF) membranes represent an intermediate between ultrafiltration and reverse osmosis, having a pore size of 0.5–2 nm and operating pressures of 5–15 bar. These membranes achieve the effective removal of all types of microbiological contaminants (bacteria, virus, cysts), as well as colloids, organic solids and multivalent ions. Since nanofiltration removes hardness-causing calcium and magnesium ions, it is also called "membrane softening." The nanofiltration membrane has a thin-film composite structure, comprising of a thin rejection layer (e.g., polyamide), a porous substrate layer, and a non-woven fabric support. The top rejection layer grants the membrane its selective permeability. The "crossflow" (parallel) filtration direction results in two product streams: a permeate stream with low total dissolved solids (finished water), and a high total dissolved solid "reject" or concentrate stream (waste product).

PROS

- Microfiltration and ultrafiltration operate at relatively low trans-membrane pressure, requiring **low energy** or even solely gravity power.
- Membranes **remove a broad spectrum of contaminants** and pathogens. Ultrafiltration and nanofiltration achieve complete microbiological safety of drinking water at the point of treatment.
- Water quality following treatment is highly **consistent.**

CONS

- Membrane systems may have a **higher cost** relative to other, locally available water treatment supplies. Among the membrane filtration processes, microfiltration has the lowest cost.
- All membranes are **prone to fouling** by deposits of organic or inorganic material, which eventually causes pore blockage. Periodic backwashing is required to prolong membrane lifespans, and over time membranes must be replaced. Nanofiltration membrane maintenance requires anti-scalants and clean-in-place routines.

- All membranes have a **smaller size** footprint than conventional water treatment plants (using coagulation, sedimentation, and filtration through sand, gravel, or charcoal), making them practical for remote transport and reducing construction challenges.
- Membrane filtration systems can be **automated** and require relatively little onsite operation and maintenance effort, giving operators more flexible hours.

- Higher **maintenance costs and training** are needed to support more advanced systems. Nanofiltration, for example, has relatively high capital expenditures and operating expenses.
- Nanofiltration **requires more electrical power** for operation.
- **Supply chain limitations** may affect membrane manufacturers' production.
- Backwash and concentrate **byproducts must be safely disposed.**

EXAMPLE

One growing membrane technology application is for modular, decentralized community-level water treatment systems, which have been increasingly explored in recent years to meet the challenges of the availability and accessibility of safe drinking water in rural and peri-urban settings (Cuscuna 2021). Modular units can be transported where piped water is unavailable and then locally owned and operated, with automation for around-the-clock service. Decentralized membrane systems typically consist of prefiltration, primary treatment, and post-treatment stages. They treat water from ground or surface water sources to a high standard (relative to other conventional treatment approaches) before dispensing it to consumers. These systems can be tailored to local conditions, such as the size of the community to be served, source characteristics, available resources, and availability of skilled or trainable personnel (Cherunya, Janezic, and Leuchner 2015).

Decentralized small-scale water treatment systems have been trialed in numerous small rural villages in low- and middle-income countries, with research demonstrating their technical and financial feasibility. For instance, a small-scale solar-powered ultrafiltration system was used for direct filtration treatment without any coagulant or chemical additives for a low-turbidity rural river water source in Perak, Malaysia (Chew and Ng 2019). Compared with a conventional sand/media filtration system, the ultrafiltration system obtained a higher quality of treated water with lower operating costs and carbon emissions. Use of the crossflow filtration operation mode eliminated a daily intermittent backwash sequence, which further simplified the daily operational routine for rural areas. Local residents were trained in basic operation and troubleshooting, so skilled technicians could visit just once a month.

In a rural Tanzanian training center, a nanofiltration water treatment system was set up and monitored for nine months (Bouhadjar et al. 2019). It successfully removed high concentrations of fluoride from the groundwater supply, serving as a prototype for potential marketing in fluoride-affected regions. Small volumes of the filtered water could be used as a weekly flush medium for the membranes, while the concentrate was reused for non-potable purposes. Other pilot studies using decentralized nanofiltration were conducted for one year in a rural Sri Lankan community affected by chronic kidney disease due to high water hardness and salinity (Cooray et al. 2019) and for one month in a rural Ghanian community lacking an affordable and economically productive safe water source (Ramaswami et al. 2016).

STAGE OF DEVELOPMENT

Membrane filter systems are becoming increasingly popular in high-income settings for drinking water production and in advanced applications like desalination and wastewater treatment for water recycling (Pearce 2007). In the past decades, the scale of usage has increased and therefore costs of membranes have decreased substantially, making membrane filtration more economically viable for use in underserved remote, rural, or peri-urban areas. Several manufacturers supply membranes as well as complete systems (examples in Table 3).

TABLE 3. EXAMPLES OF MEMBRANE FILTRATION DEVICES FOR COMMUNITY DRINKING WATER TREATMENT

PRODUCT	CAPACITY*	ESTIMATED LIFETIME*	ESTIMATED COST*	SCALE OF APPLICATION
LifeStraw® Max	150 LPH	Up to 100,000 L (membrane life)	$650	India, Philippines, Malaysia, Myanmar, Ukraine
Wateroam® ROAMfilter™ Ultra	1,500 LPH	2 years	$4,500	Malaysia, Indonesia Vanuatu, Philippines, Cambodia
SkyJuice Foundation SkyHydrant™	10,000 LPD	5–10 years	$3,500	Global (63 countries)
Aqua-Cura Solar	500 LPH	5+ years	$17,000–28,000	India, Western Africa, Congo
Healing Waters International Gravity Pure UF	500–10,000 LPD 40–550 LPH	2–5 years (membrane life)	$67,000 (starting)	US, Haiti, Dominican Republic, Guatemala, Mexico

*As stated by manufacturer. LPD = Liters per day; LPH = Liters per hour.

STATUS

Membrane filtration devices are commercially available, with new technologies consistently under development.

MARKETABILITY

Membrane filtration technologies can support rural, off-grid water treatment, if upfront costs and technical capacity needs are feasibly met compared to other options. Membrane filtration with larger pore sizes may be used as a pretreatment step for reverse osmosis applications (e.g., seawater desalination).

SCALE OF DISSEMINATION

Application examples from around the globe appear in Table 3.

USAID
FROM THE AMERICAN PEOPLE

INNOVATION 4: REVERSE OSMOSIS

CATEGORY

Treatment

STATUS

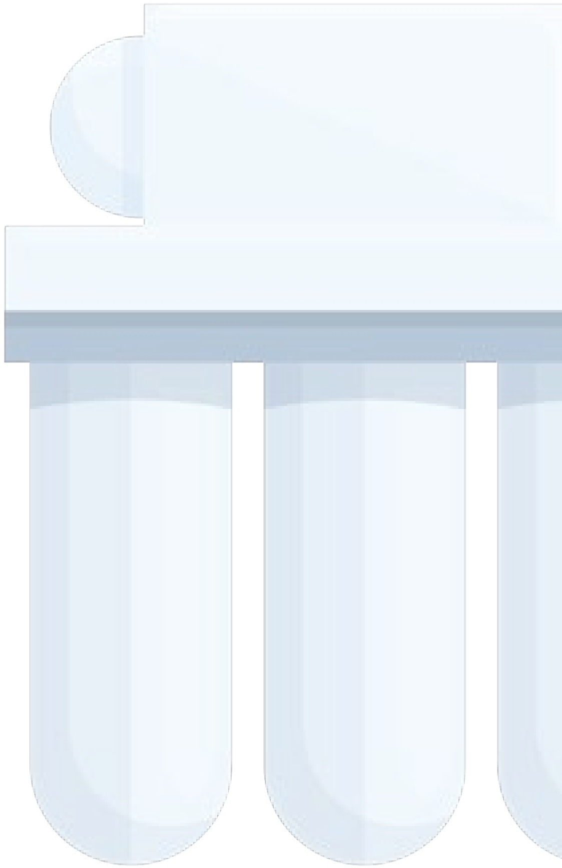
Commercially available

BACKGROUND

Groundwater serves as a primary drinking water source for many rural populations; however, many locations suffer from chemical contamination, either naturally occurring (e.g., salinity, fluoride, and arsenic) or arising from human activities (e.g., fertilizer application, mining, industrial operations). Some of these chemicals resist traditional water treatment approaches. In water-stressed regions with high contamination levels, communities must import water, rely on treatment to make water fit for consumption, or suffer negative health consequences. For example, arsenic toxicity, which causes cancer as well as disease of the gastrointestinal symptoms, skin, and nervous system, occurs in more than 30 countries (Kabir and Chowdhury 2017).

SOLUTIONS

Reverse osmosis (RO) or hyperfiltration is the most energy-intensive form of membrane filtration, but offers the greatest performance at separating impurities and consistently removes a wide range of contaminants (Figure 13). Where energy supplies are plentiful and freshwater resources less so (e.g., Middle Eastern desert or Mediterranean climates), this mature technology has been commonly used to produce freshwater from seawater, brackish groundwater, or wastewater in water recycling operations. RO treats more than 80% of desalinated water globally (Pal 2020). Over the past few decades, significant developments in RO membrane technology in materials, synthesis techniques, modifications, and modules (Shenvi, Isloor, and Ismail 2015) have improved performance and driven down prices. RO systems are becoming more cost-effective relative to other pressure-driven membrane technologies as their use expands.



A typical RO system consists of pre-treatment, a high-pressure feed pump, a membrane or membranes housed in pressure vessels, and post-treatment steps, such as pH correction and/or residual disinfection. RO uses crossflow filtration (also called tangential flow filtration), where the water flow direction is parallel to the surface of the membrane. The trans-membrane pressure pushes the water out of the membrane, collected as the permeate (treated water). In contrast, contaminants are retained on the feed side of the membrane as the concentrate (reject) water stream. RO membranes have a pore size of less than 0.1 nm, and require electricity to achieve operating pressures of 7–55 bars (Backer 2013). The permeate recovery (produced water) varies from 25% of the initial volume in single-stage RO up to 80% in multi-stage installations. This largely depends on feed water characteristics, especially total dissolved solids, the Langelier Index (approximate saturation of calcium carbonate), and fouling characteristics.

PROS

- RO removes **95–99% of all dissolved contaminants**, including monovalent ions (Pal 2020), all particulates (including colloids), and microbiological contaminants down to the smallest viruses.
- RO **can be used to treat non-potable water sources** with high total dissolved solids, including hard groundwater, coastal aquifers with saline intrusion, or pretreated seawater.
- The energy efficiency of RO far **outstrips other technologies** for treating water with high total dissolved solids. Its energy consumption ranges from 0.8 to 2.5 kWh per kiloliter of produced water (Sarai Atab, Smallbone, and Roskilly 2016), which compares favorably against other desalination technologies (Qin et al. 2019; Patel, Biesheuvel, and Elimelech 2021).
- With well-designed and properly executed maintenance, RO membranes can be expected to **last 4–6 years**.
- While relatively sophisticated, RO system **operation and maintenance training is widely accessible** because of its popularity and prevalence.
- Prices have become more affordable as RO systems are **distributed at larger scales.**

CONS

- RO systems are **expensive,** with the membranes costing the most among the consumables.
- RO **requires more energy** than other membrane filtration techniques, and may not be optimal for all water sources.
- **Skilled operators and technicians are essential** to reliable operation and maintenance of RO systems and their long-term sustainability. Less complex treatment approaches, such as adsorbents for arsenic contamination, might be better suited to local conditions (Kumar et al. 2019; Kabir and Chowdhury 2017).
- **Environmentally responsible disposal** or reuse of rejected water (with concentrated impurities) is an essential aspect of RO application. Some communities are able to repurpose the reject water for cleaning, washing, gardening, or toilet flushing (Safe Water Network 2015).
- Like other membrane filtration technologies, **fouling** poses a challenge, especially with hard source waters (Pandey et al. 2012). To control this, operators must add anti-scalants and regularly clean membranes.
- RO-treated water **lacks electrolytes** and thus may taste unpleasant to some consumers (Cooray et al. 2019).

EXAMPLES

Use of RO in compact household and community-scale water purification systems is growing globally, especially in high-income countries. Military use, government initiatives, and corporate social responsibility campaigns have led in pilot expansion into hard-to serve peri-urban and rural portions of low- and middle-income countries. For instance, RO is used in Honeywell India and Safe Water Network's iJal Safe Water Stations, which empower female managers, as well as "Water ATMs" (automated water dispensers open around the clock; see Innovation 6: Digital Payments).

Not-for-profit "Safe Water Enterprise" implementors have facilitated RO-based water treatment and sale kiosks in many parts of India; these include: Piramal Sarvajal, Waterlife India, WaterHealth India, SOPAR-Bala Vikasa, Naandi Community Water Services, Safe Water Network, and Rite Water Solutions. Safe Water Enterprises usually follow a company-owned, community-operated model, wherein the community is an active stakeholder in the financing, installation, and operation of the water treatment system. With capital expenditures and startup costs ranging from $20,000–40,000 to serve a population of 3,000–5,000 people, RO combined with UV disinfection can provide affordable, reliable, and safe drinking water for approximately $1 per person per year (Safe Water Network 2018). Safe Water Enterprises using RO are similarly widespread throughout Southeast Asia, including in the Philippines, Indonesia, and Vietnam.

The government has likewise facilitated installation of rural RO plants in many Indian States. Local elected bodies, local committees, "self-help groups" (small groups of ~10–20 rural women focused on micro-economic empowerment), or cooperatives manage these operations. Table 4 demonstrates the extent of state-supported community RO water purification plants in India (sanctioned between approximately 2014 and 2022). To improve the performance of these plants, India's Rural Drinking Water Supply & Sanitation Department engaged Safe Water Network's Technical Assistance program in 2019 to provide support and training to the operators, technicians, contractors, and government officials.

STAGE OF DEVELOPMENT

For low-income rural applications, the costs and technical sophistication of RO systems remain largely impractical; however, they have been widely piloted in India in recent years as part of the Indian government's Jal Jeevan Mission, which ambitiously aims to provide piped drinking water to every rural household by 2024. RO has been used in the majority of new community water purification plants (Jal Javeen Mission 2022).

TABLE 4. STATE-SUPPORTED COMMUNITY WATER PURIFICATION PLANTS USING REVERSE OSMOSIS IN INDIA (JAL JAVEEN MISSION 2022)

STATE	NUMBER OF PLANTS	TOTAL POPULATION SERVED
Andhra Pradesh	947	690,790
Assam	18	689,083
Bihar	97	272,489
Chhattisgarh	46	128,594
Haryana	15	73,347
Karnataka	18,500*	20,039,042
Kerala	12	13,540
Madhya Pradesh	5	125,585
Maharashtra	1	66,025
Punjab	371	720,627
Rajasthan	2,665	4,019,810
Uttar Pradesh	12	487,049
West Bengal	6	3,162,080

*The Government of Karnataka installed RO water purification plants with automatic dispensing to expand drinking water access, selling water at $0.07 (INR 5) for 20 liters.

STATUS

Commercially available

MARKETABILITY

Like the other membrane filtration technologies, RO is a mature and proven technology at a limited scale, but is relatively expensive and more complicated than other water treatment methods. For these reasons, further development is needed to make it a viable option for widespread use in rural settings.

SCALE OF DISSEMINATION

Rural RO applications serving low-income populations have primarily been piloted in India and Bangladesh, due to high naturally occurring arsenic contamination.

INNOVATION 5: SMART WATER METERS

CATEGORY

Storage/Distribution

STATUS

Commercially available

BACKGROUND

Water meters have traditionally been used at the household to help utilities track the volume of water used by customers and bill them accordingly. Water production and distribution system meters (covering a "district-metered area") have also been used to identify leaks, theft, pipe breakages, or other sources of water loss. Lost water, also known as "non-revenue water," undermines financial sustainability of the water supplier, as well as conservation of the source water, energy, and consumables used to treat the water. Good bill collection practices also improve the creditworthiness of service providers and access to commercial finance while reducing operating expenses. Thus, adopting smart metering can promote better service and resource management.

The term "smart" originally came from an acronym: self-monitoring analysis and reporting technology. The meaning has evolved to encompass devices that collaborate with human users to sense information and adapt services, rendering a sort of cognitive awareness to inanimate objects. Smart technologies have been introduced into many aspects of our daily routines, including communications, security, and commerce. Water and wastewater managers have begun to follow this trend as well, due to the increase in information and communications technology solutions across sectors. Manually read meters are gradually being replaced, as today's smart energy and water meters can monitor and transmit water usage data from distributed consumer properties back to a utility's central command post in real time, without human intermediaries. Data analytics can then be applied to alert operators to abnormalities and dispatch them to the appropriate location to investigate and remediate issues more quickly (Boyle et al. 2013).

SOLUTIONS

Where available, smart water meters' digital data logging and (optionally) data transmission from communal or household-level water distribution points can help to stabilize revenue and lead to more responsible water consumption. Smart meters store only recently measured data. Usually, the automated meter reading and transmission frequencies are flexible and can be set to transmit daily, hourly, or even in real-time. Water consumption data are uploaded to a physical or cloud-based server for long-term storage and processing. Smart meters offer a wide range of potential benefits to both water suppliers and consumers, such as greater customer satisfaction stemming from accurate billing and greater insight into water usage trends (Monks et al. 2019).

Smart meters track water usage through two communication technologies: Automatic Meter Reading (AMR) and Advanced Meter Infrastructure (AMI) (Figure 14):

- AMR is used by utility companies to automatically collect meter status and water consumption data. Consumption data are received and stored locally on a collection device (usually a laptop) via a network within the range of the water meter. In large communities, utility personnel may walk or drive through neighborhoods in person with a collection device (in close proximity to the meters) to download the consumption data ("walk-by"). In small communities, a central data logger and transmitter can receive signals from hundreds of water meters and transmit data to the utility's centralized database and management system ("fixed network").

- AMI systems automatically transmit data directly to a database, without requiring utility personnel to collect the data. While AMR is a one-way communication system from meter to utility (Bayliss and Hardy 2012), AMI allows two-way communication. Newer AMI systems use Internet of Things (IoT) communication technologies (physical objects that connect and exchange data with other devices and systems over the Internet or other communications networks), such as broadband power line communication (using existing cable lines), low-power wide-area networks (allows low-power, long-range communication), Narrowband IoT (a type of low-power wide-area network for cellular devices and services), LoRa ("long range," another type of low-power wide-area networks using proprietary radio modulation over unlicensed frequencies), and M-Bus ("Meter-Bus," a European standard).

Narrowband IoT has the advantage of lower cost, low bandwidth, and power efficiency over many IoT devices. Smart water meters that use the narrowband IoT communication systems promise a new path for smart water metering in densely populated suburbs, offering strong signal penetration to reach water meters installed indoors, underground, or in basements. Low power consumption enables narrowband IoT smart meters to fully perform their basic functionality with 10 or more years of battery life, and to perform local operations via short-distance communication.

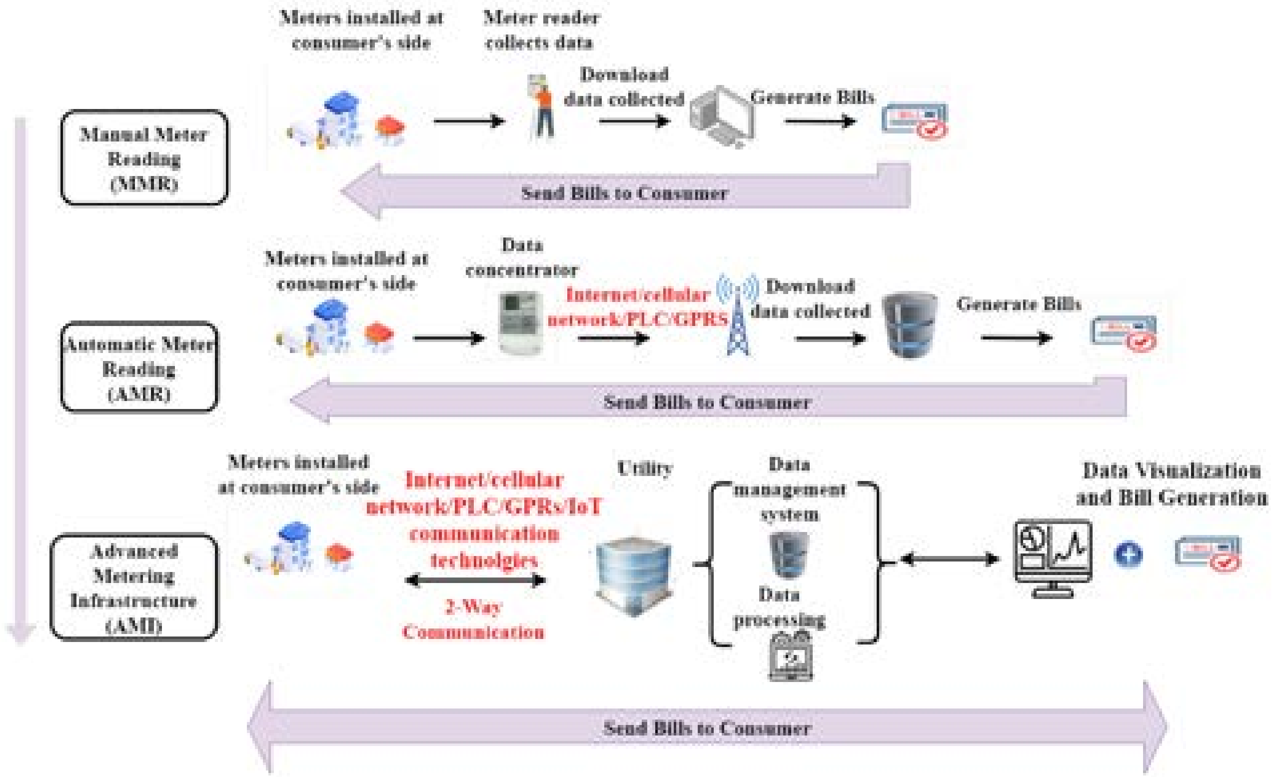


Figure 14. Evolution of meter reading techniques/technology (Source: Gaggero et al. 2021). GPRS = general packet radio service (part of the mobile phone network); IoT = Internet of Things; PLC = power-line communication.

PROS

- Distribution and point-of-use smart water meters proactively **capture information** (with increasing resolution) about leakage, pipe breaks, meter tampering, flow reversal due to inadequate system pressure, absence of water, and lost electronic signals or equipment tampering. Timestamped data, in comparison with totalizing flow meters, can be used to infer usage peaks, troughs, and uptime.

CONS

- Upfront **costs are higher** (approximately $150–300 per unit; Hope et al. 2011; Costa and Soares 2020) compared to traditional or no meters; in many cases, though, increased long-term revenue recovery justifies the investment.

- **Telecommunication failures** may cause a disruption in data transmission.

- Prompt data communication can help water suppliers achieve **faster response times** to carry out needed tests, repairs, and maintenance. This reduces service downtime, water loss, the possibility of system contamination, and unexpected bills.
- Larger treatment facilities can adjust their operations to **optimize energy consumption** and reduce their carbon footprint by matching consumers' water demand patterns (Siemens 2022).
- Billing is more **accurate and labor-efficient** than with manually read meters.
- Smart meters can **support prepayment and digital payment** systems (see Innovation 6) that enhance cost recovery.
- **Satellite-based** data transmission is possible in the most remote areas that lack telecommunications coverage.
- Consumers can **aid conservation** efforts by observing and adjusting their consumption habits.
- Utility workers do not require frequent access to a consumer's property, increasing convenience for users and **reducing safety issues.**
- The low radio frequency emissions produced by smart meters **do not pose a health risk** (Open Government UK 2020).

- Customers may be charged **variable rates for usage at certain times of day** when water demand is high, making it harder to plan.
- Transmitters **must be secured** and consumer water usage data must be kept private, to avoid interception by unauthorized parties.

EXAMPLES

Smart meters can be used for residential, communal, and institutional water metering and data transmission. A rising trend is to replace or retrofit old meter designs to enable automation (Figure 15). To combat non-revenue water loss, the Ghana Water Company Limited (GWCL) initiated a campaign in August 2019 to replace traditional meters (at no cost to consumers) with smart meters for customers in some parts of Ghana, beginning in Accra. As of 2021, GWCL had installed 100,000 Kamstrup smart meters, commissioned a smart metering lab, and refurbished offices to allow virtual asset management (Akornor 2021). The smart meters require a drive-by meter reader or remote reading to capture data. Providers such as Susteq in Kenya, Uganda, and Tanzania (Ingram and Memon 2019), and Safe Water Network in Ghana, have paired smart meters with prepayment methods to enhance revenue recovery. The Ugandan National Water and Sewerage Corporation and Uganda Industrial Research Institute are partnering to is developing a prototype for a new prepaid meter, which would reduce reliance on imports (Kiva 2021).

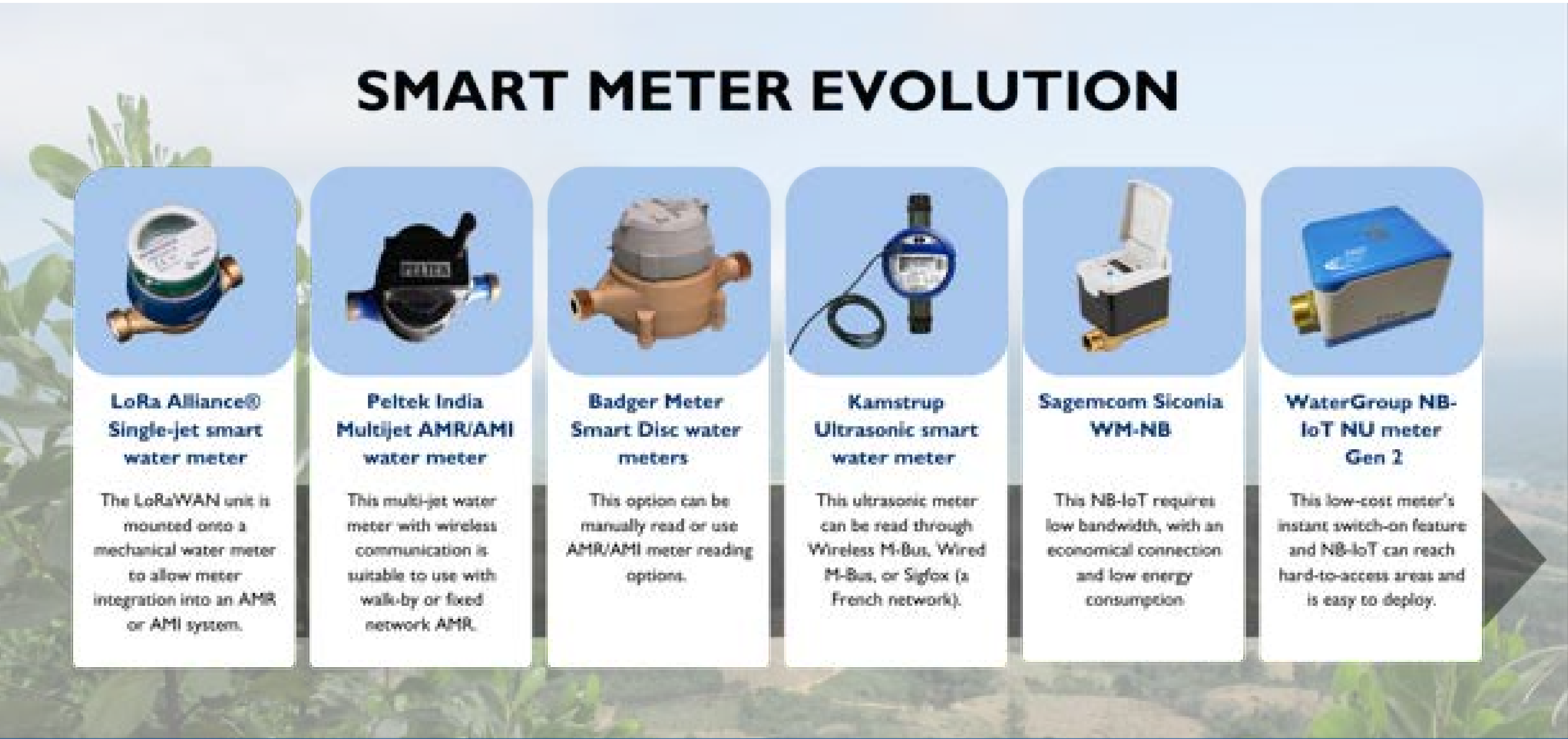


Figure 15. Smart meter examples highlight stepwise advances in technology

STAGE OF DEVELOPMENT

STATUS

Commercially available

MARKETABILITY

A variety of smart water meters and retrofit devices have been developed as information and communications technologies have rapidly advanced in recent decades. Smart devices are becoming more affordable even as their functionalities increase. Most have targeted high-income urban areas, especially those with high levels of water stress; for instance, the GSM Association's Mobile for Development Utilities Innovation Fund (open 2013–2018) supported pilot projects in Niger (with CityTaps) and China (GSMA 2018).

SCALE OF DISSEMINATION

SSmart water meters are following in the footsteps of smart energy meter rollout, restricted primarily to urban areas of high-income countries, albeit with some penetration into low-income peri-urban and rural piped water networks. This includes shared community water supplies, for example in rural Kenya, Uganda, and Tanzania (Ingram and Memon 2020; 2019).

INNOVATION 6: DIGITAL PAYMENTS

CATEGORY

Storage/Distribution

TYPE

Commercially available

BACKGROUND

Manual billing and cash payments are becoming inconvenient for water suppliers, among other businesses and service providers, as digital technologies have rapidly advanced in recent years. With limited payment alternatives, some consumers have had to wait in long lines or face disconnection due to unpaid bills. Payments may be constrained to utility offices or banks, and only available during business hours. Further, paper-based record-keeping and the labor required for enforcement more easily allow theft and corruption. Such inefficiencies contribute to high billing-to-collection ratios, low working capital, and revenue loss.

Two basic payment models exist for water services:

- "Postpaid" fee collection, wherein a utility bills customers following water use for the previous period and they pay at the end of the billing cycle; and
- Newer "prepaid" water metering options, wherein consumers pay for water before consumption, in some cases by adding funds to a prepaid card.

SOLUTIONS

Digital payment technologies offer increased convenience to both utilities and customers. Water service providers can accept digital payments for postpaid or prepaid water consumers using online payment platforms, server-connected remote points of sale, smartphone applications, or Global System for Mobile Communications Unstructured Supplementary Service Data (GSM USSD) codes, also called "quick codes," (often used for phone-based services, with some advantages over text messages). Smartphone applications used for paying water bills may be developed and maintained by the water supplier or a third-party vendor, and offered through common mobile "app stores" for digital download. Payments can be more easily facilitated by existing mobile money (electronic wallet) or digital banking transactions, if users have access and adopt these services (Lorentz, n.d.; Grundfos, n.d.). Real-time status updates and past payment records might be viewable in confirmation messages or through a web browser, if individual log-in is available.

Payment kiosks offer self-service and may be located indoors or outdoors in public places such as food markets or shopping centers. These technologies accept cash (sometimes with no change), personal checks, and debit or credit cards. They provide real-time confirmation (paper receipt, email, or text message) following payment. Point-of-sale (POS) devices can accept water payments, with the advantage of being small and easily portable (even handheld or attached to a mobile phone). These small hardware devices read the magnetic strips or chips embedded in debit and credit cards or other devices. Payments can be accepted at any location staffed by or having an agreement with the water provider.

Smart water dispensers (called "water ATMs," after automated teller machines for banking transactions) offer shared prepaid water outlets that are always open. Behind the interface, they are designed to either collect and treat water onsite (e.g., using membrane filtration – see Innovations 3 and 4), connected to a piped water supply, or stocked like a vending machine. The key user interface components are the smartcard or token (digital payment) and the dispenser. After dispensing water to the customer, the machine deducts credit from the smart card and communicates the transaction to the data management system via near-field communication. The system's data may be stored on a local server and/or cloud system.

PROS

- Paperless billing is relatively **convenient and less expensive** for water suppliers.
- Giving customers **flexible** payment avenues may increase ability to pay and total revenue.
- Use of **existing payment infrastructure** requires no startup costs.
- Employees **do not need to be stationed** at the point of sale at all times. Flexible work hours may promote work opportunities.
- Customers benefit from low fees, and have to purchase only what they need, making water **more affordable** overall and possible to tailor closely to individual budgets. The most vulnerable customers may be entitled to a minimum quantity of water at no cost.

CONS

- Digital payment kiosks come with a high **initial capital expenditure,** which may or may not be offset by long-term revenue recovery.
- Water access may remain inhibited in remote areas **farther** from water payment and access points.
- Some **customer service** is required to familiarize users with the payment service, address issues, ensure security of users' financial assets, and promote correct use.
- Improved knowledge of unpaid bills colud lead suppliers to more rapidly **disconnect users** from water services. Safeguards must be in place for those who are unable to pay.

- Increased access time (24 hours a day) directly translates to **less queueing**, which affords users more time for school attendance, household chores, or income-producing work.
- Digital payment data can be useful for **understanding water demand** and (to some degree) consumer preferences, which is essential to the water supplier's ongoing reach and viability.

- Additional small **percentage fees** may be charged for transactions using mobile money or bank accounts or costs of meter upgrades may be passed on to consumers, making water less affordable.
- **Payment cards or tokens** can be damaged, misplaced, or stolen.
- Digital payment systems risk software "bugs," system outages, malware, fraud, and theft of sensitive information. Appropriate **cybersecurity** measures and digital literacy training are essential.

EXAMPLES

Several technology examples are shown in Figure 16. Common online payment platforms include expressPay and Slydepay. Payment kiosk examples include DivDat and CityBase. Prepaid phone-based payment for water customers started in South Africa in the late 1990s (Heymans, Eales, and Franceys 2014). It was later piloted in Namibia, Uganda, Kenya, and Zambia for both communal prepaid standpipes and individual residential water customers. Safe Water Network in Ghana implemented the "pay-as-you-drink" model (Waldron, Hwang, and Yeboah 2018), accepting prepaid mobile phone payments to unlock smart water meters (see Innovation 5).

Examples of smart water ATMs include the Grundfos AQTaps and Lorentz smartTAP water dispensers (Figure 16). Water ATMs are used in Africa (e.g., Ghana, Uganda, South Africa, Tanzania, Kenya; Heymans, Eales, and Franceys 2014) and South Asia (e.g., Bangladesh, India, Pakistan; Schmidt 2020). For Water ATMs in India, the government is providing some operating subsidies, alongside private operators and corporate social responsibility initiatives (Chopra and Gogia 2017). Throughout the country, more than 30 Safe Water Enterprise implementors have set up approximately 50,000 Water ATMs (Safe Water Network 2018). In Ghana, Project Maji and the Practica Foundation implemented a small modular piped network of water kiosks with a digital (Maji Mini) or coin-based prepaid device (TokenTap). Pilot evaluation found that customer uptake was hard to predict, but the modular design allowed modification of the kiosk layout to achieve financial sustainability (van Kinderen and de Vries 2021).

Grundfos AQtap water ATM and waterCard | **LORENTZ smartTAP water ATM and tag** | **expressPay point-of-sale device** | **CityBase payment kiosk**

Figure 16. Digital payment technologies, including Water ATMs and personal access token technologies (Sources: Grundfos, Lorentz, expressPay, CityBase)

STAGE OF DEVELOPMENT

The payment avenues highlighted have primarily emerged to serve urban water customers, including marginalized populations within high- and low-income countries. Digital payment technology is evolving rapidly and its use for peri-urban and rural water services will likely expand, given its substantial benefits. Barriers to its use may include a lack of technological literacy, the need for reliable energy to power electronic devices, less existing infrastructure, and mistrust of electronic banking or credit providers.

STATUS

Commercially available

MARKETABILITY

The benefits of digital payments have made it worthwhile for water suppliers worldwide to invest resources and collaborate with technological companies. In Ghana, the national public water supplier (GWCL) has actively partnered with telecommunication operators (e.g., MTN Ghana, Vodafone Ghana, AirtelTigo) and banks. Customers of Iringa Water Supply and Sanitation Authority in Tanzania also use GSM

USSD codes to pay their water bills and prepaid meters, connecting to the payment application through phone messaging. Compared to West African countries, the use of mobile money has further penetrated East Africa, with greater uptake among males who are older, more educated, richer, and part of the workforce (Coulibaly 2021). However, mobile money market penetration has grown rapidly in Ghana, quadrupling between the 2013 and 2016 fiscal years (Bank of Ghana 2017), with continued growth through 2020.

SCALE OF DISSEMINATION

Digital payment acceptance is quickly growing among consumers. A number of service providers in Africa have adopted it as an alternative to conventional walk-in payment. South Africa, Kenya, Zambia, Tanzania, Malawi, Angola, Nigeria, Botswana, Namibia, Eswatini (formerly Swaziland), Ghana, Uganda, and Ethiopia are among African countries using digital payments for day-to-day goods and services such as water, at a minimum in urban areas. Digital water payments are also promoted in some Asian countries such as Bangladesh, India, and Pakistan.

INNOVATION 7: DECENTRALIZED WATER QUALITY TESTING

CATEGORY

Monitoring/Management

STATUS

Traditional

Commercially available

Advanced

Limited production

Under pilot evaluation

Conceptual

BACKGROUND

Although proactive risk management practices are recommended for all water supplies (World Health Organization 2012), the only way to verify water safety is to conduct regular tests. Even well-protected water supplies can transmit pathogens or harmful chemicals that lead to short- or long-term diseases (Kotloff et al. 2013; Khalil et al. 2018; Chase and Damania 2017; Prüss-Ustün et al. 2019). Monitoring results usually come too late to completely prevent exposure, but they can help managers detect vulnerabilities in the system and protect consumers from further exposures.

National governments often specify minimum test requirements and acceptable methods for large water supply systems, but these fail to translate to small and self-supply systems (Peletz et al. 2016). Temporal and spatial monitoring data resolution poses a challenge, as many water contamination events are intermittent. Water quality testing programs should be integrated into each water supply's ongoing operation and maintenance, focusing initially on near-term risks such as microbial contamination that can lead to acute illness and mortality. Ideally, water monitoring programs would also assess long-term risks, for example from bioaccumulative and carcinogenic substances. To avoid wasted labor and spending, data collection and follow-up steps need to be tailored to address actionable questions that managers might have about how to best manage the water system.

SOLUTIONS

Water quality monitoring activities can be performed either in the field (in situ with sensors or onsite with portable equipment) or in a laboratory (samples collected and transported offsite for analysis; Figure 21). Sensors (Innovation 8) perform simple, automated tests, detecting signals such as turbine rotations (for water flow), the electrical potential of water around a probe (for pH), or light scattering (for turbidity). They are limited to a fairly small range of water quality parameters.

Field-based water quality monitoring equipment may consist of simple test strips, "color disc" kits that use manual preparation steps and visual comparison (color matching) to determine parameter concentrations, or handheld digital instruments. These methods require human operation, adequate supplies, and periodic calibration; however, most field tests can be completed at the water system sampling point within minutes. Portable (e.g., suitcase) versions of laboratory setups offer more capabilities (e.g., filtration, incubation, microscopy), but also require more time, surface space, and procedural intricacy. Laboratory-based testing procedures can be used to analyze water samples for a wide range of contaminants. These may require larger and more complex instruments, energy, temperature control, sterile conditions, or less-stable chemical reagents.

Testing procedures for different water quality parameters may be grouped into acceptability (e.g., taste, odor), physical (e.g., color, turbidity, suspended solids), chemical (e.g., heavy metals, chlorine, conductivity, pH), microbiological (e.g., total coliforms, fecal coliforms, *E. coli*), and radiological (radionuclides) aspects (WHO 2017b). Dissolved contaminants, or "dissolved solids", include any minerals, salts, metals, or ions dissolved in water. Suspended solids (including clay, algae, silt, organic debris, and bacteria) make water turbid. Turbidity measures scattering or blocking of light transmitted through water. High turbidity itself may not pose adverse health risks depending on the type of suspended solids; however, the solids may interfere with disinfection, for instance by consuming chlorine, harboring pathogens, or blocking UV light.

Microbiological culture (growth-based) methods assess proxies for fecal exposure with visible counts, chromogenic, or fluorogenic substrates; these exclude viable but non-culturable organisms (Rompré et al. 2002). Molecular detection methods include immunological, polymerase chain reaction (PCR), and in-situ hybridization techniques. The gold standard for microbiological tests at present is quantitative polymerase chain reaction (qPCR) to assess the quantity of a given microorganism's DNA in a sample, although this approach also detects non-viable microorganisms (e.g., those inactivated by disinfection).

While water quality monitoring methods are well-established and common in urban water systems, this activity is often deprioritized in rural and under-resourced settings due to the lack of central oversight, poor governance, and inadequate facilities, funds, or capacity. Thus, the technology itself is less of a hindrance than facilitating its application (Peletz et al. 2018). Appropriate, user-friendly high-technology solutions may in part help to overcome distance, capacity, and cost barriers. Management arrangements such as "water quality assurance funds," which reduce the financial risks of urban laboratories offering testing services (Press-Williams et al. 2021), may also help to move the needle toward more efficient and informative testing arrangements that serve rural populations (also see companion report, *Financial Innovations for Rural Water Supply in Low-Resource Settings*).

PROS

- While putting systems in place to provide ongoing water quality monitoring might seem challenging, many decentralized testing procedures are **fairly uncomplicated.** With some support and training, even private homeowners and part-time rural operators can be empowered to test basic water quality parameters.
- **Low-cost, rapid tests** are available to evaluate certain water quality parameters quickly, cost-efficiently, and with greater regularity.
- Laboratory certification programs and water quality testing by third parties (e.g., for regulatory compliance or public health surveillance) can **increase accountability** and trust in the water supply.

CONS

- Water quality testing moderately increases operational **costs** to cover equipment, labor, and supplies.
- Some water quality parameters, such as turbidity, chlorine, and fecal indicator bacteria, only represent **proxies** for the likelihood of fecal contamination in a given water supply, and their interpretation may require additional evidence (Mraz et al. 2021). Measuring the actual microorganisms that pose a health concern or analyzing disease surveillance data remain more costly and complicated than is possible in many rural or low-resource settings.
- Only relatively simple water quality tests can feasibly be performed in **remote areas**. For advanced tests, samples often need to be transported or shipped.
- Water quality test results are usually **delayed** given the sample processing time. Testing should be paired with proactive steps (such as sanitary inspections or water safety plans) to ensure adequate barriers are in place to prevent contamination.
- Basic competencies, including **quality assurance and quality control** measures, must be built into water quality monitoring and data sharing systems.

EXAMPLES

In low-resource areas, hydrogen sulfide tests have been used to test for bacteria associated with mammalian intestinal flora (Saha and Thomas 2016). They detect formation of a black precipitate with iron, but the method is susceptible to false positives from other bacteria.

E. coli is the most recommended indicator of fecal contamination, suggestive of the presence of fecal contamination and the probable presence of pathogenic microorganisms (Motlagh and Yang 2019). Lab tests using membrane filtration work by drawing water (usually 100 mL) through a filter with gravity or vacuum suction, and then transferring the filter to a Petri dish that contains a growth medium specifically designed for growing coliforms. It is somewhat time-consuming, typically requiring setup of a clean area, preparation of growth media, 24–48 hours of incubation, and manual or automated reading. Field testing can be achieved with portable equipment, using lightweight incubators, pre-prepared growth media (e.g., 3M™ Petrifilm™, Hardy Diagnostics/ Nissui Pharmaceutical CompactDry™ plates; Figure 20), or even body heat incubation (where electricity is unavailable) to grow bacteria overnight (Nam et al. 2014).

Another approved lab technique for enumerating *E. coli* in water is the "most probable number" method. It uses statistical methods to estimate the number of bacteria in 100-mL samples based on color change (e.g., within a set of bottles or a grid of small wells for the heat-sealed IDEXX Quanti-Tray® system), with no need to count small bacterial colonies. For field testing, the Aquagenx compartment bag test (a most probable number method; Figure 21) is becoming popular among civil society organizations around the world. A proprietary growth medium is added to a 100 mL sample, which is then added to a specially designed compartment bag and incubated for 20–48 hours. The total coliform count can be enumerated under UV light, while the color change in the compartments of the bag under ambient light correspond to the number of *E. coli*.

- Low-resource rural areas may benefit from **centralized arrangements** rather than onsite monitoring services, although financial instruments and agreements to incentivize larger, certified laboratories from nearby urban areas to offer testing services in rural areas must be in place (Press-Williams et al. 2021).

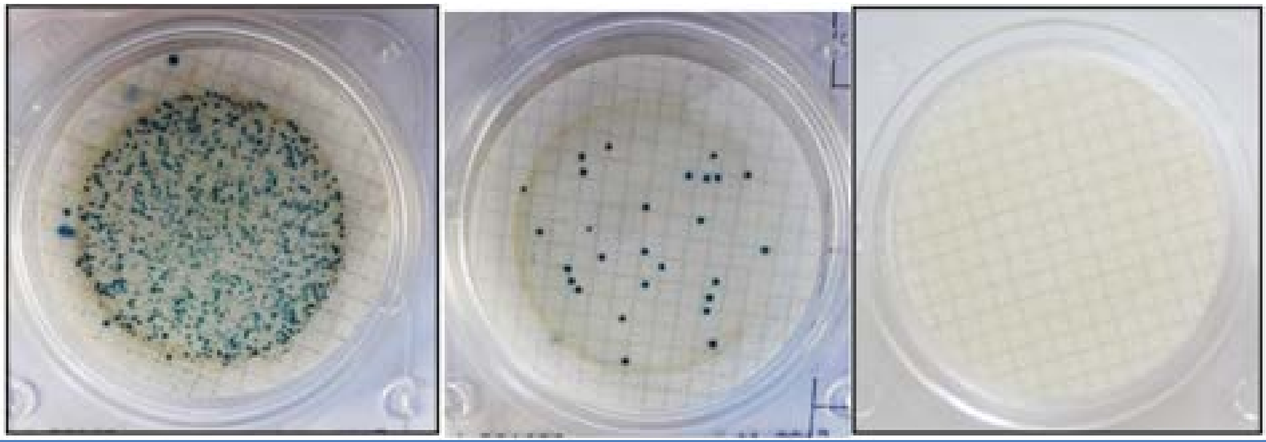


Figure 20. Post-incubation CompactDry plates filtered from a 100-mL water sample showing (from left to right) high, moderate, and no countable fecal indicator bacteria levels. Blue circles show *E. coli* colonies (Source: (UNICEF 2017)

Figure 21. Water sample added to an Aquagenx compartment bag (Source: Engineering for Change)

A few other priority pollutants, such as arsenic (Figure 22) and fluoride, can also be measured in the field, although improvement is needed, particularly for detecting difference arsenic forms. Test strip methods for arsenic testing are generally considered only semi-quantitative (Rajakovic and Rajakovic-Ognjanovic 2018; Reddy et al. 2020)chemical and biogeochemical processes and condition of the environment, various arsenic species can be present in water. Water soluble arsenic species existing in natural water are inorganic arsenic (iAs and generate mercury waste. One company, AquAffirm, is piloting a rapid, enzyme-based arsenic test in Mexico and Bangladesh (Zainzinger 2019) that does not generate mercury waste. Its technology works similarly to a finger-prick glucose test for diabetes monitoring. For fluoride, both test strips and ion-selective probes can be used for field testing (e.g., Hach; YSI, a Xylem brand). Test strips and field colorimetric kits are also commonly used to measure approximate ranges of total and free chlorine (i.e., chlorine that has not yet reacted with contaminants or is still "free" for disinfection).

Figure 22. An arsenic colorimetric test applied to harvested rainwater helped to trace its contamination to dust from mining opertions in Bolivia (Source: Riley Mulhern, Engineering for Change)

Cutting Edge: Many innovative bacterial detection methods are developed for biotechnology applications, although relatively few have been taken up as for widespread drinking water monitoring (Rompré et al. 2002). UNICEF launched a standing challenge in 2016 for innovators to develop methods with same-day results that match a Target Product Profile (UNICEF 2019). Advances from may ultimately aid the supply market for rapid and more accurate pathogen testing of water samples, especially as the COVID-19 pandemic has expanded the market and pushed some formerly lab-based techniques into the realm of field use.

TThe FISH technique using oligonucleotide probes (which seek specific DNA segments) promises quantitative data in 6–8 hours but requires additional research effort (Rompré et al. 2002). A microfluidic device ("lab on a chip") that uses a genetically engineered bacteriophage to identify E. coli within 5.5 hours is being researched for field-based water quality monitoring in low-resource settings (Alonzo et al. 2022). Tryptophan-like fluorescence detects microbial activity without reagents or culturing, and showed promise as a precautionary indicator of fecal contamination for groundwater in Zambia (Sorensen et al. 2015). WaterScope is developing a rapid (<2 hours), low-cost bacterial test using a small, battery-powered microscope, which can detect and quantify individual bacterial cells. Finally, Fluidion has developed both a compact, in situ analyzer and a portable laboratory for optically quantifying E. coli based on absorbance and fluorescence within 2–14 hours.

Akvo Caddisfly and mWater have been working to directly link common water quality test kit hardware with smartphone data systems for ease of access and tracking.

STAGE OF DEVELOPMENT

Water quality testing is common in urban water utilities and government and university laboratories throughout the world. However, remote and field-based monitoring approaches with low costs and high replicability are still required for rural, low-resource areas. This will require major shifts in public accountability, technological and managerial design, and local capacity building.

STATUS

Traditional water quality tests are commercially available. Advanced methods are largely in the conceptual research or limited production phase, with implementation spearheaded by high-income, urban utilities.

MARKETABILITY

Although it performed well in ideal conditions, an earlier "Aquatest" effort to scale-up fecal contamination diagnostic methods for resource-poor settings faced commercialization challenges due the small sizes of developing world markets (Rahman, Khush, and Gundry 2010; Brown, Bir, and Bain 2020). In contrast, burgeoning demand for the Aquagenx compartment bag test suggests the market for simple-yet-effective microbial test methods is expanding. More side-by-side comparisons of new field water quality tests with existing laboratory methods could increase confidence and buy-in among potential users and decision makers.

SCALE OF DISSEMINATION

While in global use in urban settings, water quality testing is often limited to a few parameters or nonexistent in rural areas of low-income countries. Since 2000, many national governments (e.g., Sierra Leone) are increasingly sampling water quality for representative surveys in rural areas, as influenced by the JMP's Multiple Indicator Cluster Survey program (JMP 2020, 2020; Bain et al. 2021).

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INNOVATION 8: SENSORS

CATEGORY

Monitoring/Management

STATUS

Limited production

BACKGROUND

Monitoring activities provide valuable feedback to support sustainable, safely managed water supplies (World Health Organization and International Water Association 2009). In particular, monitoring can verify water system functionality, quality, and quantity:

- **Functionality:** At a minimum, daily flow data would help to verify that a community or customer is receiving drinking water. Foster et al. (2020) estimated that one-quarter of all handpumps in the world are broken at any given time. This statistic has shown moderate improvement over time, albeit not nearly enough progress to achieve sustainable water access for all (Thomson 2021). Capturing and transmitting data about breakdowns could allow managers to respond more quickly, if skilled technicians, funds, and spare parts are readily available (Greaves 2022).

- **Quality:** Ensuring that water is safe to drink requires testing for microbial contamination (or a proxy indicator) and priority chemicals. To verify water disinfection, residual chlorine concentrations need to be monitored to verify the treatment is benefitting consumers at the point of consumption. Other parameters such as turbidity, conductivity, pH, and pressure levels may provide valuable information for water supply operations and maintenance.

- **Quantity:** To ensure sustainable groundwater management, long-term monitoring of groundwater levels (when the pumps are off and water returns to the water table level) can help to demonstrate that the aquifer is not being over-drafted, or if increased recharge is needed to replenish it. Monitoring the groundwater level while the pump is on also provides important data about the functionality of the borehole and verifies the pump's suitability for the aquifer.

Monitoring a large number of water systems across expansive areas is challenging, though. When monitoring depends on trained personnel, there can be delays in receiving data, different monitoring practices, and in some situations a lack of transparency and reliability. In many locations, it is difficult to find and train skilled, local technicians to collect and report water monitoring data. In addition, equipment, transportation, and laboratory costs can quickly become unaffordable when serving a dispersed population.

SOLUTIONS

Automated monitoring of water system functionality (including remote handpumps) may offer a pathway to extend water security while reducing the redundant labor burden on field technicians, lab technicians, and managers. An estimated 200 million people in Sub-Saharan Africa rely on handpumps as their main water source (Danert 2022). Using remote water system monitoring to inform handpump maintenance deployment offers potential for widespread improvement of water security in cases where speed or consistency of information is the primary barrier. Sensors can also be used to understand consumption patterns, identify overused or congested handpumps, and support performance-based payment systems (e.g., McNicholl et al. 2019).

The most basic sensors can assess energy use and flow, for example using electrical current on mechanized pumps (Fankhauser et al. 2022). Commonly available sensors measure groundwater depth and water quality parameters such as pH, temperature, oxidation-reduction potential, dissolved oxygen, turbidity, total organic carbon, or conductivity (Thomas et al. 2018). More advanced sensor technology, which can collect water samples, add reagents, process camera images, and generally mimic simple laboratory processes, is advancing the potential to measure crucial water quality parameters such as fecal indicator bacteria (Bedell et al. 2020; Sorensen et al. 2021).

Sensor monitoring systems include both field sensors and a data logger; many also have a data transmitter connected to a central database (Thomas et al. 2018). The data logger collects the data from the sensors, either through a wired or wireless (e.g., WiFi or LoRa) connection. Because only a limited amount of data can be stored and transmitted, data loggers might organize and reduce the data. For example, they may sum the amount of water passing the sensor in a day or tally hours of the day that water was flowing. The data are then stored locally for collection or transmitted at regular intervals to a database, either via a cellular or satellite modem or (if the system is attached to the internet) through an internet modem or router. In the absence of a data transmitter, a field operator can visit and collect data via wired or wireless download. At the receiving end of remote data transmitters, an online dashboard presents these data so that water suppliers in the field or a central office can easily interpret and act upon them.

Importantly, interpreting automated data collection and data processing outputs will always require some level of human interpretation to confirm meaning and avoid bias. Qualitative data collection methods such as surveys, ethnographies, and direct observation can add context to more continuous and objective electronic data (Andres et al. 2018).

PROS

- In piped systems, sensors that collect information about water flow or volumes can be used to **identify when pumps have failed or pipe breaks have occurred,** potentially reducing downtime (Thomas et al. 2021).
- Handpump sensors that report both stroke number and water volumes can be used to detect pump problems and perform maintenance to **prevent failure**.
- **Telecommunications infrastructure can be leveraged** to support sensor data transmission, with cellular coverage reaching 93% of Africa's land area in 2015 (Thomson 2021). GSM (cellular) modems can transmit sufficient amounts of data to capture daily flow and water quality. Satellite systems such as Iridium or Swarm have much smaller packets of data transfer packets (36 bytes) than cellular packets (1,000 bytes), but are accessible in most places where cellular networks are not available.
- When paired with robust analysis, sensor data enable more accurate asset mapping and management. They can **drive accountability** through timely understanding of what equipment is working, where, and who is responsible. However, the data has to be accessible and understandable, and active processes need to be in place to clarify and incentivize good service performance, including dedicated funding for operation and maintenance.

CONS

- Depending on the water system characteristics (e.g., size, remoteness, alternative monitoring methods), sensor monitoring may **add to operating costs**, from additional sensor installation, data capture, and data analysis activities.
- **Energy is required** to power the sensor and data storage equipment.
- An organized service provider and **efficient maintenance system** (including accountability, funding, equipment, and skilled technicians) must be in place locally to translate sensor data on water system failures into quicker repairs.
- Sensor or **data transmission failures** can obfuscate true water system downtime.
- Remote sensing and data transmission equipment can be damaged or stolen, requiring some **security** and maintenance measures.
- Most **advanced water quality** tests (including most pathogen and chemical analyses) still require water sampling and laboratory processing (see Innovation 7).
- Sensor data alone is **often insufficient** to improve local water system maintenance, without an externally subsidized maintenance scheme.

EXAMPLES

Virridy (formerly SweetSense) has installed thousands of handpump and borehole sensors to monitor water supplies serving more than three million people in East Africa (Figure 17). Their sensor relies on solar-power generation with a satellite modem to transmit the collected data. On large electrical borehole systems, Virridy demonstrated that sensor data could be used to support operation and maintenance by local water agencies (Thomas et al. 2021). Sensor data was also extended to forecast groundwater demand in concert with the Kenya National Drought Management Authority and the Famine Early Warning Systems Network (Fankhauser et al. 2022; Thomas et al. 2020). Virridy similarly demonstrated that handpump sensors supported improved functionality in Rwanda (Nagel et al. 2015), but they are more prone to vandalism when installed in remote areas (Kathuni 2022). Water user committees had a limited capacity to perform water system repairs, and government-funded repair teams faced similar problems.

Figure 17. A satellite-enabled Virridy remote handpump sensor, mounted in green casing (Source: Virridy)

The non-governmental organization charity: water developed four generations of handpump sensors, which have been deployed since 2015 in several countries, including Ethiopia, Nepal, Ghana, and Malawi. The sensors fit onto existing, unmodified handpumps, which are widely used in rural settings (Figure 18). They detect both water volume and the number of strokes. The design includes a battery with a reported 10-year lifespan and a cellular modem without a breakable external antenna. Via the global telecom network, data are transferred using Amazon Web Services to a convenient dashboard for stakeholders to view. If the stroke number per volume of water increases, this data can indicate that the pump seals are wearing out and warrant sending a repair team (Gorder 2022).

Figure 18. Handpump equipped with an integrated remote sensor (in black casing) developed by charity: water (Source: Hazel & Pine and Esther Havens)

The Fundifix and University of Oxford's handle-stroke sensor used successfully to reduce handpump downtime in Kenya is being trialed in Bangladesh in collaboration with UNICEF (Dahmm et al. 2018). The focus of their predictive-failure trial is to further shift handpump downtimes from an average of three days to zero, to prevent users from reverting to unsafe water sources and suffering health impacts. The *WellDone*® Mobile Monitor (MoMo) custom-built sensor collects handpump information including activity and performance metrics. The Aquaya Institute, Everflow, and Stanford University are investigating its use in Uganda.

Coupling improved handpump design with sensor data collection can make pumps more suitable for remote locations where regular maintenance visits are challenging. In partnership with World Vision, Design Outreach has been re-engineering an older handpump design since 2012, in the lab and field in several African countries (Chisenga et al. 2021). Their LifePump is able to go much deeper than other handpump designs (100–150 m belowground) and data collected via their LifePumpLink system on the SonSet Solutions platform confirm its high reliability. This data has been essential to providing evidence to support official adoption of the pump design in Malawi and Zambia. The LifePumpLink system is also being integrated into national government strategies, such as Zambia's Sustainable Operation and Maintenance Project.

Water Mission works with sensors for piped water systems. In collaboration with SonSet solutions and IBM jStart, they developed a remote sensing system (called the SatWater Communicator; Figure 19) that enables reception of real-time data from any type of sensor, such as flow rate, groundwater level, or pressure. The communicator transmits data from anywhere in the world to a web-based data alert and analysis dashboard called the "Monitoring and Alerting Platform." At present, this system transmits data via the GlobalStar satellite network, but Water Mission expects to have cellular-based transmission available in 2022. Approximately 350 SatWater Communicators have been deployed in 15 countries. Water Mission has also installed groundwater-level sensors in 40 locations. With UNICEF funding, they expect to install an additional 90 sensors in 8 different countries.

Figure 19. Water Mission SatWater Communicator connected to a pulse water meter in a pumphouse (Source: Water Mission)

CUTTING EDGE: One demonstration of an advanced prototype sensor for fecal indicator bacteria using tryptophan-like fluorescence (light emitted from substances associated with bacterial activity) showed a fast processing time (near real time) with no need for reagents or incubation (Bedell et al. 2020). It does not replace traditional bacterial count methods, but was capable of distinguishing among microbial risk levels.

Mobile phone systems enabling human customers to effectively report the types of data collected by sensors, through a "missed" phone call or text message, has also been piloted for water services in Africa by SeeSaw and Mobile for Water, a collaboration among Makerere University, the Ugandan Ministry of Water and Environment, IRC, WaterAid and SNV.

STAGE OF DEVELOPMENT

Sensors for automated monitoring continue to show technical potential and have been the subject of intensive research over the last decade, with several teams engaged in iterative rounds of development. Piloting and scale-up is starting to happen, but uptake has been relatively uneven across geographies and dependent on wider contextual factors. In most cases, supporting maintenance funding schemes are necessary to make sensor data actionable.

STATUS

Limited production

MARKETABILITY

Sensors have two distinct purposes, which may require different product tailoring:

1. Operational sensors (the "minimum viable product") for providing essential information to maximize service uptime, while being inexpensive and robust enough for use at scale; and
2. Sensors that incrementally improve understanding of the water supply system, e.g., user behavior, user choices, types of malfunctions, seasonal fluctuations, water quality, and longer-term trends.

A 2022 learning forum convened innovators working on remote sensing technologies for use in rural water supply (Greaves 2022). It revealed that technology scale-up is occurring, but it is hindered by some factors:

- Water flow or volume sensors are only helpful when the community, organization, or enterprise has the capacity to respond. This includes personnel training and compensation, transportation to go to the sites or onsite capacity, available parts and tool to make the repairs, and a systematic, clear process for evaluating the problem and making the necessary repairs (e.g., checklists).
- Remote sensor technology still needs market incentive and development to reduce costs and increase stability and reliability when manufactured and deployed at scale.

Large urban water systems have led sensor integration into water supply systems, which may not directly translate to good performance in low-income rural areas. Affordable, low-maintenance sensors are still needed to ascertain chlorine levels, as well as other water quality parameters. To reduce operational costs while assuring water quality standards, Water Mission is investigating installation of remote monitoring sensors for continuous chlorine, turbidity, and conductivity measurements. Chlorine concentration measurements, for example, are frequently taken at different points along urban water distribution systems to verify the water maintains a sufficient free chlorine residual. Maintaining adequate disinfection in remote and rural communities would similarly benefit from verification efforts (see Innovation 2: Community-scale disinfection).

SCALE OF DISSEMINATION

Remote water supply monitoring has penetrated much of Africa, as well as parts of Asia, Latin America and the Caribbean, and Central and South America. Virridy has remotely reporting sensor systems in Ethiopia, Uganda, Kenya, Rwanda, Sierra Leone, and Nigeria. They promote broad use of remote monitoring technologies for large-scale water suppliers, but only sample-based monitoring of handpumps, given the unit economics. charity: water has remote monitoring systems in Bangladesh, Burkina Faso, Cambodia, Central African Republic, Cote D'Ivoire, Ethiopia, India, Kenya, Laos, Madagascar, Malawi, Mali, Mozambique, Nepal, Niger, Rwanda, Senegal, Sierra Leone, Tanzania, Uganda, and Zimbabwe. Design Outreach has had their pump design and remote monitoring system approved by the governments of Malawi and Zambia; the system has also been used on pumps in Mali, Central African Republic, South Sudan, Kenya, Ethiopia, Zimbabwe, Haiti, and Guatemala. Water Mission has remote monitoring systems in 15 countries: Bahamas, Burundi, Ethiopia, Guatemala, Haiti, Honduras, Indonesia, Kenya, Liberia, Malawi, Mexico, Peru, Puerto Rico, Tanzania, and Uganda.

INNOVATION 9: DIGITAL MANAGEMENT APPLICATIONS

CATEGORY

Monitoring/Management

STATUS

Commercially available

BACKGROUND

Rural drinking water supply managers, often volunteers from the community, may engage in varying degrees of system monitoring or keep no or severely outdated system records. Depending on monitoring locations, frequencies, and storage approaches, data may be discontinuous, cover only a few (most accessible) points in the network, or be archived locally (e.g., on paper). Thus, it becomes difficult to efficiently access and analyze data, or equitably prioritize needed actions. Objective data for decision-making may increase the ability to take corrective actions quickly after water supply failures. Inaction leads to wasted public funds, and negatively affects the socioeconomic condition of rural families (Jal Javeen Mission 2021).

Some key challenges facing rural water suppliers include:

- Efficiently identifying routine issues (e.g., pump failures, insufficient water quantity or quality, hidden leakages, inadequate pressure, consumer complaints, unexplained spikes in household water use, or unauthorized connections);
- Allocating sufficient resources for system management (e.g., time, number of people, operations and maintenance training, and money spent), given competing priorities;
- Achieving sufficient spatial and temporal resolution and timeliness of data (e.g., to enable alert systems); and
- Understanding longer-term issues that may be on the horizon.

Many countries use geographic information systems (GIS) to digitally map infrastructure (e.g., pumps, pipes, valves, treatment equipment, distribution points). They may collect and transmit data from geotagged sensors (see Innovation 8) through information dashboards, which allow continuous monitoring of even dispersed water systems by a single person in real time. Mapping and geo-coding of water supply schemes can enable rich, dynamic visualization of water sources, hazards in the watershed, and water service areas. Growth in wireless networks and cloud technology has bolstered data storage, sharing, and conservation of computational resources, offering several key advantages to these efforts. Individual water suppliers no longer need to purchase their own high-performing computer server. In addition, the reliability of technology has improved and the chances of system failure have decreased, as data backup and software upgrades take place centrally, rather than facility by facility.

SOLUTIONS

Digitalizing data from water supply ecosystems and infrastructure could address challenges and accelerate adaptive management in rural areas. Over the last decade, digital mapping and sensing systems for water supplies have become increasingly sophisticated. The earliest version of digital infrastructure systems was Supervisory Control and Data Acquisition (SCADA), whereby networked sensors collect data and regulate automated functions such as chemical dosing and pump functions. Next came the IoT, with low-energy sensors connected over a wireless network. The most futuristic technology, at present used mainly in urban water systems, is called "digital twins": a complete virtual reality of the current environment, with advanced levels of information that facilitate prediction and simulation of different scenarios.

SUPERVISORY CONTROL AND DATA ACQUISITION

SCADA systems emerged in the mid-20th century to continuously monitor, manage, maintain, and control infrastructure systems, including water and wastewater treatment plants. It allows for remote monitoring and control (e.g., valve opening and closing through a virtual command) of the water distribution system as well as collecting information on various parameters such as flow, pressure, and water quality.

Originally, SCADA systems were housed on the premises, which required a costly server and onsite tech support (Sagues 2018). Real-time data was collected and analyzed by a single, powerful, onsite computer that issued alerts to operators and enabled them to turn valves and machinery on and off as needed. The SCADA system helped water managers increase overall efficiency, keep a proper maintenance schedule, and assess historical data to optimize water production timing. With the general shift toward cloud computing, modern "SCADA+" internet systems rely on cloud-based IoT platforms. Authorized individuals can operate a modern SCADA+ system from anywhere by installing the software on their desktop or laptop.

INTERNET OF THINGS (IOT)

As infrastructure systems have increased in size and complexity and physical distances between devices have expanded, the labor, costs, and computational power required to manage and maintain infrastructure also grew. IoT, a system of a collection of devices or sensors connected to a cloud-based server, offers a "smart" way to obtain real-time information on the ground with minimal human interaction. Sensors provide data, while transformative data analysis offers valuable insights to adaptively manage systems and better meet service standards. Because

IoT systems entail a significant reduction in computational costs, they have increasingly been accompanied by AI-based tools to detect and analyze patterns in the data and more adaptively manage water systems, something that was not possible with first-generation SCADA systems.

Importantly, IoT systems allow for data interoperability and can thus synthesize data from different sources or types of sensors, even including integration with social media. Because data are stored on the cloud, they can be accessed from anywhere through a mobile phone or laptop. Reduction in sensor costs as well as expansion of mobile and wireless networks have further opened opportunities to adopt IoT technologies in low- and middle-income countries.

DIGITAL TWINS

"Digital twins" are part of the evolving digital transformation, providing a virtual graphic representation of actual water systems. They evolved in applications such as the nuclear and aerospace industry, where experimenting with complex systems was expensive and/or risky, and high-end simulations of physical systems were necessary to make decisions. These dynamic simulation models change continuously using the data received from SCADA or IoT sensors and meters (Conejos Fuertes et al. 2020). In a water distribution network, a detailed digital twin enables the user to have a holistic view of the entire supply system using linked real-time data.

Digital twins are designed to monitor, control, and optimize the functioning of the water distribution system, but they also serve as a decision support system allowing the user to perform what-if analyses and simulate risks and failures. They can be used to make predictions and weigh the consequences of alternative future scenarios.

EXAMPLES

In India, many urban and some rural water authorities have adopted SCADA technology for managing their existing water distribution networks and infrastructures (Smart Utilities 2021), including the Delhi Jal Board, Bangalore Water Supply and Sewerage Board, Ahmedabad Smart City, Vijayawada Municipal Corporation, and many cities in Maharashtra State. A district in West Bengal was the first rural water supply scheme where the Public Health and Engineering Department implemented SCADA for arsenic-prone areas (Dutta 2007). Jorhat district in the state of Assam introduced SCADA to efficiently manage and operate the entire rural drinking water supply system. SCADA systems using the "Mitsubishi Adroit Process Suite" are widely used in South Africa, including for remote and rural areas (Adroit Technologies, n.d.).

IoT systems are being adopted in various sectors around the globe. Handpump monitoring is a prime area of development for sensor-based IoT systems in Africa and Asia (Tan 2020). In India, the National Jal Jeevan Mission suggested that states use IoT-based platforms with indigenously made sensors for water service delivery monitoring (Figure 23). The use of IoT systems in rural water delivery systems align with the Govt. of India's "Smart Village" initiative and Atmanirbhar Bharat Abhiyaan or "Self-reliant India" campaign.

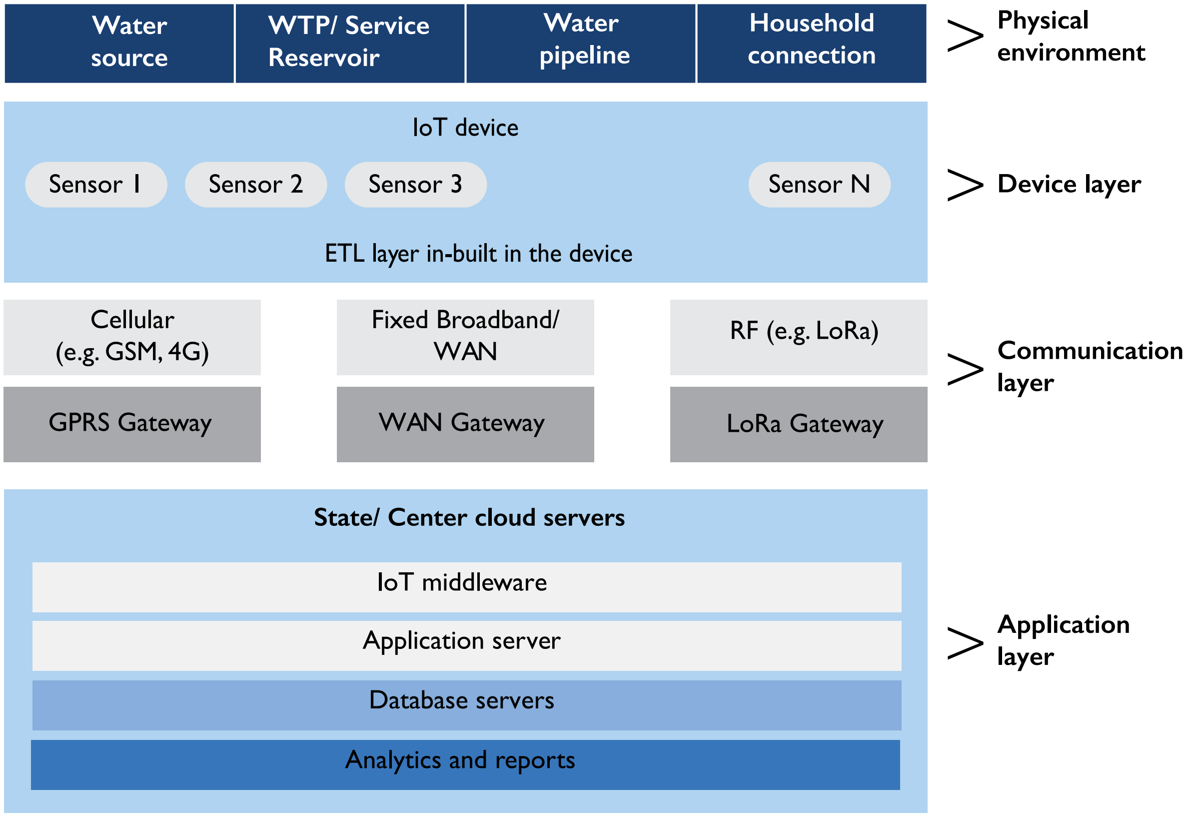

Figure 23. Internet of things architecture proposed under the Jal Jeevan Mission of India (Source: Ministry of Jal Shakti, Department of Drinking Water & Sanitation). ETL = extract, transform, and load; GPRS = General Packet Radio Service; GSM = Global System for Mobile Communications; IoT = Internet of things; LoRa = long range; RF = radio frequency; WAN = wide area network; WTP = water treatment plant.

Digital twin technology has largely been applied for urban systems, and many private companies offer digital twin services to improve system efficiency and asset management. In the Indian State of Assam, the government employed a digitized water supply system to improve the water distribution, water quality, and water pressure for northern cities covered by the Guwahati and Dibrugarh Water Supply Project, using technology from Bentley Systems.

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Many private companies are providing customized solutions for digital mapping and maintenance of urban water systems. Some are specifically tailored for rural and small water utilities in high-income countries, and may eventually become more widely applied in low- and middle-income countries. Examples include:

- Campbell Scientific systems for rural water monitoring and control
- Esri Water Utility for Small and Rural Systems
- Digital Water Works

Although the data are not necessarily directly communicated with water systems, several organizationsw provide rural water supply data collection, visualization, storage, and analysis services in various stages of development (Boulenouar and Lockwood 2020). These include:

- Akvo Foundation
- mWater
- Rural Water and Sanitation Information System (SIASAR)
- Uptime Catalyst Facility
- Water Point Data Exchange (WPdx)
- The Aquaya Institute's Project W

PROS

- Moving from manual to digital management systems enables **timely monitoring and analysis** of water quality and quantity issues.
- Data on the quantity of water produced and consumed can help water suppliers become more **environmentally conscious** and work toward resource conservation goals.
- Alert mechanisms and control systems can help improve efficiency of water supply schemes, **reducing downtime.**

CONS

- Rural water suppliers must be **trained** to properly use digital technologies and work proactively toward ensuring safe water.
- The **initial investment** in setting up digital mapping of rural water supply systems can be high and require substantial staff capacity building.
- Sensors, data storage, and user interfaces **consume energy,** either locally or on a remote server.
- Overreliance on digitalization may result in a **loss of local intuition** and understanding of the system.

- Newer tools **automate key functions**, reducing the requirement of advanced technical training for rural operators.
- **Data compilation** can detect non-revenue water loss, predict equipment maintenance needs, estimate demand from historic water usage, and identify inequities.
- Digitally-enabled water supply infrastructure could aid **evidence-informed policymaking**. Budding versions of digitalization (e.g., digital twins) have predictive capabilities that may help to anticipate and address future challenges, such as climate change.

- It can be challenging to maintain **reliable service** in some remote or rural areas; power outages or network issues can cause system outages.
- Data anomalies (e.g., due to outages) may not be immediately and properly recognized, triggering **spurious responses** from the IoT system.
- Intermittent water supplies (those that deliver water for only part of the day) require **tailored algorithm development.**
- Some off-the-shelf software solutions cannot be easily **customized** to local conditions (e.g., software systems that assume continuous pressurized piped supply perform poorly in intermittent supply situations).
- There may be challenges related to unique social settings in rural communities. If human understanding of social structures is not adequately integrated, **systemic discrimination** (e.g., marginalization of communities historically relegated to the outskirts of villages) may be reinforced by digitalization.

STAGE OF DEVELOPMENT

STATUS

Digital management applications for rural water supply are viable, but in limited commercial application at present.

MARKETABILITY

Digital management applications are on the rise among urban water suppliers, with a smaller portion of the market producing specialized products for remote, rural, and low-resource settings.

SCALE OF DISSEMINATION

SCADA systems are used in different parts of the world, including many Asian countries.

Sensors linked with data processing and visualization interfaces (as described in Innovation 8) represents one type of IoT for rural water systems. For example, charity: water is coupling handpump sensors with predictive algorithms to trigger repairs in Asian and African countries (Tan 2020). IoT is being set up in different states of India under the Jal Jeevan Mission as a pilot for village drinking water supply schemes. IoT is also increasingly used in South Africa, although mainly in the urban areas (Kotzé and Coetzee 2019).

Digital twin technology has not yet been adapted to water supply schemes in rural areas. It is employed in many high-income countries around the world; major water providers using it include Toronto Water and the Regional Municipality of York in Canada, the Municipality of Linköping in Sweden, Sydney Water in Australia, and Newcastle in the United Kingdom. Other adoption examples come from China, Brazil, South Africa, India, and Portugal.

COMMERCIALIZATION AND UPTAKE OF INNOVATIONS

Rogers' 1962 Theory of Diffusion of Innovation, now in its fifth edition, carried a seminal explanation of the social science surrounding the spread of new ideas and technologies (Rogers 2003). The theory purports that most people look to their social peers before adopting new ideas, and therefore spread circulates outward into larger social circles until reaching critical mass and ultimately winning over those who resist change ("laggards"). Adopters fit under a bell curve, with the majority somewhere in the middle, while market share increases at a faster rate following mass adoption and eventually levels off at full saturation. "Innovators" fall at the left (earliest) portion of the spectrum, and typically have greater social status and financial resources, making them more risk tolerant.

Similar models further dissected human acceptance of innovations related to perceptions, attitudes, experience, personal characteristics, social norms, and intentions. These include the Technology Acceptance Model, extending from the Theory of Reasoned Action, and the Unified Theory of Acceptance and Use of Technology (Alshammari 2020). In addition, many behavior change models have been adapted to specifically understand uptake of water and sanitation interventions (Dreibelbis et al. 2013). These often acknowledge multiple dimensions (e.g., context, psychosocial factors, and the technology itself) operating on multiple levels (e.g., larger governance structure, community, household, and individual).

In the parallel domain of evidence-informed clinical healthcare interventions, the fields of dissemination and implementation research refocused attention on active promotion of innovations, rather than passive diffusion (Green et al. 2009). Implementation research programs, such as REAL-Water, seek to systematically understand the implementation context, identify barriers to implementation of evidence-informed practices, and match these to strategies that should ultimately bring about performance improvement (Haque and Freeman 2021; Setty et al. 2019).

For example, Rouillard et al. (2016) specifically examined urban water governance factors that support innovation uptake, including committing to compromise, building political support, and having active "entrepreneurs" and coalitions. Factors needed to create a broader sociopolitical (and financial) "enabling environment" for rural water supply, such as regulations that protect consumers, adequate local operation and maintenance budgets, and professional licensing, may differ among countries (e.g., Machado et al. 2019). Similarly, common "building blocks" of sustainable service delivery across rural areas include alternative management models, cost-recovery accounting, and performance monitoring (Smits and Lockwood 2015).

General theories of innovation uptake are harder to apply to low-income rural development, as these efforts differ from private profit-focused marketing of technology. Work in development applications to move large numbers of consumers to become middle class consumers of emerging "no-frills" or reduced complexity technology markets has been coined "frugal innovation" (Wehn and Montalvo 2018). Advocates suggest steps can be taken before, after, or throughout the innovation process that may lead to more environmentally sound, high quality, and affordable products, services, and systems for resource-constrained populations. Still, innovation for development markets is fraught with persistent challenges, including tracing the social responsibility of low-cost suppliers and stimulating user demand.

One commentary on the WASH innovation ecosystem found it to be "reasonably coherent," although tending to encourage incremental rather than more radical innovations (Rush and Marshall 2015). Other challenges are shifting priority from more charismatic (e.g., water supply) to less-alluring (e.g., sanitation) topics, and from front-end technology investment to ongoing adoption support. Further, coordination efforts may be haphazard and exclude newer or unfamiliar actors, such as local stakeholders. Given greater challenges, rigorous research programs may fall by the wayside or lack incentive, especially if the topic is no longer considered novel (Haque and Freeman 2021). At a macro level, Wehn and Montalvo (2018) taxonomized water innovation research by its type, stage, and level of analysis. They recommend additional study of water supply and demand sides, innovation support systems, and the unique dynamics introduced by rapid information and communications technology advances.

...targeted investments by public actors (e.g., government or civil society) often precede establishment of an initial market, which can in turn demonstrate potential for return on private investment.

Throughout this report, we observe that targeted investments by public actors (e.g., government or civil society) often precede establishment of an initial market, which can in turn demonstrate potential for return on private investment. For example, UNICEF offers a sure market for rapid water quality tests that meet certain cost and performance criteria (UNICEF 2019). Another example, recognizing the importance of handpump technology scale-up in rural community water supply, is shown in Box 2. A global evaluation of water supply–related patents between 1990 and 2016 showed a number of diverse countries have contributed to innovation, led by Korea, the United States, and Germany (Leflaive, Krieble, and Smythe 2020). The markets for each innovation category featured in this report will vary across world regions, countries, and localities. Thus, one surety is that individual technology scale-up efforts must be carefully and regularly adapted to the users, setting, and context in question.

One surety is that individual technology scale-up efforts must be carefully and regularly adapted to the users, setting, and context in question.

BOX 2. HOW DO SOCIAL GOOD TECHNOLOGIES SCALE IN LOW-RESOURCE SETTINGS? EXAMPLE OF HANDPUMPS IN BANGLADESH

Around 1975, the private sector was not involved in providing rural water or sanitation services in Bangladesh (Robinson and Paul 2000). Initial installation of UNICEF's "Number 6" handpumps (simple suction handpumps well-suited to extract the country's prominent shallow groundwater) was carried out by the public sector. Their low cost and simple installation quickly drove up demand, and private manufacturers and traders began to take interest. By 2020, more than 65% of handpump tube wells had been installed by private operators. Versions of the handpump, spare parts, and repair services are now available from a number of competitive suppliers throughout Bangladesh. Factors that encouraged private sector participation included: removal of pricing restrictions, low start-up costs, market competition among a range of products and services, and network building among private suppliers.

CONCLUSIONS

SUMMARY AND RECOMMENDATIONS

The pros and cons of each technological innovation are summarized side-by-side in Table 5. Each category of innovation was also plotted approximately along Rogers' Diffusion of Innovations curve (Figure 24), to demonstrate their differing degrees of adoption. All hold promise for improving rural water supply efforts in low-resource settings. At the same time, technology will continue to benefit from additional research and development, supplier competition, and marketing to address drawbacks and awaken new possibilities. **Effective long-term application of these technologies relies on local institutions to create a supportive enabling environment (e.g., governance, finance, maintenance capacity) while encouraging scale-up.** Appropriate and functional service delivery models and coordination mechanisms among public and private sector actors must be in place for water supply innovations to provide lasting benefits.

TABLE 5. OVERVIEW OF TECHNOLOGICAL INNOVATION PROS AND CONS

Innovations	Pros	Cons
Solar Pumps	• Enable mechanized water pumping, treatment, and storage in areas with unreliable electricity access and expensive fuel supplies • Reduce carbon emissions and other environmental impacts, such as air pollution, associated with mechanized water systems • Reduce water supply vulnerabilities during natural disasters that affect electrical grids and fuel supply chains	• Complex engineering and technical requirements for solar pump installation and maintenance • Reduced performance during overcast and rainy conditions • High installation costs that can reduce the affordability of water services • Risk of theft
Community-scale disinfection	• Effective at treating many types of microbial contamination • Relatively low cost	• Taste and odor of treated water is objectionable in some settings • Disinfection is less effective in highly turbid waters

	• May provide residual protection for stored water	• Quality and consistency of commercially available chlorine consumables vary • Works better when coupled with safe household transport and storage
Membrane filtration	• No or minimal energy requirements • Relatively few operational and maintenance requirements for microfiltration and ultrafiltration systems • Small physical footprints • Effective for removing a broad range of contaminants	• High procurement costs • Tendencies to foul under certain water quality conditions • Regular backwashing is needed to maintain membranes • Higher maintenance costs, training, and electrical supplies for more advanced nanofiltration systems
Reverse osmosis	• Effectively treats hard-to-remove contaminants • Rapid advances are improving technical efficiencies, lowering costs, and reducing energy requirements	• High energy requirements • Requires high technical capacities to operate and maintain systems • "Rejected" water requires careful disposal to minimize environmental contamination
Smart water meters	• Accurate, real-time data on water consumption for suppliers and consumers • Support efficient billing systems • Facilitate detection of water losses (e.g., leaks and pipe breaks)	• Reliance on telecommunication systems that are prone to disruptions in low-resource settings • Best suited for piped water supplies • High upfront costs
Digital payments	• Greater convenience for both consumers and water suppliers • Lower fee collection costs for suppliers • Options for prepayment	• Consumers require training to use connected devices • Low-income assistance programs must be available • Cybersecurity risks

Decentralized water quality testing	• Increasing availability of low-cost and simple technologies for both field-based and laboratory testing of water supplies • Better data for informing management priorities and apprising consumers about water quality	• Data collection has to be linked to effective systems for evaluating and responding to water quality information • Ongoing testing costs may exceed available operational budgets
Sensors	• Real-time functionality data for both piped and community water point sources • Enable asset monitoring and accountability post-installation	• High costs and technically challenging to implement at scale • Requires reliable energy supplies • Requires water system personnel with capacity to maintain system, and monitor and respond to data
Digital management applications	• Ability to link sensors directly to automated controls (e.g., alarms, pumps, chemical dosers) • Improved data for management (e.g., demand estimates, non-revenue water reduction) • Increased operational efficiencies	• High upfront financial investments • Requires reliable energy supplies • Requires water system personnel with capacities for monitoring and responding to electronic data and alarms

Water suppliers will most likely continue to benefit from **incremental uptake** of technology improvements, as financial resources continue to substantially limit service development around the globe. Free or subsidized water services have commonly been implemented in underserved areas, although most literature points to setting **achievable price points** and cost-sharing as the most feasible paths forward (Cook, Fuente, and Whittington 2020). Expectations of free water decrease the value users place on it and impair management and conservation efforts that serve public wellbeing. Low consumer valuation translates to more difficulty recovering costs, which limits non-essential maintenance, service improvements, expansions, and investments in increasing efficiency. Even in high-income areas, water suppliers may struggle to gain the political will to build lifecycle costs, incremental safety improvements, and externalities into user fees. Improving services may increase willingness-to-pay to pay for water if the benefits are clear and well communicated, even as ceilings remain for affordability. Advanced water supply technologies can ultimately help to conserve water or reduce long-term spending and unexpected risks; these potential financial advantages (outside of increased user fees) should be considered in cost-benefit analyses and decision-making.

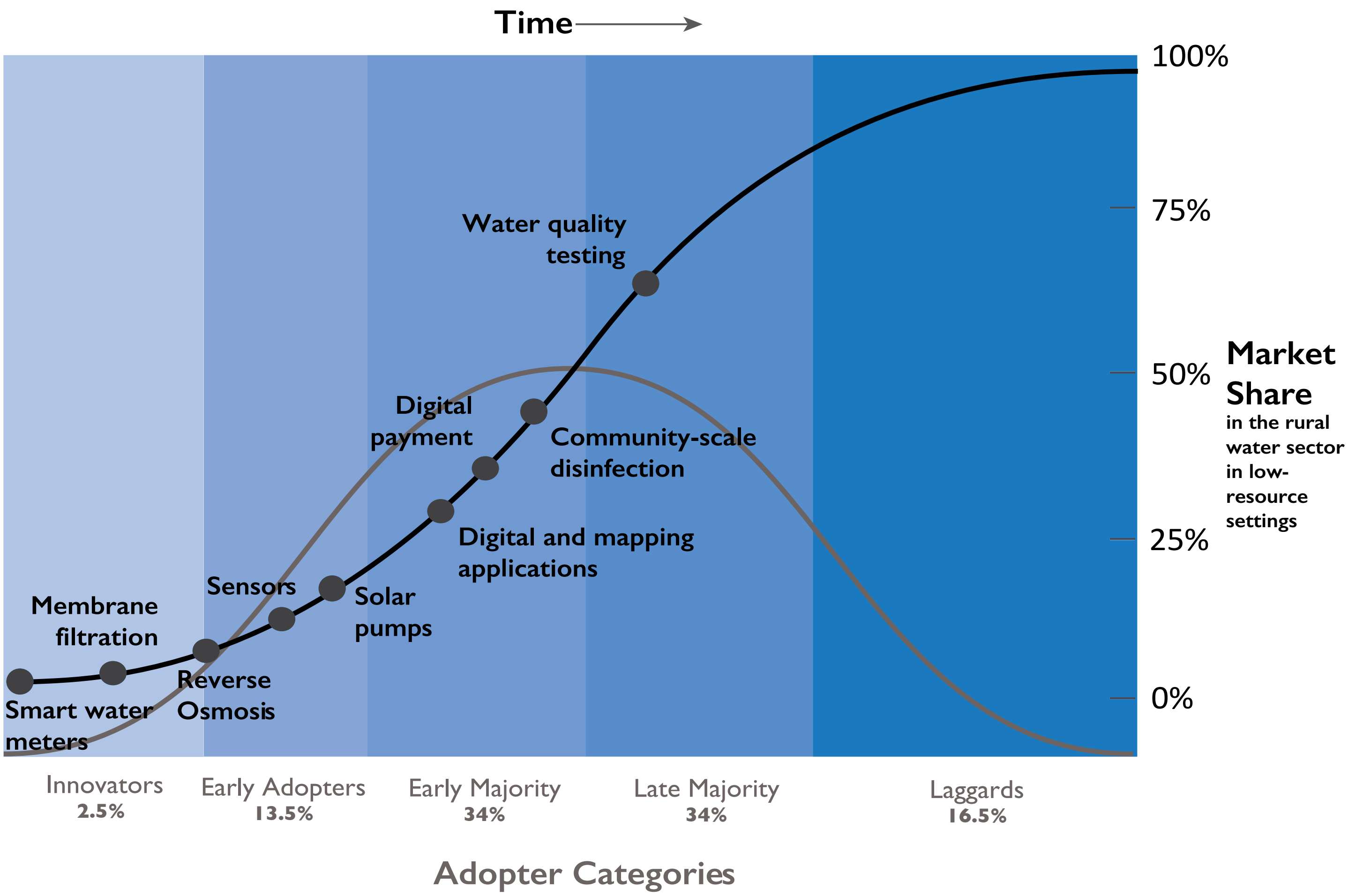

Figure 24. Approximate relative positions of each technology on a diffusion of innovation curve (adapted from Rogers 2003), as applicable to the "market share," in this case the estimated portion of water supplies in rural areas of low- and middle-income countries that stand to benefit (Source: The Aquaya Institute).

Figure notes: This diagram is generalized to a global scale; results differ by geography. In addition, full market saturation is not necessarily a goal for all technologies, as the optimal suite of water supply solutions will depend on local context.

Whenever a new technology is introduced, the potential for eventual **failure** must be considered. Actionable monitoring programs and decision support systems can help to enhance timeliness of feedback and data visibility, sustain functionality of equipment, and increase longer-term accountability among donors, implementers, service providers, governments, and beneficiaries (Thomas and Brown 2021). Ideally, monitoring data collection, processing, and delivery systems would be built into the technology itself, require minimal manual burden, or have sustainable financial mechanisms to support its continuation. As recommended in the proactive Water Safety Planning approach (World Health Organization 2012; WHO 2017a), specifying clear thresholds for action and the steps to be taken would help decision-makers to translate data into appropriate remediation activities.

Specifying clear thresholds for action and the steps to be taken would help decision-makers to translate data into appropriate remediation activities.

In terms of **prioritizing** implementation and dissemination, the local context, stakeholder needs, and financial feasibility must be considered foremost. More broadly, low-risk, high-impact technologies such as community-scale disinfection (Figure 25) could be considered low-hanging fruit. "Risk" may stem from financial investment, technological complexity, potential for breakdown or theft, loss of reputation, or other factors. "Impact" represents additional access to safe water for otherwise unserved or underserved populations. High-risk, high-impact technologies, such as reverse osmosis, may make the most sense in areas where other water supply options are constrained or have failed. Low-risk, low-impact technologies such as decentralized water quality testing should not be disregarded; when backed by effective financing and water supply management efforts (e.g., water quality assurance funds), they can potentially push remaining swaths of the population over the safe water adoption hump and move the needle closer to universal access. Low-impact, high-risk technologies, such as smart telemetry systems, may benefit from redesign to further reduce costs and improve resilience.

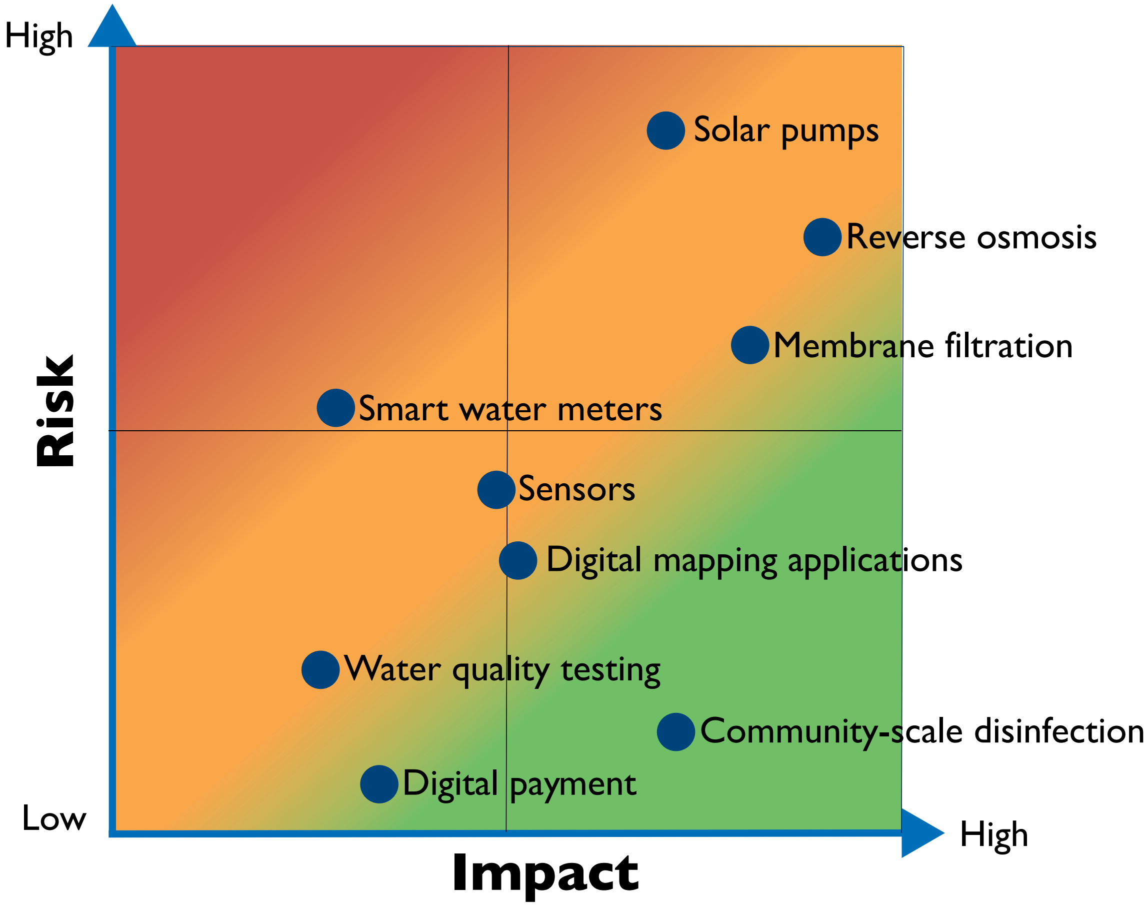

Figure 25. Approximate grid positions of each rural water supply technology category, depending on its generalized risk (e.g., financial, technological, physical) and impact (i.e., water service improvements for low-resource rural settings) (Source: The Aquaya Institute).

Figure notes: Placement of each innovation topic is subjective and aggregated at a global level. The REAL-Water program welcomes ongoing input as to missing or differing future priorities.

LIMITATIONS

Many of the aforementioned technologies have begun in high-income, urban settings, which may not translate well to marketability and effectiveness in low-income settings. Rolling out new technologies in practice may be fraught with difficulty, and even the best-planned products and services may suffer from low acceptability, poor timing, or slow spread. In many cases, water supply infrastructure requires a large startup investment and is difficult to retrofit or relocate. This makes it challenging for providers to quickly pivot their services (e.g., handpump location, treatment method) to keep up with changes in population, demand, supply, or emerging water quality issues. Water supply technologies are continuing to shift toward the goal of **community-engaged, ecologically sustainable** engineering approaches that inform whole-life design (Ashley and Cashman 2006). Technologies and roll-out strategies must then be locally validated and adapted in practice as needs change.

Digital mapping applicaitons

Many **techniques and tools** have emerged in recent years to help promoters actively disseminate rather than await passive diffusion of innovations (Green et al. 2009). These include user-centered design (IDEO 2015), translational research methods such as implementation or improvement science (Setty et al. 2019; Haque and Freeman 2021), and hybrid social and commercial marketing strategies (van der Kerk et al. 2019). These techniques require ongoing resources to support, mainly in the form of basic training, follow-up work effort, and inputs from targeted participants; however, they represent fairly low-cost, low-tech techniques that can help to promote and carry out high-tech interventions. Some organizations (e.g., KickStart International, UNICEF) emphasize design and marketing specifically for low-income rural populations. Implementation cycles alternating observation of and adjustment of approaches, as they are piloted in new contexts, can help to improve long-term outcomes (Setty et al. 2019).

CATALOG OF SERVICE PROVIDERS

Table 6 compiles a number of service providers referenced in this report. For additional information on rural water service providers and available technologies, also see the RWSN directory (Deal, Furey, and Naughton 2021) and the online Engineering for Change Solutions Library. The WASH Innovation Hub compiles innovative service providers in India (ASCI 2022).

TABLE 6. RURAL WATER TECHNOLOGY PROVIDERS

CATEGORY/SECTION	ORGANIZATION	WEBSITE
Solar Pumps, Digital Payments, Community-Scale Disinfection	Grundfos	https://www.grundfos.com
Solar Pumps	LORENTZ	https://www.lorentz.de
Solar Pumps, Digital Payments	Practica Foundation	https://www.practica.org
Solar Pumps, Digital Payments	Project Maji	https://www.projectmaji.org
Community-Scale Disinfection	Population Services International WaterGuard	https://www.psi.org/practice-area/wash
Community-Scale Disinfection	Aquatabs	https://www.aquatabs.com
Community-Scale Disinfection	P&G Purifier of Water	https://csdw.org/pg-purifier-of-water-packets
Community-Scale Disinfection	Saha Global	https://sahaglobal.org
Community-Scale Disinfection, Sensors, Digital Management Applications	Water Mission	https://watermission.org/equipping
Community-Scale Disinfection	Dosatron	https://www.dosatron.com
Community-Scale Disinfection	LMI	https://www.lmipumps.com
Community-Scale Disinfection	Pentair Aquatic Eco-Systems	https://pentairaes.com
Community-Scale Disinfection	Milton Roy	https://www.miltonroy.com
Community-Scale Disinfection	Cantaro Azul	http://en.cantaroazul.org
Community-Scale Disinfection	Davis & Shirtliff	https://www.davisandshirtliff.com
Community-Scale Disinfection	EaSol Private Limited	http://www.easol.in
Community-Scale Disinfection	Water4	https://water4.org
Community-Scale Disinfection	Mountain Safety Research (MSR)	https://www.msrglobalhealth.com
Community-Scale Disinfection	PATH	https://www.path.org
Community-Scale Disinfection	Antenna Foundation	https://antenna.ch/en/activities/water-hygiene
Community-Scale Disinfection	Swiss Bluetec Bridge	https://swissbluetecbridge.ch
Community-Scale Disinfection	Aqua Research	https://aquaresearch.com

Community-Scale Disinfection, Reverse Osmosis, Smart Water Meters, Digital Payments	Safe Water Network	https://safewaternetwork.org
Membrane Filtration	Lifestraw by Vestergaard	https://lifestraw.com
Membrane Filtration	Wateroam	https://www.wateroam.com
Membrane Filtration	SkyJuice Foundation	https://skyjuice.org.au
Membrane Filtration	Aqua-Cura	http://www.aqua-cura.co.za
Membrane Filtration	Healing Waters International	https://healingwaters.org
Reverse Osmosis	SOPAR-Bala Vikasa	https://sopar.ca
Reverse Osmosis	Naandi Community Water Services	https://www.danonecommunities.com/naandi-community-water-services
Reverse Osmosis	Piramal Sarvajal	https://www.sarvajal.com
Reverse Osmosis	Waterlife India	https://www.waterlifeindia.com/solutions.html
Reverse Osmosis	WaterHealth	https://www.waterhealth.com
Reverse Osmosis	Rite Water Solutions	https://www.ritewater.in
Smart Water Meters	Siemens	https://www.siemens.com
Smart Water Meters	LoRa Alliance®	https://lora-alliance.org
Smart Water Meters	Peltek India	https://www.peltekindia.in
Smart Water Meters	Badger Meter	https://www.badgermeter.com
Smart Water Meters	Kamstrup	https://www.kamstrup.com
Smart Water Meters	Sagemcom	https://www.sagemcom.com
Smart Water Meters	WaterGroup	https://www.watergroup.com.au
Smart Water Meters	CityTaps	https://www.citytaps.org
Smart Water Meters, Digital Payments	Susteq	https://susteq.nl
Digital Payments	DivDat	https://www.divdat.com
Digital Payments	CityBase	https://thecitybase.com
Digital Payments	expressPay	https://expresspaygh.com
Digital Payments	Slydepay	https://www.slydepay.com
Decentralized Water Quality Testing	3M	https://www.3m.com/3M/en_US/food-safety-us/foodandbeveragetests

Decentralized Water Quality Testing	Hardy Diagnostics	https://hardydiagnostics.com
Decentralized Water Quality Testing	IDEXX	https://www.idexx.com/en/water
Decentralized Water Quality Testing	Aquagenx	https://www.aquagenx.com
Decentralized Water Quality Testing	AquAffirm	https://aquaffirm.com
Decentralized Water Quality Testing	Hach	https://www.hach.com
Decentralized Water Quality Testing	YSI, a Xylem brand	https://www.ysi.com
Decentralized Water Quality Testing	WaterScope	https://www.waterscope.org
Decentralized Water Quality Testing	Fluidion	https://www.fluidion.com
Decentralized Water Quality Testing, Digital Management Applications	Akvo Foundation	https://akvo.org
Decentralized Water Quality Testing, Digital Management Applications	mWater	https://www.mwater.co/kits
Sensors, Digital Management Applications	Virridy	https://virridy.com
Sensors, Digital Management Applications	Fundifix	https://fundifix.co.ke
Sensors, Digital Management Applications	Design Outreach	https://doutreach.org
Sensors, Digital Management Applications	SonSet Solutions	https://sonsetlink.org
Sensors, Digital Management Applications	WellDone	https://www.welldone.org
Sensors, Digital Management Applications	SeeSaw	https://express.adobe.com/page/jc8XS9BMUPBae/
Digital Management Applications	Bentley Systems	https://www.bentley.com
Digital Management Applications	Campbell Scientific	https://www.campbellsci.asia/rural-water
Digital Management Applications	Esri	https://www.esri.com/en-us/industries/water-utilities/segments/small-systems
Digital Management Applications	Digital Water Works	https://digitalwaterworks.net

Digital Management Applications	Rural Water and Sanitation Information System (SIASAR)	https://globalsiasar.org
Digital Management Applications	Uptime Catalyst Facility	http://www.uptimewater.com
Digital Management Applications	Water Point Data Exchange (WPdx)	https://www.waterpointdata.org
Digital Management Applications	Project W	https://aquaya.org/project-w
Digital Management Applications	charity: water	https://www.charitywater.org

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