The Citizen Field Engineer: Crowdsourced Maintenance of Connected Water Infrastructure

Scenarios for smart and sustainable water futures in Nairobi, Kenya

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***Abstract*—Sustainable water supply is a profound problem in slums in Nairobi, Kenya. Smart water management that integrates information and communication technology (ICT) to monitor water resources, diagnose problems, improve efficiency and coordinate management can help to overcome supply challenges as well as strengthen public participation in governance. This study applies scenario planning methodology to analyze the potential of a novel smart water concept, Citizen Field Engineer, to address water challenges in Nairobi's slums, for example problems with water pollution and intermittent supply. The concept combines multi-functional sensors to monitor water supply with an innovative ICT-based governance model where residents in the local community are employed as service engineers. Looking at how this concept would apply in Nairobi's slums, the scenario analysis suggests that the concept could potentially help to improve water availability, affordability and quality, including gender equality as women bear the main responsibility for collecting water. The analysis also suggests that an implementation of the concept could have a positive impact on children's school attendance as water related diseases are an important factor behind low educational attainment. The study concludes that smart water management that integrates ICT is an important step to address challenges around sustainable water supply.**

Keywords*—ICT; smart water management; drinking water; sustainability; social impacts; slums; urban development; Nairobi; scenario analysis

I. INTRODUCTION

Sustainable access to safe drinking water is a pressing issue in many cities across the world. Safe drinking water is not only central to human health, but can also help break the vicious circle of poverty, for example by enabling children to stay at school and women to engage in productive work [1]. According to the United Nations Declaration of Human Rights, every person is entitled to sufficient, safe, physically accessible, and affordable water near their home, workplace and school [2]. Although significant progress has been made towards reducing the proportion of people without access to improved water sources, as many as 748 million people still lack access to safe drinking water; nearly half are in sub-Saharan Africa [3].

While urban populations in sub-Saharan Africa tend to have better access to improved water supply compared with rural populations, there are often profound intra-urban disparities in access between different groups [3]. Intra-urban disparities in access are likely to increase as rapid urbanization and climate change pose increasing challenges to the provision of financially and environmentally sustainable water services [4]. Supply challenges are further exacerbated by weak political leadership and poor governance [4][5]. For example, outdated management practices and limited civic participation cause decisions to be made without adequate information, often resulting in poor implementation [6]. Further problems include insufficient and poorly maintained infrastructure and lack of capacity for revenue collection [6]. In Kenya's capital Nairobi, for example, it is estimated that 38 percent of the water is lost due to leakages or are delivered to customers but is not invoiced [7].

The ongoing water crisis in developing countries is commonly referred to as a crisis of governance [8]. As a result, significant attention has been put on the importance of water sector reforms to improve water supply services [9]. In principle, reform policies propagate a shift from government to governance where actors from the state apparatus, private sector and civil society engage in deliberative policy making to improve water supply [10]. Rogers and Hall [11] have proposed six principles for 'good' water governance. The first principle is that management agencies should work in an open manner that can be understood by citizens and that decision making processes should be transparent. The second principle emphasizes the need for broad stakeholder participation. The third principle draws attention to the need for strong leadership and effective political bargaining. The forth principle focuses attention on equity concerns, both inter-generational equity for future generations and intra-generational equity among socio-economic groups, and equity in relation to gender and ethnicity. The fifth principle stresses the need for accountability and the last the importance of efficiency to improve economic performance. Yet, the challenge is how to design and facilitate mutually beneficial partnerships between government, private sector actors and civil society [12].

'Smart water management' that integrates information and communication technology (ICT) to monitor water resources, diagnose problems, improve efficiency and coordinate management can help to overcome challenges to provide every citizen with sustainable water supply [4]. Levering the potential of ICT to strengthen public participation in policy making can further help to improve the provision of social services such as water [13]. Smart water management is increasingly emphasized in many smart city concepts targeting highly developed cities but has not been given sufficient considerations in contexts where water supply challenges are most profound, such as in slums[1] in sub-Saharan Africa. A focus on how smart water management could materialize in this context is increasingly important given the high growth rate in both urbanization and ICT use [14][15].

This study summarizes results from a joint research project between Ericsson and UN-Habitat to explore the use of ICT to support water governance and urban development in Nairobi, Kenya. The study is based on scenario planning and aims to analyze potential social impacts (i.e. residents' access to sustainable water supply and service performance) of a novel concept on water supply in Nairobi's slums. Under the concept, sensors and connected infrastructure are used to improve service performance and water access, and an ICT-based governance model is used to foster collaboration between community and the water service provider as well as to increase cost effectiveness of service delivery. By community we refer to a group of people living in the same geographical area, sharing basic values and organizations [16] in this case from a defined slum area.

With the study, Ericsson and UN-Habitat seek to be at the forefront of exploring the potential of smart water management in the alleviation of global challenges associated with this important resource. Nairobi was chosen as a site for the scenario analysis because of UN-Habitat's physical presence in and extensive knowledge about the city, and because the city experiences severe intra-urban disparities in water access.

The first section describes water governance and challenges with water supply in Nairobi. Following this, the smart water concept, Citizen Field Engineer, is described. We then discuss the scenario planning method used to conduct the analysis. The subsequent section includes two scenarios developed for the Citizen Field Engineer concept where social impacts are elaborated and assesses. We end with a discussion of the broader system dynamics influencing and occurring as a consequence of the imagined implementation and use of the Citizen Field Engineer solution.

II. WATER SUPPLY IN NAIROBI, KENYA

Nairobi is one of the most populous cities in East Africa with over 3.2 million inhabitants [17][18]. Population growth and slum proliferation has challenged the local authority's capacity to provide sustainable water supply to all citizens [18]. Nearly 60 percent of Nairobi's population live in slums where access to safe and affordable drinking water is a profound problem [19].

In slums, frequent leaks and bursts allow pollutants to enter into the water distribution network causing serious problems with water contamination and as a consequence also water-related diseases. The prevalence of such diseases in slum areas decrease children's educational attainment and the number of adults engaged in productive work, especially for women who often care for sick children [1]. Water contamination therefore increases families' health care expenditures, while at the same time decreasing consumption of other vital goods and services [1]. Moreover, water contamination is a central reason behind the high under-5 mortality rate in slums [20].

The frequent leakages cause intermittency in supply and poor water pressure [19]. The water service provider in Nairobi estimates that 38 percent of the water is lost because of leaks, bursts and unauthorized consumption [7]. This translates into a substantial commercial loss hindering new investments in infrastructure and service coverage. Insecurity and intermittency in water availability also leads to challenges related to local price volatility and difficulties of knowing where to find water [6][19]. Women bear the main responsibility for providing their families with water and on bad days collecting water can take several hours [21].

Another key problem is that metered customers in tapped neighborhoods buy water to set tariffs while slum residents often pay much more for an inferior quality water supply [19][22]. They often pay 12.5 times the price that metered customers pay for water [13]. The higher price for water is due to the fact that water supply points in slums are often managed by illegal operators ("water cartels") who are not registered with the water service provider [23]. One estimate indicates that many households may spend up to 20 percent of their income on water [21].

The reasons for poor water supply include (but are not limited to) budget constrains as well as inefficiency in revenue collection, lack of professional tools for monitoring service

[1] A slum is a group of households in an urban area who lack one or more of the following conditions: (1) Durable housing, built in a non-hazardous location and with a structure permanent and adequate enough to protect its inhabitants from the extremes of climatic conditions. (2) Sufficient living area, with no more than three people sharing the same room. (3) Access to improved water, a sufficient amount of water for family use, at an affordable price, available to household members without being subject to extreme effort, especially on the part of women and children. (4) Access to sanitation, an excreta disposal system, either in the form of a private toilet or a public toilet shared with a reasonable number of people. (5) Secure tenure, the right of all individuals and groups to effective protection against forced evictions [17].

performance, limited communication between residents and management entities, and underutilization of civil participation [6][19][24]. Keeping up with demand from population growth in Nairobi's slums is another challenge [18].

Improving the efficiency and quality of piped water delivery, while at the same time expanding water services, is therefore a key priority for city authorities and the water service provider. This includes the daunting task of improving the condition of the existing distribution network, putting in place mechanisms for managing frequent leaks, and installing incentives for new investments in water infrastructure and services [19].

III. THE CITIZEN FIELD ENGINEER

The smart water concept, Citizen Field Engineer (described below), was developed by researchers at Ericsson and UN-Habitat through a human-centered design and innovation process [25]. This is a user-driven approach to the development of new products, services, or processes based on the study of users (including their needs and behaviors) [25]. A special emphasis is placed on desirability (i.e. what do people need and desire), feasibility (i.e. what is technically and organizationally feasible) and viability (what can be financially viable). One central practice in human-centered design is to integrate design and assessment methods, and thereby enable the developed solutions to evolve based on real-world impacts [25]. Emphasis is put on desirability rather than feasibility and viability. However, the concept is a valuable tool to stimulate concrete discussions of how to design and implement a real-world solution in the right way.

The work to develop the concept is a response to the need for sustainable water supply and the potential to support urban sustainable development with the help of ICT. The concept draws on ideas of urban computing, which consider the ways in which new technologies enable and disrupt feelings of community and belonging, create new places, reappropriate urban infrastructure and influence navigation and movement within cities [26]. It was also inspired by Lanfranchi and colleagues' [27] citizen observatories approach in which a small number of traditional, high-cost and high-maintenance sensors are supplemented by a large number of cheap sensors, supported by citizens to measure water flow and water levels.

The Citizen Field Engineer builds on the idea of using sensor networks to monitor water supply and water quality, but also applies an innovative, crowd sourced governance model where citizens perform maintenance tasks to minimize costs for service delivery, while generating income. Under the concept, existing pipes, meters and access points are connected with sensors to measure service performance (supply, flows and leakage) and environmental data (contamination). Citizen field engineers (i.e. trained residents from local communities) are automatically notified upon the need for maintenance and are remunerated via a mobile money service. By using local skills rather than technicians employed by the water service provider, who often lack system knowledge and may experience personal safety risks when entering the slums, the concept seeks to lower operational costs for service delivery and improve infrastructure maintenance. Promoting participatory governance the Citizen Field Engineer also aims to develop social capital as well as to stimulate a mutual responsibility for public commons and water resources.

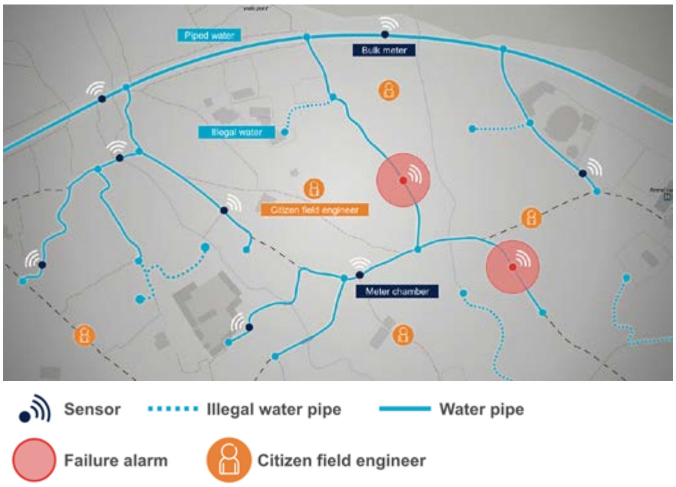

Figure 1: Illustration of the Citizen Field Engineer concept applied on a generic map over a water distribution network in a slum area. The illustration is a derivative of the OpenStreetMap. Copyright: OpenStreetMap contributors.

The following actions are enabled by the Citizen Field Engineer ecosystem:

1) Connected water meters provide real-time data on water supply through measurements of flow and pressure.

2) Environmental sensors placed in strategic locations in the water network provide real-time data on water quality.

3) The data is stored in a cloud service that enables different presentation formats in web and mobile applications.

4) Any failure or need for maintenance is automatically detected and reported to the water service provider.

5) Failures can be reported manually by residents through a smartphone app, mobile phone text message, or other mobile service.

6) Depending on the complexity, work tasks are sent out to registered citizen field engineers near the failure, either manually or automatically.

7) When a field engineer has performed a work task a payment is transferred via a mobile payment service.

Figure 2: Illustration of a sensor sending out a failure alarm and a citizen field engineer receiving the alarm in his mobile phone. This illustration is a derivative of the original image (https://www.flickr.com/photos/khym54/54584738) by kmym54, used under the CC BY license.

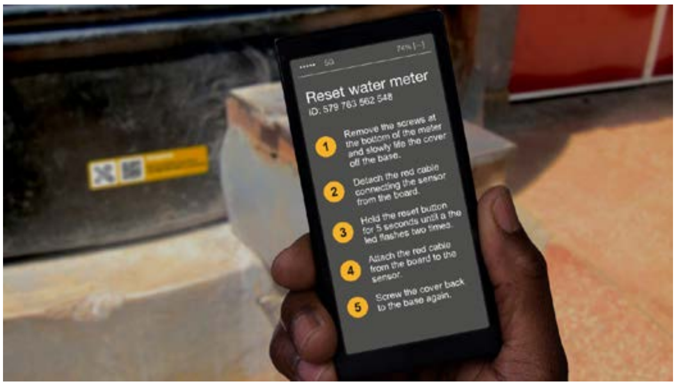

Figure 3: Illustration of a work task description received by a citizen field engineer upon accepting the work task.

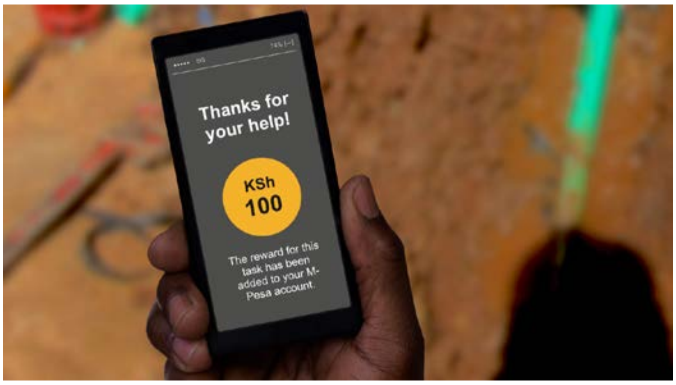

Figure 4: Illustration of a citizen field engineer receiving a payment for a completed work task through a mobile payment service.

IV. Methods

To analyze potential social impacts of the Citizen Field Engineer we used a scenario planning approach [28]. Two contrasting scenarios for the implementation of the Citizen Field Engineer in a slum in Nairobi were developed.

Scenario planning is a systematic method for creatively analyzing complex futures [28]. Each scenario tells an internally consistent and plausible narrative about how the future may unfold (in ways both good and bad) based on existing conditions and processes, as well as potential future ones [29]. Scenarios describe contrasting futures that could be rather than futures that will be, focusing on central uncertainties in the system and relationships between environmental factors, management choices and system dynamics [30]. Given the multiple uncertainties facing water governance and the implementation of smart water solutions, scenario building is a method to improve our systemic understanding of future possibilities, including risks, challenges and opportunities. Insights can then be used to inform strategic planning processes and to identify robust strategies with greater potential to advance governance towards more preferable futures [31].

Below follows a brief description of the six steps used for developing the two scenarios for the Citizen Field Engineer:

Step 1: Analysis of the current system

A literature study was conducted to learn about and analyze the current water governance system in Nairobi's slums as well as to identify central stakeholders (institutions, organizations and people of relevance to water governance). Existing studies on water supply often focus on Kibera [23][32][33], which is Nairobi's largest slum, and the scenarios were developed with reference to this particular site. However, it has to be emphasized that slums exhibit many commonalities in terms of existing and emerging challenges. Background information upon which the scenarios were created is explained in *Section 2*.

Step 2: Selection of indicators

To structure the scenario analysis we identified a set of indicators that the scenarios could be built around and by which the sustainability potential of the concept could be evaluated (i.e. the potential of the Citizen Field Engineer to improve sustainable access to water in slums and service performance of the water service provider).

The indicators where derived from the literature study and are listed below:

Sustainable water access indicators:[2]

- **Safe water** (bacterial organisms per ml water)
  Water must be free from harmful substances that could jeopardize human health.
- **Accessible Water** (time needed to fetch fresh water. Water facilities must be within appropriate physical reach, approximately 2 km, and in a secure location.
- **Affordable Water** (price of water per liter).
  Price should not exceed 3 percent of household income/reduce households' ability to acquire other goods and services needed for an appropriate living standard.

Service performance indicators:

- **Non-revenue water**[3]
  The difference between system input volume and billed authorized consumption, for example, unbilled authorized consumption, water theft and metering inaccuracies and real losses due to leaks and bursts.
- **Quality Assurance** (monitoring of service quality with the help of sensors)
  Quality Assurance refers to administrative, technical and procedural activities implemented in a system so that quality requirements for a product or service will be fulfilled.

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[2] Sustainable water access indicators were derived from the Human Right to Water in the UN Declaration of Human Rights for which parameters are well-defined and agreed upon by the international community [2].

[3] The non-revenue water indicator was derived from the Smart Water Networks Forum [27].

Step 3: Qualitative interviewing

Besides the literature review, a number of qualitative interviews were conducted to inform scenario building and analysis [34]. All interviews (n =10) were conducted in Nairobi with water experts from academia, NGOs, international organizations, and the private sector during three weeks in November 2014. Interviews aimed to elicit information on 1) water service delivery, water access and infrastructure in slums, 2) challenges associated with water management and governance, and 3) strategies to improve water services. A number of field visits in slums were conducted to complement qualitative interviewing and to gain contextual knowledge of water supply. In the majority of the interviews, the Citizen Field Engineer visualizations (e.g. Figure 1-4) were used as stimuli material to frame the discussions and exemplify novel ways of applying ICT for water distribution, as well as to enable informants to provide input on the concept. The need for careful security arrangements when visiting the slum areas constrained access to these areas as well as the ability to conduct interviews with slum dwellers. We are aware that the interview sample is biased towards the viewpoints of experts and officials and that this is a serious limitation of the study. Yet, we believe that the study provides an important contribution to the ongoing discussion around smart water management and the complexity of addressing water supply challenges in slums.

Interviews were recorded when informants gave their consent and when filed conditions were conducive to audio-recording. Detailed notes of the interview conversations were taken and clarified and elaborated after the completion of interviews. The interview accounts were systematically analyzed to find regularities in viewpoints and experiences and then organized into two coherent scenario narratives. In the first scenario, we primarily summarized informants' viewpoints on preferable policy changes and community responses that could connect the present to a desirable water future. In the second scenario, we gathered views on undesirable policy changes, imminent risks and negative social trends that would challenge the integration of the concept into the water sector, or risk worsening supply challenges.

Step 4: Identify social trends/drivers and barriers

A next step was to identify important broader social trends that would influence the nature of the future environment within which the water sector operates and thus had to be taken into account in scenario building (i.e. policy/governance, civic participation, urbanization, community cohesion, climate change and technology adaptation). Barriers and drivers were identified using scientific literature and policy reports on water governance and through an exploratory ideation process. Interviewees were asked to elaborate on barriers and drivers for improved water governance.

Step 5: Overall assumptions

To support scenario building, including transparency of the analysis, a set of assumptions were specified. For both scenarios it was assumed that: 1) Smartphone penetration is high and the price of smartphones is significantly lower than today; 2) sensors are economically and technologically viable; 3) sensors and connected infrastructure can monitor water quality and other supply features; and 4) there is an interest from residents in slums to work as citizen field engineers.

Step 6: Development of exploratory scenarios

The next step was to develop two contrasting scenarios linking the combined insights from the literature review and qualitative interviews with the identified barriers and drivers to provide a meaningful framework for the assessment of the selected indicators. The two scenarios aim to cover various aspects and provide a range of plausible alternative paths in into the future. The first scenario describes a desirable future, including needed policy change to reach this future, and the second an undesirable future characterized by challenging social trends and a governance failure. The two scenarios are highly hypothetical and told in the form of narratives.

V. WATER FUTURES

Based on the scenario approach described in the methods section, we developed two alternative scenarios for the integration of the Citizen Field Engineer into water sector governance in Nairobi's slums. Scenarios are described as if implemented at a particular site (modeled on Kibera) in 2020.

A. *Scenario 1: Collaborating towards a sustainable water future*

In Nairobi, increasing problems with waterborne diseases and rising public expenditures on healthcare led to a renewed effort by city authorities to improve the distribution and quality of drinking water in slums. Seen from the perspective of the water provider, a major incentive was to reduce non-revenue water (i.e. the difference between system input volume and billed authorized consumption). This incentive coincided with a growing interest by the water service provider to integrate the benefits of new technologies into management, as well as an interest by tech companies to create new applications and services to support water infrastructure. These developments created a momentum for change and a growing demand for smart water systems by the water provider.

Therefore in this scenario, the water service provider has substantially improved its digital infrastructure and competence. By investing in the Citizen Field Engineer the water service provider saw a chance to decrease the proportion of non-revenue water and improve collaboration with slum communities, two long sought-after results.

Through a carefully planned community participation process, slum residents were involved in the design and implementation of the project. For example, a series of workshops with the stakeholders that make up the water sector in the slum, including informal community leaders, the elected local administration, elected community water oversight committees and special interest groups such as youth, women and disabled people, were held over a longer time period. Care was taken to involve all groups in the process, while still attempting to take into consideration existing formal and informal hierarchies. Through this process, distrust between slum residents and water supplier staff reduced significantly, leading to a better designed intervention. At the same time, technical experts from the water company felt more comfortable to work outside predefined policy silos leading to better designed policies and interventions. This means the implementation of the Citizen Field Engineer is aligned with related social programs and infrastructure investments to cascade positive impacts.The implementation of the crowdsourced infrastructure project means that the water service provider now loses less water due to fewer leaks and illegal connections. By reducing daily water losses by half (=104 000 cubic meters) the water service provider could save an estimated US 9 million annually [7]. Such commercial gains have enabled a series of small investments in improved service coverage and customer support. However, these achievements are intimately linked with forceful efforts to curb corruption and the activities of water cartels. For example, the water service provider has collaborated with Nairobi City County to design and implement a training and employment program for former water cartel members. Such measures were also a requirement from the international donor providing funds for digital skills training. Consequently, the proliferation of illegal water connections and displacement of meters has partly been restrained. As corruption has decreased so has also the price that residents pay for water, leading to a rise in families' disposable income. Nevertheless, water accessibility remains a problem because of rapid slum proliferation meaning that the water service provider needs to cater for an increasing number of people.

The majority of people enrolling in in the citizens' observatory were unemployed or part-time working young adults seeing an opportunity to earn additional income. The participants have been able to continuously develop their competence through dedicated skills training and the contextual learning tools that are part of the solution. In this way, they are well suited to maintain the local water infrastructure and cater for customers.

To create momentum for change, the water service provider shares sensor and crowdsourced data with residents' committees and community-based organizations. The existing residents committees also played an important role in sensitizing local communities about the rationale and advantage of the ICT solution. This means that there is a high level of communication and real-time information sharing between the different public, private and civil society actors involved in water management. Through these knowledge networks and the crowdsourced data, information about water resources and water consumption has been shared more widely. As a consequence local communities are increasingly aware of where to find safe water, as well as how to purify unknown water resources and apply appropriate hygiene practices to avoid health risks.

As water services have improved, peer-pressure to safeguard common water resources has emerged in the local community. The implementation of the Citizen Field Engineer has also installed an impetus for improved accountability and transparency, which makes it increasingly difficult for the water service provider to neglect grievances and maladministration.

Improved water quality has decreased illness and improved school attendance, while at the same time freeing up time for adults, especially women, to engage in productive activities. Families are now less likely to lose their loved ones, especially their young children, to waterborne diseases. Decreased health care expenditures, as well as fair tariffs, mean that families can use their income to consume other vital goods and services. As governance has improved, the time needed to fetch water has become more predictable as access at the nearest water point is more stable. These developments could potentially decrease the total time spent on household activities, further freeing up time to engage in other activities or leisure, especially for women.

To secure the long-term sustainability of the Citizen Field Engineer there is an ongoing effort to only use climate-proof materials and construction methods. This is important as the existing water infrastructure is extremely vulnerable to a changing climate with reoccurring flooding events. Looking to the future, climate adaptation is a key challenge requiring major investments beyond the small-scale investments enabled through the Citizen Field Engineer.

Because of the increasing use of ICT and smart city applications within all industry sectors there is now an international ITU standard on Internet of Things applications regulating data security and integrity issues in public service delivery. In Kenya, this standard is in the process of becoming integrated into the water sector. However, public awareness of privacy issues is still low in the majority of Nairobi's slums.

The below figure summarizes changes in the social impact indicators, as described in scenario 1:

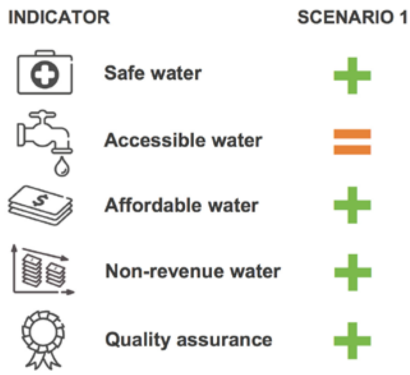

Figure 5: Changes in the social impact indicators.

B. Scenario 2: One step forward, two steps back

In Nairobi, water related issues in slums receive little attention. The focus of the Kenyan government has mainly been on providing sustainable water supply in rural areas. Due to contested land rights in many of Nairobi's slums, formal household water connections are difficult to implement, reducing the willingness to invest in formal water infrastructure. As a consequence there is little positive reinforcement or support for investing in smart water management at the city level. Furthermore, the government's future development plans for the site where the Citizen Field Engineer is being implemented are unclear. The site's location near the Nairobi city center means that the value of the land has increased steadily over the last decade as the market for property development has boomed. The government has therefore considered the prospect of selling the land to a property developer, but a decision on how to develop the area has been postponed to the future. Tenure rights remain insecure and residents worry about the future and the risk of being evicted. Moreover, slum proliferation means that a growing number of people need to share the already limited basic services available. As the government lacks a strategy for dealing with slum proliferation, the severity of the water problem is likely to exacerbate.

By investing in the Citizen Field Engineer the water service provider saw a chance to decrease the proportion of non-revenue water, a long sought result. However, the Citizen Field Engineer was implemented in a top-down fashion, working only with the local administration and selected community leaders. The locally elected water oversight committees and special interest groups were only informed towards the end of the project. Local buy-in is thus limited to a small group of community leaders and the recruited citizen field engineers and many residents look at the ICT solution with skepticism. False promises and failed expectations of previous slum upgrading projects reinforce skepticism. Accordingly, there is little communication of sensor data and collaboration between residents, local organizations and the water service provider. Public awareness of where to find safe water and how to avoid risks associated with unsafe water is still limited.

Due to the lack of a comprehensive community participation process, involving all relevant stakeholders in the community, the enrolled Citizen Field Engineers have started enjoying an elevated position in the slum area. They have been given technical skills and are being paid regularly by the water provider. Social tensions arising as a direct result of the implementation of the solution is therefore starting to emerge.

Despite limited community involvement, the implementation of the Citizen Field Engineer has led to improved monitoring and control as sensors cover a substantial part of the distribution network. However, there is a general lack of action to systematically analyze and tackle water pollution sources. The prevalence of water-related diseases is still high and buying water is a major expense in families' household budget, leaving little room for other investments and savings. Instead, the water service provider has used sensor data to increase surveillance and suppress illegal activity. A common approach has been to shut down or reroute water ways where illegal activity seems to occur. While this has made residents' water supply more intermittent, it has also improved the economic performance of the water service provider. Yet, this form of collective punishment (shutting down and rerouting water) has led to lower levels of trust in the water service provider among residents. Anger over poor service delivery and/or anger over top-down management have resulted in sporadic theft of sensors and vandalism. From this it follows that slum residents are still challenged with substandard and overpriced water supply. In fact, a worsening situation regarding access to affordable water can be observed as illegal activities are more effectively being shut down at the same time as the coverage of authorized water remains the same.

Moreover, due to low levels of local buy-in there is an imminent risk of tampering with the water meters and sensors. The water provider has therefore initiated a program to improve temper resistance to reduce the risk of unauthorized interference in the smart water system.

A complicating factor related to the use of technology is the lack of policies on data security. There is a general distrust of the government's and corporations' use of private information such as the amount of water purchased using a mobile payment service. Due to the rapid technological development experienced in Kenya, many people feel that the government has to review its privacy laws to protect everyone's right not to be subjected to unsanctioned invasion of privacy. Distrust in the existing regulatory framework means that many people are suspicious towards the use of sensor networks to support urban management. This has a negative effect on knowledge sharing and significantly limits innovative practices to spread.

Social tensions, illicit activities and violence in the slum are still widespread, especially in times of water scarcity when people need to compete for water resources. While water scarcity partly reflects a governance failure it also reflects impacts of climate change, both in terms of increasing problems with droughts and flooding events. Flooding events are often also followed by a periodic rise in the number of people infected with waterborne diseases and seriously weaken the water infrastructure. A comprehensive strategy and action plan for climate change adaptation in informal settlements is still missing.

Below is a summary of changes in the social impact indicators, as described in scenario 2:

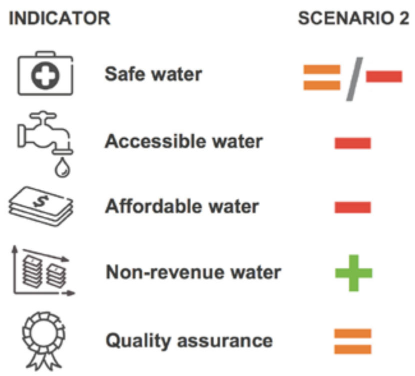

Figure 6: Changes in the social impact indicators.

Table 1: Summary of scenario details

Scenario details	**Scenario 1**	**Scenario 2**
Governance	Collaborative management Sharing of data	Top-down management Limited communication and community involvement
Policy focus/issues	Health/water supply ICT4D Integrated policy	Rural water supply Contested land rights Non-revenue water
Investments	Investments in water infrastructure ICT & digital training	Limited investments in water infrastructure ICT & surveillance
Urbanization	Slum proliferation	Slum proliferation
Climate	Climate proofing	Lack of action plan

change		
Community	Peer-pressure to care for common water resources	Social tensions
Public awareness	Improved	Limited
Data security	ITU standard	Lack of policy/standardization

VI. DISCUSSION

In the following section, we first discuss drivers and barriers for implementing smart water management in Nairobi's slum. We then discuss wider societal impacts of smart water management and the Citizen Field Engineer on human well-being and urban development. However, a more comprehensive understanding of the sustainability potential of the Citizen Field Engineer would require an in-depth assessment of a broader array of social, economic and environmental impacts, including an analysis of impacts outside the use stage. An important aspect of such an analysis would also be to identify risks as well as appropriate means of addressing risks to reduce or mitigate negative impact.

A. Drivers and barriers for positive impact

In relation to smart water management, it is interesting to note that Nairobi is often described as Africa's Silicon Valley - 'Silicon Savannah' - where tech startups have created an important technology hub [36]. Key to the success of these developers is the recognition that while most Kenyans do not own computers, the vast majority of people have access to a mobile phone. While many ICT innovations have been developed to fill the gaps left by poor governance and lack of infrastructure investment, these innovations have become a strong driver for business development and investments [36]. The opportunities for city authorities to tap into these developments to improve management and service delivery are many [37][38].

ICT maturity will strongly influence the type of ICT solutions that can be deployed to improve water supply or other social services [15][38]. Many urban researchers argue low ICT maturity will increase the need for citizen action and innovation. As shown by this study, and supported by other research [38], there is need for a conceptual shift of the debate around urban technologies from large, centralized systems to decentralized, open urban infrastructures that can drive change in a proactive, holistic and collaborative way. This conceptual shift is also important to focus better attention on both the immediate and long-term needs of citizens. While many cities show commonality in terms of underlying challenges, the needs of citizens must be the drivers of the way smart water management evolves. Enabling a dialogue between the city, citizens and businesses and allowing collaborative bottom-up creativity is an important driver for technology adaptation and urban sustainability.

In Kenya, smart water management, as well as other smart city concepts, can gain momentum by actively involving youth. Their entrepreneurial spirit and creativeness is often mentioned as a key asset. Kenyans in the age bracket of 30 years and below constitute about 75 percent of the country's population, thus forming the largest human resource [39]. Their digital competence is often higher than other age groups and mobile connectivity, social media and online communities are becoming important life style factors. Connecting with peers to share resources and responsibilities is an idea that is deeply embedded in many African cultures [40]. Such cultural values to support and share with one's community can be synchronized with the potential of ICT to drive and promote new solutions to persistent problems. This potential of the networked society is especially interesting considering that ICT solutions, such as the Citizen Field Engineer, may create new public spheres bringing new kinds of social interaction and opportunities for social change [41][42]. Such new public spheres may also help to overcome the 'digital divide' by improving ICT literacy and promoting effective and constructive use of the Internet for other democracy enhancing activities [43].

In terms of barriers, low awareness of water-related issues among residents, poor governance [21][24], collaboration difficulties between city authorities and residents [23], climate change impacts [22][44], land rights [23], the digital divide and slow technology adaptation within the water sector [4][15] may all hinder the materialization of the Citizen Field Engineer as well as the implementation and sustainable use of other ICT solutions. Moreover, as policy may be a driver for change it may also be a barrier against change. For example, the lack of policy integration between water and sanitation is a key barrier as inadequate sanitation exacerbates water contamination [3]. While community engagement would be an important driver, aspects such as vandalism, theft and illegal operations by residents are major barriers [19].

Another barrier to smart water management is the widespread but flawed belief that improving service delivery in slums would accelerate urban migration [3]. From this misconception it follows that many governments in sub-Saharan Africa are ambivalent or reluctant towards expanding water, sanitation, health and education services for the increasing number of people living in slums [3].

B. Wider societal impacts

Access to sustainable water supply improves health which opens opportunities for education [1][22]. Education not only empowers people, but also boosts economic development as a prosperous city depends on skilled workers [45]. Educated people are also more likely to apply appropriate health and hygiene practices. For example, it is estimated that under-5 mortality rate would fall by approximately 50 percent if all women in low and lower middle income countries completed secondary education [45]. Besides the potential positive impact of smart water management on education, mobility, broadband and the cloud are playing a pivotal role in improving education. For example, cloud-based ICT solutions, combined with hand-on training in ICT, can improve access to quality education in underserved areas, serve unfulfilled education needs and improve teacher training [46]. Yet affordability and accessibility of ICT remains a serious barrier, calling for coordinated policy efforts at both national and international levels [15].

The lack of accessible, sufficient and affordable clean water hampers productivity. Investments in smart water management would create conducive conditions for entrepreneurship and small-scale business development in slums [1][17]. From a broader perspective, lack of affordable water reduces poor households' consumption of other commodities and services [1], which affects productivity at a city level. Investments in smart water management and infrastructure could also strengthen residents' feeling of being included in society, supporting community cohesion and social stability [17].

In Nairobi, women are the hardest hit by urban poverty [21][24]. Improving water access is an important means to reduce gender inequality as women bear the main responsibility for collecting water and caring for sick family members [1]. However, merely improving access to safe and affordable water is not sufficient to improve gender equality. The voices of women and other vulnerable groups are often the last heard when planning and implementing infrastructure projects as men often act as community representatives [18][22]. This highlights the need to actively include these groups in the process of designing and setting up water services, not only to improve the positive impact of a certain smart water solution, but also to foster an inclusive culture where the voices of marginalized groups are successfully heard and integrated. Yet, including marginalized groups in water governance may be difficult and actively thwarted because of gender stereotypes, traditional beliefs, micro-politics and local power structures [22]. It is therefore interesting to note that a number organizations and governments are increasingly using ICT as a participatory tool to support the integration of marginalized groups, such as women, in urban planning and design processes [47][48].

Supporting community participation in water governance may increase local knowledge of water, instill new values and shift attitudes to change existing forms of environmentally harmful behavior (e.g. vandalism on water pipes or sanitation and hygiene practice). Fostering community participation within an area such as water governance would also be important because of the potential spillover effect to foster civic engagement also within other areas. This is particularly important given that civic engagement is a basis for democracy [49].

VII. CONCLUSIONS

Our experiences of working with water and ICT in the slums of Nairobi highlight the importance of anchoring technical solutions in the local population. Slum residents are often suspicious of outsiders and fiercely protective of their property, rights and income generating activities. In addition, there are also a range of formal and informal structures and hierarchies to consider, including the local administration and politicians as well as informally elected water oversight committees and community groups. Without the buy-in from these types of groups, slum improvement projects often fail.

Therefore, the Citizen Field Engineer, by combining a technical solution with a community-based water maintenance approach, has the potential to improve water supply (both from a customer and service provider perspective) as well as collaborative governance in slums. However, if implemented in the wrong way and failing to consider the existing community structures, it could risk deteriorating the situation. Social impacts of ICT solutions like the Citizen Field Engineer will always reflect, to various degrees, how broader social trends and micro-politics play out. The study therefore concludes that there is a need to look at ICT as part of sociotechnical systems, recognizing the interaction between human behavior, society and its institutions (i.e. informal and formal laws, structures, hierarchies, regulation and norms) and technology. As the two scenarios show, the approach that is taken with regards to human interaction can have widely differing outcomes

The Citizen Field Engineer illustrates how ICT can support a balance between citizen action and city management. In the concept, local knowledge is combined with a technology platform for public and private service provisioning, enabling both local innovation and boundary spanning citywide collaboration. However, the fundamental building blocks in such a platform would have to be flexible enough to serve local needs and opportunities, while at the same time build on common components for efficiency, cost-effectiveness and knowledge sharing beyond the local [38]. The analysis of two alternative water futures provides valuable input and a necessary baseline for the ongoing work to refine and realize both the solution and the required support system.

The potential of ICT to support urban sustainable development, such as citizens' need for fundamental utilities and their ability to influence policy making, is a relevant research field that complements the extensive work around smart cities in highly developed regions (where central utilities are already in place). This focus is increasingly important given that 70 percent of the world's population will live in cities by 2050 and much of the urbanization will take place in emerging economies, which often suffer from poor infrastructure (including ICT infrastructure) and governance [14][15][17].

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