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Sustainability of novel water treatment technologies in developing countries: Lessons learned from research trials on a pilot continuous flow solar water disinfection system in rural Kenya

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ABSTRACT

The transition from laboratory research to pilot scale trials can be challenging for novel water treatment technologies. This transition is even more complex for technologies intended for use in a developing country context due to cultural, infrastructural, financial and capacity related challenges. This research looks at the lessons learned from a pilot installation of a continuous CPC solar water disinfection system in a rural community of Kenya. This project was implemented with local and international partners, however the monitoring and evaluation phase collapsed due to the breakdown of these partnerships. A visit to the project site three years after installation revealed significant problems with the system due to drought and flash flooding. A second project phase was funded through crowdfunding in order to rehabilitate the damaged system and provide an alternative water source for the community during periods of drought. Post project evaluation of both project phases showed that the engagement of local implementing partners is essential for ensuring community participation and effective monitoring and evaluation, as the priorities and presence of international implementing partners can easily change in the medium to long term. More external assistance is required for pilot projects using novel technologies than for those using well-established water treatment systems, particularly in terms of operation and maintenance challenges which may arise in the short to medium term. This requirement for external support significantly impacts the sustainability of these interventions. The performance of the continuous flow system while it was in use was found to be satisfactory and feedback from the community regarding operation of the system and quality of water was positive. Both project phases revealed the need for some small design changes, such as inclusion of air-bleed valves, which would significantly improve system operation for future pilot projects. The project experience also illustrated the need for better understanding of the behaviour of both surface and groundwater, given increasingly unpredictable weather patterns as a result of climate change.

1. Introduction

The transition from laboratory scale research to full scale trials for new water treatment technologies can be challenging. This transition can be complicated further if the technology is intended for use and requires trials in a developing country context, where issues such as cultural preferences, poor infrastructure, financial constraints and insufficient capacity are often present. The history of water treatment projects in developing countries over the past number of decades has shown significant problems with regard to sustainability (Nauges and Whittington, 2010; Esposto, 2009; McConville and Mihelcic, 2007), even when well-established systems are employed, and this paper aims to put some focus on the particular challenges faced when attempting to trial a new

water treatment technology for use in developing countries.

Water treatment methods are often categorised as either household water treatment (HWT) or community water treatment systems. HWT (also called point of use treatment) has been promoted extensively over recent years as the most appropriate way to deal with the issue of contaminated drinking water in developing countries, particularly in rural environments. It can be a good option for relatively small quantities of water transported by hand from a contaminated source and when community resources are insufficient for a central system (UNICEF et al., 2012). The extent of reported household water treatment in low and middle income countries is high, with 33% of households or 1.1 billion people treating their drinking water at home (Rosa and Clasen, 2010). One limitation of HWT is that it does not address issues of water supply,

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which is frequently the main problem faced by communities, particularly in arid regions. Community based water treatment methods often address supply issues more comprehensively than HWT. Such decentralised systems can be appropriate when a water source, even though it may be somewhat contaminated, is able to serve a larger population than can be served by household level or individual treatment systems and where community resources are adequate to cover the cost of construction, operation and maintenance of a simple community-level treatment system (UNICEF et al., 2012).

The particular water treatment method being trialled in this case study is a continuous flow solar disinfection system, aimed at providing a community water treatment solution for a rural village in Kenya. The use of sunlight for water disinfection is now well established and given that approximately 663 million people in the world still lack access to safe drinking water and over 2.4 billion to adequate sanitation (UNICEF and WHO, 2015), technology based upon this process could provide a low cost, low maintenance solution for village scale water treatment. The UV fraction, red and infrared radiation from solar light inactivate pathogens using three distinct mechanisms: absorption of UV disrupts organism DNA, photochemical reactions create highly reactive species which damage/oxidise cellular components and temperature related effects due to the absorption of red and infrared light by water (Davies et al., 2009). A variety of solar disinfection systems have been tested over the past number of decades and these can largely be grouped into batch and continuous flow solar systems.

SODIS (solar water disinfection) is the most common and simplest approach to solar disinfection. It is a batch method of treating water and consists of filling clear polyethylene terephthalate (PET) bottles or clear plastic bags (e.g. Gutiérrez-Alfaro et al., 2017) with water and exposing them to direct sunlight for 6 h, after which pathogens are inactivated or destroyed. Preliminary treatment such as filtration is recommended if turbidity is greater than 30 NTU. The system has been shown to be effective against a wide range of bacteria and viruses (McGuigan et al., 2012; Meierhofer et al., 2002). The concept is simple and so it is ideal for individuals, households, small communities and refugee camps. The SODIS method is currently used by an estimated 4.5 million regular users worldwide, predominately in Africa, Latin America, and Asia, and is recognised and promoted by the WHO, UNICEF, and the Red Cross as an effective household water treatment method for developing countries (EAWAG, 2014; McGuigan et al., 2012; Byrne et al., 2011).

Specific drawbacks to the basic SODIS system include that the capacity of the bottles (or bags) is limited to a maximum of 3 L of water at a time and two days of consecutive exposure are needed under skies with more than 50% cloud. In addition, the user has no means of knowing when water has been treated sufficiently (Polo-López et al., 2011). SODIS reactor bottles are also only illuminated on the upper side, so a large fraction of the available radiation cannot actually reach the water. Efforts have been made to address the drawbacks of the basic SODIS system, with considerable success. For example, using various low cost reflectors and enhancing absorption by painting areas of the bottles black (Martín-Domínguez et al., 2005); use of mirrors and foil behind bottles (Hindiyeh and Ali, 2010) and use of SODIS bags as an alternative to PET bottles is also being tested as a way of maximising the illuminated area and penetration of UV (Gutiérrez-Alfaro et al., 2017; Lawrie et al., 2015; Saladin, 2010).

There is a large body of research on SODIS and other HWT methods and their impacts. This includes SODIS trials in Cambodia, Kenya and South Africa which found significant reduction in the frequency of diarrhoeal episodes among trial groups of children under 5 (Du Preez et al., 2011; McGuigan et al., 2011; Du Preez et al., 2010; Conroy et al., 2001). Despite this growing body of research, a review of HWT (filtration, chlorination, chlorination with flocculation, and SODIS) in terms of acceptability, scalability, adverse effects, and non-health benefits by Schmidt and Cairncross (2009) showed inconclusive results. Hunter (2009) also found that while sufficient evidence existed as to the efficacy of, for example ceramic filters, it is imperative that proper trials of all

HWT disinfection methods be carried out, including SODIS, before further projects are implemented, as the effectiveness of these systems is not clear in terms of improvement in public health in the long term.

Although the majority of solar disinfection research has been on batch systems, some continuous flow solar disinfection systems, which have the potential to act as larger scale community systems, have been designed, including the system examined in this paper. Acra et al. (1990) tested two separate solar reactors in the late 1980s, which proved effective against *Streptococcus faecalis*, *coliforms* (present in the fresh clarified sewage obtained from the city sewer) and cultured *E. coli*. Vidal and Diaz (2000) performed experiments at both the pilot scale and the laboratory scale on a low-cost compound parabolic concentrator (CPC) reactor with results showing the inactivation of *E. coli* and *Enterococcus faecalis*. Equally, McLoughlin et al. (2004a,b) and Rincón and Pulgarín (2004) carried out tests to investigate *E. coli* inactivation on small-scale continuous flow reactors using different shaped solar collectors. Ubomba-Jaswa et al. (2009) examined recirculating photoreactor systems with volumes of 14 and 70 L. Water was exposed to sunlight for 5 h but findings revealed that the interrupted nature of the UV dose, due to the recirculating nature of the system, had a negative effect on disinfection. Polo-López et al. (2011) developed a single-pass sequential batch photoreactor. The enhanced CPC photoreactor automatically dispensed treated water into a collection tank, once a pre-determined UV dose had been received. Fabbricino and D'Antonio (2012) studied thermal effects on a pilot scale continuous plug flow reactor capable of serving about six people. Temperature was found to play an important role in the disinfection process, even in cases of limited solar radiation intensities, and a solar concentrator facilitated better performance. A comparison between transparent and black-painted glass reactors showed no difference. Kalt et al. (2014) developed a rudimentary continuous modular CPC system, using 50 mm diameter borosilicate glass tubes and improvised materials for construction of the CPC. With three modules running in series, they successfully treated 34 L of water in 4 h producing a 4-log reduction in *E. coli* with a residence time of less than 30 min. This was based on an average solar-based UV-A flux ranging from 24 to 36 W/m².

Other solar energy-based water treatment systems include solar distillation (Bounds, 2012; Muslih et al., 2010; Koning and Thiesen, 2005), which is important where salinity of the water sources is an issue, and pasteurisation (Onyango et al., 2009; Safapour and Metcalf, 1999; Burch and Thomas, 1998), where solar energy is used to reach water temperatures in excess of 65 °C.

The advantages of continuous systems include increased volumes treated, maximised use of solar radiation during daylight hours and centralised community treatment. In the context of community water systems, Kolb deWilde et al. (2008) carried out an evaluation of an underperforming community-based safe water programme in rural Mexico, which revealed that the water systems were not underused because they had become dysfunctional, but rather, they had become dysfunctional because they were underused. User convenience and household preferences, which traditionally have often been neglected in the design of rural water interventions, emerged as the fundamental issues to be addressed for programme improvement (Kolb deWilde et al., 2008). Gill and Flachenberg (2015) conducted a survey of hand-dug wells in Tanzania and found that the sustainability of the water points seemed to increase when the number of users per well was higher which could indicate that the more highly used water points are more valued by the community. Research by Hunter et al. (2009) showed that where improved community water supplies were unreliable and prone to interruptions, risk of infection was significantly greater on days that people had to revert to untreated water consumption. They also proposed that exposure to only a few days of untreated water consumption resulted in the loss of the annual health benefits attributed to consumption of water from an improved supply. Majuru et al. (2011) confirmed this, observing that while the implementation of improved water systems appeared to be associated with a reduction of diarrhoeal disease in communities, the health impact was most obvious where systems were reliable. They

suggested further research to determine whether public health gains from community water supply interventions could be leveraged by occasional use of HWT during supply failures.

In an effort to address the growing need to provide flexible, sustainable water treatment systems which could potentially service small-scale communities in both rural and urban areas not serviced by piped systems, a continuous flow solar water disinfection system was developed at Trinity College Dublin (Gill and Price, 2010). A case study of this pilot continuous flow solar disinfection system which was installed in a village in Kenya is presented in this paper in the context of sustainability and the factors which impact the success of trials on novel water treatment technologies. Kenya is classified as a water scarce country and faces huge challenges as a result of climate change, which has caused widespread drought in recent years (Carty, 2017). In order to address problems with water supply and achieve sustainable access for all by 2030, the Government of Kenya introduced the 2002 Water Act. Reforms were aimed at separating water resource management from service provision; moving water sector administration and service delivery from Nairobi to local government institutions; improving accountability and communication between consumers and water service providers; increasing investments in rural areas; and promoting beneficiary participation in planning, implementation, and management of water systems (Marks and Davis, 2012; Government Of Kenya, 2002). In 2015, Kenya showed little or no progress with regard to access to improved sanitation with only 18% of the population gaining access since 1990 but 42% of the population had gained access to improved water supplies, showing good progress in this area (UNICEF and WHO, 2015). In addition, the percentage of water points in the country which were estimated to be functional increased

from 70% in 2009 to 86% in 2016, again showing significant progress (Banks and Furey, 2016).

In this context of improving but low levels of water access in rural areas and a governmental commitment to achieving sustainable water access, a pilot continuous flow solar water disinfection system was installed in the village of Ndulyani, in Kitui County, Kenya in the summer of 2008 (Gill and Price, 2010). This project was carried out in cooperation with the Irish non-governmental organisation GOAL and the Diocese of Kitui. GOAL is an international humanitarian agency and had been carrying out numerous water projects in Kenya at that time (Gill and Price, 2010). The pilot project was funded using private donations, which will be discussed further in Section 3. This paper explores the project in the context of findings from two subsequent visits to the region, which resulted in follow-up work on the pilot system and a further project to provide an alternative water source for the village.

2. Materials and methods

The design of the pilot compound parabolic collector (CPC) reactor which was installed in Ndulyani, Kenya, (see map in Fig. 1) was based on previous laboratory scale research carried out at Trinity College Dublin (McLoughlin et al., 2004a,b). A schematic of the system is shown in Fig. 2 and the CPC profile is shown in Fig. 3. The system was designed to be fed by a continuous water source, which in this case was a river dam which had been constructed recently as part of a water supply project led by GOAL. This project site was chosen by the implementing partner GOAL and it was envisaged that the dam would provide a sustainable year-long source of water for the continuous flow system. The idea was that the

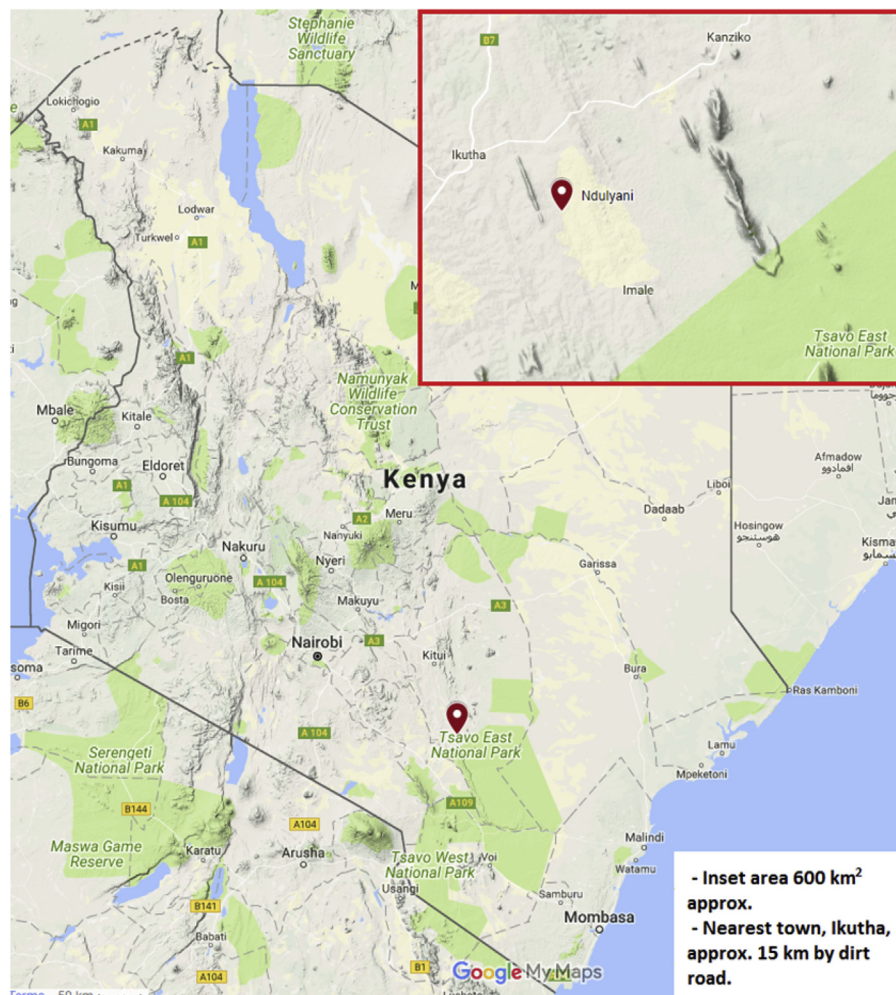


Fig. 1. Map showing location of Ndulyani village in Kitui County, Kenya.

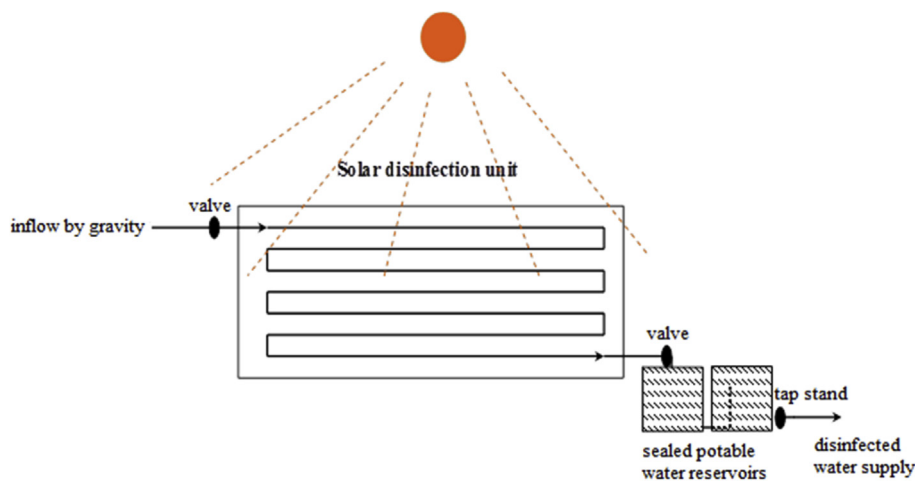


Fig. 2. Schematic continuous flow solar water disinfection system.

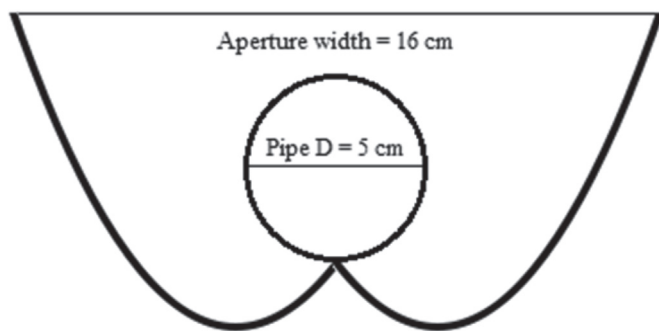


Fig. 3. CPC profile.

storage dam would fill from surface runoff during the rainy season and also gradually infill with sediment over time, which would reduce evaporative losses and provide some degree of water pre-treatment. However, such a source could not be regarded as fully protected, and so the water required additional treatment. The treated water from the solar reactor then discharged into large storage vessels which allowed water to be collected at any time. All water flowed by gravity in order to keep the system as simple as possible. Water passed through an initial inlet filter prior to entering the reactor in order to reduce the turbidity of water as much as possible. The construction of the inlet filter proved to be very challenging, however, due to the fact that the dam was completely full at the time of installation. In addition, several days of operation were required once it was installed before it effectively removed particles of sediment from the water.

The design parameters which were used to determine the size of the required system included:

- The population size and per capita daily requirement of water
- The daily amount and intensity of solar radiation
- The threshold solar UV intensity required to ensure disinfection
- The initial concentration of contaminants
- The disinfection rate coefficient

For the pilot project, a target population of 500 people in the village was taken for the preliminary design, informed by the Sphere guidelines (The Sphere Project, 2011) as well as surveys by implementing partner GOAL. A water consumption of 10 L per person per day for drinking, cooking and personal hygiene was assumed on the basis of the previous surveys in the region, yielding a required total of 5000 L per day. The system design was then based upon a threshold solar UV intensity of 25 W/m^2 which local measurements showed were met or exceeded for at

least 8 h every day (i.e. between 9am and 5pm) at the project site. Measurements were taken using a PMA2100 radiometer, with UV-A and UV-B sensors. From this, the mean continuous flow rate during the 8 operating hours per day was calculated to be 10.4 L/min. The microbiological quality of the water from the dam was conservatively assumed to contain *E. coli* concentrations of 10^5 CFU/100 mL and an inactivation constant (k) of $1.7 \text{ L/kJ}_{\text{UV}}$ was used for the design on the basis of previous work on a similar reactor. Using the collector area receiving the threshold solar UV intensity and the mean flow rate, a total length of reactor pipe of 128 m was then calculated in order to achieve complete disinfection, equating to 8.6 panels. Due to the conservative estimate of threshold solar UV, a total of 8 panels (120 m of reactor pipe) were used, giving contaminated water a residence time of 20 min in the system. Initial results for the pilot system, shown in Fig. 4, indicated effective disinfection. Influent concentrations entering the system were measured to be in the order of 1000 CFU/10 mL or less, and outlet samples were observed to reach the detection limit after passing through the system (Gill and Price, 2010).

The project was carried out with full community participation in an effort to engender community ownership and strengthen prospects for sustainability. Community members were involved in the planning of where the system should be located, as well as the preliminary works (site clearance, supply of local materials and provision of non-skilled labour). Community members also participated in the construction and commissioning of the system, which assisted in familiarisation with such a novel treatment technology. A water committee was established and full training on system use and maintenance was provided.

Due to unforeseen circumstances, however, the implementing partner GOAL ceased operations in the area soon after installation and commissioning of the system was complete and so the planned monitoring and evaluation phase of the project was unable to proceed. Further laboratory research commenced on the system in 2011 at Trinity College Dublin but the pilot site had not been visited in over two years. A field visit was organised in July 2011 in order to assess the condition of the solar disinfection system and evaluate its performance unsupervised during this period, three years after the system had been installed. The findings of the 2011 field visit and the follow-up project which was carried out in 2013, will be discussed in the following sections in the context of implementation and sustainability of novel research-based projects.

3. Post installation experience and lessons learned

A timeline for laboratory and prototype research on the continuous solar disinfection system (which was carried out in Ireland and Spain) and the installation of the pilot scale project in Kenya is provided in Fig. 5. The timeline includes follow-up visits to the project site and



Fig. 4. Continuous flow solar water disinfection system and river dam feeding the system, 2008.

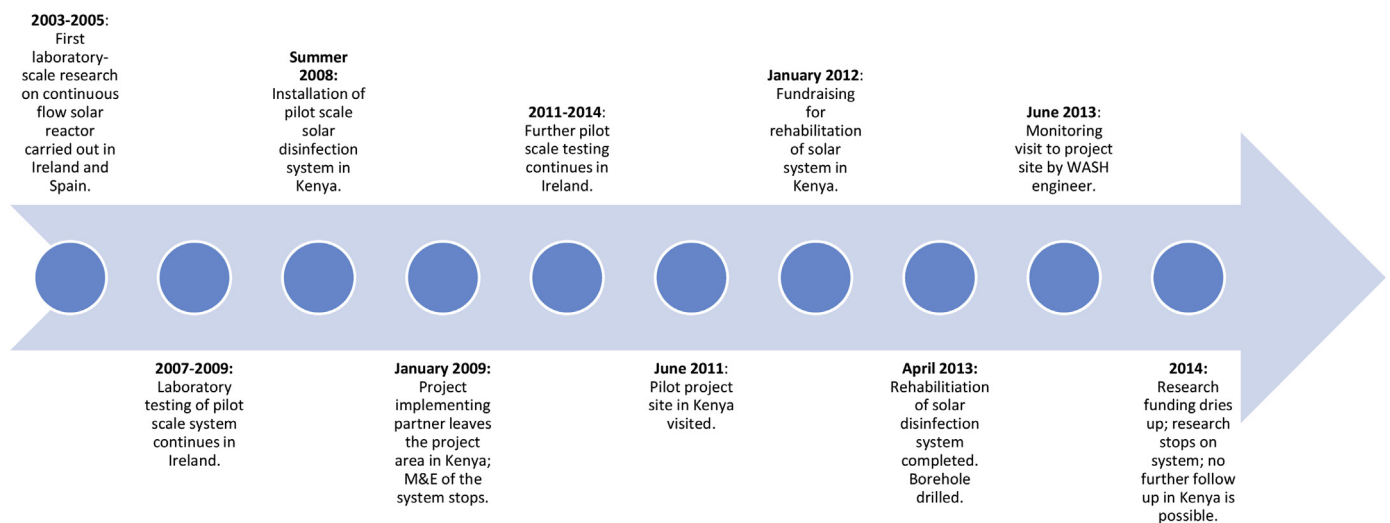


Fig. 5. Timeline of research and pilot project interventions in Kenya.

fundraising efforts to allow further work to be carried out on the system in Kenya. Extensive laboratory scale and pilot scale testing was also carried out in Trinity College Dublin and Plataforma Solar de Almería during this timeframe on various enhancement possibilities for the system, including the introduction of photocatalysis, stroboscopic and thermal effects (e.g. Mac Mahon et al., 2016; Misstear et al., 2013; Misstear and Gill, 2012a,b; McLoughlin et al., 2004a,b).

3.1. Phase 1: assessment of pilot project, 3 years on

During the 2011 project site visit meetings were held with the water committee which had originally been set up during the initial project's implementation in 2008, the women of the village who were the primary users of the system (see Fig. 6), and a representative of the Diocese of Kitui, which had been involved in implementation. Discussions revealed that the system had worked well for approximately one year until the river bed had dried up and a water supply was no longer available to feed the reactor (see Fig. 7). Severe drought had been experienced across Kenya between 2008 and 2011 (GFDRR, 2012) and rains had failed in the area for three consecutive years. Heavy rains are usually expected around April to June each year and to a lesser extent in November. The river bed was completely dry but a few water holes had been dug upstream of the dam (see Fig. 7).

While the system was in operation, the villagers had been satisfied

with the quality of water it produced, improving the colour, smell and taste compared to the untreated source which they had been using heretofore. They requested additional capacity, however, as the system had been serving more than the intended 500 people.

The solar disinfection rig was generally in good condition when inspected but required one replacement glass tube and six reflectors (see Fig. 8.) It also needed to be cleaned thoroughly to remove accumulated dirt and grit in the tubes and collection tanks. The water collection point had become overgrown and inaccessible. While the system had been out of use, the galvanised steel outlet pipe had been stolen. Unlike the other steel pipes in the system, this had not been set into concrete and so was easy to remove. The inlet filter at the dam wall had also fallen apart and needed to be rebuilt.

The main observations from the field visit were that the villagers seemed motivated to operate and maintain the system but were disappointed with the lack of follow up and support that had been provided after the project was completed in 2008. The village was now without a clean water source and women were forced to make a 14 km round trip to collect drinking water. Due to unreliable rainfall and extended periods of drought, the river would no longer be a sustainable water source for year-long water supply but had the potential to become a seasonal water supply option when rains returned. A back-up water supply in the form of a borehole was proposed as a potential solution to the acute water supply issues, which would serve the village during periods of drought when the



Fig. 6. Meeting with the women of Ndulyani village, 2011.

river bed was dry and would not require further treatment, as it would be supplied by uncontaminated groundwater. Given the significant investment which had been made in the original pilot project by private donors, as well as the investment in terms of time and effort made by the community during the project construction, it was decided to proceed with a second phase for the project to repair the system and provide a back-up borehole supply.

3.2. Phase 2: fundraising in 2012 and implementation in 2013

Due to the nature of funding for this research to date, which had involved public academic funding for individual research students and private donations for fieldwork, difficulty was encountered when attempting to source funds through usual academic sources or through development/humanitarian agencies in order to continue work on the pilot project. It was therefore decided to test a new fundraising method in the form of a web-based crowd-funding campaign. Crowd-funding has just started to become an alternative source of money for scientific academic research and has been used successfully as both an addition and a substitute to typical grant funding (Perlstein, 2013). According to Marshall (2013), crowd-funding 'is giving researchers the opportunity to take their research in new directions, funding graduate students or undergraduates who can do a lot with a little bit of money.' In addition, it is a good way of generating interest in a research area.

The crowd-funding campaign was launched in January 2012 and involved six weeks of intensive fundraising. The total project fund collected at the end of six weeks exceeded the original target of €22,000 and was the result of over 200 individual online donations, as well as money raised through specific fund-raising events during the campaign



Fig. 8. Solar disinfection reactor, 2011.

period. Significant interest in the project was generated within the university and beyond, with considerable media coverage, which showed the power of the crowd-funding mechanism in terms of spreading interest in the research area among a broader group.

Once the project funds had been raised, implementation needed to be planned, which proved to be a big challenge given the lack of resources and capacity at the location in Kenya. The first step was to carry out a comprehensive hydrogeological survey to identify potential drilling sites for the borehole. This was completed in March 2012 by a local hydrogeological consultancy based in Nairobi (previously used and recommended by UNICEF), and was overseen by the original project implementer from Trinity College Dublin. During this time, consultations were also carried out with the water committee and village representative regarding the proposed project implementation. Once project implementation had been agreed with the community, tenders were drawn up and sent to several drilling contractors recommended by humanitarian agencies. The drilling contractor was chosen with plans to complete the project in April 2013, including application for the necessary drilling permits by the contractor.

On arrival in Kenya in April 2013 it was observed that the reactor and collection tanks had been badly damaged in flash floods the previous year (see Fig. 9) and the river dam was completely dry, despite some rains during the rainy season in November. The following repairs on the system were required:

- Piece together remaining tubes and reflectors (including spares which had been provided as part of original project).



Fig. 7. Dry river dam with piping to reactor; dry river bed upstream of dam wall; hand-dug water hole in river bed, 2011.



Fig. 9. Reactor found badly damaged in April 2013.

- Level the reactor; repair sunken supports.
- Repair the collection tanks and tap-stand area.
- Repair the inlet pipe and filter.
- Repair and reinforce gabions surrounding the reactor area in order to protect reactor from any future flash flooding.
- Replace the outlet pipe and valve from reactor to the collection tanks.
- Leak test the system.

Work was carried out with people from the village over a period of three weeks which helped to familiarise people with working with the system. All of the repairs were duly completed, although considerable problems were encountered when trying to make the system leak-tight, as O-rings were missing from many of the pipe connections. Heavy rains arrived during the second week of the project and the river dam was once again full. It was therefore possible to get the reactor fully functioning before the project time came to an end. Fig. 10 shows local men fitting together the reactor whilst Fig. 11 shows repair of the collection

tanks and tap-stand area and the river dam full after heavy rainfall.

The drilling aspect of the project proceeded separately to the reactor rehabilitation. A 60 m borehole was drilled at the most suitable location for groundwater, as recommended in the hydrogeological survey (Fig. 12). It was originally envisaged that the borehole could be connected to the solar disinfection system, acting as an alternative supply to the system during drought. However, the distance between the points was too great to achieve this and it was decided to keep the borehole as a stand-alone back-up supply, given that microbial contamination issues with the groundwater source were unlikely. Water was reached at 20 m and 24-h pumping tests revealed ample recharge to ensure the sustainability of the well. A flowrate of 3.1 m³/hour (52 L/min) was maintained without drawdown for 24 h, which far exceeded the predicted use and capacity of the India Mark II pump. The maximum daily use of the well was estimated to be 6.5 m³ with a maximum flowrate of 13 L/min from the pump, which was well within the capacity of the borehole in the long term. Water analysis later, however, showed that the water was saline and so could only be used for livestock and washing. Salinity is often an issue for groundwater supplies across this part of East Africa and while the result was disappointing, feedback from the community since project implementation suggests that the borehole has been a boost to the community.

The water committee was trained in basic operation and maintenance of the India Mark II pump and they planned to meet regularly, taking small fees from users which would be put towards a maintenance fund for the system. Fig. 13 shows women using the well and a water committee meeting two months after project installation. The water committee had a large female representation, as they would be the major users of the system.

3.3. Design and installation issues for the continuous flow reactor

Some problematic design and installation issues emerged during commissioning of the continuous flow reactor. A significant problem was the difficulty in filling the system without trapping large air bubbles in the tubes, which then remained trapped during operation. There was no easy way to bleed airlocks from the system and therefore it is recommended that air-valves be placed intermittently at tube connections in future installations to enable the tubes to be completely filled.

Valuable items such as galvanised pipe and valves are vulnerable to theft. While the system was being repaired, efforts were made to secure all valuable fixtures by fixing them in concrete and covering them. In addition, expensive pipes and fittings were avoided and cheaper PVC



Fig. 10. Local men rebuilding the reactor with remaining tubes and reflectors.



Fig. 11. Repair of tanks and tap-stand area and river dam full after heavy rains.



Fig. 12. Borehole drilling.



Fig. 13. Women using new borehole and water committee meeting two months after project implementation.

alternatives were used wherever possible, which would also make replacement of parts more affordable for the village. The issue emphasises the need to keep systems as simple as possible to avoid unwanted attention and to facilitate the replacement of broken or stolen items by the community. It was also discovered, when the reactor was dismantled and rebuilt, that O-rings were missing from several of the plastic tube

connections, making it extremely difficult to get the reactor leak tight. It is important therefore to provide sufficient spare parts and minimise the number of removable parts in the system which can be lost easily.

The rebuilt filter system used to treat the river water up-front of the reactor was very simple, consisting of a mixture of sand and stones, which was designed to silt up as dirty water passed through over a period of



Fig. 14. River dam and reactor following rains.

time. After the initial rains, the water flowing through the reactor from the river dam was highly coloured, full of fine particles, which did not settle out easily (see Fig. 14). However, a week of operation was sufficient to allow the filter to silt up and the water was observed to be much clearer passing through the reactor. Adequate T-valve points for flushing and cleaning the inlet pipe and reactor are recommended in order to remove any dirt which builds up over time.

In terms of weathering, the reactor was found to be in good condition five years after initial installation, once it had been rebuilt and cleaned. Reflectors had weathered slightly, with scratches from dust and debris, but still had very high reflectivity when cleaned. However, dust collection on the reflectors was significant and so regular cleaning is needed in dry dusty climates. The reactor had been badly damaged in flash floods in 2012 despite the reactor being positioned well above the water level of the river during the rainy season in an effort to protect it from flooding. This shows the importance of considering extreme flooding events when choosing a location for this system, particularly as lower ground which is conducive to a gravity water feed, may cause higher risks during periods of heavy rainfall. Flooding patterns are very difficult to predict or identify in an unfamiliar area, however, and it is essential to seek local knowledge in order to evaluate risks sufficiently. In addition, the design of gabions and other protective methods should take extreme conditions into account. It is also important to place adequate fencing around the system to prevent animals and children from interfering with equipment.

The final issue involved the severe drought experienced in Kenya since the original project was carried out in 2008, which highlights sustainability challenges in light of changing weather patterns. The experience in Ndulanyi shows that rivers which previously replenished adequately during the rainy season to give year-round water supply, can no longer be relied upon to do so. Understanding the behaviour of both surface and groundwater given the unpredictable nature of rainfall is a significant challenge for new water projects. In order to avoid the problems encountered with this pilot project in terms of reliable water supply, sites should be chosen carefully and take the full implications of climate change into consideration, as far as is practicable.

4. Discussion

4.1. Capacity and logistical challenges

4.1.1. Engaging implementing partners for research pilot trials

The experience of carrying out the initial pilot project and the follow-up rehabilitation of the system underlined the importance of engaging suitable implementation partners. While international development or humanitarian agencies are attractive partners and generally have excellent capacity in terms of logistical support, uncertainty surrounding the long term presence and priorities of international NGOs in areas,

particularly isolated areas of developing countries, highlights the need to involve local partners with a vested interest in maintaining a relationship with the project in the long term. It should also be noted that it proved difficult throughout this research project to identify organisations that were willing to be part of a research trial. There was a general reluctance among the development and humanitarian agencies which were approached to invest time and money in a water treatment system which was novel and required trial, which was understandable given the funding pressures many organisations experience. This challenge in attracting support was particularly problematic, however, given that the need for local presence and support from an implementing partner is essential for projects with a research element, where monitoring and evaluation are critical to ensuring that a full understanding of the effectiveness and appropriateness of the system is obtained. The departure of the international project implementing partner soon after installation of the first stage of this project had a detrimental impact in terms of the monitoring and evaluation needed to assess the system properly. In addition, the community lost much needed support to guide them through operation and maintenance issues associated with the new system.

Despite efforts before and during implementation of the second phase of the project to engage local organisations, it was carried out by two engineers from Ireland and the community, in addition to the Kenyan drilling contractor. Contact was made with the previous local implementing partner, The Diocese of Kitui, as well as the local governmental water officer, although their ability to get directly involved was limited due to lack of resources. The lack of logistical support and local capacity, which could have been provided by a local implementing partner, was very challenging. However, local businesses in the neighbouring towns proved to be invaluable when it came to sourcing parts and expertise, particularly for the rehabilitation of the reactor, which required considerable time and materials.

A further issue, particular to carrying out the project as an outside implementing partner with the community, was the time constraint for completing the project. Only three weeks were available to implement the project, which was very challenging as delays were experienced from the outset, including several breakdowns of the drilling rig. Delays are to be expected when carrying out any such projects and can be dealt with more easily for an implementing partner based in the region. However, given the limited time that the engineers had to work on this project, all delays were critical. Although the project was finished within the allotted three-week duration, time which had been earmarked for valuable additional community meetings and training was lost due to setbacks.

4.1.2. Monitoring and evaluation

The conclusions drawn from the experience of carrying out the second phase of the project, independent of a local implementing partner, were

that it is possible to install this type of system if the local community is fully involved. In fact the experience showed that local businesses and suppliers can be extremely innovative and pro-active when it comes to finding solutions for project implementation, particularly in terms of sourcing materials and expertise. However, the major constraint lies beyond the physical project installation, in terms of providing medium-to long-term support for the community and for carrying out monitoring and evaluation. This is particularly relevant for a novel system such as the continuous flow solar system and it would be extremely beneficial to collaborate with local universities or research-based organisations, which may be in a position to oversee the monitoring and evaluation stage and so become part of the overall research effort. Due to the remote location of the village, it proved very difficult to provide follow up support. A field visit by an experienced water and sanitation engineer was organised two months after the project had been implemented and it was found that both the reactor and borehole were still in operation and feedback from the community was positive.

Originally, it was envisaged that the Diocese of Kitui could be engaged again as a local partner for the second phase of the project in 2013, in order to provide some monitoring and evaluation, as well as support for the water committee. It was hoped that technical support could be provided by the implementing engineers at Trinity College Dublin remotely through the Diocese water officer (via email) but it did not prove possible to engage the partner. In addition, it was expected that further research funding for the system would allow future visits to the pilot site to assess the system. Funding for the project finished in 2014, however, and so resources have not been available to provide further support to the community or to obtain reports on the condition or use of the systems since installation.

4.2. Social and economic factors

4.2.1. Community participation

Community participation in the planning and construction of water interventions has become an integral part of projects in an effort to improve acceptability, support and sustainability of projects (Dungumaro and Madulu, 2003). In particular, participatory planning is thought to play a large part in giving community members a sense of ownership for the water system, which helps to ensure long term commitment from users to its operation and maintenance. Marks and Davis (2012) attempted to measure the sense of ownership in communities of Kenya where water projects had been carried out and found that it was significant in cases where households had individual water taps and where users were involved in key decisions related to the system, contributed towards the capital costs of system construction, and participated directly in planning and construction activities. Prokopy (2005) also found that in village scale projects in India, capital cost contributions and household involvement in decision making were independently significant predictors of household satisfaction, equal access, and time savings. Kleemeier (2000) examined water projects performed under the Malawi rural piped water scheme programme and found that long term performance of projects was best where cash contributions from consumers had been implemented and smaller schemes were constructed.

Community members did not provide capital cash contributions towards phases 1 or 2 of this pilot project but a scheme of charging for use of the borehole and continuous flow disinfection system was agreed during phase 2 of the project. In addition, community members were involved in the preparatory and construction phases of the project and were trained in the operation and maintenance of both systems. However, the ability to get the community involved in phase 2 of this project, particularly in decision making prior to implementation, was difficult given the limited time in Kenya. A consultation session was carried out with the community when the hydrogeological survey was carried out a year prior to project implementation and communication was continued by phone with the village representative prior to travelling to Kenya in 2013. In addition, the drilling contractor and village representative were

in communication during project planning and follow-up stages. These consultations facilitated participation during the three-week project implementation period in Kenya but it was evident that sufficient community involvement is difficult to achieve when projects do not have a local implementing partner to engage the community for more extended periods of consultation prior to and post-implementation. This aspect of community involvement and ownership was much easier to accomplish during phase 1 of the project, which had both a local and international implementing partner operating in the area and a longer project duration (3 months). This was a significant limitation to the overall project success and the authors would again stress the need to engage implementing partners located in the area where possible in order to maximise community involvement during all phases of the project, including planning, implementation and monitoring/evaluation.

The water committee which was set up during phase 1 of the project was brought together again during phase 2 (with some new members) and included a mix of men and women of different ages from the village, with a higher female representation given that they would be the primary users. Prokopy (2005) found that transparency in water committee operations was a significant determinant of both tariff payment and community belief in the system's ability to be sustainable. This was also confirmed by Isham and Kahkonen (2002), who found that monitoring of contributions was important for project outcomes. Madrigal et al. (2011) observed that the most important mechanisms linked to high performance of community-based drinking water organisations in rural Costa Rica were working rules enforced by the local communities and properly defined local accountability, as well as the capacity of local leaders to generate appropriate incentives to involve the community in sustainable solutions. They found that a combination of these attributes led to a situation in which communities expressed a high sense of ownership and desire to assume the costs necessary to run the systems properly. During this project, every effort was made to ensure that elected members of the water committee were considered to be trustworthy and dependable, particularly in terms of handling community money. The inclusion of a majority of women was considered to be a significant advantage in this regard by female members of the community. It should be noted that this type of participatory approach sets up community organisations capable of managing very small rural schemes but it does not address the need of larger schemes for support from a competent external agency (Kleemeier, 2000).

4.2.2. Sustainability

Sustainability is a particularly challenging issue for novel research-based projects which are still in the pilot phase and therefore not fully established or accepted as viable technologies. In fact even water supply projects and programmes which use common and well established technologies have a long history of failure, particularly in the rural context. Hundreds of millions of euros have been spent on projects over the past number of decades in rural areas but the vast majority of these have fallen into disrepair and are now abandoned (Nauges and Whittington, 2010). Problems lie in the fact that projects are often implemented without adequate community participation and ownership, with systems being implemented that people do not want or that they do not want to maintain (Nauges and Whittington, 2010). Several factors have been attributed to low levels of access to improved water supply in developing countries including installation of unsuitable systems, inadequate water resource management, rent-seeking behaviour, and insufficient capacity at an institutional level (Marks and Davis, 2012).

Over recent years, sustainability has become a requirement of most donor funded projects, as donors want to see value for the money they are investing. Sustainability requires a project to last in the community for a reasonable period without external assistance (Esposito, 2009). Achieving this is possible if consideration is given to the costs of running and maintaining the project, and how the solution or technology proposed will match with the local environment. The ultimate goal is to make the project and its beneficiaries independent of the need for further external

assistance (Esposito, 2009). The experience gained from the project in Kenya showed very clearly that more external assistance is required for projects using novel technologies than for those using well-established water treatment systems and this requirement for external support significantly impacts the sustainability of these interventions.

Integrating community, government and other relevant stakeholders into the process of systems development and implementation is essential if the outcome is to be appropriate to local circumstances and sustainable in the long term (Ali, 2010; UNICEF et al., 2012). Nauges and Whittington (2010) have suggested the following when implementing water projects in order to ensure sustainability:

- Involve households in the choice of technology, service level and institutional and governance arrangements.
- Give women a larger role in decision making.
- Require households to pay all of the operation and maintenance costs and at least some of the capital costs.
- Transfer ownership of the facilities to the community.
- Involve households in the design of cost recovery systems and tariffs to be charged.

Gill and Flachsenberg (2015) in a review of hand-dug wells across Tanzania found that the lack of specific activities and budget targeted towards analysis and development of the supply chain and maintenance capacity in water programmes, as well as the weakness of some of the local back-stopping agencies, tended to threaten the long term sustainability. In addition the importance of ownership was suggested through the fact that each time a repair was needed and despite the failure of the cost-recovery scheme put in place, WASH committees were able to collect enough money to perform the needed repairs. Access to a good mechanic, whether the water point committee caretaker, local private operator or local government technician, seemed to be a key element for long term sustainability, which points to a need for some level of technical support (Gill and Flachsenberg, 2015).

A significant body of research demonstrates that many rural people can and will pay for improved water supplies (Gadgil, 1998). In a study of water vending in Onitsha, Nigeria, for instance, the revenues collected by water vendors were found to be about ten times the revenues collected by the formal water utility, showing that the poor do in fact pay for their water (Whittington et al., 1989). The low ability of the poor to pay for water services is the general explanation given for continuing high levels of government subsidy for water services. However, it is largely the rich sectors of society and not the poor who tend to benefit disproportionately from subsidised water services in developing countries (Briscoe, 1997; Briscoe and Garn, 1995). The general consensus now is that water has an economic value and must be recognised as an economic good (ICWE, 1992).

Local culture and traditions are also an important point of consideration when any new water technology is to be introduced to a community, and it is necessary to explore these issues with the people who are the intended users and owners of the system. Aspects such as taste, domestic uses, collection and distribution methods, maintenance and tradition in terms of water must be considered or implementation, acceptance and sustainability of the project will be compromised (Martín-Domínguez et al., 2005; Mara, 2006). Water disinfected by means of solar radiation has advantages in terms of acceptance in a rural context in that the treatment does not affect taste and no additions are made to the water which might be considered unacceptable. Changes in habits in terms of water collection and use, as well as maintenance of new systems are key issues to be addressed to ensure acceptance and sustainability of these systems (Martín-Domínguez et al., 2005).

McConville and Mihelcic (2007) have proposed a logical framework for identifying and analysing the factors that affect sustainable development of water and sanitation projects in an effort to help overcome the historically low sustainability rates of development projects. This framework takes into account five sustainability factors that are common

in development literature and the policies of international aid organisations: (1) sociocultural respect, (2) community participation, (3) political cohesion, (4) economic sustainability, and (5) environmental sustainability. A life-cycle thinking approach is then used to assess how project sustainability can be improved throughout the project life. Five life stages are identified to represent the life of a development project: (1) needs assessment, (2) conceptual designs and feasibility, (3) design and action planning, (4) implementation, and (5) operation and maintenance. This framework could provide a very useful tool for planning trials in the context of novel water technologies.

4.3. Physical factors

4.3.1. Water scarcity and sources

The significant changes in water availability experienced in the period between initial project implementation and completion of the final stage of this project shows the real challenge faced in planning and implementing water treatment projects in areas affected by climate change. Local water tables in many regions are facing major changes due to weather variability, such as longer periods of drought and more intensive rainfall events. These changes can affect the pattern of agricultural run-off, sedimentation and erosion, and groundwater recharge rates (Gadgil, 1998), as well as leading to potential contamination of shallow groundwater sources (MacDonald et al., 2009). In many parts of the developing world, the rate of groundwater consumption far exceeds recharge rates, particularly when water is used for agricultural irrigation, which can impact drinking water quality and access (Gadgil, 1998). In coastal areas, diminishing water tables and rising sea levels can lead to saline intrusion into aquifers and wells, making water unsuitable for human consumption (Comte et al., 2016).

The pilot project implemented in Kenya attempts to provide a technology that can provide a community-level (rather than household-level) decentralised system to address water needs in a rural context but could equally be applied in a peri-urban context. Ongoing research is also looking at how the system can be used to remove arsenic from water (O'Farrell et al., 2016), which is a prevalent problem with groundwater supplies in many areas. Water scarcity has traditionally occurred in areas of low water availability or rainfall, but is increasingly occurring in regions which have high levels of water consumption due to high population densities and/or high water demand for agricultural or industrial activities (UNESCO et al., 2006; Bithas, 2008). Water use has been growing at more than twice the rate of population increase in the last century (FAO, 2012) and conventional centralised treatment and distribution infrastructure has been unable to keep up with growing demand in rapidly expanding urban and peri-urban slums. Decentralised water treatment options are being promoted as potential solutions in these areas (Ali, 2010).

Investigating the water source choices already being made by households can help to make better informed decisions when planning water projects (Nauges and Whittington, 2010). Water demand in the developed world is well documented and understood but in the developing world the picture is not always clear as households often use a variety of water sources to meet their needs including groundwater, surface water, rainwater, and water vendors (Nauges and Whittington, 2010). Piped water is generally unavailable and unlikely to be an option in the medium term for families living in the expanding slums of cities in the developing world, who typically earn under \$150 per month, and for households living in rural areas of Sub-Saharan Africa and South East Asia on less than \$1 per person day (Nauges and Whittington, 2010).

4.3.2. Problems with the system design

As previously discussed, both phases of the pilot project provided valuable insights into the design of the pilot solar disinfection system. In particular, the need to make the system more robust against both environmental threats and the possibility of vandalism or theft was made very clear. In addition, simple design flaws which could cause big operational

problems were revealed such as the need for air bleed valves and T-junctions for cleaning tubes out. The problems which were revealed during both the installation and rehabilitation phases of the project show how important full-scale trials are in teasing out the design of new water treatment technologies.

4.4. Moving beyond laboratory and pilot trials

The final point to be addressed in this assessment is what is the most suitable next stage for the technology? The purpose of the trial was to provide a sustainable water treatment point for the community of Ndulyani and to learn from the project experience in order to inform further pilot scale trials, including modifications to the system as necessary. The trial did not work out as originally envisioned, however, and the critical period of monitoring and evaluation, essential for learning from the experience was unsatisfactory for both phases of the project. Despite the shortcomings, however, the system proved to be of use to the community for a short period before water supply problems emerged and therefore it would seem reasonable for further trials to be carried out with some modifications according to the recommendations outlined earlier. It would be essential for any further trials to be implemented with a detailed monitoring and evaluation plan in place incorporating local partners. In addition, a longer pre-construction phase is recommended, again including local partners, in order to encourage community ownership and to design a management system that would work for the users. A peri-urban environment or less isolated location might prove more amenable to this type of trial.

Beyond more comprehensive pilot trials to prove the suitability of this system, significant barriers exist to scaling up new technologies for widespread manufacture and use. It would be envisaged that the continuous flow solar disinfection system could be modified and adapted to enable local construction and use of locally available materials. In this way, the need for external resources and support could be reduced over time and a more sustainable system developed - it must be noted, however, that further laboratory trials on alternative construction materials would be necessary to ensure that disinfection was not compromised. However considerable financial investment would be required to get the system to a final full-scale prototype and to establish a viable and sustainable model for sourcing materials, manufacturing and distributing the system on a larger scale. The complexity of this transition is not the focus of the current research but it highlights the challenges of transitioning new water treatment technology further from pilot scale to full scale implementation in a developing country context.

5. Conclusions

Making the transition from laboratory to pilot testing in the field is challenging for novel water treatment projects intended for use in developing countries, particularly in terms of funding and capacity. Difficulty can be encountered in persuading development agencies or government bodies to try a new approach to water treatment and so identification of suitable implementing partners is problematic. The continuous flow solar water disinfection pilot project shows the importance of having local capacity when implementing pilot projects, and although this is not essential in terms of successful installation of a system, it is invaluable with regard to ensuring community participation and therefore the sustainability of the system. In addition, due to the novel nature and research element of this type of project, monitoring and evaluation capacity is essential. This is again very difficult to achieve without local implementation resources and the authors would recommend that future pilot projects of this nature would try to collaborate with local universities or organisations with a research interest, in order to ensure the necessary capacity in the field to manage all stages of the project, from planning to implementation and finally monitoring and evaluation.

Sustainability is a particularly problematic issue for novel research-

based projects which are still in the pilot phase and therefore not fully established or accepted as viable technologies. More external assistance is required for projects using novel technologies than for those using well-established water treatment systems, particularly in terms of operation and maintenance challenges which may arise in the short to medium term. This requirement for external support significantly impacts the sustainability of these interventions. Ensuring community participation in all aspects of project implementation is a crucial element of maximising project sustainability and acceptability and for creating a sense of ownership of the system within the community.

In terms of funding, a web-based crowd-funding campaign proved to be a very promising alternative to traditional sources of academic funding and was found to bring a much broader interest group to the research area beyond academia. This may be an important funding option for future projects of this type, which aim to bring research from the laboratory to field-testing stage.

Finally, the performance of the continuous flow system while it was in use was found to be satisfactory and feedback from the community regarding operation of the system and quality of water was positive. In addition, the pilot project revealed the need for some small design changes such as inclusion of air-bleed valves, which would significantly improve system operation for future pilot projects. The project experience clearly shows the need for better understanding of the behaviour of both surface and groundwater, given increasingly unpredictable weather patterns as a result of climate change, as well as the need for systems to be robust enough to weather increasingly extreme weather events.

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References

- Acra, A., Jurdi, M., Mu'alle, H., Karahagopian, Y., Raffoul, Z., 1990. Water Disinfection by Solar Radiation: Assessment and Application. International Development Research Centre.
- Ali, S., 2010. Alternatives for safe water provision in urban and Peri-Urban Slums. *J. Water Health* 8, 720–734.
- Banks, B., Furey, S.G., 2016. What's Working, where, and for How Long. A 2016 Water Point Update to the RWSN (2009) statistics, GWC/Skat, RWSN, St. Gallen, Switzerland.
- Bithas, K., 2008. The sustainable residential water use: sustainability, efficiency and social equity. *The European experience. Ecol. Econ.* 68, 221–229.
- Bounds, M., 2012. Solar Distillation: Technical Brief. Schumacher Center for Technology and Development (Technical report).
- Briscoe, J., 1997. Financing and Managing Water and Wastewater Services: a Global Perspective [Online]. The World Bank. Available: <http://siteresources.worldbank.org/INTWRD/926910-1112690201445/20434187/Financing&ManagingWater&WasteWater.pdf>. (Accessed August 2017).
- Briscoe, J., Garn, H.A., 1995. Financing Water Supply and Sanitation under Agenda 21. *Natural Resources Forum. Wiley Online Library*, pp. 59–70.
- Burch, J.D., Thomas, K.E., 1998. Water disinfection for developing countries and potential for solar thermal pasteurization. *Sol. Energy* 64 (1–3), 87–97.
- Byrne, J.A., Fernandez-Ibanez, P.A., Dunlop, P.S., Alrousan, D., Hamilton, J.W., 2011. Photocatalytic enhancement for solar disinfection of water: a review. *Int. J. Photoenergy* 2011.
- Carty, Tracy, 2017. A Climate in Crisis: How Climate Change Is Making Drought and Humanitarian Disaster Worse in East Africa. OXFAM Media Briefing 27 April 2017 Ref: 01/2017. https://www.oxfam.org/sites/www.oxfam.org/files/file_attachments/mb-climate-crisis-east-africa-drought-270417-en.pdf. (Accessed August 2017).

- Comte, J.C., Cassidy, R., Obando, J., Robins, N., Ibrahim, K., Melcholi, S., Mjemah, I., Shauri, H., Bourhane, A., Mohamed, I., Noe, C., 2016. Challenges in groundwater resource management in coastal aquifers of East Africa: investigations and lessons learnt in the Comoros Islands, Kenya and Tanzania. *J. Hydrol.: Reg. Stud.* 5, 179–199.
- Conroy, R.M., Meegan, M., Joyce, T., McGuigan, K., Barnes, J., 2001. Solar disinfection of drinking water protects against cholera in children under 6 Years of age. *Arch. Dis. Child.* 85, 293–295.
- Davies, C., Roser, D., Feitz, A., Ashbolt, N., 2009. Solar radiation disinfection of drinking water at temperate latitudes: inactivation rates for an optimised reactor configuration. *Water Res.* 43, 643–652.
- Dungumaro, E.W., Madulu, N.F., 2003. Public participation in integrated water resources management: the case of Tanzania. *Phys. Chem. Earth, Parts A/B/C* 28, 1009–1014.
- Du Preez, M., Conroy, R.M., Ligondo, S., Hennessy, J., Elmore-Meegan, M., Soita, A., McGuigan, K.G., 2011. Randomized intervention study of solar disinfection of drinking water in the prevention of dysentery in Kenyan children aged under 5 years. *Environ. Sci. Technol.* 45, 9315–9323.
- Du Preez, M., McGuigan, K.G., Conroy, R.M., 2010. Solar disinfection of drinking water in the prevention of dysentery in South African children aged under 5 Years: the role of participant motivation. *Environ. Sci. Technol.* 44, 8744–8749.
- EAWAG, 2014. SODIS Method [Online]. Available: http://www.sodis.ch/methode/index_EN. (Accessed August 2017).
- Esposto, S., 2009. The sustainability of applied technologies for water supply in developing countries. *Technol. Soc.* 31, 257–262.
- Fabbriano, M., D'Antonio, L., 2012. Use of solar radiation for continuous water disinfection in isolated areas. *Environ. Technol.* 33, 539–544.
- FAO, 2012. *FAO Water Reports. Coping with Water Scarcity: an Action Framework for Agriculture and Food Security*, vol. 38. Available at: <http://www.fao.org/docrep/016/i3015e/i3015e.pdf>. (Accessed August 2017).
- Gadgil, A., 1998. Drinking water in developing countries. *Annu. Rev. Energy Environ.* 23, 253–286.
- GFDRR, Republic of Kenya, European Union, United Nations and World Bank, 2012. *Kenya Post-Disaster Needs Assessment (PDNA) 2008-2011 Drought. GFDRR*. http://www.gfdr.org/sites/gfdr/files/Kenya_PDNA_Final.pdf. (Accessed August 2017).
- Gill, L., Flachenberg, F., 2015. Sustainability of hand-dug wells in Tanzania: results from a post-evaluation. Conference Paper. In: 38th WEDC International Conference. Loughborough University, UK, 2015.
- Gill, L., Price, C., 2010. Preliminary Observations of A Continuous flow solar disinfection system for a rural community in Kenya. *Energy* 35, 4607–4611.
- Government of Kenya, 2002. The water act, national water services strategy (Nwss). In: T. M. O. W. A (Ed.), *Irrigation* (Nairobi, Kenya).
- Gutiérrez-Alfaro, S., Acevedo, A., Figueredo, M., Saladin, M., Manzano, M.A., 2017. Accelerating the process of solar disinfection (SODIS) by using polymer bags. *J. Chem. Technol. Biotechnol.* 92 (2), 298–304.
- Hindiyeh, M., Ali, A., 2010. Investigating the efficiency of solar energy system for drinking water disinfection. *Desalination* 259, 208–215.
- Hunter, P.R., 2009. Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environ. Sci. Technol.* 43, 8991–8997.
- Hunter, P.R., Zmirou-Navier, D., Hartemann, P., 2009. Estimating the impact on health of poor reliability of drinking water interventions in developing countries. *Sci. Total Environ.* 407, 2621–2624.
- ICWE, 1992. The Dublin statement on water and sustainable development. In: *International Conference on Water and the Environment*. ICWE, Dublin.
- Isham, J., Kahkonen, S., 2002. How do participation and social capital affect community-based water Projects? Evidence from Central Java, Indonesia. In: *The Role of Social Capital in Development: an Empirical Assessment*, pp. 155–187.
- Kalt, P., Birzer, C., Evans, H., Liew, A., Padovan, M., Watchman, M., 2014. A solar disinfection water treatment system for remote communities. *Procedia Eng.* 78, 250–258.
- Kleemeier, E., 2000. The impact of participation on sustainability: an analysis of the Malawi rural piped scheme program. *World Dev.* 28, 929–944.
- Kolb deWilde, C., Milman, A., Flores, Y., Salmerón, J., Ray, I., 2008. An integrated method for evaluating community-based safe water programmes and an application in rural Mexico. *Health Pol. Plann.* 23, 452–464.
- Koning, J., Thiesen, S., 2005. Aqua Solaris – an optimised small-scale desalination system with 40 litres output per square meter based upon solar-thermal distillation. *Desalination* 182 (1–3), 503–509.
- Lawrie, K., Mills, A., Figueredo-Fernández, M., Gutiérrez-Alfaro, S., Manzano, M., Saladin, M., 2015. UV dosimetry for solar water disinfection (SODIS) carried out in different plastic bottles and bags. *Sensor. Actuator. B Chem.* 208, 608–615.
- MacDonald, A.M., Calow, R.C., MacDonald, D.M., Darling, W.G., Dochartaigh, B.E., 2009. What impact will climate change have on rural groundwater supplies in Africa? *Hydrol. Sci. J.* 54 (4), 690–703.
- Mac Mahon, J., Pillai, S.C., Kelly, J.M., Gill, L.W., 2016. Solar photocatalytic disinfection of E. coli and bacteriophages MS2, ΦX174 and PR772 using TiO₂, ZnO and ruthenium based complexes in a continuous flow system. *J. Photochem. Photobiol. B Biol.* 170, 79–90.
- Madrigal, R., Alpizar, F., Schlüter, A., 2011. Determinants of performance of community-based drinking water organizations. *World Dev.* 39, 1663–1675.
- Majuru, B., Michael Mokoena, M., Jagals, P., Hunter, P.R., 2011. Health impact of small-community water supply reliability. *Int. J. Hyg. Environ. Health* 214, 162–166.
- Mara, D., 2006. Modern engineering interventions to reduce the transmission of diseases caused by inadequate domestic water supplies and sanitation in developing countries. *Build. Serv. Eng. Technol.* 27, 75–83.
- Marks, S.J., Davis, J., 2012. Does user participation lead to sense of ownership for rural water Systems? Evidence from Kenya. *World Dev.* 40, 1569–1576.
- Marshall, J., 2013. Kickstart your research. *Proc. Natl. Acad. Sci.* 110, 4857–4859.
- Martín-Domínguez, A., Alarcón-Herrera, M.T., Martín-Domínguez, I.R., González-Herrera, A., 2005. Efficiency in the disinfection of water for human consumption in rural communities using solar radiation. *Sol. Energy* 78, 31–40.
- McConville, J.R., Mihelcic, J.R., 2007. Adapting life-cycle thinking tools to evaluate project sustainability in international water and sanitation development work. *Environ. Eng. Sci.* 24 (7), 937–948.
- McGuigan, K.G., Conroy, R.M., Mosler, H.-J., Preez, M.D., Ubomba-Jaswa, E., Fernandez-Ibanez, P., 2012. Solar water disinfection (SODIS): a review from bench-top to roof-top. *J. Hazard Mater.* 235, 29–46.
- McGuigan, K.G., Samaiyar, P., Du Preez, M., Conroy, R.M., 2011. High compliance randomized controlled field trial of solar disinfection of drinking water and its impact on childhood diarrhea in rural Cambodia. *Environ. Sci. Technol.* 45, 7862–7867.
- McLoughlin, O., Ibanez, P.F., Gernjak, W., Rodriguez, S.M., Ill, L., 2004a. Photocatalytic disinfection of water using low cost compound parabolic collectors. *Sol. Energy* 77, 625–633.
- McLoughlin, O., Kehoe, S., McGuigan, K., Duffy, E., Touati, F.A., Gernjak, W., Alberola, I.O., Rodríguez, S.M., Gill, L., 2004b. Solar disinfection of contaminated water: a comparison of three small-scale reactors. *Sol. Energy* 77, 657–664.
- Meierhofer, R., Wegelin, M., Del Rosario Torres, X., 2002. *Solar Water Disinfection: a Guide for the Application of Sodis*. EAWAG.
- Missteard, D., Gill, L., 2012a. CFD modeling of fixed photocatalytic inserts for a continuous flow reactor for water disinfection. *J. Adv. Oxid. Technol.* 15, 153–162.
- Missteard, D.B., Gill, L.W., 2012b. The inactivation of phages MS2, ΦX174 and PR772 using UV and solar photocatalysis. *J. Photochem. Photobiol. B Biol.* 107, 1–8.
- Missteard, D.B., Murtagh, J.P., Gill, L.W., 2013. The effect of dark periods on the UV photolytic and photocatalytic disinfection of Escherichia coli in a continuous flow reactor. *J. Sol. Energy Eng.* 135, 021012.
- Muslihi, I.M., Abdallah, S.M., Husain, W.A., 2010. Cost comparative study for new water distillation techniques by solar energy. *Appl. Sol. Energy* 46 (1), 8–12.
- Nauges, C., Whittington, D., 2010. Estimation of water demand in developing countries: an overview. *World Bank Res. Obs.* 25, 263–294.
- O'Farrell, C., Mac Mahon, J., Gill, L.W., 2016. Development of a continuous flow solar oxidation process for the removal of arsenic for sustainable rural water supply. *J. Environ. Chem. Ecotoxicol.* 4 (1), 1181–1190.
- Onyango, E.A., Thoruwa, T.F.N., Maingi, S.M., Njagi, E.M., 2009. Performance of 2-element plane reflector augmented galvanised pipe flat plate collector for solar water pasteurization. *J. Food Technol.* 7 (1), 12–19.
- Perlstein, E.O., 2013. *Anatomy of the Crowd4discovery Crowdfunding Campaign*, vol. 2. Springerplus, pp. 1–3.
- Polo-López, M., Fernández-Ibáñez, P., Ubomba-Jaswa, E., Navntoft, C., García-Fernández, I., Dunlop, P., Schmid, M., Byrne, J., McGuigan, K.G., 2011. Elimination of water pathogens with solar radiation using an automated sequential batch CPC reactor. *J. Hazard Mater.* 196, 16–21.
- Prokopy, L.S., 2005. The relationship between participation and project outcomes: evidence from rural water supply projects in India. *World Dev.* 33, 1801–1819.
- Rincón, A.-G., Pulgarin, C., 2004. Field solar *E. Coli* inactivation in the absence and presence of TiO₂: is UV solar dose an appropriate parameter for standardization of water solar disinfection? *Sol. Energy* 77, 635–648.
- Rosa, G., Clasen, T., 2010. Estimating the scope of household water treatment in low-and medium-income countries. *Am. J. Trop. Med. Hyg.* 82, 289.
- Safapour, N., Metcalf, R., 1999. Enhancement of solar water pasteurisation with reflectors. *Appl. Environ. Microbiol.* 65 (2), 859–861.
- Saladin, M., 2010. SODIS Bags for Humanitarian Aid [Online]. Available: <http://WWW.SODIS.ch/index>. (Accessed March 2014).
- Schmidt, W.P., Cairncross, S., 2009. Household water treatment in poor populations: is there enough evidence for scaling up now? *Environ. Sci. Technol.* 43, 986–992.
- The Sphere Project, 2011. *The Sphere Project. Humanitarian Charter and Minimum Standards in Humanitarian Response*. Practical Action Publishing, Rugby, UK.
- Ubomba-Jaswa, E., Navntoft, C., Polo-López, M.L., Fernandez-Ibáñez, P., McGuigan, K.G., 2009. Solar disinfection of drinking water (SODIS): an investigation of the effect of UV-a dose on inactivation efficiency. *Photochem. Photobiol. Sci.* 8, 587–595.
- UNESCO, World Water Assessment Programme, UN Water, 2006. *The United Nations World Water Development Report 2. Water: A Shared Responsibility*. [Online]. Available: <http://unesdoc.unesco.org/images/0014/001454/145405E.pdf>. (Accessed August 2017).
- UNICEF, The Open University, Federal Democratic Republic Of Ethiopia Ministry Of Health, Amref, 2012. *Hygiene And Environmental Health, Part 2: Blended Learning Module for the Health Extension Programme* [Online]. Available: http://www.open.edu/openlearncreate/pluginfile.php/71967/mod_resource/content/2/Hyg_Env_Part_2.lo.pdf. (Accessed August 2017).
- UNICEF, WHO, 2015. *Progress on Drinking Water and Sanitation: 2015 Update* [Online]. Available: http://files.unicef.org/publications/files/Progress_on_Sanitation_and_Drinking_Water_2015_Update.pdf. (Accessed August 2017).
- Vidal, A., Diaz, A., 2000. High-performance, low-cost solar collectors for disinfection of contaminated water. *Water Environ. Res.* 271–276.
- Whittington, D., Lauria, D.T., Mu, X., 1989. *Paying for Urban Services: a Study of Water Vending and Willingness to Pay for Water in Onitsha, Nigeria*, vol. 40. World Bank Publications.