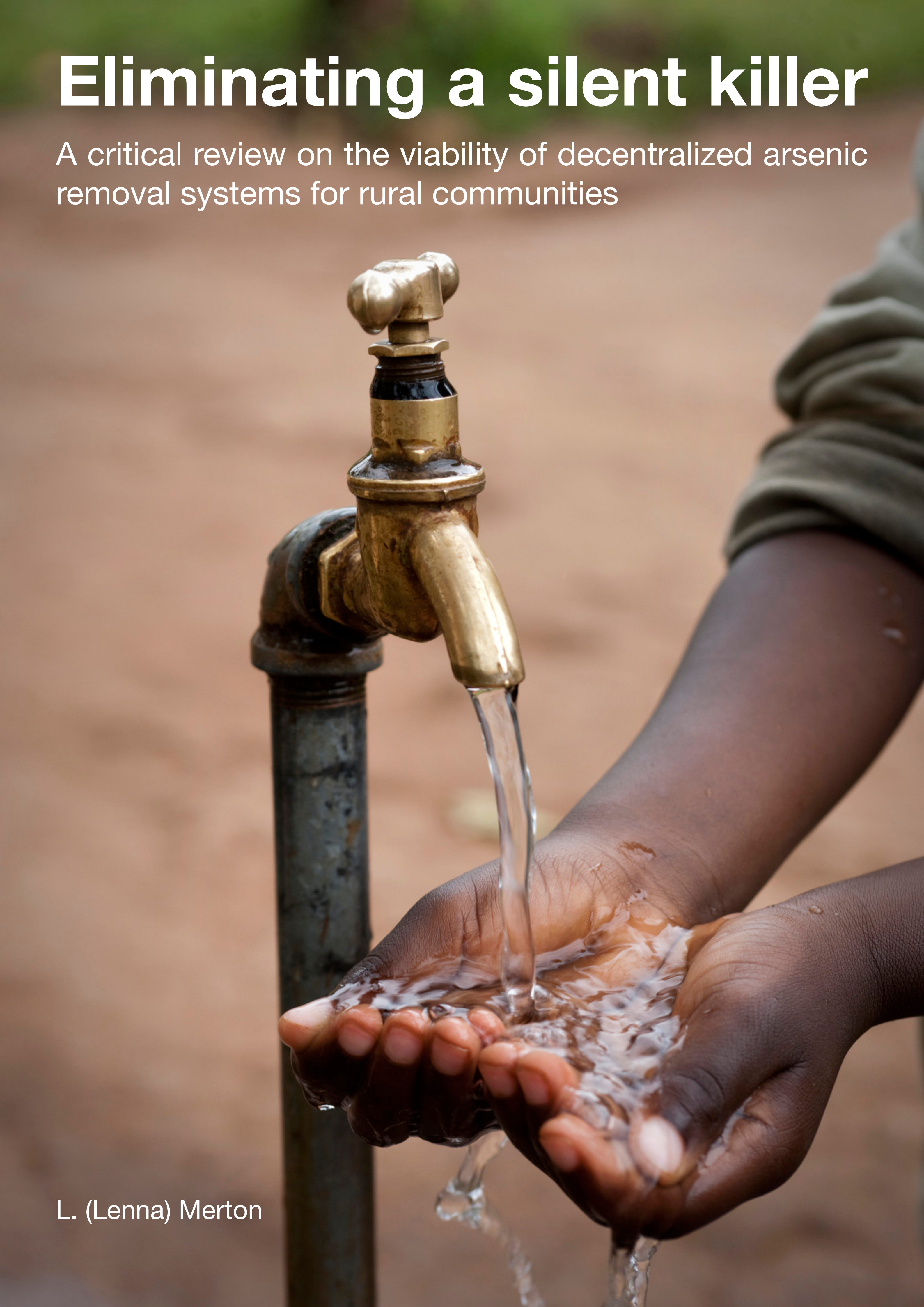
Eliminating a silent killer

A critical review on the viability of decentralized arsenic removal systems for rural communities



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Eliminating a silent killer – a critical review on the viability of decentralized arsenic removal systems for rural communities

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ABSTRACT

Arsenic is a global environmental health issue. Since it was recognized in the nineties many techniques have been developed on the remediation on arsenic contaminated drinking water. Solving people's exposure through drinking water to arsenic is, however, a complex problem. Rural communities with an income level of less than $4 per person per day that rely on decentralized arsenic removal technologies, are still facing the same problem as thirty years ago. Many of the technologies have drawbacks and are not feasible at a household level. In order to achieve structural impact not only the technology is going to decide whether a treatment technique is feasible. This paper looked at the viability of decentralized treatment technologies by including an institutional, social, financial and technical analysis. It turned out that many of the available technologies have disadvantages that relate to the context of people having an income level of less than $4 per person per day. Existing technologies are not making structural sustainable impact, as they are not properly adapted to the context of these people. The key to an arsenic resilient society is that a treatment solution should be owned by someone who is able to adequately deal with it under sustainable financial circumstances. Further research and projects on arsenic treatment solutions for people living with an income level of less than $4 per day should question themselves whether they should look for decentralized or central solutions.

Key words: arsenic treatment; income level 1 and 2; decentralized solutions; viability

1. Introduction

Arsenic (As) is a global environmental health issue. Natural groundwater arsenic contamination is reported from more than 100 countries, affecting an estimated 200 million people (Singh, 2017). Arsenic may cause acute orchronic toxicity, it harms the skin and increases the risk of cancer (Prasanta Mandal et al., 2016).

Arsenic occurs naturally in the environment. The element, known as As, ranks as the 20th most occurring trace element in the earth's crust, 14th in seawater, and 12th in the human body (Singh et al, 2015). Human contamination of As occurs naturally via direct consumption of inadequate treated drinking water or by ingestion of food and beverages prepared using contaminated drinking water. Arsenic is released into groundwater through various geochemical processes, like the oxidation of As-bearing sulfides, desorption of As from hydro-oxides such as iron, aluminum and manganese oxides, reductive dissolution of As-bearing iron hydro-oxides and the release of As from geothermal water (Hashimi and Pearce, 2009). Contamination of As also occurs due to industrial and anthropogenic activities. The application of phosphate fertilizers in agriculture triggers As release and unconfined sewage reduces hydrous ferric oxide that releases As into groundwater (Hashimi and Pearce, 2009). These activities not only increase As concentrations in the soil and contamination of groundwater, but they also contribute to (further) contamination of freshwaters, marine waters and food consumption. Singh et al (2015) studied that geothermal inputs, like thermal stratification that releases As into surface water due to the depletion of O2 levels, evaporation, mining activities and groundwater contamination are the main cause of high concentrations of As in rivers. Arsenic is thus prominent in the environment and maintained due to its natural occurrence via geochemical reactions and various anthropogenic activities. Human exposure to As is inevitable, and adequate water treatment or alternative water sources is a requisite for an As-resilient society.

This exposure is associated with major health consequences. Arsenic threatens many people all over the world and treatment of As contaminated water is necessary to minimize health impact. Keeping this in view, since 1993 the dangers of As has been recognized and the World Health Organization (WHO) set a provisional 'unsafe' (total) As threshold at 10 micrograms per liter (Ahmad and Bhattcharya, 2017). Since then many technologies have been reported on the remediation of As contamination (Singh et al., 2015; Hashimi and Pearce, 2009; Dhadge et al, 2018; Rahman et al., 2014; Singh, 2017), but many of these technologies have drawbacks, their by-products can be a further potential source for secondary As pollution or they are not feasible at a household level where most problems occur (Singh et al., 2015). In addition, for the mitigation of As not only the technology decides whether contamination could be prevented. Also socio-economic, demographic, socio-behavioral factors of As-affected communities, as well as awareness of As contamination and its associated health risk should be taken into account for the implementation of As mitigation policies (Singh, 2017; Ahmad et al., 2017). Consequently, preventing human exposure to As is complicated. This is apparent as despite the amount of research that has been done and new treatment technologies have been developed and tested in the field, the magnitude of the problem did not change since it was recognized in the nineties.

Removing As from water is a challenging task (Ahmad et al., 2017), especially for people that rely on a certain income level. There are four income levels defined by Rosling (2018), representing the world population in 2017. Each icon in the chart of figure 1 represents 1 billion people, and the seven icons show how the current world population is spread out across four income levels, expressed in terms of dollar income per day (Rosling, 2018). This paper focuses on arsenic removal systems for rural communities in income Level 1 and Level 2.

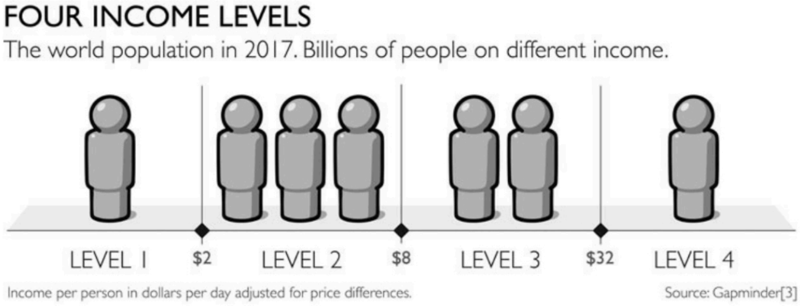

Figure 1 Four income levels. Source: Rosling, 2018

Available technologies are often expensive and require expertise knowledge. People with an income of more than $64 dollars per day (Level 4) facing problems with As are in general successful in implementing remediation technologies. However, people that rely on an income level of less than $4 per day (Level 1 and Level 2) are staying behind due to this complexity. Millions of dollars have been invested on research in areas where people on Level 1 or Level 2 live, and mitigation technologies are tested in the field. However, these approaches yet did not turn out to be successful in the long term and there are still substantial knowledge gaps about the treatment of As contaminated water (Rahman, Naidu and Bhattacharya, 2009; Litter, Morgada & Bundschuh, 2010). One of the current problems income Level 1 and 2 are struggling with, is that water supply systems are highly decentralized without treatment. In order to reduce the risk of illness many countries encouraged citizens to utilize groundwater via wells, as this is often considered a much safer water source when looking at biological contamination (Hashmi and Pearce, 2009). In various countries, however, groundwater wells are often contaminated with high concentrations of As. In India for example 48% of 140.000 hand tubewells have As concentrations above 10 μg/l and 24% have As concentrations above 50 μg/l (Rahman et al., 2009). In most cases, As concentrations in individual wells are unknown. So people do not know what they are consuming: health effects of As exposure only becomes visible over a long period and human senses do not recognize this silent killer: you cannot see, smell nor taste it. So, water from contaminated wells needs to be treated or treatment at household level needs to be done, but this has not yet been succeeded on a large scale. Alternative water sources are often not present or too expensive (e.g. drill a deeper well).

Most literature sources discuss treatment technologies (Ahmad et al, 2017; Singh et al., 2015; Hashimi and Pearce, 2009; Dhadge et al, 2018; Rahman et al., 2014) and some cost-effectiveness of As-mitigation options (Singh, 2017; Koundouri, 2005). They often, however, do not take into account institutional, social, cultural and economic factors. Treatment of As for people on Level 1 and 2 may not be solved with technological solutions alone. This is apparent as a variety of approaches for the provision of safe drinking water have been implemented for people within these two levels, but community acceptance of many of these approaches has not been encouraging (Rahman et al., 2009). The complexity of this problem asks for an interdisciplinary view on whether a remediation technology will work in daily practice in certain regions.

The aim of this study is to analyze the viability of decentralized treatment technologies for As contaminated drinking water for people with an income Level 1 or 2. This is done by reviewing literature on As remediation technologies for decentralized systems at community or household level. Specifically, this paper analysis (i) remediation technologies for As contaminated water (ii) how these technologies fit within the context of people on Level 1 and 2 and (iii) what lessons can be drawn for the future to mitigate As contaminated water for these people. Discussion of the limitations and difficulties for implementing mitigation technologies for As contaminated water for Level 1 and 2 in a range of technical, cultural, social and institutional circumstances are central to this paper.

2. Methodology

A comprehensive literature review is undertaken for this paper. In order to conceptualize and quantify the viability of existing As treatment technologies the FIETS sustainability principles are used as defined by the Dutch Water And Sanitation Hygiene (WASH) Alliance. It describes five key indicators that need to be addressed in order to achieve structural impact: Financial, Institutional, Environmental, Technological and Social sustainability (WASTE, 2015). As there is no "silver bullet" approach to remove As (Ahmad and Bhattacharya, 2017), the FIETS-indicators help to identify whether existing As-treatment solutions are sustainable and if they are also able to be scaled-up. In this paper the emphasis lies on the *Institutional*, *Technical* and *Social* indicators. The *environmental* indicator is excluded as it focuses on whether specific treatment technologies contribute to sustainable waste- and water flows and resources, and if they could be locally financed (WASTE, 2015). This paper does not go in depth into specific treatment technologies and thus the *environmental* indicator is not taken into account. The same holds for the *financial* indicator. The financial aspects of individual products will not be discussed, but financial sustainability also captures broader aspects. The business approach of As-projects should be sustainable where local entrepreneurs take up a serious role (WASTE, 2015). This will be discussed in addition to the other three indicators.

To further operationalize these indicators some criteria will be taken into account in the analysis. The *institutional* component means that the roles, tasks and responsibilities of the users of As treatment systems, authorities and service providers at the local and national level are clear and supported, and if they are capable of fulfilling these roles effectively. If these technologies help to create healthy and livable communities is included in the *social* part. For the *technological* component it is analyzed whether these treatment technologies could be maintained, repaired and replaced by local people (WASTE, 2015). It is also checked whether it fits the concentration limits for As, set by the WHO at 10 μg/l, or 50 μg/l set as a national standard by various countries where people on Level 1 and 2 live, like Bangladesh, Myanmar and Nepal (Rahman et al., 2009).

3. Results

3.1 Remediation of As-contaminated water

Once As is present in aqueous environments it is hard to remove it. From a *technological* point of view, physicochemical and microbiological characteristics of the water source and available materials in the region will determine the most convenient technology for removal of As (Litter et al., 2010). In-depth analysis of the chemistry and operation of each of the available treatment technology is essential to understand the exact functioning of it, but this is outside the scope if this paper. Interested readers can gain an excellent comprehensive overview (Ahmad et al., 2017; Jain and Singh, 2012; Litter et al., 2010; Singh et al., 2014). This paper will provide a brief overview of the available technologies and discuss in this chapter their advantages and disadvantages in terms of *technological* sustainability.

To gain an overview on the available methods for As removal different technologies are grouped. Litter at al. (2010) stated that all technologies rely on a few basic chemical/physical processes: oxidation/reduction, coagulation–filtration, precipitation, adsorption and ion exchange, solid/liquid separation, physical exclusion, membrane technologies, biological methods etc. Jain and Singh (2012) abridged this by stating that there are six principles for removal of As from water: oxidation and filtration, biological remediation, co-precipitation, adsorption, ion exchange and membrane technology. This is confirmed by Ahmad et al (2017) who grouped adsorption and ion exchange and added a sixth remediation technology: *source substitution*. In this paper the use of alternative drinking water sources will not be discussed and the prescription of the available remediation technologies will be based upon the five other technologies grouped by Ahmad et al (2017).

Overview arsenic remediation technologies for drinking water

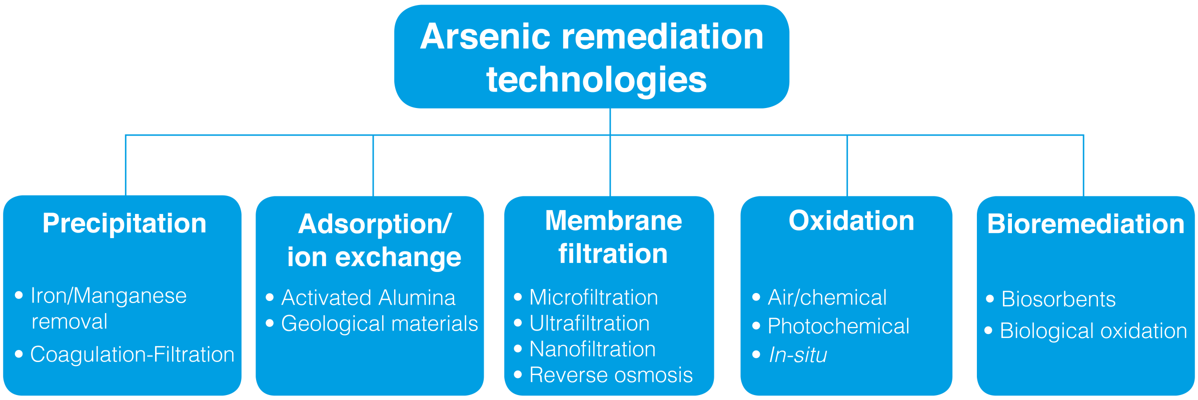

Figure 1 Overview arsenic remediation technologies. Source: Ahmad et al., 2017

3.1.1 Precipitation

Precipitation takes the advantage of the insolubility of certain As inorganic compounds to remove As from water (Litter et al., 2010). Suitable oxidizing agents, like calcium or magnesium, are added followed by coagulation, sedimentation and filtration (Jain and Singh, 2012). This method is frequently used in numerous pilot- and full-scale applications (Jain and Singh, 2012), but it has several disadvantages to use it in practice and especially at the level of well treatment. Both Litter et al (2010), Ahmad et al (2017) and Jain & Singh (2012) state that the removal efficiency is highly dependent on several operational parameters. The technology is difficult to optimize, it fails to remove As under rural operation conditions to the desired level of 50 μg/l, not even mentioning 10 μg/l. It produces toxic sludge being a potential contamination, challenging pre-treatment may be required and it is generally not suitable because of the instability of most of the solids.

3.1.2 Adsorption/Ion exchange

Applying *adsorption* and *ion exchange* is a very suitable technology for use at point of entry or point of use scale according to Ahmad et al (2017). Litter et al (2010) confirms this mentioning that the technology is very simple, does not require chemical addition, high efficiencies are obtained and it is useful at community or household levels. Materials are commercially available with good results in Bangladesh and India (Litter et al., 2010; Ahmad et al., 2017). *Ion exchange* is less regularly used than *adsorption* because it is relatively expensive, water should be pre-treated (Ahmad et al. 2017) and hand pump attached removal with *ion exchange* needs meticulous attention for operation as well as for regular backwashing (Jain and Singh, 2012; Litter et al., 2010). A disadvantage to the chemical process of adsorption is that there is a large complicated factor due to competitive adsorption and complex interactions in natural waters (Ahmad et al., 2017). In addition, Litter et al (2010) states that the method usually fails in lowering As concentration to acceptable levels. This relates to what Ahmad et al (2017) and Jain & Singh (2012) state by mentioning that *adsorption* has a variable effectiveness.

3.1.3 Membrane filtration

Membrane filtration is currently less applicable at a smaller scale for decentralized wells. The majority of membrane development has focused on large-scale applications (Ahmad et al., 2017). Filtration involves the physical separation of solid particles from water by passing trough a filter medium that holds the particles, while allowing the water to pass trough (Hashimi and Pearce, 2009), Generally there are four membrane types that differ in pore size. For As remediation two technologies with the smallest pore size and highest pressure, nano-filtration (NF) and reverse osmosis (RO), are adequate (Ahmad et al., 2017; Litter et al., 2010). Litter et al (2010) states that the main disadvantages are low water recovery rates, high electrical power consumption (high pressure). Based upon recent improvements, Ahmad et al (2017) claims that cost is no longer a major barrier to NF/RO, but that is especially the case when economies of scale are considered for larger systems. This is thus less applicable for decentralized small-scale solutions for people on Level 1 and Level 2. Both Ahmad et al (2017) and Ahmed (2001) confirm the disadvantage of high operation and maintenance as the operating conditions have a major impact on the membrane performance. This makes membrane filtration challenging in developing countries where people on Level 1 and 2 live.

3.1.4 Oxidation

The process of *oxidation* creates a reactive site that attracts As ions (Hashimi and Pearce, 2009). As it is not a removal technology in itself, it plays a significant role in improving the performance of all of the As removal technologies (Ahmad et al., 2017). The available technologies are simple and the installation costs are small. For the removal of As additional treatment is however necessary and the technology in itself will thus only solve part of the problem.

3.1.5 Bioremediation

Like *oxidation*, the process of *bioremediation* is also seen as an indirect As remediation method (Ahmad et al., 2017). Litter et al (2010) described bioremediation as an emergent technology with high potential for small scale or household treatment, but yet based upon lab testing.

3.2 Arsenic treatment for Level 1 and Level 2: how do these technologies fit within this context?

As most of the described technologies are confident and well understood in large and medium scale treatment plants for centralized services (Litter et al., 2010), effective decentralized removal at scale for Level 1 and Level 2 remains unsolved.

Many papers exclude *financial, social* and *institutional* indicators as these are complicated topics. This section will elaborate on three papers written by the World Bank (2005), Johnston et al

(2014) and Khan & Yang (2014) who analyze these indicators for As mitigation but not interlink it with the five treatment technologies that were mentioned in section 3.1. Khan & Yang (2014) did two case studies in Bangladesh in which 25 stakeholders involved in arsenic mitigation and 650 household respondents in 13 arsenic-affected rural villages that rely on drinking water via tubewells were interviewed. Johnston et al (2014) summarized the institutional analysis of Khan & Yang and added psychological and technical aspects to the analysis for enhancing As mitigation. The World Bank (2005) document provides a more comprehensive view on what should be considered and undertaken for the mitigation of As in South and East Asian countries.

The institutional and social analysis by Khan & Yang (2014) describes people's perspective on what achievements have been made in As mitigation, what the limitations are for As mitigation activities, what people's preferences are for mitigation options and their willingness to pay and walk for water. It turned out that only 11% of the stakeholders achieved to ensure As free water within their mitigation activities and 16% introduced safe alternative water options. This corresponds to what is earlier described about the extent to which the scope of the As problem has not changed throughout the years. Limiting As mitigation activities was found mainly due to lack of clear responsibilities, coordination and accountability from and between the involved organizations (Khan & Yang, 2014). Also insufficient funding, shortage of skilled man power and commitment among both providers and end-users played a role. The stakeholders highly preferred deep tube wells (95%) or piped water systems (58%). In addition, they also asked for the stakeholder's opinion on selection and operation of community filters and a household filters. Interestingly, the results showed that majority agreed (68%) with community based solutions and 63% were against any household level water treatment because community based systems allowed for better water management, provided wider safe water coverage and also reduced the risk of localized contamination of the aquifer (Khan and Yang, 2014).

The additional study of Johston et al (2014) identified several psychological factors for behavioral change. The study showed a relationship between the commitment of people to gain safe water and the type of water source. Piped water supply, community filters and well sharing were mostly used. The study indicates that more committed persons have higher confidence in their abilities to collect safe water, find safe water collection less time consuming and effortful, and who perceive more approval from others to collect As-safe water are more likely to use As safe water (Johston et al., 2014). If the majority of people thus prefer external supply and treatment, like piped water supply, this will ask for less behavior change and more people will be committed to use these safe water supplies. As people in these rural areas are less willing to walk long distances (Johnston et al., 2014), people will be less committed and more effort is necessary to convince them to use these safe water supplies. The World Bank (2004) confirms this by stating that identifying people's preferences are necessary for designing an appropriate mitigation system and that it involves an institutional change in attitude towards listening to communities. The key question is whether people find these desirable and are willing to adapt and sustain them (World Bank, 2004).

The report of the World Bank (2004) highlights three important *social, institutional* and *financial* issues. First, a cost-benefit analysis of 10 mitigation options that were analyzed in rural Bangladesh shows that the use of pond sand filters (30 households/pond sand filter), an adsorption/ion exchange technology, turned out to be superior to other technologies. An economically sustainable As mitigation technology should have a realistic operational policy and this turned out to be the point where a cost-benefit analysis outlines an incomplete view on viable treatment technologies (WASTE, 2015). Pond sand filters are often very polluted, increasing the threat of re-contamination of water and adding a very high shadow price for health care, cleaning and replacement of the filters (World Bank, 2004). Also due to population growth there is a lack of space for accommodating so many treatment ponds and adds additional costs for the price of land where the pond will be situated. Further, from a *social* and *institutional* perspective there are two dilemmas for As mitigation for local governments and international aid agencies. During the Water Decade (1981-1990), international aid agencies strongly promoted groundwater as a safe source because of biological contamination of surface water. Governments, politicians, these agencies and NGOs financed and constructed groundwater wells, but these turned out to be contaminated with As. As a result governments and politicians have been reluctant to promote alternative sources, that might be detected to be inappropriate again, raise awareness and prefer to avoid dealing with the As issue (World Bank, 2015). In addition they worry about reelection in their constituencies. As development partners do not have to worry about elections, they play an active role in financing As-related interventions in groundwater. They spent a lot of effort on the detection and prevention, but not much on integrating into water supply decision-making (World Bank, 2004). Most research has focused on hydrogeology rather than on social aspects. This highlights the lack of government leadership and direction, and donors and international finance to cover a serious lapse through ostensive action, rather than taking a more comprehensive operational view (World Bank, 2004). People that are being exposed to As contamination should however become customers of local solutions instead of recipient of support (WASTE, 2015). These mitigation systems should run by mandated local parties, on local finance and they should be sustainable.

3.3 What lessons can be drawn for the future of As mitigation?

From a *technological* point of view there are several methods available to treat As contaminated water. However, from all papers describing usefulness of different technologies, it is still difficult to conclude whether a technology works in practice in decentralized rural settings. Litter et al (2010) occasionally mentions for some of the technologies if they were tested in the field and if there are commercial products available. Hashimi & Pearce (2009) even describe small-scale technologies in detail by mentioning their prices, capacity and efficiency. However, none of these papers describe whether these technologies were implemented on a large scale in the field and if they proved effective in treating As contaminated wells for Level 1 and 2. The disadvantages of the different technologies are not in line with the critical success factors for sustainable technologies, as they lack either functionality and/or reliability and safety, reparability and maintenance or affordability (WASTE, 2015). Technologies should be based on a viable business model and be adapted to the context by involving local entrepreneurs and train local stakeholders (WASTE, 2015), but it seems to be excluded how these technologies are going to create value in a social, cultural, economic and other contexts (Fljedstad & Snow, 2017). There is a lack of support structures as the technologies are not sustainably adapted to the context. The WHO (2017) confirms this, stating that there is an increasing number of effective and low-cost options for removing As from small or household supplies, but there is still limited evidence about the extent to which such systems are used effectively over sustained periods of time. It is clear that there is there is no single technology that is going to solve the problem of As contamination. Each country has a unique situation in terms of knowledge, scale and scope of the problem (World Bank, 2004).

In case there is no centralized water supply and treatment and people are dependent on house hold filters, social inequalities will occur. This due to differences in income knowledge on how to use a filter properly, supply chain problems etc. In case of more centralized treatment, at a tube well or dug well, also someone needs to pay for the treatment systems and be responsible for the operation and maintenance, as for example precipitation or adsorption/ion exchange require pre-treatment and attention for operation. In this case, however, centralized treatment makes it easier to regulate contamination of As. To organize this, local conditions should be strengthened and the initiators at a project level should pay more attention to let these remediation technologies function at a local level (WASTE, 2015).

In light of more centralized systems, at national level As removal should be embedded in strategic water supply policy/investments and cannot be seen as an isolated issue (World Bank, 2004). Similar issues are found for fluoride, manganese and boron, and thus similar considerations and recommendations can also be applied to those elements (World Bank, 2004). More assertive action from governments is necessary for implementing solutions at various levels.

Further research is necessary on the ability to take down the scope of the As problem via decentralized or centralized systems. The advantage of centralized treatment of As is that it decreases the points of failure, takes away the responsibility of operation and maintenance (O&M) of individual households, higher investments are possible and an organization that has in-depth knowledge on the used treatment system can take O&M responsibility. It creates the possibility for scalable solutions, which is an advantage as shown earlier in chapter 3.1.3 for technologies like NF/RO. Advantages of decentralized solutions are that it is relatively stable and a single failure does not impact a large group of people, as centralized treatment could have its own implications with recontamination for example. For centralized systems proper infrastructure and large investments are necessary, while household solutions might be less complicated to introduce and distribute over communities. Private sector involvement could be considered in both central and decentralized treatment solutions. This requires the development of a sound business case. Feasibility of private sector involvement depends on lots of factors amongst which local institutional (private/public) arrangements for safe water service delivery.

4. Conclusion and recommendations

Solving people's exposure to As through drinking water is a complex problem. This paper looked at the viability of decentralized treatment technologies for As contaminated drinking water for people with an income Level 1 or Level 2. It first reviewed five general treatment solutions for As contaminated water. Various treatment technologies have been developed but the magnitude of the global As problem has yet not changed. It turned out that the available technologies are challenging for Level 1 and 2 as their operation and maintenance requires in-depth knowledge, effort and impacts the removal efficiency. As some of them also have variable effectiveness it is difficult to ensure long term, self-sustaining and effective decentralized removal technologies. The feasibility of these treatment solutions depend in addition on local specific technical, social, institutional and economic factors, and the question is whether the existing decentralized solutions are capable to cope this. Further research is therefore necessary on the distinction between decentralized and central technologies in terms of scalability, viability and how there are able to make structural sustainable impact. Recommendations are:

• Financial: international aid agencies/NGO's should not only support investment in hardware, but also focus more on locally financed operation, management, maintenance, budget training and transferring responsibilities to local stakeholders.
• Technological: adapt to context by involving and training local stakeholders and private sector. Hardware needed for the services should be as much as possible be produced, delivered, maintained, and replaced by local organizations with local staff.
• Institutional: at national level governments should take more responsibility by explicitly integrating safe water service delivery in national policy. Authorities should be clear about their roles and tasks at all levels. Development partners should partner with governments and supporting them to include the issue of As in national policy
• Social: look at key factors determining social acceptance, stimulate behavioral change and find solutions to enhance empowerment of local people. Understanding behavior will contribute to decide for and design proper technological solutions.

Besides the fact that a technology should treat As properly, involvement of local people is key to achieve a sustainable solution. The main message is that centralized or decentralized treatment should be "owned" by an organization/people who take(s) the responsibility, has the financial means based upon a sustainable business case, is willing to invest and understands the impact of As on health supporting behavioral change.

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