Science of the Total Environment xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Multi-criteria assessment of community-based fluoride-removal technologies for rural Ethiopia

Lars Osterwalder [a,*], C. Annette Johnson [a], Hong Yang [a,b], Richard B. Johnston [a]

[a] Eawag, Swiss Federal Institute of Aquatic Science and Technology, 8600 Duebendorf, Switzerland
[b] Department of Environmental Sciences, Faculty of Sciences, University of Basel, Switzerland

## HIGHLIGHTS

- No single most-preferable technical solution for fluoride removal in rural Ethiopia.
- MAVT procedure offers a structured and transparent decision making framework.
- Data collection for different fluoride removal options used in Ethiopia.
- Results may facilitate the development of better options.

## ARTICLE INFO

*Article history:*
Received 7 May 2013
Received in revised form 27 September 2013
Accepted 19 October 2013
Available online xxxx

*Keywords:*
Fluoride
Water treatment
Technology
Multi-criteria decision analysis
Ethiopia
Rural

## ABSTRACT

Elevated concentrations of naturally-occurring fluoride in groundwater pose a serious health risk to millions of people living in the Ethiopian Rift Valley. In the absence of low-fluoride water resources of sufficient capacity, fluoride removal from drinking water is the accepted mitigation option. To date, five different community-level fluoride-removal technologies have been implemented in Ethiopia, although only a few units have been found in a functional state in the field. Which technology should be promoted and up-scaled is the subject of controversial debate amongst key stakeholders. This paper describes a multi-criteria decision analysis exercise, which was conducted with the participation of stakeholders in Ethiopia during a one-day workshop, to assess in an objective and transparent manner the available technology options. Criteria for technology comparison were selected and weighted, thus enabling the participants to assess the advantages and disadvantages of the different technologies and hear the views of other stakeholders. It was shown that there is no single most-preferable, technical solution for fluoride removal in Ethiopia. Selection of the most suitable solution depends on location-specific parameters and on the relative importance given to different criteria by the stakeholders involved. The data presented in this paper can be used as reference values for Ethiopia.


## 1. Introduction

Elevated concentrations of fluoride in drinking water are a serious health concern, with dental and skeletal fluorosis being the most commonly reported fluoride-related diseases (Fawell et al., 2006). In the Ethiopian Rift Valley (ERV) many sources of drinking water are contaminated with naturally-occurring fluoride. Over 40% of wells are contaminated with fluoride that has leached from volcanic ash. The concentrations found (up to 26 mg/L) significantly exceed the present WHO guideline value of 1.5 mg/L (Tekle-Haimanot et al., 2006). It is estimated that up to 14 million people in the ERV depend on fluoride-contaminated water for drinking (Zewge and Emiru, 2011). Cases of dental and skeletal fluorosis are widespread (Tekle-Haimanot, 2005).

Although other sources of fluoride should not be neglected (Devotta et al., 2007), drinking water is the most important dietary source of fluoride in Ethiopia (Scheidegger et al., 2011). Thus, provision of drinking water with naturally low fluoride concentrations is the fluorosis-mitigation option preferred by the Ethiopian government, which sees fluoride-removal technologies merely as interim solutions. However these technologies will be required for at least another decade until all rural communities are supplied with fluoride-free water from alternative sources of sufficient capacity.

Water providers generally prefer community-level over household-level defluoridation systems because of lower monitoring and maintenance costs and because, unlike microbial contamination, there is no risk of recontamination during transport and storage. Five community-level fluoride removal technologies (Table 1) have been implemented in Ethiopia to date. These are:

- Activated alumina (AA): Starting in the late 1960s six fluoride-removal filtration units were installed in the Wonji sugar estate

* Corresponding author at: Desert Rose Consultancy, Kirkos Subcity, P.O. Box 70977, Addis Ababa, Ethiopia. Tel.: +251 912 79 58 17.
*E-mail address:* lars.osterwalder@gmail.com (L. Osterwalder).

0048-9697/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.scitotenv.2013.10.072

**Table 1**
Fluoride removal technologies and implementation strategies considered.

| Technology | Technical details | Technical design | Mode of implementation |
|---|---|---|---|
| Activated alumina (AA) | Granulated form of aluminum oxide with large surface area, used as filter media. | One 5000 L treatment tank (plastic) containing 3800 kg activated alumina, central regeneration of spent material, raw water and treated water storage tanks of 5000 L each | The filter construction and promotion is done by a NGO and the filter is managed by a local water committee supported by the district water office. |
| Bone char (BC) | Charred, crushed and washed animal bones, used as filter media. | One 5000 L treatment tank (plastic) containing 3500 kg bone char, central regeneration of spent material, raw water and treated water storage tanks of 5000 L each | The filter construction and promotion is done by a NGO and the filter is managed by a local water committee supported by the district water office. |
| Contact precipitation (CP) | Bone char and calcium-phosphate pellets are mixed and used as filter media. | Two 2000 L treatment tanks (plastic) both containing a first layer with 900 kg filter media (pellets to bone char 3:1) and a polishing layer with 300 kg (bone char only), flow interchangeable between the tanks, spent material sold as fertilizer, raw water and treated water storage tanks of 5000 L each | The filter construction and promotion is done by a NGO and the filter is managed by a local water committee supported by the district water office. |
| Nalgonda technique (NT) | Alum and lime are added to the water in a treatment tank, stirred rapidly and then let to settle. | One 4000 L treatment tank (stainless steel) fitted with an electrical stirrer, raw water and treated water storage tanks of 5000 L each, 1500 kg raw chemicals delivery at the time | The Nalgonda unit construction and promotion is done by a NGO, managed by a local water committee and operated by an employed local technician, supported by the district water office. |
| Reverse osmosis (RO) | A synthetic semi-permeable membrane removes all contaminants. | High-quality unit with a treatment capacity of 750 L/h, raw water and treated water storage tanks of 5000 L each | The reverse osmosis unit is installed by a NGO and managed by a private service provider located in a nearby town. |

using AA as the filter media (Tekle-Haimanot, 2005). The efficiency of the units deteriorated after 2001 and they were finally abandoned after the sugar estate gained access to the piped water supply system of Adama town.

- Nalgonda technique (NT): Research at Addis Ababa University in the early 2000s suggested that the NT may be the most appropriate technology for rural Ethiopia (Tekle-Haimanot, 2005), and several dozen community units have been installed since 2004. However, after half a decade many units have been found to be unused or non-functional. In 2011 the National Fluorosis Mitigation Project Office (NFMPO) analyzed the short-comings of the units and installed three new NT units using an improved design.
- Bone char (BC): The Oromo Self-Help Organization (OSHO), in collaboration with Swiss Interchurch Aid (HEKS) and the Swiss Federal Institute for Aquatic Science and Technology (Eawag), initiated the implementation of community filters using BC. Initially, BC was imported from Kenya (Johnson et al., 2011) and in 2011 OSHO started local production in Ethiopia.
- Contact precipitation (CP): This technology, combining bone char and calcium-phosphate pellets, was developed by the Water Quality Program of the Catholic Diocese of Nakuru, Kenya (Mutheki et al., 2011). CP was introduced to Ethiopia by OSHO with the support of HEKS and Eawag.
- Reverse osmosis (RO): A few privately operated reverse osmosis units have been installed in the Ethiopian Rift Valley, providing fluoride-free drinking water to the surrounding communities.

All five technologies described above are readily available for implementation. However, many concerns have been raised by different stakeholders about why certain technologies are not suitable for the Ethiopian context. These include, for example, high costs and maintenance difficulties for AA and RO; problems with electrical stirrers and missing chemical supply chains for NT; and rejection of BC and CP for cultural and religious reasons. Currently, only a few properly working fluoride removal units can be found in the field. The discussion about which technology should be promoted and up-scaled is the subject of controversial debate amongst key stakeholders in Ethiopia. We believe that a comprehensive assessment of different technologies based on the principles of social acceptance, affordability and accessibility, with the involvement of stakeholders, will be a key to the success of any national fluorosis mitigation strategies.

Multi-criteria decision analysis (MCDA) methods are increasingly being used to facilitate stakeholder involvement in technology-selection processes and in decision support (Coelho et al., 2012; Karvetski et al., 2009; Prato and Herath, 2007; Reichert et al., 2013; Weng et al., 2010). The advantage of MCDA is that it is interactive and facilitates transparent and participatory assessment. By open dialog and negotiation, different viewpoints and possible conflicts of interests between stakeholders can be identified. The MCDA approach can foster collaboration and learning in a situation in which a diversity of interests are openly represented. During the process, participants' knowledge and preferences evolve as the result of accessing to complete information on pros and cons of certain technologies. With the assistance of a computer-aided spreadsheet, stakeholders can visualize how their opinions are reflected in the ranking of different suitable fluoride removal technologies. Such an understanding has proven important for effectively involving of stakeholders in the MCDA process (Hostmann et al., 2005; Stefanopoulos et al., 2014; Karjalainen et al., 2013). In the case of fluoride removal in rural Ethiopia, the existence of different technologies and diverse views among stakeholders on the technical feasibility of options warrants a need to conduct a MCDA analysis to facilitate the selection of technology options most suitable to the local conditions.

There are different approaches in the MCDA family. The selection of commonly used approaches, which include Multi Attribute Value Theory (MAVT), Multi Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP) and Simple Multi-Attribute Rating Technique (SMART), depends on both the nature of the question and the experience and educational level of the stakeholders involved (Kiker et al., 2005). The MAVT is one of the most commonly used approaches, partly because it has conceptually straight forward procedures that are relatively easily understood (Karjalainen et al., 2013).

This study applies the MAVT approach to evaluate the technological options for Ethiopia with involvement of stakeholders. The analysis presented in this paper is based on three hypothetical cases that are generally representative of the prevalent situations in rural communities in the ERV. For each case, the suitability of the currently available fluoride removal technologies was assessed in a MAVT exercise at a workshop held in April 2012 by the authors together with the local collaborators and stakeholders. Key criteria and quantitative aspects of each technology ('attributes') were estimated in consultation with sector stakeholders. Due to limitations in the

Please cite this article as: Osterwalder L, et al, Multi-criteria assessment of community-based fluoride-removal technologies for rural Ethiopia, Sci Total Environ (2013), http://dx.doi.org/10.1016/j.scitotenv.2013.10.072