

## COMPARING DEFLUORIDATION AND SAFE SOURCING FOR FLUOROSIS MITIGATION IN THE ETHIOPIAN CENTRAL RIFT VALLEY

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**SUMMARY:** In the Ethiopian Central Rift Valley (ECRV) an estimated 8 million people are exposed to high levels of naturally occurring fluoride. Consumption of drinking water, beverages, and food puts them at risk of dental and skeletal fluorosis. This paper describes the outcomes of a study comparing the efficacy of the two main mitigation measures, defluoridation and safe sourcing, in terms of sustainability, cost-effectiveness, and vulnerability. The study's outcomes suggest that sourcing drinking water from safe sources is the preferred approach, because it reduces management burden and enables wider coverage. When safe sources are absent, community based bone char fluoride removal systems are proven to be a good alternative. Community involvement before the project is implemented plays a crucial role in the success of defluoridation.

**Keywords:** Defluoridation; Ethiopia; Fluoride; Fluorosis mitigation; Safe sourcing.

### INTRODUCTION

Fluorine is a common element, widely distributed in the earth's crust. It exists as the Bach anion fluoride (F<sup>-</sup>) in natural waters, with higher concentrations often prevailing in ground water.<sup>1</sup> Although the evidence that topical fluoride (F) has a protective effect against dental caries is considered to be strong, the scientific evidence that the systemic application of F via drinking water is beneficial is less convincing.<sup>2</sup> Doses of F over 0.1 mg F/kg body weight/day weaken the skeleton and teeth.<sup>3</sup> According to UNESCO<sup>4</sup> more than 200 million people worldwide rely on drinking water with F<sup>-</sup> concentrations exceeding the present World Health Organization (WHO) guideline of a "desirable" upper limit of 1.5 mg/L.<sup>5</sup> Long-term consumption of this water can lead to severe health effects like dental (DF) and skeletal fluorosis (SF).<sup>3,6,7</sup> In 2006, the WHO listed 28 countries where the prevalence of the diseases DF and SF is a consequence of a long-term consumption of drinking water with high levels of F. Among these, the most affected countries are India, Ethiopia, and China.<sup>3,8</sup>

Fluorosis does not only affect people's health; it also has serious economic and social consequences. For instance, appearance-related and psychological problems are caused by the repulsive effect of dental fluorosis, particularly among the youth. The prevalence of fluorosis and the related widespread health problems stigmatize entire villages.<sup>9-12</sup> Studies have shown that the prevalence of dental fluorosis in the Ethiopian Central Rift Valley (ECRV) is above 80%.<sup>1,7,12</sup> It is difficult to obtain accurate prevalence figures for skeletal fluorosis because of the wide symptomatology, which ranges from mild radiological evidence to crippling fluorosis with or without neurological manifestation. Estimations set the

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prevalence of skeletal fluorosis at 40 to 50% among inhabitants living in areas where groundwater sources are characterized by high F concentrations.<sup>7,10,12</sup> People with skeletal fluorosis are forced to retire early from working life and become dependent on others. Melkau and Shabbir describe this scenario in their study involving local employees at the Wonji sugarcane factory (Ethiopia) between 1976 and 1984.<sup>10</sup>

The fluoride levels in the waters of the Ethiopian Central Rift Valley (ECRV) are amongst the highest in the world, putting some 8 million people at risk of developing fluorosis.<sup>6,7,13</sup> The ECRV is part of a larger basin that extends from Syria and Jordan to Malawi and Mozambique. Due to its geological and climatic characteristics, the ECRV has some of world's highest concentrations of F, found mainly in deep wells in the semi-arid parts of the region.<sup>14</sup> The main source of F in the ECRV is the presence of acidic volcanic rocks which have both high F and low soluble calcium concentrations. Over 40% of deep and shallow wells are contaminated with concentrations up to 26 mg F/L.<sup>14</sup> However, the distribution of F in the deep wells is variable, even among wells that are closely spaced.

The options for reducing the F concentrations in drinking water include the provision of alternative surface-water supplies (river water, rainwater harvesting), dilution, groundwater treatment, or sourcing for alternative sources of safe ground water. The search for alternative safe sourcing is considered the most cost efficient in the Western experience, in particular in the United States.<sup>15</sup> In arid conditions, the range of alternative water sources is often limited, and defluoridation is the only option. Groundwater defluoridation options vary in scale (from household to community level), efficacy, sustainability, and user acceptance. Acceptance depends significantly on social problems experienced from fluorosis and on local beliefs, and experience has shown that awareness campaigns can play a significant role in determining acceptance.<sup>16</sup> Nonetheless, as alternative supplies of surface water and/or treatment technologies are not universally available, effective, or affordable, the security of supply is heterogeneous. The quality of raw local groundwater remains a critical factor in determining F exposure and access to safe sources of drinking water.

Little data is available regarding the current status of F mitigation programs implemented in the ECRV, their costs, benefits, and vulnerabilities. Furthermore, assessing the coverage of water supply schemes helps to explain how many people remain dependent on unreliable groundwater sources.

The main objective of this paper is to compare the two main approaches of fluorosis mitigation in the ECRV by analysing costs, benefits, and vulnerabilities of both defluoridation schemes (Nalgonda and bone char) and Multiple Village Water Supply Schemes (MVWSS).

#### *Water Access and Governance*

According to the latest publication of the National Fluorosis Mitigation Project Office (2013) in Ethiopia, the regions with excessive fluoride in groundwater are Afar, Oromia, and the Southern Nations and Nationalities Regional State

(SNNPR). All regions are located in the Ethiopian Rift Valley region of the Great African Rift Valley.

The study area of this project is the part of the ECRV located within the administrative borders of Oromia National Regional State and the Southern Nations, Nationalities and Peoples Region (SNNPR). Important sub-basins are Ziway-Shalla, Abaya-Chamo, and the Awasa catchment. Surface water sources contribute 38% of the annual water balance in this area.<sup>17</sup> Important lakes in the region are Ziway, Langan, Abijata, Shalla, Awasa, Abaya, and Chamo, some of which also have high fluoride concentrations (Figure 1). Key rivers are Meki, Bulbula, and Ketar. Groundwater contributes 62% of the annual water balance.<sup>17</sup> Although appropriate sources of water are available in Oromia, only 50.2% of the rural population has access to an improved system of water supply within 1.5 km of their household.<sup>18</sup> According to the same report, 25% of the rural water schemes in Oromia Region are non-functional. However, an official report from the Oromia Water, Mines and Energy Bureau claims that current coverage is just above 70%.<sup>19</sup>



**Figure 1.** The lakes in the study area in the Ethiopian Central Rift Valley. Lakes: 1: Ziway, 2: Langan, 3: Abijata, 4: Shalla, 5: Awasa, 6: Abaya, 7: Chamo. Map from Wikipedia. Available from: [https://upload.wikimedia.org/wikipedia/commons/3/3c/Ethiopia\\_shaded\\_relief\\_map\\_1999%2C\\_CIA.jpg](https://upload.wikimedia.org/wikipedia/commons/3/3c/Ethiopia_shaded_relief_map_1999%2C_CIA.jpg)

Several policies at the national level (e.g., the Universal Water Access Plan, which targets fluoride control) and at the regional level (e.g., the National Fluorosis Mitigation Project, which establishes fluoride steering committees) were designed to manage impacts and map the prevalence of fluoride. The National Fluorosis Mitigation Project (NFMP), in collaboration with the Oromia and

SNNPR Water Bureaus, aims to map the distribution of fluoride, assess the chemical risk of water sources, and perform feasibility studies for alternative water supply.

Stakeholders such in non-governmental organizations (NGOs) (e.g., OSHO and CRS) and research institutes (e.g., Eawag and UNICEF) have carried out studies and piloted defluoridation schemes to test ways to supply low fluoride water in the ECRV. An overview of the experiences of the above-mentioned organizations is provided below.

In the ECRV, the low-income population relies on agriculture and cattle rearing as their main source of income. Access to water is limited. In vulnerable households, children and women are in charge of collecting water for their families, walking an average of 10 to 15 km per day.<sup>20</sup> During the dry season, access to water becomes even more problematic due to increased pressure on water sources and the lowered water tables, which lead to pump failure. However, communities do not always recognize the link between potable water and fluorosis. Cultural beliefs remain in place; for instance; some water users link dental fluorosis to the will of local spirits.<sup>21</sup> This awareness is changing thanks to the various intervention programs in the region.

#### **MATERIALS AND METHODS**

Data were collected on current fluoride mitigation programs implemented in the ECRV to understand the socioeconomic and institutional context of the water supply systems. Data collected concerned installation and operation and maintenance costs, benefits, and vulnerabilities of both defluoridation schemes and MVWSS. All defluoridation schemes are village sized and community owned. The safe sourcing schemes are multi-village sized and owned by the regional government, as low fluoride water sources are scarce and such systems are developed to serve multiple large areas simultaneously. Data were also collected on local acceptance, perceptions, and functionality (quality of the service) of the water supply systems. In addition, data were collected on the users understanding of water consumption patterns, the causes of fluorosis, and the reasons for drinking water supply failure. Through a cost-benefit-vulnerability analysis of defluoridation and safe sourcing schemes, this paper improves the understanding of challenges and opportunities of current fluorosis mitigation programs in the ECRV and hopes thereby to better inform decision making processes on what strategy is favourable in a given context.

The study utilized a qualitative method consisting of two different parts. The first was an expert consultation on the current state of art on fluoride mitigation in ECRV. The second consisted of field visits to the defluoridation sites and MVWSS and interviews with governmental, non-governmental, and non-profit stakeholders (Appendix 1).

Figure 2 shows the location of the ten defluoridation and five MVWSS surveyed. Defluoridation schemes included six community bone char filters implemented by Oromia Self Help Organization (OSHO), eight Nalgonda schemes developed by Catholic Relief Service (CRS) (half of which were non-functional), and two Nalgonda schemes developed by Lay Volunteer International



Association (LVIA) (both non-functional). The LVIA schemes were visited in order to understand the vulnerabilities of defluoridation schemes. As for MVWSS, water supply offices were visited in Adama, Ziway, Bulbula, Arsi Negelle, Siraro, and Shashamane.



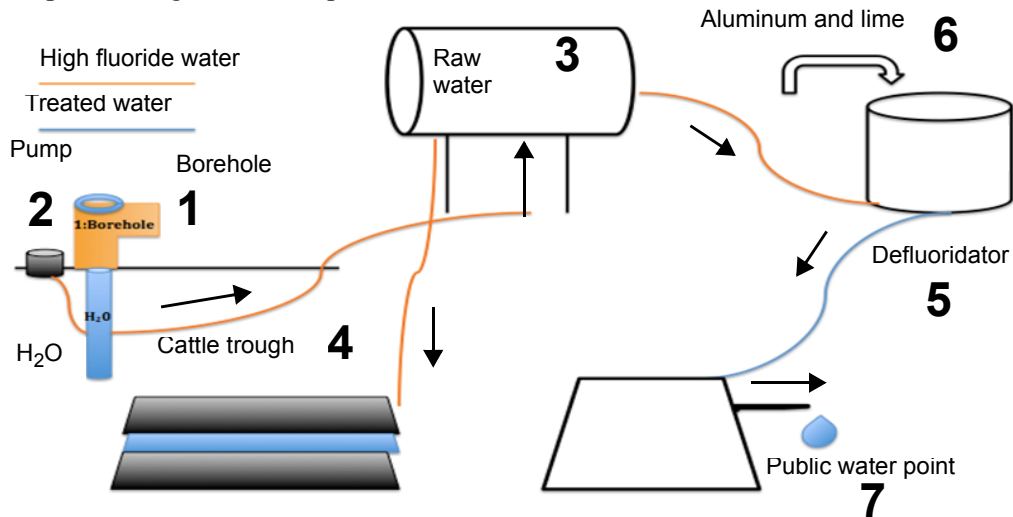
**Figure 2.** Study area: Defluoridation schemes and MVWSS, visited and not visited, in Ethiopian Central Rift Valley (Source: Google Earth).  
Symbols: 1 Lay Volunteer International Association (LVIA) Nalgonda scheme (non-functional, visited); 2 Catholic Relief Service (CRS) Nalgonda scheme (functional, visited); 3 Catholic Relief Service (CRS) Nalgonda scheme (non-functional, not visited); 4 Catholic Relief Service (CRS) Nalgonda scheme (functional, not visited); 5 Oromia Self Help Organization (OSHO) bone char scheme (functional, not visited); 6 Oromia Self Help Organization (OSHO) bone char scheme (functional, visited); 7 Single village water supply scheme (functional, visited); 8 Multiple village water supply scheme (functional, visited).

During the visits to both MVWSS and defluoridation schemes, interviews were conducted with water officers, local water users, and NGO project managers.

*Implemented fluorosis mitigation strategies:* In the ECRV, two main fluorosis mitigation strategies are in place: safe sourcing and community defluoridation schemes.

Since the discovery of high fluoride levels in drinking water in the ECRV in 1970, scientists have developed various ways to reduce the F- concentration in drinking water. At present, a wide range of techniques exists for F- removal.<sup>7</sup> The most common defluoridation techniques are absorption, precipitation, coagulation and membrane processes. Ion exchange and/or adsorption are widely accepted technologies used on a full-scale basis in various countries worldwide.<sup>3,4</sup> Although multiple technologies have been developed, the Nalgonda and bone char techniques are the most widely implemented at the local level, as seen in Kenya, India,<sup>22</sup> and Ethiopia.<sup>23</sup> The Ethiopian government is also investing in the search for alternative safe sourcing and in up scaling the existing safe sourcing schemes through the multi-village water supply schemes.

*Nalgonda:* The Nalgonda technique was developed and adapted in India by the National Environmental Engineering Research Institute (NEERI) to be used at either community or household level. It uses the process of aluminum sulphate based coagulation-flocculation-sedimentation, where the dosage is designed to ensure F- removal from the water. In Ethiopia, under the fluorosis mitigation project promoted by UNICEF and the Federal Water and Energy Ministry, the Nalgonda technique has been piloted in several rural communities. CRS has been implementing this technique in communities in the ECRV since 2005.



**Figure 3.** Nalgonda defluoridation scheme. Water (H<sub>2</sub>O) from a borehole (1) is pumped by a pump (2) to a raw water storage tank (3) from which some untreated high fluoride water is piped to a cattle trough (4) while some is piped to a defluorinator (5) where aluminum and lime are added (6) after which the water is distributed to a public water point (7)

Over the last 10 years, 20 Nalgonda systems have been installed in the ECRV. Half of them are no longer functional, and some of them were never used. The Nalgonda functioning schemes are those implemented by CRS (in cooperation with the National Fluoride Steering Committee, NFSC). Some NGOs that tried to establish Nalgonda systems faced several constraints.

In the following section, an account of the Nalgonda implementation experience of CRS is presented. In Dodo (Bora woreda) an 85 m deep borehole pumps  $F^-$  rich water into a 10 m<sup>3</sup> water tank. This raw water is then diverted into the defluoridator (Figure 3, number 5) where the technician treats it with aluminum sulphate and lime. This tank has a steer root to mix the chemicals. This process takes five minutes. After the mixing, flocculation occurs over three to four hours. The treated water is then released to the common water point. On the other side, a cattle trough is attached to the raw water tank.

*Bone char:* The bone char technique uses a locally produced filter media of activated carbon and hydroxyl apatite (using bones collected from local butchers, mainly from cows). In Ethiopia, OSHO as implemented this technique. The community-level projects were financed by British and Swiss foundations and supported with the technical, economic, and social expertise of Eawag and Swiss Inter-Church Aid (HEKS).<sup>23</sup>

Bone char filters are made of grained cow bones. The factory processing the filters is based in Mojo (15km north of Adama), established through an Eawag project fund. OSHO's first experience with defluoridation technology was the introduction of household size bone-char filters. However, the 200 target households rejected the bone-char filters. The main reason for this rejection was the dependency on external assistance to frequently test the functioning of the filter. Figure 4 depicts a household bone char filter unit and its functions. The household bone char filter is made of two blue plastic baskets. The raw water basket has a 15L capacity. Filtered through a layer of bone sand (3kg), the water drips into the second tank. This process takes about 30 minutes. Users can keep the process going if they keep refilling the first tank with raw water. Lessons learned were integrated in a new design for bone char filters at the community level.

There are currently seven community bone char schemes implemented by OSHO in cooperation with Eawag benefitting over 3,000 households. Eawag, OSHO, and Nakaru Catholic Foundation (NCF) highlight that this is the most sustainable set-up in a rural context in developing countries, as it is fairly low-tech and can be assembled using locally available material, decreasing the need for external assistance (Figure 5).

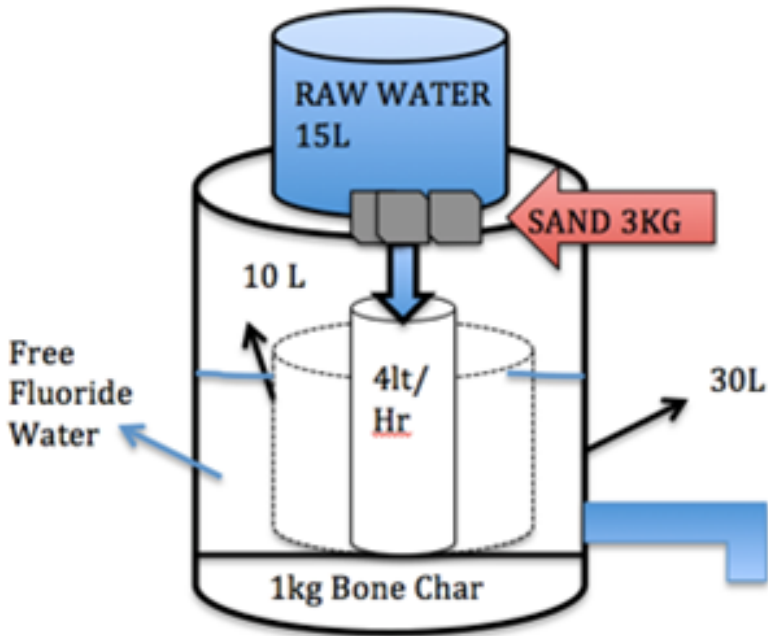


Figure 4. Household bone char filter.

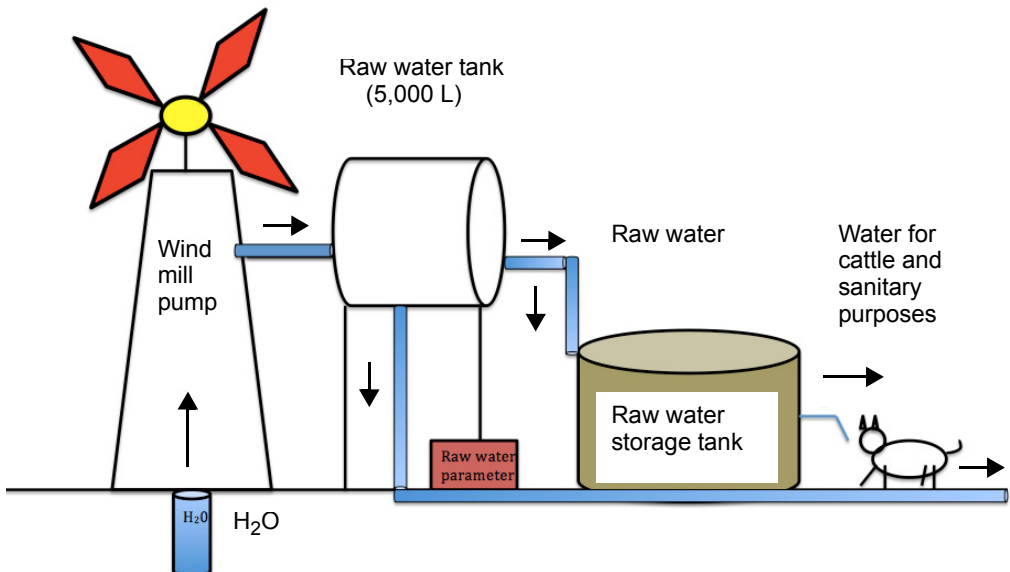
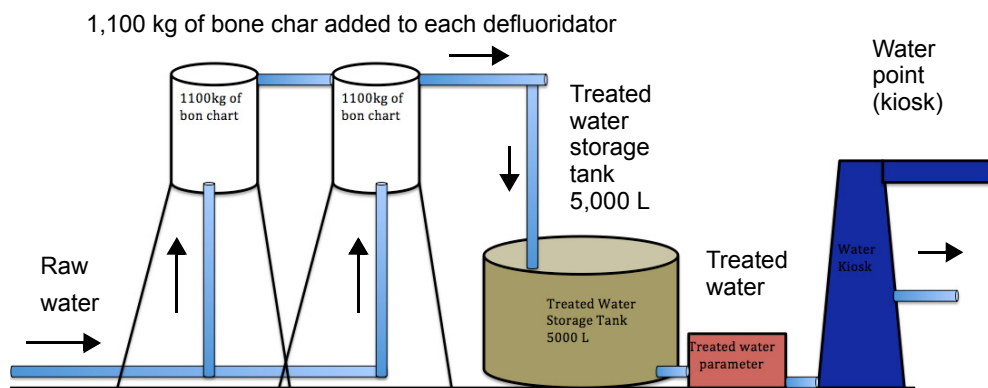


Figure 5A. Community bone char defluoridation scheme. The raw water is pumped from a bore by a wind mill pump and stored for use for cattle and sanitary purposes or piped to the bone char defluoridators.





**Figure 5B.** Community bone char defluoridation scheme. After the raw water is pumped from a bore by a wind mill pump to a 5,000 L raw water tank it is piped to two defluoridators, each containing 1,100 kg of bone char, and then to a 5,000 L treated water storage tank which supplies the water kiosks.

*Multiple village water supply schemes:* At present, five MVWSS are in operation in the study area of the ECRV: Adama, Ziway, Bulbula, Arsi Negelle/Siraro, and Shashamane. Adama, Ziway, and Shashamane are urban water supply schemes, which, according to their design, aim to supply mainly urban dwellers, but currently they are also serving rural kebeles. Bulbula, Arsi, and Negelle/Siraro are rural water supply schemes. The Bulbula Rural Water Supply Project aims to supply rural communities in 13 villages, including Bulbula town, with a fluoride-free water supply system. The Arsi Negelle/Siraro Water Supply Project supplies rural communities in three woredas with a fluoride-free water supply system (Arsi Negelle, Shashamane, and Siraro woredas). Siraro is now located in the newly created woreda of ‘Shalla’. A new MVWSS, ‘Oromia Lakes Region Water Supply Project,’ is currently under construction. It aims to supply safe drinking water to Arsi Negelle, Shalla, Shashamane, and Siraro woredas through a 170 km distribution network (with 57 water points and 23 cattle troughs).

These MVWSS are supported at the regional level by the Water, Mines, and Energy Bureaus of Oromia and SNNPR, which have invested in safe sourcing strategies to deal with the high fluoride concentrations and extend safe water supply coverage to remote rural communities. The MVWSS were constructed over several years, and have been extended and renovated over time. For instance, the MVWSS in Adama was built in 2002 and extended to Wonji/Shoa villages, located 5 km south of Adama, in 2006. Supply-demand ratios do not lead the planning of MVWSS (Table 1). Three of the five MVWSS use low fluoride water from lakes or rivers and are equipped with a treatment facility. Bulbula and Arsi Negelle/Siraro rely on groundwater derived from springs and boreholes. The number of connections differs from scheme to scheme. All water offices report that water users have to pay for a private connection, while users of public water points are not charged.

**Table 1.** Main characteristics of multiple village water supply schemes (MVWSS).

Multiple village water supply scheme	Year of implementation	Source of water	Current total length of pipes including branches to each water point (km)	Treatment plant	Design criteria: number of users benefiting from MVWSS	Current number of water users benefiting from MVWSS
Adama extension to Wonji/Shoa water scheme	2002	Awash River	DNA*	Yes	200,000	295,000 out of a total population of 422,000
Ziway water scheme	2002	Ziway Lake	85	Yes	20,000	41,420 out of a total population of 43,610
Bulbula water scheme	2008	Tufa Spring + 3 springs	111	No	–	73,000
ArsiNegelle/Siraro water scheme	1995 - 1998	13 wells drilled; 10 are productive	153	No	120,000	257,000
Shashamane water scheme	2010 boreholes 1999 Wesh river	Wesh river + 2 boreholes	DNA*	Yes	–	160,000 out of a total population of 300,000
Current total number of water users benefiting from MVWSS						826,420

\*Data not available.

*Costs, benefits, and vulnerability:* Sixty randomly selected water users were interviewed. An average of seven beneficiaries at each water defluoridation scheme and MVWSS were interviewed, among whom three were women. Data on the reasons for failure, water consumer patterns, and perception of the fluoride problem were collected.

Six parameters were used to calculate the costs for both types of schemes: (i) initial investment costs; (ii) total operational costs; (iii) investment costs per m<sup>3</sup>; (iv) operational costs per m<sup>3</sup>; (v) profit per m<sup>3</sup>; and (vi) water tariff.

The benefits were calculated by identifying the number of beneficiaries per defluoridation scheme and MVWSS. The number of beneficiaries includes daily water users from the communities and irregular users from external kebeles. This indicator estimates the population with access to low-fluoride water.

The vulnerability of the schemes was measured by calculating the reliability of the water supply. The local community expressed that a waiting time of more than 15 minutes was unreliable. Furthermore, NGOs implementing defluoridation plans were visited, such as CRS, OSHO, and LVIA.

## RESULTS

### MULTIPLE VILLAGE WATER SUPPLY SCHEMES (MVWSS)

*Costs:* Collecting data on the costs of individual MVWSS proved difficult because of the absence of systematic and standardized financial reports. In Table 2 an estimation of the total operation costs is presented, based upon which the profit and monthly return on investments could be estimated.

**Table 2.** Investment and operational costs for multiple village water supply schemes

Multiple village water supply scheme	Initial investment cost (Birr)	Total operational costs* (Birr/yr)	Investment cost <sup>†</sup> (Birr/m <sup>3</sup> )	Operational cost (Birr/m <sup>3</sup> )	Profit <sup>‡</sup> (Birr/m <sup>3</sup> )	Water tariff (Birr/m <sup>3</sup> )
Adama extension to Wonji/Shoa water scheme	110,000,000	5,450,000	1.63	1.61	2.44	4.05
Ziway water scheme	29,500,000	4,474,203	1.17	3.55	2.45	6
Bulbula water scheme	26,000,000	3,000,000	0.19	0.43	9.57	10
ArsiNegelle/Siraro water scheme	48,000,000	3,696,000	15.22	23.44	-9.44	14
Shashamane water scheme	60,000,000	8,622,185	3.40	9.77	-5.27	4.50

\*The maintenance, chemical, and electricity costs are summed together to give the total operational costs. The total operational costs were calculated using the data available. Not all schemes had discrete data available for electricity, maintenance, chemical, and management costs. In these cases, estimations were made.

<sup>†</sup>The return of the investment cost was calculated over the life span of the system (20 years).

<sup>‡</sup>The profits may not represent the actual reality on the ground as management issues, such as illegal connection and non-revenue water, were not allowed for in the calculations.

The Arsi Negelle/Siraro scheme required the largest investment per m<sup>3</sup> (15.22 Birr/m<sup>3</sup>) compared to the other schemes (Table 2). This significant difference is probably due to the cost of drilling 10 wells (180–200 meters deep) as the main source of water.

Operational cost typically ranges between 0.43 and 3.55 Birr/m<sup>3</sup> (1 Euro: 26.8 Birr: 1 April 2014 used as the basis of computation). However, operational costs increase significantly when there are power cuts requiring the use of generators. Water operators in Arsi Negelle/Siraro and Shashamane, in particular, frequently experience power cuts, which is reflected in the higher operational costs, 23.44 and 9.77 Birr/m<sup>3</sup> respectively. The operational costs in the scheme of Arsi

Negelle/Siraro are further boosted due to (i) the need to treat intake water from Wondo River and (ii) the high maintenance burden (leaks and breaks) in this particle multiple village water supply scheme. The highest total operational costs are seen in Shashamane's multiple village water supply scheme. This is due to the high costs of chemicals used to treat water from Wondo River. These chemicals are all imported, except for aluminum sulphate. Furthermore, leaks and breaks in the water supply system require constant maintenance.

Water tariffs have also been raised to cover increased operational costs. In Arsi Negelle/Siraro, for example, a higher water tariff of 14 Birr/m<sup>3</sup> is now in place. However, the higher operational costs are not calculated in the water tariff in Shashamane (4.50 Birr/m<sup>3</sup>), explaining the loss posted by the Shashamane water utility.

*Benefits:* The number of people served by the MVWSS is large, ranging from 41,420 to 295,000 per system (Table 1). In each of the six MVWSS, water users from rural kebeles come to fetch water from public water points. In Adama, in addition to serving urban water users, the multiple village water supply scheme is also used by four rural kebeles. Every day, women, children, and cattle fetch water from Adama water points. The same happens in Ziway, where external water users come from five rural kebeles. In Bulbula users are from four rural kebeles, in Arsi Negelle/Siraro users are from two rural kebeles, and in Shashamane users are from five rural kebeles.

Walking distances have shortened over time (from one hour to 30 minutes). With the extension of the safe water supply networks, more villages that previously had to rely on unsafe groundwater sources, such as Wonji/Shoa, are now able to access microbiologically chemically acceptable low-fluoride water. During the fieldwork it was observed that the youth who consume water from these water points no longer suffer from undesirable effects on their appearance related to dental fluorosis (such as mottled teeth).

*Vulnerabilities:* The main problems reported with MVWSS are water shortages, leaks, and issues related to daily operational and maintenance costs. According to the data collected as presented in Table 3, Adama (3 to 5), Bulbula (3 to 4), and Ziway (3 to 4) have faced the most instances of water shortage for the longest period of time. Exceptional conditions applied in Adama city, where road construction interfered with the water line system during the reporting period. All MVWSS deal with inadequate water supply as population growth has not been included in the original designs. Clean water supply in Adama and Shashamane woreda is only guaranteed for 70 and 53%, respectively, of the population.<sup>24</sup> As reported by water officers in these areas and in Ziway, more chemicals are needed to treat the increased pollution in Awash River. Daily maintenance of the pipeline, power cuts, and problems with old pipes are the main issues in these water supply schemes. In Bulbula, daily maintenance is needed due to frequent breakdowns of the new water pipeline structure, although a life cycle of 20 years was guaranteed. Pipes and lines need to be changed, but there are insufficient funds to complete the project.

**Table 3.** Vulnerabilities of multiple village water supply schemes

Multiple village water supply scheme	Frequency of water shortage per week	Main problems reported
Adama extension to Wonji/Shoa water scheme	3 – 5	<ul style="list-style-type: none"> <li>• Leaks, from 30% to 40%</li> <li>• Old pipes in the line</li> <li>• Daily maintenance due to (road) construction</li> <li>• Increase in cost of chemicals</li> <li>• All chemical additives except for alum are imported</li> </ul>
Ziway water scheme	3 – 4	<ul style="list-style-type: none"> <li>• Operation and maintenance costs increase of 30% to 50% (over the last five years)</li> <li>• Old pipes and increase of leaks along the main line</li> <li>• Increase in pollution</li> <li>• Increase in cost of chemicals</li> <li>• All chemical additives except for alum are imported</li> </ul>
Bulbula water scheme	3 – 4	<ul style="list-style-type: none"> <li>• The system's maintenance structure is unstable</li> <li>• Frequent bursts</li> <li>• Daily maintenance needed due to frequent breakdown</li> <li>• The structure is of low quality (the system is quite new; a life cycle of 20 years was guaranteed).</li> <li>• Pipes and lines need to be changed, but at the moment there are not enough funds to do that</li> <li>• Leaks</li> </ul>
ArsiNegelle/ Siraro water scheme	2	<ul style="list-style-type: none"> <li>• Breaking pipes (3 to 4 times per week)</li> <li>• Leaks</li> <li>• Old pipes (13 years old)</li> <li>• Water pollution</li> <li>• Dirty pumps, water gets stuck</li> <li>• Interruptions in power supply</li> <li>• Water users complain about the high costs of supply</li> </ul>
Shashamane water scheme	1	<ul style="list-style-type: none"> <li>• All chemical additives except for alum are imported</li> <li>• Not enough water for the whole community</li> <li>• People use Wondo river when they face water shortages; this is a health risk</li> <li>• Illegal connections</li> <li>• Power interruptions (at least once a week)</li> <li>• Lack of transportation facilities</li> <li>• People tend to emigrate</li> </ul>

\*No water available for two hours or more.

## DEFLUORIDATION SCHEMES

*Costs of defluoridation schemes:* Table 4 provides an overview of the finance and operational costs of defluoridation schemes, including initial investments, and operational costs (in total and on a per m<sup>3</sup> basis), the treated water tariff, and profits (per m<sup>3</sup> and per month). All schemes visited had access to either a motorized or windmill driven shallow well. An overview of the costs of developing a water source are considered in Table 5.

**Table 4.** Investment, operational costs, and profit for the defluoridation schemes

Type of defluoridation scheme	Initial investment (Birr)*	Investment cost (Birr/m <sup>3</sup> ) <sup>†</sup>	Total operational costs (Birr/month) <sup>‡</sup>	Operational costs (Birr/m <sup>3</sup> )	Treated water tariff (Birr/m <sup>3</sup> )	Profit (Birr/m <sup>3</sup> )	Profit per month (Birr)
Nalgonda community <sup>§</sup>	560,000	8.52	8,449	15	11	-0.65	-349
Bone char community with fuel <sup>  </sup>	543,418	7.44	7,852	13	22	9.91	5,948
Bone char community wind-powered	543,418	7.44	2,852	4	20	15.24	9,148
Household bone char <sup>**</sup>	5,710	0.62	816	10	20	NAD <sup>††</sup>	NAD

\*For all three community defluoridation schemes the initial investments included the costs to develop a motorized shallow well. Furthermore, these data were reported considering the initial investment to set up the entire scheme (water tanks, pipe line, kiosk and water storage).

<sup>†</sup>The value is calculated considering a life span of Nalgonda and bone char schemes of ten years.

<sup>‡</sup>For the Nalgonda schemes, the total operational costs include: salary of water caretakers, fuel, guard salaries, and chemicals. For the community bone char schemes, the costs include: the water caretaker salary, maintenance, regeneration, and sampling. For the household unit bone char systems, the operational costs only consist of regeneration and sampling.

<sup>§</sup>As implemented by the Catholic Relief Service (CRS) and the Lay Volunteer International Association (LVIA). The data were collected from their reports and during the interviews. The calculations are based on the average costs and profits of the Nalgonda schemes, as constructed by both organizations.

<sup>||</sup>As implemented by Oromia Self Help Organization (OSHO). The data were collected during interviews.

\*\*Household bone char systems are managed at the household level so that profits do not apply.

<sup>††</sup> NDA: No data available.

**Table 5.** Costs of developing a water source.

Type of single water supply scheme	Initial investment (Birr)
Hand dug well	From 10,000 to 30,000 Birr
Motorized shallow well of 100 m depth*	Up to 500,000 Birr
Motorized deep well of 250 m depth*	From 1,200,000 to 1,500,000 Birr
Spring protection	Up to 50,000 Birr



In a community defluoridation scheme, the development of a water source comprises the major part of the initial investment costs while also having a direct influence on the operation costs. As household bone char filters do not require well development, the initial investment costs are much lower.

According to Table 4, which summarizes the data collected in the field, household bone char filters cost the least to the community members. However, they are not in use anymore.

Table 4 shows that the initial investment costs for Nalgonda systems are higher than those of bone char systems (8.52 versus 7.44 Birr/m<sup>3</sup>) while their treatment capacity is lower. On top of that, the operational costs of Nalgonda systems are also higher because of the relatively expensive chemicals required. Fuel costs involved in both community bone char and Nalgonda treatment methods contribute to operational costs. For this reason, bone char systems with windmill-powered pumps have lower operation costs as reflected in the water tariffs (4 Birr/m<sup>3</sup> for windmill-powered pumps compared to 6 Birr/m<sup>3</sup> for motorized pumps using fuel).

The Nalgonda systems reviewed had lower water tariffs than the bone char systems. However, this price did not reflect real operation costs, as the chemical used were subsidized by the government.

The NGO's operating community bone char systems are able to profitably exploit these systems, while in Nalgonda systems costs and income balance each other. In community bone char systems, returns on investment can be expected within 4 (windmill driven) to 7 (engine driven) months.

*Benefits:* According to the collected data, defluoridation schemes provide 39,865 people with access to low-fluoride water (Table 6).<sup>24</sup> Both the Nalgonda and community bone char schemes serve some 4,000 households in the ECRV. Almost one quarter of the beneficiaries do not live in the village with the defluoridation scheme, but come from neighboring kebeles in search of low-fluoride water.

The use of kiosks (in the OSHO schemes) and the involvement of *eder* (in the CRS schemes) are essential for the performance of both systems. *Eder* is a traditional social institution, established with the mutual agreement of community members, to help whenever community members face adverse situations. People voluntarily choose to participate.

OSHO developed a kiosk at which the water caretaker sells treated water and other items. In this way, the caretaker's commitment increases, because it is in his/her interest to stay at the kiosk and cater to customers.

**Table 6.** Benefits and vulnerabilities of defluoridation schemes

	Type of defluoridation scheme	
	Nalgonda	Bone char
Household coverage (Each rural household has 5.0 people on average)	<ul style="list-style-type: none"> <li>• 3,000 households</li> <li>• 1,000 households from external kebeles</li> <li>• Total: 4,000 Households</li> </ul>	<ul style="list-style-type: none"> <li>• 2,973 households</li> <li>• 1,000 households from external kebeles</li> <li>• Total 3,973 Households</li> </ul>
Total coverage per scheme (users)	20,000	19,865
Total unique coverage	39,865 persons covered by Nalgonda and bone char defluoridation schemes	
Management arrangements	<p>A good water committee needs to follow all the steps</p> <ul style="list-style-type: none"> <li>• Technicians need to be trained to know the quantity of the chemicals to be added</li> <li>• Caretaker should live near the treatment scheme to control the process</li> <li>• Costs of chemicals are high. If not subsidized the system will hardly be sustainable in the long term</li> </ul>	
Actual reduction of F	30% to 40% fluoride removal 0.7–3.7 (mg/L)	40% to 50% fluoride removal until 2.3–4.7 (mg/L)
Number of days per week customers experience water shortages	2–3	1
Other vulnerabilities	<ul style="list-style-type: none"> <li>• Sludge disposal. During the rainy season, the tank collecting the wastewater needs to be controlled to manage the risk of flooding.</li> <li>• At the beginning of the treatment, the water can taste salty</li> <li>• The treatment takes 4 hours. The location needs to be chosen carefully</li> <li>• Power outages</li> <li>• Breakdown of pumps</li> <li>• Leaks from the tanks</li> </ul>	<ul style="list-style-type: none"> <li>• Windmill breakdown</li> <li>• Leaks from the tanks</li> <li>• Power outages</li> <li>• Scarcity of fuel needed for the generator</li> </ul>
Side benefits	Involving eder can be a good strategy to enhance the involvement of the community	Dual function kiosks, selling not only water but also other necessary items. Availability of raw materials

In both experiences (OSHO and CRS), location was key to the functioning of the system. Water points can be reached from the main road, and in the case of technical problems users do not have to wait long for repairs. However, the location is not 'central' for a person living in a remote rural area, which means walking long distances to access water. However, MVWSS are preferred when present within their area, as the water tariff is up to 16 birr/m<sup>3</sup> lower compared to the defluoridation schemes (as observed in Meki)

*Vulnerabilities:* The main vulnerabilities of Nalgonda systems pertain to both social and technical issues. The weekly water shortage is higher in the Nalgonda systems than in the community bone chars systems (two to three times per week compared to one). Other vulnerabilities reported are common to both schemes: power outages, leaks in tanks, breaking of pumps, etc. Specific limitations of Nalgonda systems pertain to technology and the management of these systems. They include the inevitable saline taste in the treated water, the long time required to treat the water, and the necessity of employing a well-trained caretaker to manage the administration of chemicals to the high-fluoride water during the treatment process.

The main limitations of bone char systems include the need to replenish the bone char every six months, the value of choosing an appropriate site and involving people, and the need for constant monitoring (monthly) of the quality of treated water.

This cost-benefit-vulnerability analysis of defluoridation and safe sourcing systems provides several insights into the efficacy of current programs and projects to mitigate fluorosis. The analysis identifies the common causes of failures, the socio-technical vulnerabilities, and profitability of the schemes (Table 7).

Cost-benefit analyses show that MVWSS are less costly than community defluoridation methods regarding water affordability (although investment costs are much higher). On the scale of vulnerability, both methods encounter daily operational problems, but problems with MVWSS are more likely to be fixed. For defluoridation schemes, community engagement is fundamental for long-term functioning, although full economic-managerial independence was not yet in place in the schemes visited. Regarding social benefits, MVWSS are able to reach more people than community defluoridation schemes (826,420 versus 39,865). However, community defluoridation schemes are vital in areas where other safe sources are unavailable, because they allow people to access low fluoride water. Nevertheless, there is an urgency to investigate opportunities to find sustainable safe sources of water for permanent sourcing or as a backup for multi village water community schemes. Considering an average of drinking/cooking water consumption in Ethiopia of 3,650 L per person per year (3.65 m<sup>3</sup> per person per year),<sup>25</sup> and taking the average of the water tariff for the community defluoridation schemes (18.25 Birr/m<sup>3</sup>) and MVWSS (7.71 Birr/m<sup>3</sup>), the cost per person per year is much lower for safe sourcing with MVWSS (28.14 Birr/person/year) than for CDS (66.61 Birr/person/year).

**Table 7.** Benefits and vulnerabilities of multiple village water supply schemes (MVWSS) and community defluoridation schemes (CDS)

Scheme	MVWSS	Nalgonda CDS	Bone char CDS
Investment costs	4.32 (Birr/m <sup>3</sup> )	8.52 (Birr/m <sup>3</sup> )	7.44 (Birr/m <sup>3</sup> )
Operational costs	7.76 (Birr/m <sup>3</sup> )	15 (Birr/m <sup>3</sup> )	8.5 (Birr/m <sup>3</sup> )
Water tariff (unsubsidized)	7.71 (Birr/m <sup>3</sup> )	11 (Birr/m <sup>3</sup> )	20 (Birr/m <sup>3</sup> )
Fluoride removal efficacy	F is either absent or lower than 1.5mg/L	30% to 40% fluoride removal until 0.7–3.7 (mg/L)	40 to 50% fluoride removal until 2.3–4.7 (mg/L)
Main vulnerabilities	<ul style="list-style-type: none"> <li>Leaks</li> <li>Old pipes in the line</li> <li>Increase in cost of chemicals</li> <li>Pollution</li> <li>Dirty pumps, water gets stuck</li> <li>Interruptions in power supply</li> <li>Water users complain about the high costs of supply</li> </ul>	<ul style="list-style-type: none"> <li>Electricity breakdown</li> <li>Breakdown of pumps</li> <li>Sludge disposal</li> <li>Long time for filtering</li> <li>Salty taste of the water</li> </ul>	<ul style="list-style-type: none"> <li>Windmill breakdown</li> <li>Leaks from tanks</li> <li>Electricity cuts</li> <li>Not enough fuel for the generator</li> </ul>
Management arrangements	<ul style="list-style-type: none"> <li>Good management of the scheme is required</li> <li>Local Water Officers need to be constantly active in solving the operational and maintenance issues</li> <li>Problems between authorities might occur because of water boundary disputes</li> <li>Involvement of NGOs in management</li> </ul>	<ul style="list-style-type: none"> <li>A good water committee needs to follow all required steps</li> <li>Involving elder can be a good strategy to enhance the involvement of the community</li> <li>Technicians need to be trained to know the quantity of chemicals to add</li> <li>Caretakers should live near the treatment scheme to control the process</li> <li>Costs of chemicals are high. If not subsidized, the scheme will not be sustainable in the long term</li> </ul>	<ul style="list-style-type: none"> <li>Good to introduce kiosks with double functions not only selling water but also materials</li> <li>Constant monitoring and water quality tests need to be conducted by external organizations</li> <li>Necessity of training, awareness, and social operators</li> </ul>
People covered by each scheme	826,420	20,000	19,865
% covered by all schemes	95.40%	2.31%	2.29%

## DISCUSSION AND CONCLUSIONS

The following lessons can be learnt to assist agencies in their mission to provide chemical, and microbiological, acceptable water to rural communities in the ECRV.

The first lesson is to develop MVWSS from the randomly distributed, chemically acceptable water resources located in the ECRV. This study shows that these systems hold the potential to generate the required impact at the necessary scale to serve a population of over 15 million and to be more affordable than community defluoridation schemes. Such systems have shown the capability to source low-fluoride water and distribute it in a safe and cost effective way over large groups of consumers. They also serve a wide variety of rural households, as they attract people from the target communities as well as from remote rural areas. Attention should be paid to the profitability of MVWSS. The community bone char systems in operation are able to break-even and even make a small profit after covering the costs. In Nalgonda systems, on the other hand, the operational costs invariably outweigh income. In engine-powered community bone char systems, returns on investment can be expected within 7 months. Windmill-powered ones can expect returns within 4 months.

The costs of the repairs associated with frequent breakdown of pipelines, use of diesel generators during power outages, and increased pre-treatment costs of sourced low fluoride water are currently not reflected in the water tariffs, but are borne by the water bureaus. To enhance the sustainability of MVWSS it is necessary that their designs take into account possible environmental and social risks, such as drought and increase in water demand from consumptive and productive uses. These future vulnerabilities need to be factored into an integrated plan that connects climate change resilience with pollution prevention and development of specific natural standards (filters for industries and environmental impact assessment).

The second lesson is that community defluoridation systems are appropriate for isolated communities that cannot be connected to MVWSS. Such systems can also be developed in regions facing clean water shortages. These schemes require a much lower upfront investment compared to large-scale water supply schemes, and are typically constructed by NGOs and charity organizations.

Integration of lessons 1 and 2 is restricted by the limited insights into the distribution of low-fluoride groundwater sources in the ECRV. This limits the possibility of an informed decision-making process that can help MVWSS (governments) and community-level water supply schemes (NGOs) serve communities better.

The third lesson is that the capacity of NGOs to connect with local institutions, norms, and needs is decisive for the long-term sustainability of community level defluoridation schemes. It has been observed that ongoing systems and programs intensively consult the community and the traditional leadership (*eder*) in the selection of the location of the system and the choice of the defluoridation method.

Malfunctioning or abandoned systems have often seen a general lack of community involvement and sense of ownership.

The fourth lesson is that NGOs hardly manage to make community level defluoridation schemes profitable and that the running costs for the purchase of expensive chemicals (in the case of Nalgonda systems, for example) and water sampling and replacement of filters (bone char) still have to be subsidized by the government. However, based on our analysis and considering only economics, when low fluoride sources are unavailable it is possible to conclude that bone char is cheaper than Nalgonda filters because of the lower operational costs involved.

The fifth lesson is that understanding the current strategies in place to deal with high fluoride concentration is as important as understanding the distribution of fluoride in groundwater. The integration of both findings is required in order to implement efficient and locally based fluoride mitigation strategies in the ECRV.

The sixth lesson is that the Ethiopian government, under the fluoride mitigation project, is making great efforts in carrying out multidisciplinary research on fluoride. At the same time, functionality of water schemes, operation and maintenance costs, and systematic water quality checks need to be carried out in a more integrated way.

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**Appendix 1.** List of interviewed stakeholders and topics discussed

Stakeholders interviewed	Topics
National/regional State level	1. Overview of: on-going activities and programs in safe sourcing and fluoride treatment, awareness and investments plans
<ul style="list-style-type: none"> <li>• Fluoride National Steering Committee</li> <li>• Ethiopia Water and Energy Ministry</li> <li>• Oromia Water and Mines Bureau</li> </ul>	2. Planned and discussed National fluoride programs for the future 3. National vs. international WHO water quality standards 4. Dental and skeletal fluorosis assessment
NGOs	1. Type of schemes implemented
<ul style="list-style-type: none"> <li>• Lay International Volunteer Organization</li> <li>• Oromia Self Help Organization</li> <li>• Catholic Relief Service</li> </ul>	2. Scheme selection rationale and efficacy of schemes 3. Scheme location criteria 4. Number of people served 5. Operation and maintenance costs 6. Investment costs 7. Actual fluoride reduction
Water officers at the Town/woreda level for multiple village water supply schemes	1. Implementation of the scheme
<ul style="list-style-type: none"> <li>• Adama</li> <li>• Meki</li> <li>• Ziway</li> <li>• Bulbula</li> <li>• ArsiNegelle/Siraro</li> <li>• Shashamane</li> </ul>	2. Number of people served 3. Investment costs 4. Operational and maintenance practices 5. Water quality 6. Management arrangements 7. Breakdown risks of the scheme 8. Side costs (such as sludge disposal and taste) 9. Additional benefits 10. Price of water charged 11. Main issues and challenges
Local communities	1. Uses of water within the community
<ul style="list-style-type: none"> <li>• Shirkanoketa</li> <li>• Qorobotojota</li> <li>• Dodo</li> <li>• Tejitu</li> <li>• Bofo</li> <li>• Graba File</li> <li>• Gura</li> <li>• KorkeAdi</li> <li>• Serity</li> <li>• W.Gabriel</li> </ul>	2. Reliability of water schemes, expressed as waiting time to fetch water (0-15; 15-30; 30-45; 45-60 and >60minutes) 3. Water consumption per household per day 4. Perception and acceptability of the de-fluoridation scheme 5. Willingness to pay 6. Water committee management 7. Coping strategies of the community during water shortage 8. community main source of water during dry and wet season