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Fluoride in groundwater:

Overview and evaluation of removal methods

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Summary

In this report information is given about methods for the removal of fluoride from groundwater. The methods can be used by domestic well owners and communal water suppliers. Based on available information, a matrix is composed to give an idea about the applicability of the methods for some given situations.

Fluoride removal methods

Methods	domestic + low costs	community + low costs	domestic + high F removal	community + high F removal	domestic + brackish water	community + brackish water
Activated Alumina	Orange	Orange	Green	Green	Red	Red
Ion exchange	Orange	Orange	Orange	Orange	Red	Red
Reverse osmosis	Red	Red	Green	Green	Green	Green
Electrodialysis	Red	Red	Red	Green	Red	Green
Nalgonda process	Green	Green	Red	Red	Red	Red
Contact precipitation	Orange	Orange	Orange	Orange	Red	Red
Bone Charcoal	Green	Red	Orange	Orange	Red	Red
Calcined Clay	Green	Red	Red	Red	Red	Red
Water Pyramid/Solar Dew	Orange	Orange	Orange	Orange	Orange	Orange

The colours in the matrix correspond with the appropriateness of the method for the given situation:

- Green colour means that the method is very suitable
- Orange colour means average suitability
- Red colour means that the method is unattractive or not applicable for the given situation.

The Nalgonda process, Bone charcoal and Calcined clay are low costs methods for domestic use. On a community scale, the Nalgonda process is also a low cost option. If a high fluoride removal is necessary then activated alumina, reverse osmosis and electrodialysis are preferred methods.
For brackish water only reverse osmosis, electrodialysis and the Water Pyramid/Solar Dew method can be used.

1 Introduction

1.1 Special projects of IGRAC

The International Groundwater Resources Assessment Centre (IGRAC) aims to facilitate and promote world-wide exchange of groundwater knowledge. IGRAC focuses on activities that are prompted by the international groundwater community.

IGRAC's special projects intend to collect, analyse and display information on specific groundwater issues relevant to development of groundwater resources on various scales. Occurrence of hazardous compounds in groundwater is one of these issues. In 2004, IGRAC reviewed available information about groundwater contaminated with fluoride and displayed the probability occurrence of fluoride on continental maps (Brunt et al, 2004).
In this report, an overview is given of fluoride removal methods.

1.2 Occurrence of fluoride

Fluoride is an ion of the chemical element fluorine which belongs to the halogen group. Fluoride has a significant mitigating effect against dental caries if the concentration is approximately 1 mg/l. However, continuing consumption of higher concentrations can cause dental fluorosis and in extreme cases even skeletal fluorosis. The WHO guideline value for fluoride in drinking water is 1,5 mg/l (WMO, 2004). High fluoride concentrations are especially critical in developing countries, largely because of lack of suitable infrastructure for treatment.

In groundwater, the natural concentration of fluoride depends on the geological, chemical and physical characteristics of the aquifer, the porosity and acidity of the soil and rocks, the temperature, the action of other chemical elements, and the depth of the aquifer.
Because of the large number of variables, the fluoride concentrations in groundwater (e.g. in Kenya, South Africa and India) can range from well under 1 mg/l to more than 35 mg/l.

1.3 Outline of the report

In chapter 2 an overview is given of removal methods. The methods are briefly described using fact sheets. Also some new interesting technologies are mentioned. The methods are intercompared in a table according to relevant criteria such as removal efficiency, capacity, costs, required skill and advantages and disadvantages.

Chapter 3 deals with the set-up of a fluoride removal system, the scale of use and the location for application (developing country or industrialized regions).

An evaluation of the methods is given in chapter 4.

Chapter 5 deals with the selection process. To help water users by choosing the most appropriate methods for their situation, process selection decision trees were made for both industrialized regions and developing countries.

The electronic version of this report is available on the IGRAC web-site: www.igrac.nl

2 Overview of removal methods

2.1 Common methods

The common methods used for the removal of fluoride from drinking water are divided in the following four categories:

- precipitation;
- adsorption and ion-exchange;
- membrane filtration processes;
- distillation.

Precipitation
Precipitation processes involve addition of chemicals and formation of fluoride precipitates. Among these are precipitations with calcium and aluminium salts. Precipitation chemicals must be added daily in batches and precipitation techniques produce a certain amount of sludge every day.

Adsorption and ion-exchange
Adsorption processes involve the passage of water through a contact bed where fluoride is removed by ion exchange or surface chemical reaction with the solid bed matrix. After a period of operation, a saturated column must be refilled or regenerated. The different adsorbents used for fluoride removal include activated alumina, carbon, bone charcoal and synthetic ion exchange resins.

Membrane filtration process
Reverse osmosis and electrodialysis are two membrane filtration processes which can be used for removal of fluoride.

Distillation
Distillation units can also be used for treating the drinking water. Large scale electrodialysis plants are already used for making drinking water out of brackish water with high fluoride concentrations (Zakia et al., 2001; Werner and von Gottberg, 1998). In many parts of North Africa, water is brackish and contains over 1.5 mg/l fluoride.

In appendix 1, eight fact sheets are presented for the most common fluoride removal technologies. Information is given about the following aspects:

- process and technology used
- equipment required
- removal performance
- scale/flow rate
- experience/state of the art
- costs
- advantages and disadvantages
- contact details and additional information.

Reverse osmosis, electro dialysis and distillation are advanced, large scale treatment technologies which are difficult to use in less advanced regions. However reverse osmosis units are nowadays also deliverable for household scale. Small scale point-of-use techniques like Nalgonda technique, Bone Charcoal, Contact Precipitation and Clay are more suitable for developing countries. Activated alumina and reverse osmosis are the most common technologies. Activated alumina can concurrently remove other anions, such as arsenate. Reverse osmosis achieves significant removal of virtually all dissolved contaminants. An overview of the fluoride removal methods is given in table 1.

Table 1: Fluoride removal methods (based on Heidweiller, 1990; Pickard and Bari, 2004 and BGS, 2003)

Techniques	Household	Community level	Removal efficiency (%)	WHO-level feasible	Water Loss	Capacity/dose	Working PH	Interferences	Operator skill	Relative costs	Advantages	Disadvantages
Precipitation												
Alum (aluminumsulphate)	x	x	>90%	yes	1-2%	150 mg/mg F	non-specific	-	low	medium-high	established process	sludge produced treated water is acidic residual Al present
Lime	x	x	>90%	yes	1-2%	30 mg/mg F	non-specific	-	low	medium-high	established process	sludge produced treated water is alkaline
Alum + Lime (Nalgonda)	x	x	70-90%	possible	1-2%	150 mg alum + 7 mg lime/mg F	non-specific optimum pH 6.5	-	low	medium-high	low-tech established process	sludge produced high chemical dose residual Al present
Gypsum + fluorite	x	x	?	no	1-2%	5 mg gypsum + <2 mg fluorite/mg F	non-specific	-	medium	low-medium	simple	requires trained operators low efficiency, high residual CaSO4
Calcium choride	x	x	> 90%	possible	1-2%	3 mg CaCl2/mg F	6.5-8					
Adsorption/ion exchange												
activated carbon	x	x	>90%	yes	1-2%	variable	<3	many	medium	high	-	many interferences large pH changes before and after treatment
plant carbon	x	x	>90%	?	1-2%	300 mg F/kg	7	-	medium	low-medium	locally deleverable	requires soaking in potassium hydroxide
zeolites	x	x?	>90%	yes	1-2%	100 mg F/kg	non-specific	-	medium	high	-	poor capacity
defluoron 2	x	x	>90%		1-2%	360 g F/m3	non-specific	alkalinity	medium	medium	-	disposal of chemicals used in resin regeneration
clay pots	x		60-70%	possible	1-2%	80 mg F/kg	non-specific	-	low	low	locally deleverable	low capacity, slow
activated alumina	x	x	85-95%	yes	1-2%	100 mg alumina/mg F (1200 g F/m3)	5.5	alkalinity	low	medium	proven effectiveness will treat current F and As low energy consumption sludge typically non-hazardous	source water pH adjustment to 6.5 spent regeneration solution contains high F (and As) concentrations chemical and sludge handling needed efficiency dependent on source water
bone	x	x	low?	possible	1-2%	900 g F/m3	>7	arsenic	low	low	locally available	may give taste; degenerates not universally accepted
bone char	x	x		possible	1-2%	1000 g F/m3	>7	arsenic	low	low	locally available high capacity	not universally accepted
Other												
electrodialysis		x	85-95%	yes	20-30%	high	non-specific	turbidity	medium	very high	will treat current F and As and other contaminants possitive public perception	high water loss high energy consumption high (capital) costs
reverse osmosis		x	85-95	yes	40-60%	high	non-specific	turbidity	medium	very high	will treat current F and As and other contaminants possitive public perception	high water loss high energy consumption high (capital) costs

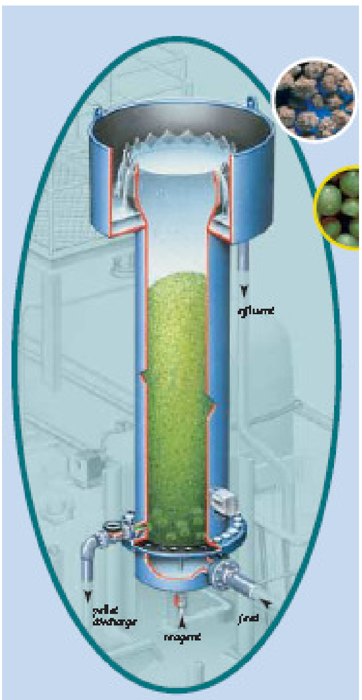
From table 1 it can be seen that majority of low -costtechnology methods rely on precipitation or flocculation or adsorption/ion-exchange processes. The Nalgonda[1] technique is probably the best known and most established method. This method uses a combination of aluminium sulphate and lime. The method can be used at a domestic scale (in buckets) or community scale. It has moderate costs and required materials are easily available. The removal efficiency is however moderate. Activated alumina and bone material are among the most appropriate removal methods (appropriate technology = most effective method). Activated alumina method also removes arsenic, but may not always be available or affordable. Bone products are not readily acceptable in some areas. Other highly efficient methods of removal include electro dialysis and reverse osmosis, but these methods tend to involve higher technology and higher costs and are therefore less suitable for many applications in developing countries.

2.2 New technologies

Besides the methods mentioned in table 1 several new methods have been introduced in recent years. These new technologies include:

- Crystalactor®
- Memstill® technology
- The WaterPyramid® solution
- The Solar Dew Collector system
- Boiling with brushite and calcite
- Use of new absorbents

Crystalactor®
In the Netherlands a new type of contact precipitator, named the Crystalactor®, is developed by DHV (Giesen, 1998). The Crystalactor® is a fluidized-bed type crystallizer also called a pellet reactor.

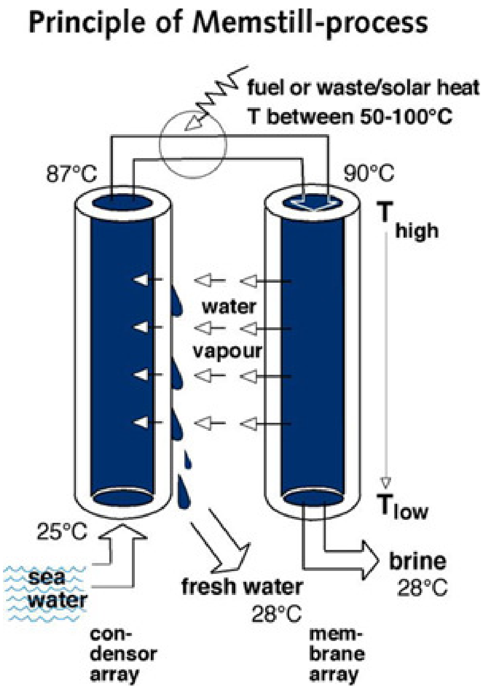


Source: DHV

In the reactor fluoride is removed from the water while calcium fluoride pellets with a diameter of 1 mm are produced. The major advantages of the Crytalactor® are that (1) the installation is compact, (2) calcium fluoride pellets with a high-purity are produced, (3) the produced pelltes have an extremely low water content 95% tot 10% moisture) and (4) the pellets can be reused. Costs comparisons show that the total treatment costs are typically approximately 25% of the costs for conventional precipitation. However the Crystalactor® is more suitable for wastewaters with high fluoride concentrations (> 10 mg/l). For treating drinking water, the Crystalactor® is only advisable in case of high fluoride concentrations (> 10 or 20 mg/l). For reaching a concentration below 1 mg/l fluoride, a second technique must be used afterwards (for example I.E).

[1] The Nalgonda technique is named after the Nalgonda District in India where it was first developed.

Memstill® technology
The Netherlands Organisation of Applied Scientific Research (TNO) has developed a membrane-based distillation concept which radically improves the economy and ecology of existing desalination technology for seawater and brackish water. This so-called "Memstill® technology" combines multi-stage flash and multi-effect distillation modes into one membrane module (Hanemaaijer et al., 2007).



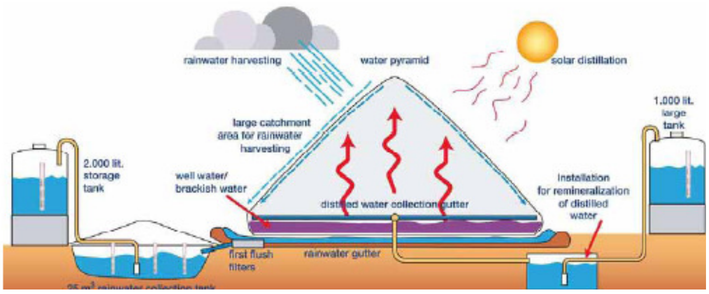
Source: TNO

Cold feed water takes up heat in the condenser channel through condensation of water vapour, after which a small amount of (waste) heat is added, and flows counter currently back via the membrane channel. Driven by the small added heat, water evaporates through the membrane, and is discharged as cold condensate. The cooled brine is disposed, or extra concentrated in a next module.

The Memstill® technology can produce (drinking)water at a cost well below that of existing technologies like reverse osmosis and distillation.
With the Memstill® technology also anions like fluoride and arsenic are removed. It is expected that the Memstill® technology will be also developed for small scale applications using solar heat.

The WaterPyramid® solution
http://www.aaws.nl/home.htm - #http://www.aaws.nl/home.htm - #Aqua-Aero WaterSystems has developed the WaterPyramid® concept for tropical, rural areas (Aqua-Aero, 2007).
http://www.aaws.nl/home.htm - #http://www.aaws.nl/home.htm - #http://www.aaws.nl/home.htm - #The WaterPyramid® makes use of simple technology to process clean drinking water out of salt, brackish or polluted water. One of the pollutants could be fluoride. Most of the energy needed to clean the water is obtained from the sun.

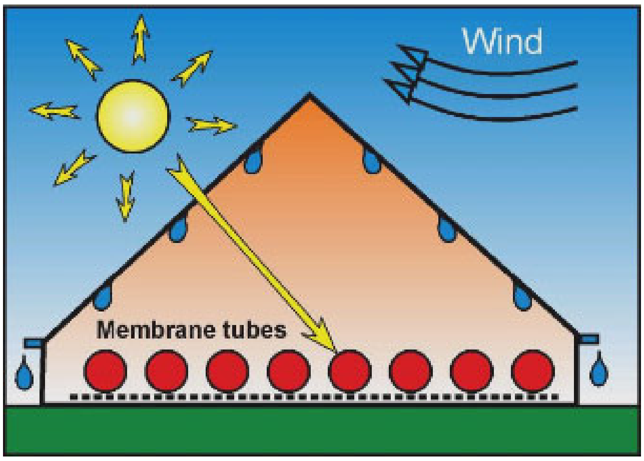
WaterPyramid® with a total area of 600 m^2 and situated under favourable tropical conditions, can produce up to 1250 litres of fresh water a day. The production rate is dependant on site specific factors such as climate and temperature, cloudiness and wind activity. Desalination is driven by the sun and the energy needed for pressuring the WaterPyramid® is obtained using solar cells in combination with a battery back-up system. Intermittent peak demands in electricity, related to e.g. (borehole) pumping and maintenance, are covered using a small generator system.



Source: Aqua-Aero WaterSystems

The Solar Dew Collector system
Solar Dew (Solar Dew, 2007) developed a new porous membrane to purify water using solar energy. The technique is similar to the WaterPyramid®.
Water sweats through the membrane, evaporates on the membrane's surface and increases the air humidity in the evaporation chamber.

Based on a temperature difference, pure water condenses on the cooler surfaces of the system.



Source: Solar Dew

The product water quality is very constant and similar to that of distilled water. The quantity depends on the intensity of the solar radiation. To avoid crystallization, the brine has to be drained periodically.

The system is able to process: sea-, brackish or contaminated waste water (e.g. with heavy metals, oil residue, boron, fluoride) with an allowable pH range of 5-11.

Boiling with Brushite and Calcite
Existing methods for defluoridating drinking water involve expensive high technology or are slow, inefficient and/or unhygienic. In Larsen and Pearce (2002), a new method is suggested, using a suspension of the minerals brushite ($CaHPO4.2H2O$) and calcite (calciumcarbonaat) followed by boiling. On a laboratory scale, this method gave good results. It was concluded that boiling a brushite/calcite suspension rapidly converts the two salts to apatite which incorporates fluoride if present in solution. This process may be exploited to defluoridate drinking water.

New adsorbents for adsorption of fluoride
In recent years, several new adsorbents for adsorption of fluoride have been investigated. For example, lanthanum-impregnated silica-gel, La(II) and Y(III)-impregnated alumina and aluminium-impregnated carbon have been used for adsorption of fluoride successfully by Raichur and Jyoti Basu (2001). The use of waste materials and low-cost materials as adsorbents for fluoride has been examined. Raichur and Jyoti Basu (2001) paid also attention to adsorption of fluoride onto mixed rare earth oxides. The rare earth oxides are naturally occurring in Southern India. The method is simple and has shown great potential for selective removal of fluoride. It was found that the mixture of rare earth elements adsorb fluoride rapidly and effectively. Most of the adsorption took place in the first 5-10 min. The adsorbent was found to load as high as 12.5 mg of fluoride per gram of adsorbent. The optimum pH was found to be about 6.5 for fluoride adsorption which makes it very suitable for use in drinking water treatment. Other ions such as sulphate and nitrate (up to 100 mg/l) did not greatly affect the adsorption of fluoride thereby indicating that the rare earth oxide is a selective adsorbent for fluoride.

3 Setup, scale of use and location

Defluoridation of drinking-water is technically feasible at point-of-use (at the tap), for small communities of users (e.g. wellhead application) and for large drinking-water supplies. Point-of-use systems can produce sufficient quantities of treated water for drinking and cooking requirements of several persons. Numerous plumbed-in, small distillation units are marketed that have been tested and can produce 10 litres per day or much larger volumes. Many certified low pressure reverse osmosis units are available with rated capacities in the range of 30-100 litres per day. Point-of-use defluoridation using activated alumina anion exchange is capable of removing fluoride from small volumes of water, but international performance standards have not been developed to date.

Community-sized, commercially available, package water treatment systems that use activated alumina or reverse osmosis technology also exist. They can be purchased as a complete unit that can be readily shipped and installed on-site.
These can produce hundreds of litres or more of treated, low fluoride water per day. Large defluoridation systems can also be designed and constructed on-site to engineer's specifications.

Conventional water treatment, as carried out in both rural and urban areas in industrialized countries, takes place typically:

- in a water works without direct involvement of the users,
- under the supervision of skilled operators, and
- where the affordability of treatment is taken for granted.

In such cases the method of treatment is well established and well controlled. However, it requires major input of resources and may have serious limitations or disadvantages in less-developed countries, especially in rural areas where the water users are scattered or the supply is entirely local. Here treatment may only be feasible at a decentralized level, e.g. at community village level or at household level (see table 2).

Table 2: Differences in characterization of water treatment methods in conventional systems in industrialized and developing countries (Fawell et al., 2006)

Criteria	**Industrialized Countries**	**Developing countries**
Set-up and water flow	Always continuous, often in columns	Often discontinuous in columns Fill and draw in batch
Scale and treatment site	Always at water works, usually close to water source	At water works At village community level At household level
Treatment media/process	Contact precipitation Activated alumina Synthetic resins Reverse osmosis Electrodialysis	Bone charcoal Contact precipitation Nalgonda Activated alumina Clay Other naturally occurring media

4 Evaluation

There is not a universal method which is appropriate under all social, financial, economic, environmental and technical conditions. None of the methods has been implemented successfully at a large scale in many parts of the world. All available defluoridation methods do have disadvantages, such as:

1. *High Cost-Tech;* i.e. either the price and/or the technology is high, demanding imported spare parts, continuous power supply, expensive chemicals, skilled operation or regeneration, etc. Reverse osmosis, ion exchange and activated alumina may thus be categorized as high cost-tech methods.

2. *Limited efficiency;* i.e. the method does not permit sufficient removal of the fluoride, even when appropriate dosage is used. As in the Nalgonda technique, the residual concentration would often be higher than 1 mg/l, unless the raw water concentration itself is relatively low.

3. *Unobserved breakthrough;* i.e. the fluoride concentration in the treated water may rise gradually or suddenly, typically when a medium in a treatment column is exhausted or even when the flow is out of control. As in the case of bone charcoal and other column filters, these techniques necessitate frequent monitoring of fluoride residual, or at least the rate and the volume of treated water, if unobserved breakthrough or the loss of removal capacity is to be avoided.

4. *Limited capacity;* while the removal capacity of bone charcoal or activated alumina may be about 2 mg of fluoride per gram of medium, much higher amounts of calcined clay for example have to be used in order to obtain appropriate removal.

5. *Deteriorated water quality;* this would by nature result in excessively high pH values, normally above 10. The water quality may also deteriorate due to bacterial grow, poorly prepared medium (bone charcoal) or due to medium escaping from the treatment container, e.g. ion exchange, alumina, Nalgonda sludge, etc.

6. *Taboo limitations;* in particular, the bone charcoal method is culturally not acceptable to Hindus. Bone charcoal originating from pigs may be questioned by Muslims. The charring of bones has also been reported to be unacceptable to villagers in North Thailand.

General comparison of the methods is given in table 3.

Table 3: General comparison of the most promising defluoridation methods used in developing countries (Fawell et al., 2006).

Advantages	**Defluoridation methods**				
	BC	**CP**	**Nal**	**AA**	**Cl**
No daily dosage of chemicals, i.e. no daily working load	+	-	-	+	+
Dosage designed for actual F conc. Independent of unit or plant	-	+	+	-	-
No risk of false treatment due to break point	-	+	+	-	-
Removal capacity of medium is independent of F concentration	-	+	-	-	-
No regeneration or renewal of medium is required	-	+	+	-	-
High removal efficiency can be ensured	+	+	-	+	-
Easy to construct, even by the users	+	+	++	+	+
Construction materials are cheap and widely available	+	+	++	+	+
Can be sized for one or several families or a group, e.g. a school	+	++	+	+	-
No risk of medium/chemicals unacceptability	-	-/+	+	+	-
No risk of deterioration of the original water quality	-/+	+	-/+	-/+	-

BC = bone charcoal; CP = contact precipitation; Nal = Nalgonda technique of aluminium sulfate and lime; AA = activated alumina; Cl = calcined clay; "risk" means in some cases

\+ = advantage
\- = disadvantage

5 Selection

For the selection of an appropriate fluoride removal method in industrial and developing countries two process selection decision trees have been made.

A decision tree for the industrialized countries is shown in figure 1.
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Figure 1: Decision tree for fluoride removal techniques applicable in industrialized countries

Activated Alumina and RO/ED are the favourite techniques for industrial countries when high capacity and proven technology is needed.

For small applications contact precipitation or ion exchange (in case the water contains only high concentrations of fluoride) is recommended.

A decision tree for the developing countries is shown in figure 2.

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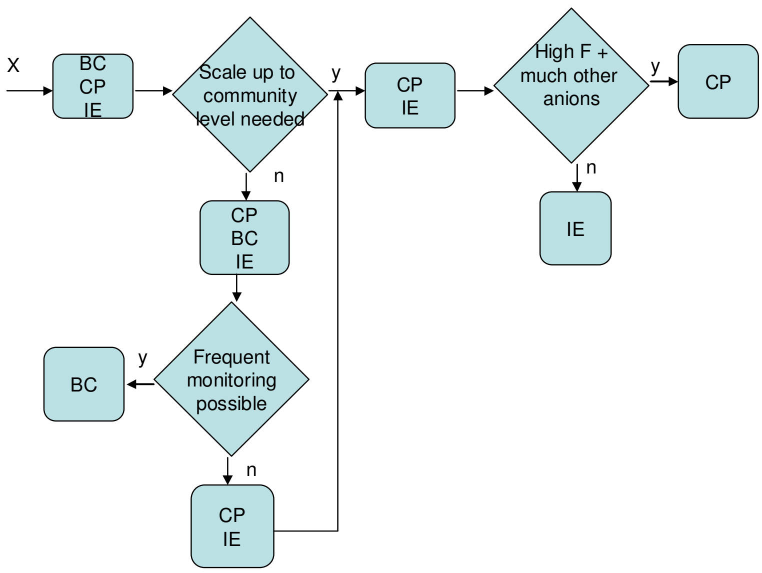

Figure 2: Decision tree for fluoride removal techniques applicable in developing countries.

Activated alumina is the favourable technique for developing countries in case high removal efficiency and high capacity is needed.

For situations where moderate removal efficiency is sufficient, the Nalgonda technique is preferable.

In other situations (high removal efficiency, small scale) contact precipitation or ion exchange (only high F-ions) is advisable. Bone charcoal can also be used if frequent monitoring is possible.

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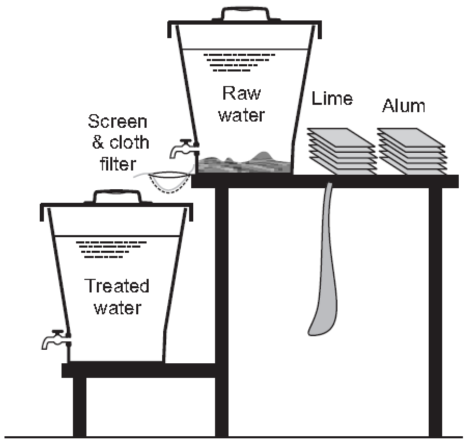
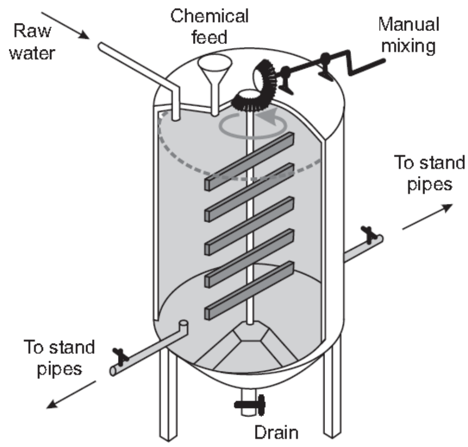
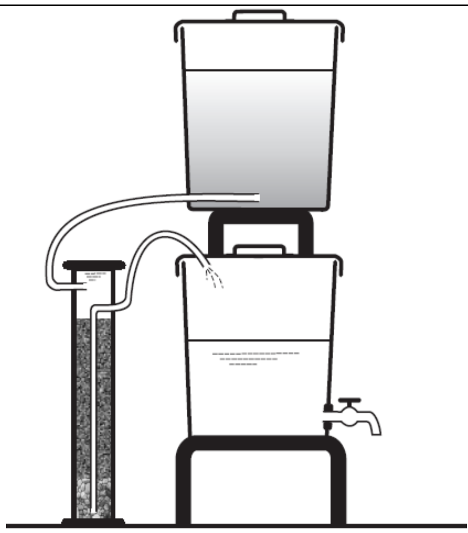
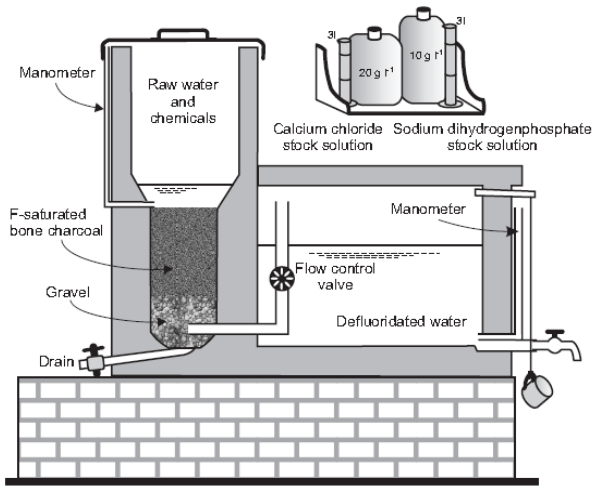
Appendix 1: Fact sheets fluoride removal technologies

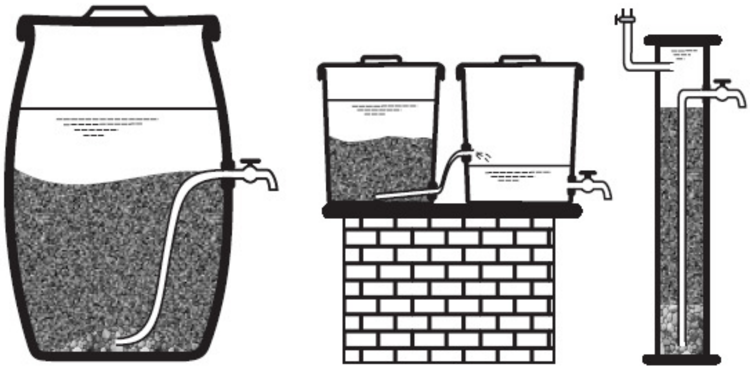
1. **Nalgonda process**
2. **Contact precipitation**
3. **Bone Charcoal**
4. **Activated Alumina**
5. **Clay**
6. **Reverse osmosis**
7. **Electrodialysis**
8. **Ion exchange**

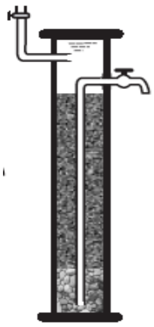
<table>
<tr><td>Technology</td><td>Nalgonda</td></tr>
<tr><td>Process</td><td>Aluminum sulphate based Coagulation-flocculation sedimentation</td></tr>
<tr><td>Technology Description</td><td>The Nalgonda process was adapted and developed in India by the National Environmental Engineering Research Institute (NEERI) and developed to be used at both the community or household levels. The process is aluminium sulphate based coagulation-flocculation sedimentation, where the dosage is designed to ensure fluoride removal from the water.</td></tr>
<tr><td>Equipment</td><td>

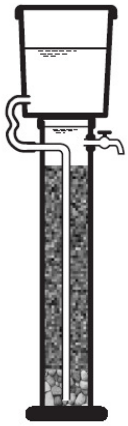


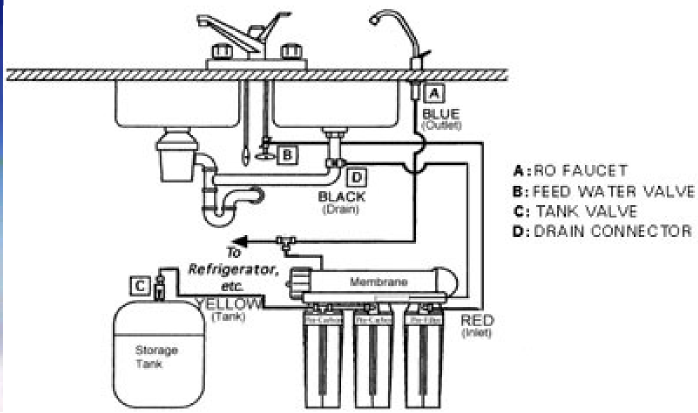
The Nalgonda defluoridation as adopted for community domestic use in the United Republic of Tanzania.
The Nalgonda technique for domestic and defluoridation</td></tr>
<tr><td>Removal performance</td><td>The method does not permit sufficient removal of the fluoride, even when appropriate dosage is used. The residual concentration would often be higher than 1 mg/ l, unless the raw water concentration itself is relatively low.</td></tr>
<tr><td>Scale/flow rate</td><td>20-60 litre basket (household)
10-100 litre/h (household)</td></tr>
<tr><td>Experience</td><td>Established process in India and Tanzania. The aluminium sulphate and lime process was proposed for defluoridation of water when fluoride in water became a health concern in the USA as the agent behind mottling of teeth. Four decades later the process was adopted by NEERI as the Nalgonda technique and developed for low cost use at all levels in India (household, village community and waterworks levels).</td></tr>
<tr><td>Costs</td><td>Low- costs. See http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf</td></tr>
<tr><td>Advantages</td><td>• Widespread knowledge about the possibilities of solving the treatment problems at different levels, even at very low cost.
• Understanding of the non-stoichiometric co-precipitation mechanisms for removal of fluoride in the flocculation process.</td></tr>
<tr><td>Disadvantages</td><td>• The treatment efficiency is limited to about 70 per cent. Thus the process would be less satisfactory in case of medium to high fluoride contamination in the raw water.
• A large dose of aluminium sulphate, up to 700–1,200 mg l–1, may be needed. Thus it reaches the threshold where the users start complaining about residual sulphate salinity in the treated water.
• The large dose also results in a large sludge disposal problem in the case of water works treatment.</td></tr>
<tr><td>Contact details/More information</td><td>National Environmental Engineering Research Institute (NEERI) http://www.neeri.res.in/
Fluoride in Drinking water WHO-report:
http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf</td></tr>
</table>

Technology	**Contact precipitation (general)**
Process	Precipitation
Technology Description	Contact precipitation is a technique by which fluoride is removed from the water through addition of calcium and phosphate compounds and then bringing the water in contact with an already saturated bone charcoal medium.
Equipment	 Contact precipitation for household use  Contact precipitation of fluoride as invented in Ngurdoto
Removal performance	> 90% removal of F
Scale/flow rate	Several (household, community)
Experience	Although it has so far only been implemented at village level in the United Republic of Tanzania and in Kenya, contact precipitation is probably suitable for implementation at any required level. The figures show contact precipitation plant as developed for household use and installed at various schools in the rural areas of the Arusha region, the United Republic of Tanzania.
Costs	low
Advantages	The process seems to be promising, because it implies: _ relatively low daily working load; _ high reliability without the need of surveillance of flow or effluent concentration; _ high removal efficiency, even in case of high raw water concentrations; _ low operating cost; and _ no health risk in the case of misuse or over-dosage of chemicals.
Disadvantages	
Contact details/More information	Fluoride in Drinking water WHO-report: http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf Household water treatment: http://www.irc.nl/page/8028#fluoride

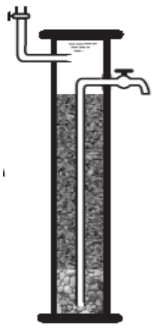
Technology	**Bone Charcoal**
Process	adsorption
Technology Description	Bone charcoal is a blackish, porous, granular material. The major components of bone charcoal are calcium phosphate 57–80 per cent, calcium carbonate 6–10 per cent, and activated carbon 7–10 per cent. In contact with water the bone charcoal is able, to a limited extent, to absorb a wide range of pollutants such as colour, taste and odour components. Moreover, bone charcoal has the specific ability to take up fluoride from water.
Equipment	 Three most common domestic units for sorption defluoridation [WHO]. The figure above illustrates the three most common types of domestic bone charcoal filters. One of the differences concerns the water flow in the filter. Another difference between the various configurations is whether the filter allows the filter medium to drain water, if treated water is withdrawn without ensuring an adequate influent, allowing the medium to become dry. “Drying” the medium results in disturbance of the sorption process and more contact time would be required to re-establish treatment. Unfortunately this point is overlooked in many household filter designs.
Removal performance	Fluoride concentration can be reduced to less than or equal to 1 mg/l
Scale/flow rate	20-60 litre basket (household)
Experience	Bone charcoal is the oldest known water defluoridation agent. It was used in USA in the 1940s through to the 1960s, when bone charcoal was commercially widely available because of its large scale use in the sugar industry (WHO). The first domestic defluoridators were developed in the early 1960s as column filters similar to the one shown in the figure above. Today bone charcoal defluoridation at waterworks has been replaced by the use of ion-exchange resins and activated alumina. At a domestic level, bone charcoal defluoridation seems to work well in Thailand and Africa, but so far there is no experience of wide scale implementation.
Costs	low
Advantages	locally available simple and easy to build
Disadvantages	may give taste; degenerates not universally accepted
Contact details/More information	Fluoride in Drinking water WHO-report: http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf

Technology	**Activated alumina**
Process	adsorption
Technology Description	Activated alumina is aluminium oxide (Al2O3) grains prepared to have a sorptive surface. When the water passes through a packed column of activated alumina, pollutants and other components in the water are adsorbed onto the surface of the grains.
Equipment	  column filter household filter The activated alumina process is carried out in sorption filters as shown in the figure above. In order to avoid the monitoring of the water quality, the unit is supplied with a water meter allowing for direct indication of the cumulative water flow. After treatment of, for example, 2,000 litres equivalent to 250 BV of water containing about 5 mg/l, the unit is opened for renewal of the 8 kg of medium. Alternatively the unit is dismounted for regeneration by the dealer.
Removal performance	According to WHO the fluoride removal capacity of alumina is between 4 and 15 mg g^{-1}. Experience from the field, however, shows that the removal capacity is often about 1 mg g^{-1} (Fawell et al., 2006). Thus there seems to be a large difference in the degree of "activation" of alumina products. One of the explanations may be due to variation in pH. The capacity of alumina is highly dependent on pH, the optimum being about pH 5.
Scale/flow rate	Suitable for both household and community scale
Experience	Activated alumina was proposed for defluoridation of water and a drum filter was patented for domestic use as early as 1936 (WHO). Since then activated alumina has become the subject of several patents and, due to commercial interests, one of the most advocated defluoridation methods. The activated alumina process was evaluated for fluoride removal from an underground mine water in South Africa in the early 1980s and it was found that potable water could be produced from an underground mine water with a fluoride concentration of approximately 8 mg/l. Two 500 × 10^3 litres per day defluoridation plants were installed as a result of the investigation (WHO-report).
Costs	It was previously considered that the activated alumina process, due to high chemical cost and non-availability in markets, was not a consideration for most developing countries. This is no longer the case. Experience, mainly from India, Thailand and China, indicates that activated alumina may under certain conditions be affordable for low income communities.
Advantages	Proven effectiveness, will treat current F and S
Disadvantages	Spent regeneration solution contains high F concentrations
Contact details/More information	http://www.thewaterexchange.net/fluoride-water-filters.htm http://www.crystalquest.com/data%20sheet%20fluoride.htm Fluoride in Drinking water WHO-report: http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf

Technology	**Clay**
Process	Adsorption
Technology Description	Clay is an earthy sedimentary material composed mainly of fine particles of hydrous aluminium silicates and other minerals and impurities. Clay is fine-textured, plastic when moist, retains its shape when dried and sinters hard when fired. These properties are utilized in manufacture of pottery, brick and tile. Both clay powder and fired clay are capable of sorption of fluoride as well as other pollutants from water.
Equipment	 Stratified column of brick chips, pebbles and coconut shells as used in Sri Lanka. Domestic clay column filters are normally packed using clay chips found as waste from the manufacture of brick, pottery or tile. The figure beneath illustrates such a column filter. It resembles the filter used in Sri Lanka (WHO-report) The filter is based on up-flow in order to allow for settling of suspended solids within the filter bed. The filter does not have a clean water reservoir and the filtration rate is controlled by slow withdrawal through the tap.
Removal performance	60-70%
Scale/flow rate	Household scale
Experience	According to Fawell et al. (2006) nearly 80 per cent of 600 clay column defluoridators installed in households in Sri Lanka were found in operating condition after being monitored for different periods from two years onwards. The described technology was found to be sustainable, but only if the users were motivated through information and motivation campaigns (Fawell et al., 2006).
Costs	low
Advantages	locally available
Disadvantages	low capacity, slow, low removal efficiency, hygienic aspects because of use of clay
Contact details/More information	Fluoride in Drinking water WHO-report: http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf

Technology	**Reverse osmosis**
Process	Membrane technology
Technology Description	Reverse osmosis is a membrane technology that uses pressure to force water through a semi-permeable membrane, thereby removing dissolved solutes from solution based on particle size, dielectric characteristics, and hydrophilic/hydrophobic tendencies. RO can be used as a stand-alone treatment for most source waters, Beside fluoride molecules also other molecules will be retained. RO is listed as a fluoride removal BAT (Best Available technique).
Equipment	  RO water filter for household Reverse Osmosis Water Filter Diagram
Removal performance	85-95% removal of F-
Scale/flow rate	Varies, there are RO-filters for household use and RO-units for community level
Experience	State of the art (small scale and community scale)
Costs	Very high
Advantages	RO is EPA-listed BAT for both F and As Familiarity with membrane separation system; Will treat current (F/As) and possible future contaminants of concern; Positive public perception
Disadvantages	High water loss (20-40%) due to high source water silica concentrations (for RO); High energy consumption; High treatment technology capital costs; Pre- (filtration) and post- (pH/alkalinity adjustment) treatment may be needed; Chemical handling facilities needed; Multiple systems needed to achieve water conservation goals (<5% water loss); Skilled operator required.
Contact details/More information	www.thewaterexchange.net/fluoride-water-filters.htm www.crystalquest.com

Technology	**Electrodialysis (ED)**
Process	Membrane proces
Technology Description	Electrodialysis (ED) is a membrane process similar to RO, except that ED uses an applied d.c. potential (electric current), instead of pressure, to separate ionic contaminants from water. Because water does not physically pass through the membrane in the ED process, particulate matter is not removed. Thus, ED membranes are not technically considered filters. The EDR process product water quality is comparable to RO, and may require post-treatment stabilization. The EDR process is often used in treating brackish water to make it suitable for drinking, and tends to be most economical for source water TDS levels in excess of 4,000 mg/L.
Equipment	 EDR
Removal performance	85-95% removal of F-
Scale/flow rate	Community scale
Experience	State of the art technique for brackish water
Costs	Very high
Advantages	Familiarity with membrane separation system; Will treat current (F/As) and possible future contaminants of concern; Positive public perception.
Disadvantages	Water loss, high costs, brine discharge, see also disadvantages RO
Contact details/More information	http://www.gewater.com/index.jsp

Technology	**Ion exchange**
Process	Ion exchange
Technology Description	The most common ion-exchange removal methods are activated alumina, activated carbon, bone char, granulated bone media, ion exchange resins (defluoron 2) or clay minerals. Ion exchange removal methods using activated alumina, clay and bone charcoal are described separately. The water is filtered down trough a column packed with an ion exchange resin. When the adsorbent becomes saturated with fluoride ions, the filter material has to be back washed with a mild acid or alkali solution tot clear and regenerate it. The effluent form backwashing is rich in accumulated fluoride and must be therefore disposed of carefully tot avoid recontamination nearby groundwater.
Equipment	 column filter
Removal performance	Medium-high; Depends on quality of water
Scale/flow rate	Suitable for both community and household use
Experience	Less experience with strong anion-exchange resins because of low capacity and relative high costs
Costs	Rel. high
Advantages	
Disadvantages	High costs, low capacity, sorption of other anions, Fluoride concentration must be less than 10 mg/l.
Contact details/More information	Resins: http://www.dow.com/ Filters: http://www.ionindia.com/product_range.html

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