1-1-2009

An evaluation of defluoridation technologies in the context of decision-making strategies

Ann C. Fantin
Ryerson University

AN EVALUATION OF DEFLUORIDATION TECHNOLOGIES IN THE CONTEXT OF DECISION-MAKING STRATEGIES

by

Ann C. Fantin, B.Sc., McMaster University, 2001

A Research Project presented to Ryerson University
In partial fulfillment of the requirements for the degree of

Master of Applied Science
In the program of Environmental Applied Science and Management

Toronto, Ontario, Canada, 2009

Author's Declaration

I hereby declare that I am the sole author of this Project paper.

I authorize Ryerson University to lend this Project paper to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this Project paper by photocopying or by other means, in total or in part, at the request of other institutions for the purpose of scholarly research.

AN EVALUATION OF DEFLUORIDATION TECHNOLOGIES IN THE CONTEXT OF DECISION-MAKING STRATEGIES

© Ann C. Fantin, 2009
Master of Applied Science
Environmental Applied Science and Management
Ryerson University

ABSTRACT

Fluoride can be considered beneficial or harmful to human health dependant on the amount that is ingested. Many methods exist for the removal of excessive fluoride from drinking water; however, not all defluoridation methods are appropriate for the specific local conditions that may be present within a community. The objective of this research project is to evaluate various available defluoridation technologies against characteristics of a successful and sustainable technology, while considering decision-making strategies that may be employed by those selecting an appropriate defluoridation method to suit the characteristics of the specific community that is affected by fluoride-impacted drinking water. An evaluation of the selected defluoridation technologies supports the notion that there is not an all-encompassing defluoridation technology that would be applicable to all types of situations in which fluoride-impacted groundwater is a concern. Water treatment methods for developing countries require careful consideration and selection of a sustainable solution so as to provide long-term benefits and applicability. Formal decision-making strategies would be useful tools at the government level to provide a starting point to determine which available defluoridation methods would be viable at the end user level. Researchers, government officials and, most importantly, local inhabitants of suffering areas must work together to achieve the common goal of clean and safe potable water.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Warith, for his understanding and support during the course of my graduate studies. I would also like to thank my family for encouraging me to finish what I started, and for supporting me in all that I do.

TABLE OF CONTENTS

AUTHOR'S DECLARATION II

ABSTRACT III

ACKNOWLEDGEMENTS IV

1.0 INTRODUCTION 1

2.0 AN OVERVIEW OF FLUORIDE, FLUOROSIS AND DEFLUORIDATION TECHNOLOGIES 2

2.1 Fluoride 2

2.2 Fluorosis 2
- *2.2.1 India* 5
- *2.2.2 China* 9
- *2.2.3 Africa* 14

2.3 Defluoridation Technologies 18
- *2.3.1 Nalgonda Technique* 18
- *2.3.2 Integrated Alum-Powdered Activated Carbon (PAC) Slurry* 19
- *2.3.3 Bone Charcoal Method* 20
- *2.3.4 KRASS Process* 22
- *2.3.5 Coal-Based Sorbents* 23
- *2.3.6 Geomaterial Sorbents* 24
- *2.3.7 Hybrid Process of Adsorption and Donnan Dialysis* 26

3.0 DECISION-MAKING STRATEGIES AND AN EVALUATION OF DEFLUORIDATION TECHNOLOGIES 28

4.0 FINDINGS, RECOMMENDATIONS AND LIMITATIONS 36

4.1 Findings 36

4.2 Recommendations and Areas for Further Research 37

4.3 Limitations 39

5.0 REFERENCES CITED 40

LIST OF TABLES

Table 1: Summary of Fluoride Concentrations and Corresponding Affects

Table 2: Impact of Increasing Concentrations of Fluoride on the Human Body

Table 3: Evaluation of Defluoridation Technologies

LIST OF FIGURES

Figure 1: Countries with endemic fluorosis due to excess fluoride in drinking water.

Figure 2: Typical Nalgonda defluoridation system.

Figure 3: Schematic of the alum-PAC slurry defluoridation process.

Figure 4: Typical bone charcoal filter column defluoridation unit.

1.0 INTRODUCTION

It is commonly held that small amounts of fluoride are required for good bone development and the prevention of dental caries, yet chronic intake of excessive amounts of fluoride can result in a condition known as fluorosis (Apambire et al., 1997). Fluoride can be considered beneficial or harmful to human health dependant on the amount that is ingested. Research has shown that the prevalence and severity of fluorosis can be reduced if a community is provided with adequately defluoridated water (Zevenbergen et al., 1996). Many methods exist for the removal of excessive fluoride from drinking water; however, not all defluoridation methods are appropriate for the specific local conditions that may be present within a community. For instance, many defluoridation technologies require costly chemicals or a high level of technological skill for their management and maintenance, criteria which may not be readily available in developing countries where excessive fluoride in drinking water is a concern (Zevenbergen et al., 1996).

The objective of this research project is to evaluate various available defluoridation technologies against characteristics of a successful and sustainable technology, while considering decision-making strategies that may be employed by those selecting an appropriate defluoridation method to suit the characteristics of the specific community that is affected by fluoride-impacted drinking water.

Chapter 2 of this paper will present an overview of fluoride, fluorosis and various defluoridation technologies that may be applicable to communities affected by high levels of fluoride in their drinking water. A basic decision-making strategy will be presented in Chapter 3, which includes an evaluation of the reviewed defluoridation technologies. Chapter 4 will discuss the findings of the paper, present recommendations and areas for further research, and outline the limitations of the paper.

2.0 AN OVERVIEW OF FLUORIDE, FLUOROSIS AND DEFLUORIDATION TECHNOLOGIES

2.1 Fluoride

Fluorine is a one of the most reactive of all chemical elements and, as such, it is not found in its elemental state in the environment, but rather its ionic form of fluoride (Fawell et al., 2006) Fluoride is natural occurring and can be found in varying concentrations in water, air, rocks, plants, and animals (Nyaora Moturi et al., 2002). It has long been believed that small doses of fluoride can prevent dental decay and do not negatively impact health. As outlined in UNICEF's 1999 *Position on Water Fluoridation*, the effectiveness of fluoride in fighting dental cavities has been based on the concept that fluoride inhibits enzymes which breed acid-producing oral bacteria that eat away tooth enamel, and that fluoride ions bind with calcium ions, strengthening tooth enamel as it forms in children. While such statements may be valid, it is now largely supported that "excessive fluoride intake leads to loss of calcium from the tooth matrix, aggravating cavity formation throughout life rather than remedying it, and so causing dental fluorosis [while] severe, chronic and cumulative overexposure can cause the incurable crippling of skeletal fluorosis" (UNICEF, 1999).

2.2 Fluorosis

Fluorosis is a disease which is caused by the ingestion, inhalation and, occasionally, absorption through the skin, of fluoride (Nyaora Moturi et al., 2002). In excessive amounts, fluoride absorbed by the body can cause teeth and nail striations, dental fluorosis and skeletal fluorosis (Nyaora Moturi et al., 2002). According to the reviewed literature, a broad consensus appears to exist with respect to the concentrations at which fluoride becomes detrimental to human health. A table of various fluoride concentrations and corresponding affects as summarized from the reviewed literature is presented below.

Table 1: Summary of Fluoride Concentrations and Corresponding Affects

Fluoride Concentration (parts per million [ppm])	Comments	Source
0.5, 0.5-1.5, 1.5	Optimal level, optimal interval, and recommended maximum level, respectively	Apambire et al., 1997
0.7-0.8	Optimal range for the study area in question (i.e., Visakhapatnam region, Andhra Pradesh, India) as per temperature conditions	Rao et al., 1998

Fluoride Concentration (parts per million [ppm])	Comments	Source
0.6, 1.2	Highest desirable limit for the environmental conditions of the Indian subcontinent and the maximum permissible limit prescribed for drinking water, respectively, as per the Indian Standard Institute (1983)	Rao and Devadas, 2003
0.6-1.2	Desirable limit for drinking water purposes	Rao et al, 1998
0.7-1.2	Permissible limits beyond which damage to teeth and skeletal bones can occur	Sinha, 1997
0.8-1.7	Allowable concentrations as per the U.S. Public Health Service Drinking Water Standards (1962)	Agarwal et al., 1999
1.0	Chinese drinking-water guideline value	Yang et al, 2003
1.0	Drinking water is considered to be safe for human consumption if the fluoride concentration does not exceed this value	Sivasamy et al, 2001
1.0	Permissible limit as per the Bureau of Indian Standards	Chatterjee and Mohabey, 1998
1.0, 1.5	Desirable limit and permissible limit, respectively, as per Indian Standards for drinking water	Raichur and Basu, 2001
1.0-1.5	Recommended values	Nyaora Moturi et al., 2002
1.0-1.5	Permissible limit as per the manual on Water Supply and Treatment (Central Public Health and Environmental Engineering Organisation, 1991)	Agarwal et al., 1999
1.5	World Health Organization (WHO) guideline value. WHO indicates that the volume of water consumed and fluoride intake from other sources should be considered when setting national standards.	WHO, 2008

The optimum concentration of fluoride in drinking water that was referenced in the reviewed literature ranged from 0.5 to 1.5 parts per million (ppm), while the permissible or maximum concentrations of fluoride in drinking water referenced ranged from 0.7 to 1.5 ppm. Overall, a general similarity in the ranges of acceptable fluoride concentrations in drinking water was observed in the literature; however, it is clear that exact acceptable concentrations will vary from one population to another. Specifically, factors such as dietary fluoride intake, climate, temperature, pH, altitude, systemic and topical fluoride administration, and socio-economic status will all result in variances of both the optimum and maximum fluoride concentration in drinking water between one locale and the next (Grobler et al., 2001). It is important then that the existing conditions in each of the areas affected by fluorosis be taken into consideration when determining the maximum allowable concentrations of fluoride in drinking water.

Dental fluorosis resulting from excessive ingestion of water with high levels of fluoride can be characterized by mottling of the teeth. Initially, opaque white patches develop on the teeth, eventually turning into brown or black staining, followed by pitting of the teeth surfaces (Apambire et al., 1997). While dental fluorosis is not a life-threatening illness, it can result in severe tooth deterioration and associated increased dental costs, as well as psychological stress for those affected due to the aesthetic deterioration which occurs. Skeletal fluorosis "manifests itself as an increase in bone density leading to thickness of long bones and calcification of ligaments" (Apambire et al., 1997, 14). Rheumatic or arthritic pain in joints and muscles can also occur, along with stiffness of the joints and bending of the vertebral column (Kundu et al., 2001). In addition, fusion of bones may occur, resulting in crippling effects.

As indicated by Sinha (1997), other systems aside from teeth and bones can be affected by fluorosis: "Large doses or a persistent intake of small amounts over a number of years can affect soft tissues and be manifested as gastrointestinal, neuromuscular, respiratory and cardiovascular problems and also allergic skin lesions" (261). Table 2 below presents the effects of various concentrations of fluoride on the human body.

Table 2: Impact of Increasing Concentrations of Fluoride on the Human Body

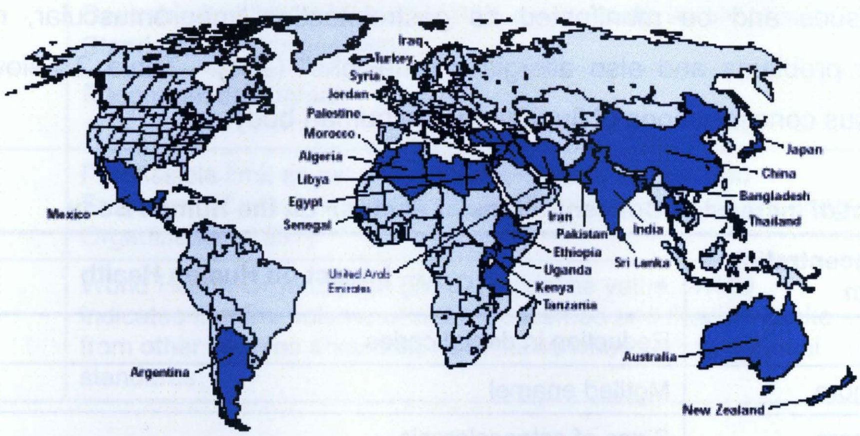
Fluoride Concentration ppm	Impact on Human Health
1	Reduction in dental caries
2 or more	Mottled enamel
5 or more	Signs of osteosclerosis
8 or more	10% osteosclerosis
20 or more	Crippling effects
50 or more	Thyroid changes
100 or more	Growth retardation
125 or more	Kidney damage
More than 5 grams	Death

Source: Sinha, R. K. 1997. Fluorosis – a case study from the Sambher Salt Lake region in Jaipur, Rajasthan, India. The Environmentalist 17:259-262.

Both natural and anthropogenic factors can cause fluoride concentrations in the environment to be elevated, thereby causing a risk to human health. Natural sources of fluoride relate to the geology of the area of interest. For instance, deep wells, mineral springs and hot water geysers can release significant amounts of fluoride into the environment (Sinha, 1997). Fluoride-bearing rocks also act as a geological source of fluoride to the natural environment. The weathering of these rocks, especially fluorapatites, can release fluoride into the environment, resulting in the contamination of groundwater (Sinha, 1997).

Industrial sources of fluoride pollution can result from the processes of aluminium, phosphate fertilizer, petroleum, refrigeration, steel, brick and tile manufacturing (Sinha, 1997). Furthermore, the burning of coal can cause fluorides to be emitted to the environment (Lian-Fang and Jian-Zhong, 1995). In addition to geological and industrial sources of fluoride contamination, the consumption of brick tea containing high fluoride concentrations has been recognized as a cause of endemic fluorosis in China (Yang et al., 2003).

As is shown in Figure 1 below, cases of endemic fluorosis are widespread throughout the world, with at least 25 countries across the globe affected (UNICEF, 1999).



Countries with endemic fluorosis due to excess fluoride in drinking water

Figure 1: Countries with endemic fluorosis due to excess fluoride in drinking water. Source: UNICEF. 1999. Position on water fluoridation: Water, environment & sanitation. Retrieved August 1, 2005 from http://www.nofluoride.com/Unicef_fluor.htm.

A literature review of a number of fluorosis case studies and examples from various regions of India, China and various countries within Africa was conducted. A summary of the information derived from the review is presented below.

2.2.1 India

It is estimated that more than 90% of India's rural population depends on groundwater for domestic purposes (Sharma, 2003). Groundwater is a major source of drinking water in both urban and rural areas of India, yet a significant portion of India's population does not have access to clean drinking water (Sharma, 2003). Excessive fluoride levels in groundwater have been a historical problem in India, with the first situation being reported in 1937 in the state of Andhra Pradesh (Meenakshi et al., 2004). An estimated 62 million people from 17 states in India suffer from fluorosis as a result of their consumption of water with high fluoride concentrations (Meenakshi et al., 2004). Fluoride-bearing rocks, such as fluorspar, cryolite, fluorapatite and hydroxylapatite, have been identified as major sources of fluoride in groundwater. It has also been determined that "the fluoride content in the groundwater is a function of many factors such as availability and solubility of fluoride minerals, velocity of flowing water, temperature, pH, [and] concentration of calcium and bicarbonate ions in water" (Meenakshi et al., 2004, 86). These factors may account for the variance in fluoride concentrations in the groundwater of India – some areas of India have fluoride concentrations of less than 0.5 ppm while other areas have reported concentrations as high as 30 ppm (Meenakshi et al., 2004).

Meenakshi et al. (2004) undertook a study of the quality of groundwater in four villages, namely Butani, Karkhana, Malar and Rojala, in the Jind district in Haryana, India. The villages have a total population of approximately 20,000 and their only source of drinking water is groundwater that is extracted with the use of approximately 80-100 hand pumps in each village. Fifteen samples in total were collected from various locations in each of the villages and the samples were analysed for the following parameters: pH, electrical conductivity, total dissolved salts, total alkalinity, total hardness, sodium, potassium, calcium, magnesium, carbonate, bicarbonate, chloride, sulphate and fluoride concentrations. Based on the data collected, Meenakshi et al. (2004) found that considerable variation in the chemical composition of the water samples existed. Notably, the concentration of fluoride at most of the sample locations was higher than the permissible limit of 1.5 ppm as per Indian drinking water standards. It was also determined that fluoride was not significantly correlated with any of the analysed parameters. Overall, Meenakshi et al. (2004) indicated that, based on the analysed water samples, the water in the study area "is not suitable for consumption without prior treatment [and that] a handpump attached filter based on Nalgonda technology or activated alumina adsorption might be the solution to this problem" (96).

In another study conducted by Rao and Devadas (2003), the factors responsible for fluoride in groundwater and methods to control the fluoride level in drinking water were investigated.

Anantapur district in Andhra Pradesh, India, an area with a high water deficit due to climatic conditions, was used as the study area. Groundwater in this area is being exploited through the use of both open dug wells and bore wells. Rao and Devadas (2003) collected water samples from drinking and irrigation wells from 53 locations during the area's dry season. In addition, 15 of the 53 well locations were sampled during the wet season in order to investigate seasonal variations in groundwater quality. The samples were analysed for the following parameters: pH, specific electrical conductivity, total dissolved solids, total alkalinity as calcium carbonate and bicarbonate, total hardness as calcium carbonate and calcium, magnesium, sodium, potassium, chloride, sulphate, nitrate, fluoride, carbonate hardness, non-carbonate hardness and excess alkalinity. Based on the data collected, Rao and Devadas (2003) found that the concentration of fluoride in groundwater in the study area varied from 0.56 to 5.80 ppm. Specifically, Rao and Devadas (2003) found that groundwater in the river courses and nearby tanks (surface water ponds) had fluoride concentrations ranging from 0.80 to 3.40 ppm; water from wells in agricultural lands had fluoride concentrations ranging from 1.10 to 5.80 ppm; and water from domestic wells had fluoride concentrations ranging from 0.50 to 3.40 ppm. In addition, it was found that fluoride concentrations were higher during the area's wet season rather than during the dry season.

As referenced by Rao and Devadas in their 2003 study, "apatite and fluorite, besides the replacement of hydroxyl by fluorine ions in mica, hornblende and soil that mostly consists of clay minerals, are the major sources of [fluoride] in circulating water" (247). It was determined that the study area consisted of rocks containing various amounts of apatite, fluorite, biotite, muscovite and hornblende. As such, Rao and Devadas (2003) investigated the influence of these rock sources on the fluoride concentrations in groundwater. It was found that fluoride is abundant in both the rocks and the soils of the study area as "most of the sources of [fluoride] for groundwater are from the country rocks, in which fluorine is strongly absorbed in soils that consist primarily of clay minerals" (Rao and Devadas, 2003, 248). The following findings were presented by Rao and Devadas (2003):

- Weathering activity in the semi-arid climate of the study area is responsible for the leaching of fluoride from the minerals occurring in the soils and rocks;
- Intensive and long-term irrigation in the study area is likely an additional factor which results in weathering and leaching of fluoride from the soils and rocks;
- The alkaline water in the area can cause fluoride to mobilize from soils and weathered rocks, resulting in the release of fluoride;

- Longer residence times of water in the aquifer zone due to a high rate of evapotranspiration and the low hydraulic conductivity of the weathered zone results in the dissolution of fluoride-bearing minerals; and
- The application of fertilizers also contributes to the higher content of fluoride in groundwater.

Based on the results of their study, Rao and Devadas (2003) offered recommendations with respect to irrigation techniques and the prevention of rock weathering and leaching of fluoride into the groundwater, the growth of vegetative cover to reduce evapotranspiration, careful use of agricultural fertilizers, and the implementation of rainwater-harvesting techniques. Especially noteworthy was the recommendation by Rao and Devadas (2003) that "an emphasis on people awareness about the adverse [effects] to human health of high fluoride concentrations in drinking water and education on the mechanisms necessary to improve the health status of the population are essential" (250).

The lack of understanding and knowledge of the problem of fluorosis that exists among those that suffer from the disease was evident in Guwahati, the capital city of Assam, India. Confusion existed among the residents of the area with respect to the use of groundwater and, as such, Das et al. (2003) conducted a survey of fluoride contamination in groundwater in order to develop an understanding of its coexistence with minerals and hydrogeological conditions. Das et al. (2003) collected and analysed 235 groundwater samples for fluoride content. Of these 235 samples, 24 representative samples with varying fluoride concentrations were analysed for other parameters, including nitrate, sulphate, chloride, phosphate, various metal ions and total hardness. Results from the analysis of the groundwater samples indicated that 10.7% of the samples had fluoride concentrations above 1.5 ppm, the WHO guideline value, while 45.5% of the samples had fluoride concentrations below 0.6 ppm (Das et al., 2003). High concentrations of iron, nitrate and chloride were detected in the collected samples; however, a correlation between these parameters and fluoride was not found (Das et al., 2003). Das et al. (2003) indicated that, as the presence of fluoride was detected in the groundwater of the study area, an investigation into the presence of other toxic elements in the groundwater would be warranted since elements such as arsenic and boron have been determined to have a positive correlation with fluoride.

It is interesting to note that although fluoride concentrations above the WHO guideline value of 1.5 ppm were detected in a significant number of groundwater samples collected as part of this study, at the time of publication, no cases of fluorosis in the area had been reported. Das et al. (2003) determined that a positive correlation exists between the depth of the sample sources and fluoride concentrations, suggesting "the source of fluoride to be fluorite or (and) apatite minerals present in the Precambrian granite or granitic-gneiss of the underground basement [of the city]" (659). It is thought that the high usage of shallow dug wells and hand tube wells in the study area, as opposed to deep tube wells, may be a contributing factor to the lack of fluorosis in the area.

As indicated in a study conducted by Chatterjee and Mohabey (1998), several cases of fluorosis have been reported from the granitic terrain of Rajasthan and Andhra Pradesh, as well as areas of Bhandara and Gadchiroli districts of Maharashtra. Granitic rocks cover the area of Chandidongri in Madhya Pradesh and approximately 0.5 million tonnes of economically workable fluorospar exists in the Chandidongri fluorite deposit. As such, Chatterjee and Mohabey (1998) conducted a study in the area to investigate any cases of fluorosis and to determine the impact of geology and fluorite mining on the water quality. Water samples were collected from the mine pit and wells in the study area and it was determined that fluoride concentrations in the samples ranged from 0.04 to 0.40 ppm (Chatterjee and Mohabey, 1998). The water in the study area was found to be alkaline and previous research indicated that "fluoride concentration and the severity of fluorosis are directly related to the alkalinity of water" (Chatterjee and Mohabey, 1998, 2). However, in this particular study area, no significant correlation was found between the fluoride content in the water and the water's alkalinity. As such, "the presence of fluoride in water … is attributed to the associated rock types" (Chatterjee and Mohabey, 1998, 2). No cases of fluorosis had been identified around the mine pit area; however, the possibility of increased mining activity in this area may result in an increase in fluoride concentrations in the water. Therefore, Chatterjee and Mohabey (1998) suggested that long-term monitoring of the water quality for increases in fluoride concentrations be undertaken.

2.2.2 *China*

Approximately 38 million people in China are reported to suffer from dental fluorosis and approximately 1.7 million people reportedly suffer from skeletal fluorosis (Fawell et al., 2006). Cases of endemic fluorosis result from the consumption of contaminated drinking water, pollution from coal burning and from certain tea drinking activities (Lian-Fang and Jian-Zhong, 1995). Endemic fluorosis caused by contaminated drinking water has been found to occur largely in the provinces and autonomous regions in the northern parts of China (Lian-Fang and Jian-Zhong, 1995). These areas are arid with high evaporation rates and are often low-lying. It has been found that fluoride concentrations in the groundwater of these areas increase with a decline in elevation (Lian-Fang and Jian-Zhong, 1995).

Endemic fluorosis related to pollution from coal burning has been found to occur in the coalfield districts of southern China. Lian-Fang and Jian-Zhong (1995) state that the residents of these areas burn coal containing high levels of fluorides to bake grain and for warmth during the winter season. The stoves used to burn the coal are not equipped with chimneys and, as such, smoke from the burning coal is emitted directly indoors, resulting in contamination of the baked grain and other foods, as well as indoor air pollution (Lian-Fang and Jian-Zhong, 1995).

According to Lian-Fang and Jian-Zhong (1995), fluorosis related to tea drinking has been found to be prevalent amongst minority inhabitants of western and northern China, in arid areas where animal husbandry production occurs. The consumption of milk tea, prepared from brick tea and known to have a high fluoride content, has become a regular drink for these populations. Significant quantities of the tea are consumed by the inhabitants of these areas, resulting in the occurrence of osteo-fluorosis and mottled teeth (Lian-Fang and Jian-Zhong, 1995).

Lian-Fang and Jian-Zhong (1995) provided an overview of China's history of fluorosis as follows:

- Evidence of cases of fluorosis had been discovered in China's history as far back as one hundred thousand years ago in the "Xiujiayo" sino-ancient men who suffered from mottled teeth;
- Cases of endemic fluorosis in China began to be reported in the 1930s;
- In the 1960s, the Central Government of China established a specialized group to be responsible for the control of endemic diseases. In addition, corresponding groups were established in each of China's provinces, autonomous regions and municipalities, demonstrating the importance of controlling endemic diseases to the Chinese government;
- In 1979, fluorosis was officially recognized as an endemic disease that needed to be nationally controlled. A national conference that provides an opportunity to share the

experiences of different areas with respect to the control of endemic fluorosis convenes at regular intervals of 2-3 years, and has done so since 1979; and

- By the end of the 1980s, campaigns were prevalent to improve water quality in the northern parts of China affected by the high fluoride content of drinking water, and pilot schemes were initiated to improve and adapt domestic stoves in areas of southern China affected by poisoning from smoke which was emitted during coal burning and contained high concentrations of fluoride.

Advances and improvements with respect to endemic fluorosis have been made over time in China. For instance, funding from local governments for pilot campaigns to improve the quality of drinking water in affected regions through defluoridation have allowed local residents improved access to safer drinking water (Lian-Fang and Jian-Zhong, 1995). However, the need for funds to improve the quality of drinking water through defluoridation continued to increase beyond the capacity of the local government. It was also found that locals in affected areas were not taking an interest in maintaining safe drinking water conditions and, instead, were relying on state investment and involvement. The result was that wells which had once been protected from fluoride contamination became neglected and poorly managed, forcing the local residents to once again consume fluoride-contaminated water (Lian-Fang and Jian-Zhong, 1995).

Despite a nationwide commitment to the control of endemic fluorosis, the affected population in China and local decision makers are often not fully aware of the harmful effects of the disease. This has resulted in a lack of informed and beneficial management actions in many provinces (Yang et al., 2003). To remedy this situation, Yang et al. (2003) suggested that information and data regarding fluorosis should be provided in a useful and simplified format. Yang et al. (2003) stated that "although extensive monitoring data on fluoride in the environment and fluorosis conditions in the disease areas have been collected over the last decades, it has been difficult to use the data for policy making" (282). Based on data available in the Chinese literature, Yang et al. (2003) presented a variety of different indicators and two indices that could be used to more effectively report and evaluate the control actions taken throughout China to manage fluorosis caused by fluoride-contaminated drinking water.

The pressure-state-response-impact causality chain was proposed by Yang et al. (2003) as an indicator framework for the transformation of fluorosis data into useful information to aid decision makers in identifying trends and promoting national action. In general, "pressure indicators … provide information on the causes of the problem, state indicators … provide basic information about the human activities that affect the environment or human health, and response indicators … provide information on efforts aimed at addressing the problem" (Yang et al., 2003, 283). Impact indicators represent the consequences of changes in the state of the environment. In addition, Yang et al. (2003) outlined three sets of conceptual indicators which are present within the pressure-state-response-impact framework: descriptive indicators describe the past fluorosis situation; responsive indicators describe current actions being taken to manage fluorosis; and performance indicators describe future outcomes of long-term policy actions.

The function of indicators is to provide a summary of information that can be understood by both the public and those in decision-making positions. However, decision makers will often require more comprehensive combined data which can be provided through the use of indices that merge two or more variables into one value. Indices "represent highly aggregated indicators that can be used to provide policy-makers with a general simplified picture of trends. Indices can also be developed at different levels of detail and spatial scales … to compare different geographical areas" (Yang et al., 2003, 283). Yang et al. (2003) proposed the use of a health impact index and a management capabilities index, which would use the indicators described above for the evaluation of the fluorosis issue in China. Overall, the indices would serve as tools for the identification of effective policies and would enable reporting of management action results within different geographical areas.

The results of the study conducted by Yang et al. (2003) are summarized as follows:

- The amount of monitoring data available in China is extensive and of variable quality, therefore, relevant data must be identified and verified;
- There is a lack of data pertaining to health care costs associated with the millions of people suffering from skeletal fluorosis. This demonstrates a need to develop useful and effective national response indicators which will allow proposed management actions to be based on sound economic principles; and
- A significant inverse relationship was evident between the fluorosis management capabilities index and the health impact index; that is, a low management capability corresponded to a high health index (health of the population was seriously impacted by

exposure to drinking water-type fluorosis) and a high management capability corresponded to a low health impact index.

Yang et al. (2003) concluded that the positive inverse relationship identified between the health impact index and the management capability index demonstrated that the "severity of the disease could be readily reduced by additional management actions by the local and provincial governments" (293-294). Yang et al. (2003) also stated that "indicators must be reported and interpreted in the appropriate context by taking into account socio-economic and structural features of [China]" (292). In so doing, indicators and indices can provide a systematic method of representing data on the management of fluorosis in China so that effective policy-making can occur.

Another study related to the fluoride content in drinking water in China was conducted by Wang et al. (2004). The study investigated the relationship between the concentration of fluoride in drinking water and dental health in 24 large cities in nine provinces and in four villages with high environmental fluoride levels. Wang et al. (2004) collected tap water samples from wellheads, water treatment plants and various homes in each of the investigated cities, as well as urine samples from between 100 to 150 subjects aged 16 to 18 years of age. All samples were analyzed for fluoride concentrations. In addition, dental epidemiological data on the incidence of dental caries in 33 large cities and 33 villages in China obtained by the National Committee on Oral Health of China (NCOH) in 1995 were used in the study.

Wang et al. (2004) found that in more than 90% of the cities investigated, the fluoride concentration in the tap water was less than 0.5 ppm. A significant positive correlation between the fluoride concentration in tap water and the concentration of fluoride in urine was also found, "indicating that the concentration of fluorine in the drinking water was the primary factor affecting the fluorine concentration in the resident's urine and that the amount of fluorine intake from foodstuff and air are minor variables" (Wang et al., 2004, 1071). Based on the low fluoride concentration in the drinking water samples collected during this investigation, Wang et al. (2004) suggested that water fluoridation in urban populations of China could be beneficial in the prevention of dental caries. In addition, Wang et al. (2004) concluded that "based on the results from the 15- to 18-year-old residents of high-fluorine villages … [the] fluorine concentration in drinking water in Chinese cities can be safely increased to not more than 1.0 mg/l without inducing dental fluorosis" (1073).

2.2.3 *Africa*

Dental and skeletal fluorosis have been reported in the African countries of Morocco, Tunisia, Algeria, Sudan, Egypt, Somalia, Uganda, Kenya, Tanzania, Senegal, Nigeria and South Africa (Apambire et al., 1997). Specifically, the East African Rift Valley is an area where high fluoride concentrations are prevalent, resulting in health problems in the inhabitants of the area. It has been found that leaching of the Rift Valley volcanic rocks significantly contributes to fluoride levels in the water (Nyaora Moturi et al., 2002). Previous investigations have found levels of fluoride in groundwater in the Rift Valley to be as high as 39.0 ppm from wells and 43.5 ppm in boreholes (Nyaora Moturi et al., 2002). A study was conducted by Nyaora Moturi et al. (2002) "to assess the contribution of drinking water to fluoride intake by the residents of Njoro in Nakuru district in the Kenya Rift Valley" (124). Although the majority of foods in Kenya contain fluoride concentrations of less than 1.0 ppm, some exceptions, such as tea and lake fish, do exist. Therefore, as there are different possible sources of fluoride in Kenya, it is important to evaluate the amounts of fluoride in drinking water ingested by people in various parts of Kenya. Nyaora Moturi et al. (2002) collected samples from 20 major community water points, both in the dry and wet seasons, as follows: six boreholes, five wells, five river sites, three dams and one spring. In addition, rainwater was sampled during the wet season. The samples were analysed for the following parameters: alkalinity, hardness, magnesium, calcium, fluoride, sodium, silica and boron. Nyaora Moturi et al. (2002) also conducted a visual examination for the presence and degree of mottled teeth in children above nine years of age in 20% of the primary schools in the study area. To supplement the analytical results, questionnaires were administered to the children examined for mottled teeth to determine the following:

- What water sources they used;
- What methods of water treatment, if any, and water storage were used in their homes;
- Water utilization patterns;
- Type of dental cleaning agents used; and
- Attitude towards dental fluorosis.

Based on the results of the chemical analyses of the collected water samples, Nyaora Moturi et al. (2002) determined that all water sources, with the exception of rainwater, have fluoride concentrations above the recommended range of 1.0 to 1.5 ppm. Surface water sources were found to have lower fluoride concentrations than groundwater. The results of the study also indicated that "most of the households consume water with fluoride levels ranging from 2.5 mgL^{-1} to 8.5 mgL^{-1}. A small fraction of the residents use water with fluoride levels less than

2.5 mgL^{-1} or more than 8.5 mgL^{-1}" (Nyaora Moturi et al., 2002, 126). The examination of children's teeth revealed that 48.3% of the children in the study area suffer from moderate to severe dental fluorosis (Nyaora Moturi et al., 2002). These children continue to be exposed to high fluoride concentrations in their drinking water and, as such, their condition will likely worsen over time.

Nyaora Moturi et al. (2002) reported the results of the questionnaire as follows:

- Since groundwater is less turbid than surface water, groundwater is perceived to be of better quality and is therefore used for cooking and washing;
- Alum treatment, which has been demonstrated to decrease fluoride concentrations in water, is used by some households but only to remove turbidity from water for washing and cleaning, not for drinking;
- Chlorination is performed on most borehole waters to kill microbes; however, chlorination does not decrease the concentration of fluoride in water;
- 45% of the residents of the study area disinfect their drinking water from microbial contamination by boiling their water. However, like chlorination, boiling water does not lower the concentration of fluoride;
- More than 80% of the respondents felt that dental fluorosis is a problem due to (i) the unsightly nature of teeth, (ii) teeth that are susceptible to breakage thereby making it difficult to chew, and (iii) induced shyness, especially in teenage girls. In spite of this opinion, 74% of the respondents were not aware of the causes of dental fluorosis or the remedies for the problem; and
- Storage of water in pots reduced the concentration of fluoride in drinking water, with the greatest reduction occurring after five days of storage. Presumably, the clay minerals contained within the pots adsorb the fluoride.

Based on the results of their investigation, Nyaora Moturi et al. (2002) recommended that alum be added to the residents' drinking water. In addition, it was recommended that rainwater be harvested for water consumption and that clay pots be used for the storage of drinking water (Nyaora Moturi et al., 2002).

In order to investigate the relationship between various concentrations of fluoride in drinking water, dental caries (i.e., decay), and dental fluorosis, Grobler et al. (2001) studied children who had resided since birth in low, medium and high fluoride areas. Grobler et al. (2001) indicated that an inverse relationship has typically been found between the concentration of fluoride in drinking water and caries experience. In addition, previous research has indicated that fluoride levels, caries experience and dental fluorosis vary from population to population, likely due to additional factors such as dietary fluoride intake, climate, systemic and topical fluoride administration, socio-economic status, and any factor that can cause urinary pH, temperature and altitude to decrease (Grobler et al., 2001).

The study was conducted on 10-15 year old children in Leeu Gamka, Kuboes and Sanddrif where the average fluoride concentration in water, based on data over the last 10 years, is 3.0 ppm (high), 0.48 ppm (medium) and 0.19 ppm (low), respectively (Grobler et al., 2001). The study subjects were of similar ethnic and socio-economic status, as well as nutrition and dietary habits. Grobler et al. (2001) indicated that the dietary habits of the subjects did not significantly contribute to the ingestion of fluoride and that the subjects "had virtually no dental care or fluoride therapy, including the use of fluoride-containing toothpaste" (373). The water sources were boreholes in Leeu Gamka and Kuboes and the Orange River in Sanddrif (Grobler et al., 2001). The study consisted of conducting dental examinations on the children for caries according to the decayed-missing-filled teeth (DMFT) index, and fluorosis. In addition, the water fluoride level was determined and analysed over a ten-year period.

Based on the results of the study, Grobler et al. (2001) found that the prevalence of fluorosis was 47% in Sanddrif, 50% in Kuboes and 95% in Leeu Gamka. In addition, it was found that a strong positive correlation existed between caries experience and fluorosis scores in the children of Leeu Gamka (the high fluoride village); however, "a low caries experience and no difference in DMFT and fluorosis between the two low fluoride areas were found" (Grobler et al., 2001, 376).

The Bolgatanga and Bongo Districts in the upper regions of Ghana are also areas that rely on groundwater-based systems for drinking water sources and are known to experience elevated concentrations of fluoride in the groundwater (Apambire et al., 1997). For the purposes of groundwater geochemical classification and data interpretation, Apambire et al. (1997) divided the rocks underlying the study area into the following major groups: Upper Birimian metasediments, Upper Birimian metavolcanics, granitoids associated with the Upper Birimian Formation, and Bongo granitic suite. Borehole wells equipped with hand pumps and hand-dug wells have become common structures from which to obtain water supplies in the study area.

Water consumption is high in this area (approximately 3-4 litres per day per individual) due to the hot climatic conditions. Apambire et al. (1997) stated that many of the wells in the study area were low yielding, resulting in the need to install a number of wells to service even a small community. As such, an increasing need to construct new water supply systems to continue to serve the communities exists and "the challenge is to ensure that chemical quality factors are not compromised by attempts to increase quantity or by such development factors as aquifer drawdown" (Apambire et al., 1997, 17).

Apambire et al. (1997) collected water samples from 371 borehole wells in the study area. Field measurements for pH, electrical conductivity and temperature were taken and chemical analyses of the samples for a variety of parameters were conducted. Based on the analytical results, Apambire et al. (1997) found that fluoride concentrations in the groundwater of the study area ranged from 0.11 to 4.6 ppm, with a mean value of 0.97 ppm. It was determined that anomalous concentrations of fluoride (that is, greater than 1.5 ppm) were limited to wells located in the Bongo granites. According to WHO guideline values, the optimal range of fluoride in groundwater for good dental health is between 0.5 and 1.5 ppm. The study conducted by Apambire et al. (1997) revealed that 49% of the wells sampled provided water that is below the optimal fluoride interval, 28% of the wells were within the optimal interval, and 23% of the wells had water with fluoride concentrations above the optimal interval.

Apambire et al. (1997) presented the data as a 'geochemical health-risk map' which could be used by health officials as an initial indicator of risk of developing dental or skeletal fluorosis in the study area. Based on this format of data presentation, the following categories were noted:

- 0.0-1.0 ppm fluoride – geographical areas largely underlain by the Birimian basement rocks, including the granitoids, where there is a risk of dental caries and poor bone development;
- 1.0-2.5 ppm fluoride – geographical areas consisting of Bongo granitic intrusions where there is a moderate risk of developing dental and skeletal fluorosis; and
- >2.5 ppm fluoride – geographical areas centred in the interiors of the Bongo, Adaboya and Sekoti intrusions where there is a high risk of developing dental and skeletal fluorosis.

Apambire et al. (1997) stated that presenting the data as a geochemical health-risk map would allow health officials to economically develop epidemiological studies and dental health education programs in the study area since the data can be altered to focus on whole or specific ages or sex groups. It is important to note that "analysis of climatic effects on water consumption, food preparation techniques, and dietary intakes" indicated that the fluoride intake of the inhabitants of the study area may be higher than measured and, as such, a larger population may in reality be susceptible to developing dental and skeletal fluorosis (Apambire et al., 1997, 23).

2.3 Defluoridation Technologies

Different methods exist for the removal of excessive fluoride from drinking water. Defluoridation technologies can generally be categorized as methods based on the addition of chemicals to cause precipitation; methods based on adsorption; and methods based on membrane separation (Garmes et al., 2002). Various hybrid and integrated methods have been developed which can result in overlap in the categorization of a defluoridation technology. Typical reactive chemicals that can be added during defluoridation processes include lime, aluminum sulphate, gypsum, and calcium chloride (Zevenbergen et al., 1996). Several defluoridation methods for which literature studies are available are briefly summarized below.

2.3.1 Nalgonda Technique

This method of water defluoridation, named after the village of India where the method was established, employs the principles of flocculation. Alum (hydrate aluminum salts), a coagulant, is added to the contaminated water in order to flocculate fluoride ions in the water (UNICEF, 1999). The process is most effective when carried out under alkaline conditions and, as such, lime is directly added to the water to maintain pH levels (UNICEF, 1999; Agarwal et al., 1999). The coagulated flocs, which are heavier than the water, settle to the bottom and are removed. This defluoridation technique has been used at both the community and household levels and has been stated to be both simple and economical (UNICEF, 1999; Mekonen et al., 2001).

Agarwal et al. (1999) did, however, identify a number of drawbacks to the Nalgonda technique as summarized below:

- It is difficult to control the alum dose required as it is dependent upon the fluoride content in the water which can differ depending on the source of water;
- The process is only suitable for water with a fluoride content of less than 10 ppm;
- A high free aluminum content, reported as ranging from 2.01 to 6.86 ppm, results in the treated water and this residual aluminum concentration is worsened by the boiling of treated water in aluminum containers;

- The taste of the treated water is questionable; and
- The technique is cumbersome and not particularly suitable for those who are illiterate or not sufficiently knowledgeable in the problems associated with high fluoride concentrations in water.

Figure 2 shows a typical Nalgonda defluoridation system that has been adopted for household use.

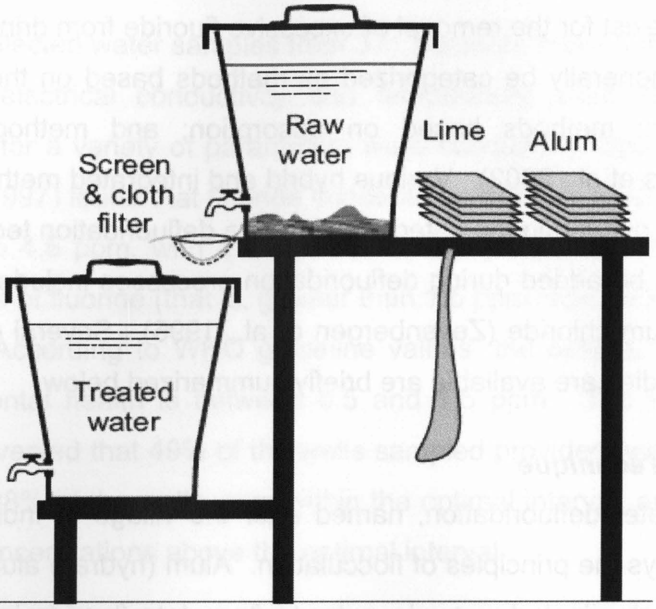


Figure 2: Typical Nalgonda defluoridation system. Source: Fawell, J., K. Bailey, J. Chilton, E. Dahi, L. Fewtrell and Y Magara. World Health Organization. 2006. Fluoride in drinking-water. IWA Publishing: London.

2.3.2 Integrated Alum-Powdered Activated Carbon (PAC) Slurry

In order to treat water with fluoride concentrations greater than 10 ppm, it is necessary to add a high dose of alum to the water, resulting in unacceptable levels of sulphate and aluminum concentrations in the treated water (Mekonen et al., 2001). It has been suggested that a combination of alum and powdered activated carbon (PAC) can be used to decrease the necessary addition of alum, thereby allowing for the improved removal of water with initial fluoride concentrations greater than 10 ppm (Mekonen et al., 2001). As indicated by Mekonen et al. (2001), previous investigations have demonstrated that fluoride removal by alum-PAC slurry occurs through the following mechanisms:

- Adsorption on or complexation with solid aluminum hydroxide, $Al(OH)_3(s)$, in the bulk solution, or with $Al(OH)_3(s)$ which covers the PAC surface (coated PAC surface);

- Adsorption directly on the PAC surface (uncoated PAC surface);
- Gradual diffusion of fluoride through the floc surrounding the particle to the PAC surface; and
- Formation of fluoroaluminum complex precipitate through the use of PAC particles as nuclei, resulting in the indirect enhancement of fluoride removal by alum.

Mekonen et al. (2001) noted that the defluoridated effluent from the use of an alum-PAC slurry contained high levels of sulphate (maximum of 400 ppm); however, these high sulphate concentrations were reported to be acceptable according to WHO drinking water guidelines as a level of sulphate in drinking water that is likely to cause adverse affects to human health has not been identified. It was also determined that improved fluoride removal efficiency through the use of the alum-PAC slurry technique for waters with fluoride concentrations greater than 15 ppm would require a high pH value (between 6.5 to 7.5), and that activated carbon prepared from fish bone could provide a suitable source for the alum-PAC method (Mekonen et al., 2001). Mekonen et al. (2001) concluded that "alum-PAC slurry appears to be a better choice for defluoridation, particularly at higher initial fluoride concentrations, compared to alum alone" (3128).

A schematic of the alum-PAC slurry defluoridation process is presented below as Figure 3.

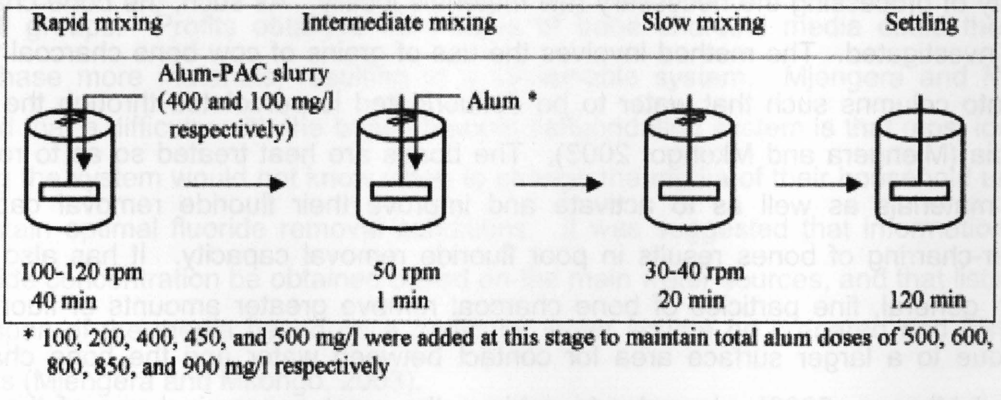


Figure 3: Schematic of the alum-PAC slurry defluoridation process. Source: Mekonen, A., P. Kumar and A. Kumar. 2001. Integrated biological and physiochemical treatment process for nitrate and fluoride removal. Water Resources 35:3127-3136.

2.3.3 Bone Charcoal Method

When bone charcoal comes in contact with water, it has the capacity for fluoride uptake, as well as the capability to absorb pollutants such as odour and taste components to a limited degree (Fawell et al., 2006). As stated by Fawell et al. (2006), "preparation of bone charcoal is crucial to optimize its properties as a defluoridation agent and as a water purifier" (47). Figure 4 below depicts the set up of a household bone charcoal filter column defluoridation unit.

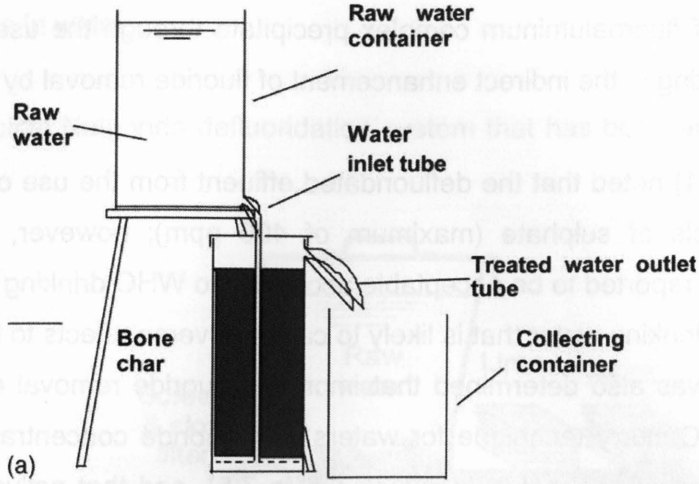


Figure 4: Typical bone charcoal filter column defluoridation unit. Source: Mjengera, H. and G. Mkongo. 2003. Appropriate defluoridation technology for use in flourotic areas in Tanzania. Physics and Chemistry of the Earth 28:1097-1104.

Mjengera and Mkongo (2003) identified a need to select a defluoridation method for Tanzania's fluoride-contaminated drinking water problem that was easy to use, had an effective fluoride removal capacity, and for which there was an availability of the necessary raw materials as well as a possibility of processing the necessary raw materials locally. As such, the bone charcoal method was investigated. The method involves the use of grains of cow bone charcoal which are packed into columns such that water to be defluoridated is percolated through the bone charcoal media (Mjengera and Mkongo, 2003). The bones are heat treated so as to remove any organic materials as well as to activate and improve their fluoride removal capacity; however, over-charring of bones results in poor fluoride removal capacity. It has also been found that, in general, fine particles of bone charcoal remove greater amounts of fluoride at faster rates due to a larger surface area for contact between water and the bone charcoal (Mjengera and Mkongo, 2003). In order to achieve the most economical use of the bone charcoal, Mjengera and Mkongo (2003) recommended that different particle sizes ranging from 0.5 to 4 mm be blended together.

Due to the fact that high raw water fluoride concentrations more rapidly exhaust the removal capacity of the bone charcoal media, a combination of the bone charcoal method and an alum/lime defluoridation method was investigated (Mjengera and Mkongo, 2003). The combined technique is outlined as follows:

> In this combined method water to be defluoridated is pre-treated by fractions of chemical dosages used in [the] alum and lime method. The chemicals are added to reduce fluoride load and to increase ionic strength of the water. After the chemical addition and the flocculation processes the water is allowed to settle before filtration [occurs] through [the] bone char column. The bone char removes the remaining fluoride in the water. (Mjengera and Mkongo, 2003, 1103)

Studies conducted by Mjengera and Mkongo (2003) indicated that the use of the two defluoridation methods in series resulted in an improved performance of the bone charcoal in decreasing fluoride levels of water, but that further investigation was required to confirm performance and costs associated with the combined techniques. Raw water with an initial fluoride concentration of 22 ppm was pre-treated with alum and lime and experienced a reduction in fluoride concentration to 11.7 ppm (Mjengera and Mkongo, 2003). Upon passing through the bone charcoal column, a residual fluoride concentration of approximately 2 ppm was achieved (Mjengera and Mkongo, 2003).

Overall, Mjengera and Mkongo (2003) stated that the bone charcoal method of defluoridation was suitable for local conditions in Tanzania as the required materials were locally available and could be processed and prepared locally by individuals for the household level or for sale to small groups. Profits obtained from sales of bone charcoal media could then be used to purchase more materials, resulting in a sustainable system. Mjengera and Mkongo (2003) noted that a difficulty with the bone charcoal defluoridation system is that most local inhabitants using the system would not know when to change the media of their household units in order to maintain optimal fluoride removal conditions. It was suggested that information on the initial fluoride concentration be obtained based on the main water sources, and that lists indicating the life span of the media based on a particular water source be prepared and distributed to the locals (Mjengera and Mkongo, 2003).

2.3.4 KRASS Process

The KRASS process for defluoridation of water is a direct flow-through type of column that requires recharging with an alum solution upon exhaustion (Agarwal et al., 1999). A study conducted by Agarwal et al. (1999) found that a maximum of four grams of fluoride could be removed per one kilogram of alum used to recharge the column. A 10% alum solution was found to be optimal for recharging and, therefore, the required alum dose can be easily regulated when the using the KRASS process (Agarwal et al., 1999). It was also found that "the fluoride removal capacity of recharged support material increased on increasing influent fluoride concentration and pH [with] the optimum ranges being 11-12 mg/l for influent fluoride concentration and 7-8 for pH" (Agarwal et al., 1999, 172). Based on the results of the study conducted by Agarwal et al. (1999), over 65 litres of water could be treated through the use of one recharge of the KRASS process through a domestic filter. This quantity of treated water would be sufficient for a medium sized rural family for one day.

Yadav et al. (1999) and Agarwal et al. (1999) listed the following as salient features of the KRASS process for water defluoridation:

- Cost effective;
- Can be situated anywhere suitable for the user;
- Easy to operate and maintain by a rural community;
- Independent of input fluoride concentration, alkalinity, pH and temperature;
- No affect on the taste of the treated water;
- Only trace amounts of aluminum detected in the treated water; and
- Can be recharged for approximately 30-40 cycles prior to being discarded.

2.3.5 Coal-Based Sorbents

Sivasamy et al. (2001) investigated the use of three different coal-based sorbents as defluoridation methods: lignite, fine coke and bituminous coal. Adsorption dynamics are affected by contact time and it was found that the adsorption of fluoride increased with time until, gradually, equilibrium was attained (Sivasamy et al., 2001). In addition, it was "noted that the nature of the pores in the sorbent also determines the magnitude of contact time for attainment of equilibrium" (Sivasamy et al., 2001, 718). Based on the results of their study, Sivasamy et al. (2001) determined that lignite is a more efficient adsorbent in comparison to fine coke and bituminous coal as suggested by the amount of fluoride adsorbed per unit surface area. Specifically, when the initial fluoride concentration of water was varied between 3 and 90 ppm, the fluoride removal efficiency was found to range from 85 to 89% for lignite, 85% for fine coke and 79 to 84% for bituminous coal (Sivasamy et al., 2001). Data also indicated that lignite has a higher defluoridation capacity when pH of the contaminated water is in the range of 6 to 12, whereas acidic pH values result in higher defluoridation for fine coke and bituminous coal (Sivasamy et al., 2001).

2.3.6 *Geomaterial Sorbents*

Clay has the ability to sorb fluoride, and can also be used as a flocculant powder in a batch defluoridation system (Fawell et al., 2006). A study conducted by Agarwal et al. (2003) investigated the use of clay containers for the defluoridation of water. Common in rural India, these containers are often used for the storage of water, especially in the summer season, as the porous clay materials of the containers promote evaporation and help keep water cool. Agarwal et al. (2003) also studied the fluoride sorption achieved by two fractions of the soil of the Agra District in India comprised of silty clay and sand. Agarwal et al. (2003) stated that the "silty clay … fraction exhibiting maximum [fluoride] sorption was further amended chemically to enhance its potential for water defluoridation – a method when extrapolated to fabrication of vessels would have enhanced potential of utilising vast naturally occurring sorbent … for defluoridation of water" (439). Chemical additions to the soil samples included hydrochloric acid, sodium hydroxide, activated alumina, ferric chloride and/or calcium carbonate (Agarwal et al., 2003).

The results of the study conducted by Agarwal et al. (2003) indicated that acidified silty clay lowered the concentration of fluoride in water from 5 ppm to less than 1.5 ppm. It was also reported that silty clay amended with 50 mg/g each of iron, calcium or aluminium was an efficient sorbent of fluoride; however, the suitability of water defluoridated with amended silty clay for consumption would need to be assessed for concentrations of iron, calcium and aluminum (Agarwal et al., 2003). A pilot study conducted by Agarwal et al. (2003) over a three-week period indicated that the use of clay vessels for defluoridation reduced the concentration of fluoride in water stored in the vessels from 150 to 60 ppm in 12 hours. Overall, Agarwal et al. (2003) concluded that "adding a calculated quantity of [fluoride] free salts of activated [alumina], [ferric chloride] and [calcium carbonate] in the clay-rich soil during fabrication of vessels might enhance the [fluoride] removal capacity of the conventionally used clay vessels (pots) considerably" (444). It was also noted that fluoride removal appeared to be concentration dependent and, as such, connecting clay pots in series and allowing fluoridated water to pass through these pots in series may gradually lower the fluoride concentration below the permissible limit (Agarwal et al., 2003). The use of chemically amended clay pots as a defluoridation technique would provide an economical, simple, user and environmentally friendly method of obtaining safe drinking water for affected populations.

The use of soil as a fluoride sorbent was also investigated by Zevenbergen et al. (1996). Specifically, Ando soils, or soils with andic properties, which are abundant in Kenya along the Rift Valley were studied. The volcanic ash from which these soils are derived has partially weathered to produce active aluminum in various forms (Zevenbergen et al., 1996). Ando soils are very porous and generally consist of volcanic glass, microlite, organic matter and clay minerals. Observations have indicated that "most regions with high fluoride concentrations in the groundwater coincide with regions with Ando soils or soils with 'andic' properties" (Zevenbergen et al., 1996, 230).

Zevenbergen et al. (1996) indicated that the high adsorption capacity for fluoride possessed by Ando soils is generally known and can be attributed to the high active aluminum content and acidic nature of these soils; however, little is known regarding the fluoride adsorption mechanism at relatively low fluoride concentrations. The results of the study conducted by Zevenbergen et al. (1996) indicated that a positive correlation existed between the time required to obtain equilibrium for fluoride sorption and fluoride concentration. The data also indicated a two step adsorption mechanism with an initial rapid phase followed by a slower uptake mechanism: "the amount of fluoride sorbed after 24 h was only slightly lower than after 7 days, indicating that a 24 h equilibrating period is adequate for [fluoride] sorption studies under the prevailing experimental conditions" (Zevenbergen et al., 1996, 228). Due to a high fluoride adsorption capacity and an abundance in areas with fluoride-rich groundwater, the use of Ando soils as a simple and economically efficient defluoridation method at the village level is plausible (Zevenbergen et al., 1996). The results of a model study conducted by Zevenbergen et al. (1996) suggested that "depending on the available soil column length, an infiltration area of 2500 m^2 will suffice for the production of potable drinking water for a sizeable village of 10 000 inhabitants for a period of over 1 year" (Zevenbergen, 1996, 231).

Previous studies as outlined by Wang and Reardon (2001) showed that a heavily weathered Pleistocene soil from Xinzhou Prefecture, China had fluoride removal capabilities, and that when heat-treated, the fluoride sorbing and hydraulic conductivity properties of the soil were increased. This soil consists of clay and has a dark red appearance, indicating its high iron content. Regeneration of the sorbent is an important factor in the search for an effective defluoridation technique. Wang and Reardon (2001) investigated the optimal procedure for the regeneration of the soil and noted that rinsing the soil with an alkaline solution, followed by a hydrochloric acid solution, followed by distilled water was the preferred procedure. It was also noted that "the regeneration procedure … more than doubles the fluoride removal capacity of the soil" (Wang and Reardon, 2001, 535).

Study results indicated that heated soil that had not undergone regeneration improved the soil's capacity for fluoride removal, and that the majority of fluoride uptake occurred within 1.5 hours of the addition of a fluoride-containing solution to the soil (Wang and Reardon, 2001). It was found that heat treatment of the soil created a permeable granular material that was suitable as a column substrate for use in water treatment (Wang and Reardon, 2001). Based on the results of their investigation, Wang and Reardon (2001) stated that "use of the soil would seem practical in fluorosis-affected areas such as Shanxi, China where groundwater [fluoride] levels are relatively low, typically in the range 1.3-5.0 mg/l" (536). However, water with fluoride concentrations greater than 5 ppm would best be treated with the combination of the soil sorbent and another technique (Wang and Reardon, 2001).

2.3.7 Hybrid Process of Adsorption and Donnan Dialysis

The membrane separation technology of Donnan dialysis has been studied as a method for the removal of fluoride from diluted sodium fluoride solutions and synthetic waters used as models of fluoride-contaminated waters in countries within Africa (Garmes et al., 2002). A study conducted by Garmes et al. (2002) investigated the combination of a Donnan dialysis procedure with adsorption on conventional solid adsorbents, such as aluminum and zirconium oxides, for the treatment of groundwater with an excessive fluoride concentration of 4.0 ppm due to phosphate mining in Morocco. A pre-industrial scale Donnan dialysis unit was used in the study and consisted of five feed and six receiver cells, separated by anion-exchange membranes with the addition of an adsorbent occurring in the receiver compartments (Garmes et al., 2002). Garmes et al. (2002) detected the following fluoride concentrations in water at the feed outlet of the Donnan dialysis unit:

- 0.82 ppm with an open receiver;
- 2.73 ppm with a closed receiver without adsorbent;
- 1.06 ppm with a closed receiver with the addition of aluminum oxide as an adsorbent; and
- 1.23 ppm with a closed receiver with the addition of zirconium oxide as an adsorbent.

Based on the results of their study, Garmes et al. (2002) noted that the hybrid process of adsorption and Donnan dialysis process allow for the continuous defluoridation of impacted water and eliminates the need for the drinking water to be in direct contact with the adsorbents. Garmes et al. (2002) stated that "under these conditions, adsorption is not dependent on pH and ionic strength of the water to be treated" (291).

3.0 DECISION-MAKING STRATEGIES AND AN EVALUATION OF DEFLUORIDATION TECHNOLOGIES

The need to make decisions is a daily occurrence. Some decisions require a brief and simple evaluation of alternatives that can be based on intuition or conducted subconsciously; other decisions are more complex and, thus, require a systematic approach to evaluate the available options. Uncertainty is inherent in these more complex decisions, and decision makers often need to "evaluate many alternatives or balance many conflicting objectives", which can require a formal decision analysis approach (Bell and Schleifer, 1995, 9). An overview of some basic steps in a decision-making approach, modified from approaches detailed by Bell and Schleifer (1995) and Banker and Gupta (1980), can be summarized as follows:

1. Identify the decision maker(s);
2. Determine the objective(s) of the decision maker(s);
3. Determine the set of potential alternatives;
4. Identify the criteria for choosing among the competing alternatives;
5. Gather information and data, including uncertainties and constraints, on the alternatives;
6. Evaluate the information provided to determine which alternative to undertake;
7. Determine if the decision is sensitive to changes in probabilities or other assumptions that have been made; and
8. Develop and implement a plan of action for carrying out the decision.

While the above noted steps outline a simplistic process for making a decision, the process can be quite complex depending on the number of available alternatives and the criteria against which the alternatives are to be evaluated. For these types of decisions, a multitude of decision-making strategies exist, varying in complexity and applicability. The objective of this research paper is not to provide a comprehensive review and discussion of decision-making processes and techniques, but to consider the general characteristics of decision-making strategies which could be used by decision makers attempting to select an appropriate defluoridation technology that best suits the needs of a particular community or group. Each of the steps in this basic decision-making process will be discussed in this context.

1. Identify the Decision Maker(s)

A decision maker can be defined as "the set of people (the individual or groups of individuals) who have the authority and responsibility to select the alternative to be implemented" (Lifson, 1972, 2-3). Oftentimes, several people will take part in the decision-making process, which can result in complications due to the characteristics inherent of human nature, including ill-defined preferences, uncertainty, conflicts, and contradictions (Roy, 1990). In the case considered herein of selecting an appropriate defluoridation technology, there may be a hierarchy of decision makers from the state or government level to representatives of the affected community. As endemic fluorosis is generally a condition prevalent in developing countries, where factors such as poverty and illiteracy must be considered, an ideal group of decision makers would be made up of those state and government officials that would be able to provide financial support towards the implementation of the decision, as well as an aid or research group working with the local community that would be aware of the specific social, cultural, and technical conditions of the affected area.

2. Determine the Objective(s) of the Decision Maker(s)

One would assume that irrespective of the potential hierarchy of decision makers, the overall objective of the group would be the same: to select a sustainable defluoridation technology that will provide a community with clean drinking water with respect to acceptable fluoride concentrations. More concrete sub-objectives may also be developed based on the conditions of the locale for which a defluoridation technology is needed (Bodily, 1985). For example, sub-objectives may be to reduce fluoride levels in drinking water by a specific percentage, or to increase the number of water access points with acceptable fluoride concentrations by a specific percentage. In order to achieve the stated objective and specific sub-objectives, decision makers will have to determine how best to choose between competing alternatives (i.e., various defluoridation technologies).

3. Determine the Set of Potential Alternatives

For certain decisions, it may difficult to identify "good" alternatives. "In some decisions we are faced with too many alternatives to thoroughly analyze, while in other situations we have too few alternatives" (Kirkwood, 1997, 44). In addition, the set of potential alternatives will be limited to those that are known to the decision makers (Lifson, 1972). With respect to the decision being considered herein, the set of potential alternatives has been limited to those defluoridation technologies for which detailed literature was available. It should be noted that this is not an exhaustive list of potential defluoridation technologies. Application of this decision-making strategy to a real world scenario could require the addition or elimination of certain defluoridation technologies, depending on factors such as additional data pertaining to a particular technology; the development of a new technology; or specific social or cultural requirements of an affected locale.

4. Identify the Criteria for Choosing Among the Competing Alternatives

Yadav et al. (1999) provided the following as criteria that are essential for an effective and high quality defluoridation technique:

- Cost effective;
- Independent of input fluoride concentration, alkalinity/pH and temperature;
- Easy to operate and maintain by a rural population;
- No affect on the taste of the water; and
- No addition of other undesirable substances (e.g., aluminum) to treated water.

These criteria should be taken into consideration, along with availability of raw materials and multi-functionality of the system (i.e., at point-of-use, community, and water works levels). Other criteria against which to evaluate the alternatives may be applicable, and could be based on the specific social or cultural values that are held by the particular affected community being considered. The criteria should be linked back to the objectives of the decision makers, as they are performance measures by which to determine if the objectives will be achieved (Bogetoft and Pruzan, 1991).

5. Gather Information on the Alternatives

As stated by Bell and Schleifer (1995), "collecting information is a valuable tool for decision makers" (103). Information may be qualitative or quantitative, and could come in the form of surveys, interviews, literature reviews, case studies, and laboratory or field experiments. Depending on the decision to be made and the alternatives to be evaluated, the collection of data may involve significant time and financial constraints. For this particular case pertaining to defluoridation technologies, information and data on the alternatives was obtained from a literature review, which included documentation on case studies, as well as field and laboratory studies. It should be noted that in December 2005 the author visited the Indian Institute of Science in Bangalore, India to interact with research students working under Dr. Sudhakar Rao on defluoridation technologies, in hopes of observing first-hand the applications of some of the available technologies. However, due to the timing of the trip it was not possible to gather direct information and data on some of the various defluoridation technologies that were being evaluated.

Data that is available on the alternatives being considered may be limited and incomplete, resulting in uncertainties. Reasons for inaccurate or incomplete information could include sampling errors, measurement bias, or a lack of representative samples (Bell and Schleifer, 1995). A potential effect of such uncertainty is that decision makers may be forced to assume a certain amount of risk when evaluating the alternatives. How this will affect a decision maker's selection process will be determined by how risk averse, risk neutral, or risk seeking the decision maker is with respect to obtaining the objective (Kirkwood, 1997).

6. Evaluate the Alternatives

As previously noted, there are numerous decision-making processes that can be applied to evaluate a set of alternatives. Some examples include decision trees, the Analytic Hierarchy Process (AHP), and simulation. Many variations of these processes exist, including the use of various mathematical and graphical models.

A "decision tree is a chronological depiction of the alternatives immediately available … as well as future alternatives and uncertainties" (Bell and Schleifer, 1995, 13). As described by Bell and Schleifer (1995), uncertainty is depicted as a node in a decision tree, and a decision-maker "must specify which alternative she would choose at every decision node" (18). A risk profile can also be developed as part of the decision strategy, and would involve describing all outcomes that may result and the probability associated with each outcome (Bell and Schleifer, 1995).

AHP is a decision-making process in which the components of a complex decision are arranged into a system of hierarchies and are evaluated through the use of a matrix (Triantaphyllou, 2000). AHP uses "paired comparisons or ratings to prioritize or rate alternatives one by one on a set of criteria arranged in a hierarchical or network structure" (Peniwati, 2007, 941). This process allows for the consideration of objective and subjective factors when evaluating the available alternatives, and provides a system for measuring the consistency of a decision maker's assessments (Mollaghasemi and Pet-Edwards, 1997).

Simulation is another decision-making strategy that is typically applied when there are a large number of uncertainties. The major components of simulations include: (i) a list of strategies to be evaluated; (ii) a list of uncertainties and associated probabilities that impact the evaluation of the strategies; (iii) a system of generating scenarios; and (iv) an evaluation system for each strategy/scenario pair (Bell and Schleifer, 1995, 73). As stated by Bell and Schleifer (1995), the statistical evaluation system associated with simulation can be a powerful tool; however, this technique is not best suited for decisions with a great number of strategies to be evaluated, as each one of those strategies would have to be evaluated in turn.

An analysis of the available defluoridation technologies will involve evaluating the characteristics of each technology while taking into account specifics of the local water supply and community, as well as uncertainty and the level of risk tolerance. "Ultimately, the decision maker must consider tradeoffs among either the objectives and attributes or among possible alternatives" (Banker and Gupta, 1980, 138).

As part of this research project, an evaluation of the discussed defluoridation technologies, based on the available information, was conducted on a nominal scale. A summary table outlining this evaluation is presented below.

Table 3: Evaluation of Defluoridation Technologies

Defluoridation Technologies	Cost Effective/Affordable	Raw Materials are Locally Available	Independent of Input Parameters (e.g. fluoride concentration, pH, temperature, alkalinity)	Easy to Operate and Maintain	No Affect on Aesthetics of Treated Water (e.g. taste, odour)	No Addition of Other Undesirable Substances to Treated Water	Multi-Functional (e.g. point-of-use, community, and water works levels)
Nalgonda[1]	●	●	○	Θ	○	○	●
Alum-PAC Slurry[2]	Θ	Θ	○	Θ	●	Θ	Θ
Bone Charcoal[3]	Θ	Θ	●	Θ	Θ	●	●

Defluoridation Technologies	Cost Effective/Affordable	Raw Materials are Locally Available	Independent of Input Parameters (e.g. fluoride concentration pH, temperature, alkalinity)	Easy to Operate and Mantain	No Affect on Aesthetics of Treated Water (e.g., taste, odour)	No Addition of Other Undesirable Substances to Treated Water	Multi-Functional (e.g., point-of-use, community, and water works levels)
KRASS[4]	●	●	●	●	●	Θ	Θ
Coal-Based Sorbents[5]	●	Θ	Θ	●	Θ	Θ	Θ
Geomaterial Sorbents (e.g., clay)[6]	●	●	○	●	Θ	Θ	●
Adsorption and Donnan Dialysis[7]	Θ	Θ	Θ	Θ	●	●	Θ

Notes:
● = Yes
○ = No
Θ = Dependent on additional factors

[1] The Nalgonda method has been found to be ineffective for waters with high fluoride concentrations and low alkalinity, such as those found in Africa (Fawell et al., 2006). Ease of operation and maintenance may be affected by the user's ability to understand requirements for appropriate mixing times and the amount of alum required (Fawell et al., 2006). The taste of the treated water can be affected, and the resulting concentration of aluminum in the treated water can be greater than the WHO guideline value of 0.2 mg/L (Agarwal et al., 1999).

[2] Limited information was available on the applicability of an integrated alum and PAC slurry defluoridation method outside of a laboratory setting. Information on cost effectiveness, raw material availability, and multi-functionality was not provided. Water with high concentrations of fluoride could be treated; however, for concentrations greater than 15 ppm, high pH values would be required (Mekonen et al, 2001). The experimental method applied required a significant amount of stirring at varying rates and for varying lengths of time, which could result in a time consuming and manually intensive treatment methodology at the household level, unless electric mixers were used. The treated water resulting from this defluoridation method was reported to contain high levels of sulphate, although these levels were reported to be acceptable according to WHO drinking water guidelines as a level of sulphate in drinking water that is likely to cause adverse affects to human health has not been identified (Mekonen et al. (2001).

[3] Generally, bone charcoal filters can be made cost effectively using locally available materials (Fawell et al., 2006). However, commercial distribution of the bone charcoal itself can be limited, and religious beliefs in some communities may make any use of animal bones unacceptable (Fawell et al., 2006). A constraint to the operation and maintenance of the bone charcoal defluoridation method lies in the proper preparation on the bone charcoal. Unpleasant tastes and odours may result from bone charcoal that is not correctly prepared (Fawell et al., 2006). In addition, operational problems may arise if the locals

responsible for the system are not properly educated as to when the media requires changing in order to maintain optimal fluoride removal conditions (Mjengera and Mkongo (2003).

[4] While reported to be below the WHO guideline value, trace concentrations of aluminum are present in the treated water when the KRASS process is applied (Agarwal et al., 1999). Although reported to be cost effective, easy to operate and maintain, independent of the input parameters of the water, and to have no affect on the taste of the treated water, information on this technology was limited to two referenced sources. Limited information was also available with respect to the multi-functionality at point-of-use, community and water works levels.

[5] Coal-based sorbents were found to be a low cost alternative to other fluoride removal techniques; however, information on the availability of the required raw materials, the aesthetics of the treated water, and the multi-functionality of this system were not provided (Sivasamy et al., 2001). Based on the laboratory method, it appears that contact time was the main procedure involved and, as such, ease of operation and maintenance is expected (Sivasamy et al., 2001). This defluoridation method is reportedly effective for various concentrations of fluoride-impacted groundwater; however, different types of coal-based sorbents work better at different pH ranges (Sivasamy et al., 2001).

[6] Clay as a sorbent of fluoride from impacted drinking water appears to be concentration dependent; however, water with high fluoride concentrations may still be treatable if clay pots are connected in series and the fluoridated water is allowed to pass through these pots over time (Agarwal et al., 2003). Agarwal et al. (2003) also indicated that studies would be required to evaluate the quality of the treated water resulting from geomaterial sorbents that had been amended with iron, calcium and aluminum.

[7] Limited information was available on the applicability of the combined adsorption and Donnan dialysis method of defluoridation outside of a laboratory setting. Specific information on cost effectiveness, raw material availability, ease of operation and maintenance, and multi-functionality was not provided. Generally, membrane separation technologies tend to be higher in cost relative to other defluoridation technologies (British Geologic Survey and Water Aid, 2009). In the laboratory setting, water with a relatively high fluoride concentration of 4 mg/L was treated; however, applicability to waters with higher fluoride concentrations is unknown (Garmes et al., 2002). Under the specific conditions analysed, pH is not a limiting factor in treatment (Garmes et al., 2002). As adsorbents are not directly in contact with the drinking water, the addition of undesirable substances to the treated water is eliminated.

7. Sensitivity Analysis

Conducting a sensitivity analysis on the decision-making process that has been used can determine how changes in assumptions made throughout the process will affect the ranking of the set of alternatives (Kirkwood, 1997). Variables in the decision-making process can be changed to determine which variables will significantly affect the outcome of the process (Bodily, 1985). As stated by Render et al. (2003), a sensitivity analysis is an important step in evaluating the decision-making process as information gathered on the available alternatives may not always be accurate, and assumptions made may not always be appropriate. As evidenced by the number of rankings which were dependent on additional factors in the evaluation of the defluoridation technologies presented in Table 3, more detailed information on the characteristics and applicability of the technologies would have resulted in fewer assumptions and a more robust evaluation system.

8. Decision Implementation

Once a decision-making strategy has been applied and a decision on the available alternatives has been made, the decision makers must act on the selected solution and develop a plan of action for moving forward. The implementation process can be more difficult than the decision-making process, especially if numerous decision makers are involved and there was difficulty in reaching a consensus during the process (Render et al., 2003). Implementation of a decision will also require monitoring to evaluate effectiveness in achieving the overall objective. Modifications to the implemented decision may need to be made over time if the desired objective is not being achieved, or a re-evaluation of alternatives may need to take place if new options or information become available (Render et al., 2003).

4.0 FINDINGS, RECOMMENDATIONS AND LIMITATIONS

4.1 Findings

As demonstrated in the evaluation of the defluoridation technologies presented in Table 3, there is not one method that would fulfill all of the desired characteristics of an effective and sustainable treatment technology. This supports the notion that there is not an all-encompassing defluoridation technology that would be applicable to all types of situations in which fluoride-impacted drinking water is a concern. It is also important to note that "none of the methods has been implemented successfully at a large scale in many parts of the world" (Fawell et al., 2006, 75).

Water treatment methods for developing countries require careful consideration and selection of a sustainable solution so as to provide long-term benefits and applicability. A specific defluoridation technology that may work in one community, may not work in another. As stated by Fawell et al. (2006), "the prevention of fluorosis through management of drinking-water is a difficult task, which requires favourable conditions combining knowledge, motivation, prioritization, discipline and technical and organizational support" (41). Developing countries will typically require water treatment methods that operate at a decentralized level, for example, at the village or household levels (Fawell et al., 2006).

Control of endemic fluorosis is essential and initiatives to educate those villages which are afflicted with the disease are necessary steps in the prevention process: "When the inhabitants become aware of the situation they are more likely to participate, actively, in control activities. Only when the inhabitants take the initiative themselves to control the disease would the control work continue" (Lian-Fang and Jian-Zhong, 1995, 1195). Empowering the locals by providing them with the necessary resources and training to sustain the use of an effective defluoridation technology is a key step towards long-term accessibility to clean water.

Leadership and coordination from local governments must also be provided if control initiatives are to be successful. Formal decision-making strategies would be useful tools at the government level to provide a starting point to determining which available defluoridation methods would be viable at the end user level. However, as stated by Roy (1990), "in general it is impossible to say that a decision is a good or a bad one by referring only to a mathematical model: organizational, pedagogical, and cultural aspects of the whole decision process which leads to making a given decision also contribute to the quality and success of this decision" (328). As such, an understanding of local cultures and conditions is necessary to ensure appropriate actions for the prevention of excessive fluoride concentrations in drinking water. Researchers, government officials and, most importantly, local inhabitants of suffering areas must work together to achieve the common goal of clean and safe potable water.

4.2 Recommendations and Areas for Further Research

Although the evaluation of the defluoridation technologies as presented in Table 3 did not provide for the definitive selection of an effective and sustainable treatment method, it is possible to recommend technologies that may be more readily applied to help communities that are affected by fluorosis based on the reviewed literature as presented herein. If decision makers were to select a technology based strictly on the greatest number of criteria that were deemed to be present and not dependent on additional information, the KRASS method would be chosen, with five of the seven criteria of a sustainable technology ranked as being present. However, the information used to evaluate the technologies introduces a significant amount of uncertainty to the decision-making process, as is evidenced by the considerable number of criteria receiving a ranking of "dependent on additional factors".

Given the limited information that was available for some of the technologies, decision makers could choose to place more value on one criterion over another, thereby making certain technologies more favourable despite a lower ranking based on the nominal yes or no evaluation. For example, decision makers may feel that technologies that are cost effective and easy to operate and maintain would be more beneficial even if those technologies produced treated water with an objectionable taste or odour. Taking this ranking of the criteria into consideration, the Nalgonda technique and geomaterial sorbents could reasonable be inferred to be effective and sustainable defluoridation technologies for many communities affected by fluorosis. The Nalgonda technique has been widely used throughout India at both the household and community levels, although with more success at the point-of use-level (Fawell et al., 2006). While not without its limitations, this technique has been proven to be cost effective and relatively easy to operate and maintain, with the necessary raw materials being widely available. Geomaterial sorbents, such as clay containers and silty clay soils, also provide an economical and simple method for defluoridation that is both user and environmentally friendly. Furthermore, the use of integrated or combined defluoridation methods, such as clay pots that have been amended with an adsorbent such as aluminum, could prove to be effective technologies for many affected communities.

Varying acceptable concentrations of fluoride in water have been noted throughout this paper. Such variances are significant in that they demonstrate the need to determine acceptable limits on a local basis by taking into consideration such factors as regional diets, ambient temperatures, daily water consumption patterns, calcium levels in drinking water, age and socio-economic status. Apambire et al. (1997) provided several examples of areas where permissible fluoride concentrations have been altered to reflect local conditions. For instance, the city of Hong Kong in China has a fluoridated water supply with two different fluoridation levels: one for the hot summer period and one for the cool winter period (Apambire et al., 1997). However, manipulation of fluoride is not possible in many rural areas where fluoridation of the water supply does not take place. As such, "detailed studies of the natural distribution of fluoride in waters, especially groundwaters, are needed before a health plan can be formulated to eleviate [sic] problems of deficient or excess fluoride in human diets" (Apambire et al., 1997, 21). A device that is effective, inexpensive and easy to implement at the village level by those who may be illiterate or minimally educated could prove useful in this regard. Such a device is detailed by Sen et al. (1998) as a light-emitting diode (LED) based colorimeter that could be used for estimating the fluoride concentration in water.

It is interesting to note that there are areas of India and Kenya where excessive fluoride concentrations in drinking water exist, yet signs of fluorosis in the individuals consuming the water are not present. It has been suggested that these individuals "be studied further to determine whether they are protected by genetic predisposition or by other environmental factors" (Nyaora Moturi et al., 2002, 127).

With respect to the use of a formal decision-making strategy in the selection of an appropriate defluoridation technology, more detailed field studies providing additional information on the applicability of the technologies at the community level would serve to eliminate the amount of uncertainty present in the decision-making process. By reducing the uncertainty, the risk of selecting a technology that will not be successful or sustainable would also likely be reduced. Furthermore, the resultant additional information on the technologies would allow for more than a nominal scale (i.e., yes/no) of criteria measurement, thereby expanding the types of decision-making strategies that could be applied.

4.3 Limitations

A number of constraints were present throughout the research of this paper, the most noteworthy being the sources and quantity of information available for review. While fluorosis is prevalent worldwide, literature was most readily available on fluorosis in India, China and Africa, perhaps because of the endemic nature of the disease in these areas of the world. In addition, information on specific defluoridation technologies was limited to published studies, despite the attempt to obtain first-hand knowledge on the applications of the technologies during a trip to India in 2005.

These limitations resulted in the inability to effectively create a decision matrix to be used as a decision-making tool by which a factor's relative importance could be systematically ranked, thereby allowing for a more robust evaluation of the selected defluoridation technologies. With only incomplete information pertaining to the capabilities of each technology with respect to the selected criteria, a proper quantitative ranking of the alternatives as would have been presented in a decision matrix was not possible. Instead, the nominal scale of evaluation selected for this research paper was sensitive to many assumptions and resulted in a high level of uncertainty in the decision-making process.

5.0 REFERENCES CITED

Agarwal, K. C., S. K. Gupta and A. B. Gupta. 1999. Development of new low cost defluoridation technology (KRASS). Water Science Technology 40:167-173.

Agarwal, M., K. Rai, R. Shrivastav and S. Dass. 2003. Defluoridation of water using amended clay. Journal of Cleaner Production 11:439-444.

Apambire, W. B., D. R. Boyle and F. A. Michel. 1997. Geochemistry, genesis, and health implications of fluoriferous groundwaters in the upper regions of Ghana. Environmental Geology 33:13-24.

Banker, R. L. and S. K. Gupta. 1980. A process for hierarchical decision making with multiple objectives. The International Journal of Management Science 8:137-149.

Bell, D. E. and A. Schleifer Jr. 1995. Decision Making Under Uncertainty. Course Technology, Inc.: Cambridge, MA.

Bodily, S. E. 1985. Modern Decision Making: A Guide to Modeling with Decision Support Systems. McGraw-Hill Book Company: New York.

Bogetoft, P. and P. Pruzan. 1991. Planning With Multiple Criteria: Investigation, Communication, Choice. Elsevier Science Publishing Company, Inc.: Amsterdam.

British Geologic Survey and Water Aid. Water Quality Fact Sheet: Fluoride. Retrieved May 24, 2009, from http://www.wateraid.org/documents/plugin_documents/fluoride1.pdf.pdf.

Chatterjee, M. K. and N. K. Mohabey. 1998. Potential fluorosis problems around Chandidongri, Madhya Pradesh, India. Environmental Geochemistry and Health 20:1-4.

Das, B., J. Talukdar, S. Sarma, B. Gohain, R. K. Dutta, H. B. Das, and S. C. Das. 2003. Fluoride and other inorganic constituents in groundwater of Guwahati, Assam, India. Current Science 85:657-661.

Fawell, J., K. Bailey, J. Chilton, E. Dahi, L. Fewtrell and Y. Magara. World Health Organization. 2006. Fluoride in Drinking-Water. IWA Publishing: London.

Garmes, H., F. Persin, J. Sandeaux, G. Pourcelly and M. Mountadar. 2002. Defluoridation of groundwater by a hybrid process combining adsorption and Donnan dialysis. Desalination 145:287-291.

Grobler, S. R., A. J. Louw and T. J. Van W. Kotze. 2001. Dental fluorosis and caries experience in relation to three different drinking water fluoride levels in South Africa. International Journal of Paediatric Dentistry 11:372-379.

Kirkwood, C. W. 1997. Strategic Decision Making: Multiobjective Decision Analysis With Spreadsheets. Duxbury Press: Belmont.

Kundu, N., M. K. Panigrahi, S. Tripathy, S. Munshi, M. A. Powell and B. R. Hart. 2001. Geochemical appraisal of fluoride contamination of groundwater in the Nayagarh District of Orissa, India. Environmental Geology 41:451-460.

Lian-Fang, W. and H. Jian-Zhong. 1995. Outline of control practice of endemic fluorosis in China. Social Science Medicine 41:1191-1195.

Lifson, M. W. 1972. Decision and Risk Analysis for Practicing Engineers. Cahners Books: Boston, MA.

Meenakshi, V.K. Garg, Kavita, Renuka and Anju Malik. 2004. Groundwater quality in some villages of Haryana, India: Focus on fluoride and fluorosis. Journal of Hazardous Materials 106B:85-97.

Mekonen, A., P. Kumar and A. Kumar. 2001. Integrated biological and physiochemical treatment process for nitrate and fluoride removal. Water Resources 35:3127-3136.

Mjengera, H. and G. Mkongo. 2003. Appropriate deflouridation technology for use in flourotic areas in Tanzania. Physics and Chemistry of the Earth 28:1097-1104.

Mollaghasemi, M. and J. Pet-Edwards. 1997. Technical Briefing: Making Multiple-Objective Decisions. IEEE Computer Society Press: California.

Nyaora Moturi, W. K., M. P. Tole and T. C. Davies. 2002. The contribution of drinking water towards dental fluorosis: A case study of Njoro Division, Nakuru District, Kenya. Environmental Geochemistry and Health 24:123-130.

Peniwati, K. 2007. Criteria for evaluating group decision-making methods. Mathematical and Computer Modelling 46:935-947.

Raichur, A. M. and M. J. Basu. 2001. Adsorption of fluoride onto mixed rare earth oxides. Separation and Purification Technology 24:121-127.

Rao, N. S. and D. J. Devadas. 2003. Fluoride incidence in groundwater in an area of Peninsular India. Environmental Geology 45:243-251.

Rao, N. S., G. K. Rao and D. J. Devadas. 1998. Variation of fluoride in groundwaters of crystalline terrain. Journal of Environmental Hydrology 6:1-5.

Render, B., R. M. Stair Jr., N. Balakrishnan. 2003. Managerial Decision Modeling With Spreadsheets. Prentice Hall: New Jersey.

Roy, B. 1990. Decision-aid and decision-making. European Journal of Operational Research 45:324-331.

Sen, A., K. Rao, M. A. Frizzell and G. Rao. 1998. A low-cost device for the estimation of fluoride in drinking water. Field Analytical Chemistry and Technology 2:51-58.

Sharma, S. K. 2003. High fluoride in groundwater cripples life in parts of India, Diffuse Pollution Conference, Dublin.

Sinha, R. K. 1997. Fluorosis – a case study from the Sambher Salt Lake region in Jaipur, Rajasthan, India. The Environmentalist 17:259-262.

Sivasamy, A., K. P. Singh, D. Mohan and M. Maruthamuthu. 2001. Studies on defluoridation of water by coal-based sorbents. Journal of Chemical Technology and Biotechnology 76:717-722.

Triantaphyllou, E. 2000. Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers: The Netherlands.

UNICEF. 1999. Position on water fluoridation: Water, environment & sanitation. Retrieved August 1, 2005, from http://www.nofluoride.com/Unicef_fluor.htm.

Wang, B., B. Zheng, C. Zhai, G. Yu and X. Liu. 2004. Relationship between fluorine in drinking water and dental health of residents in some large cities in China. Environmental International 30:1067-1073.

Wang, Y. and E. J. Reardon. 2001. Activation and regeneration of a soil sorbent for defluoridation of drinking water. Applied Geochemistry 16:531-539.

World Health Organization (WHO). 2008. Guidelines for drinking-water quality. Third edition incorporating the first and second addenda. Volume 1: Recommendations. Retrieved May 20, 2009, from http://www.who.int/water_sanitation_health/dwq/fulltext.pdf.

Yadav, S., T. I. Khan, S. Gupta, A. B. Gupta and R. N. Yadava. 1999. Fluorosis in India with special reference to Rajasthan. In Environmental modeling: Proceedings of the International Conference on Water, Environment, Ecology, Socio-economics and Health Engineering (WEESHE), edited by V. P. Singh, W. Seo and J. H. Sonu. Water Resources Publications, LLC: United States of America.

Yang, L., P. J. Peterson, W. P. Williams, W. Wang, R. Li and J. Tan. 2003. Developing environmental health indicators as policy tools for endemic fluorosis management in the People's Republic of China. Environmental Geochemistry and Health 25:281-295.

Zevenbergen, C., L. P. van Reeuwijk, G. Frapporti, R. J. Louws and R. D. Schuiling. 1996. A simple method for defluoridation of drinking water at village level by adsorption on Ando soil in Kenya. The Science of the Total Environment 188:225-232.