Water quality in sustainable water management

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Water pollution is a serious problem as almost 70% of India's surface water resources and a growing number of its groundwater reserves have been contaminated by biological, organic and inorganic pollutants. Pollution of surface and groundwater resources occurs through point and diffuse sources. Examples of point source pollution are effluents from industries and from sewage-treatment plants. Typical examples of diffuse pollution sources are agricultural runoffs due to inorganic fertilizers and pesticides and natural contamination of groundwater by fluoride, arsenic and dissolved salts due to geo-chemical activities. In pursuit of measures to achieve sustainability in water management, the Centre for Sustainable Technologies (CST) at the Indian Institute of Science (IISc) has begun to address treatment of fluoride-contaminated groundwater for potable requirements. The fluorosis problem is severe in India as almost 80% of the rural population depends on untreated groundwater for potable water supplies. A new method to treat fluoride-contaminated water using magnesium oxide has been developed at IISc. The IISc method relies on precipitation, sedimentation, and filtration techniques and is efficient for a range of groundwater chemistry conditions.

RAPID population growth, urbanization and industrialization have led to a greater demand for an increasingly smaller supply of water resources in the country. Of the present water usage in the country, majority is consumed in agriculture (70–90%), and the remaining is consumed in industrial activities and for domestic purposes like drinking water and sanitation[1].

One of the important issues that impacts sustainable water management (SWM) practice in India is related to water quality. Problems with water quality are often as severe as problems with water availability, but less attention has been paid to them, particularly in India. Water pollution is a serious problem in India as almost 70% of its surface water resources and a growing number of its groundwater reserves are already contaminated by biological, organic and inorganic pollutants. In many cases, these sources have been rendered unsafe for human consumption as well as for other activities such as irrigation and industrial needs. This illustrates that water quality decline can in effect contribute to water scarcity as it limits the availability of water for both human use and the ecosystem[2,3].

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Sources of pollution

Pollution of surface and groundwater resources occurs through point and diffuse sources. Examples of point source pollution are effluents from industries, sewage-treatment plants and untreated domestic sewage. The main sources of diffuse pollution may be anthropogenic activities, such as agricultural applications of fertilizers and pesticides or of geo-chemical origin, such as natural contamination of groundwater sources by fluoride, arsenic and dissolved salts[2,3]. Pollution from point sources can be controlled by disposal in engineered facilities, treatment and recycling of waste materials. Minimizing application of fertilizers and pesticides is a way to control pollution from agricultural activities. Natural contamination of groundwater sources by fluoride, arsenic and dissolved salts is dealt with by suitable treatment of extracted groundwater.

Pollution from point sources

Industrial pollution

In case of industrial units, effluents in most of the cases are discharged into pits, open ground, or open unlined drains near the factories, thus allowing it to move to low-lying depressions resulting in groundwater pollution. The industries, which are burgeoning at a fast rate, produce about 55,000 million m^3 of wastewater per day, out of which 68.5 million m^3 is discharged into river and streams[3]. Thus the magnitude of damage caused to our water resources can be estimated from the fact that about 70% of rivers and streams in India contain polluted water. The incidence of surface and groundwater pollution is highest in urban areas where large volumes of waste are concentrated and discharged into relatively small areas. The groundwater contamination is detected only some time after the subsurface contamination begins. Although the industrial sector accounts for only 3% of the annual water withdrawals in India, its contribution to water pollution, particularly in urban areas, is considerable[2,3].

Pollution from domestic activities

Inadequate treatment of human and animal wastes contributes to the high incidence of water-related diseases in the country. To date, only 14% of rural and 70% of urban inhabitants have access to adequate sanitation facilities. Therefore, water contaminated by human waste is often discharged directly into watercourses or seeps into the groundwater table from faulty septic tanks or pit latrines. The level of faecal coliform bacteria in most rivers often exceeds the WHO (World Health Organization) standards and is responsible for causing a number of gastrointestinal ailments among the population. All of India's 14 major river systems are heavily polluted, mostly from the 50 million cubic meters of untreated sewage discharged into them each year. The domestic sector is responsible for the majority of the wastewater generation in India. Combined, the 22 largest cities in the country produce over 7267 million litres of domestic wastewater per day, of which slightly over 80% is collected for treatment[2,3].

Diffuse pollution

Agricultural activities

Use of fertilizers and pesticides to improve soil fertility and crop protection has created an environmental menace. Both these products find their way into the food chain and have implications on human health. Fertilizers and pesticides have entered the water supply through runoff and leaching to the groundwater table and pose a hazard to human, animal and plant populations. Some of these chemicals such as hexachlorocyclohexane (HCH), dichlorodiphenyltrichloroethane (DDT), endosulfan, methyl malathion, malathion dimethoate, and ethion are considered as extremely hazardous by the WHO and are banned or are under strict control in developed countries[2,3].

Geological origin

Groundwater in certain geological formations may not be of desired quality for potable use because of geo-chemical conditions. Arsenic contamination of groundwater invariably arises from natural geological and environmental conditions. Arsenic arises in many ores and minerals and is frequently present in combination with iron and manganese oxides; under various natural conditions it can be rendered soluble and released into the groundwater. Groundwater with high fluoride content is found mostly in calcium-deficient groundwaters in many basement aquifers, such as granite and gneiss, in geothermal waters and in some sedimentary basins. Seventeen states in India have been identified as endemic to fluorosis due to abundance in natural occurring fluoride-bearing minerals. Though iron content in drinking water may not affect the human system as a simple dietary overload, in the long run prolonged accumulation of iron in the body may result in homochromatosis, where tissues are damaged. A total of 106,019 sq km area (about 31%) of Rajasthan comes under saline groundwater. Arsenic in groundwater has been reported in shallow aquifers from 61 block in eight districts of West Bengal[3].

Fluoride-removal from groundwater

Pollution of groundwater resources due to geological conditions has become a matter of serious concern. To address this problem, CST has begun work on treatment of fluoride-contaminated groundwater for potable requirements. High levels of fluoride in drinking water (> 1.5 ppm) lead to dental and skeletal fluorosis. The Indian Standard[4] specifies the desirable and permissible limits for fluoride in drinking water as 1.0 and 1.5 ppm respectively. Seventeen Indian states have been identified with the problem of excess fluoride in groundwater resources[3] till 1999. The fluorosis problem is severe in India as almost 80% of the rural population depends on untreated groundwater for potable water supplies[2]. Three major sources of fluoride are fluorspars, rock phosphates and phosphorities[5]. Because of differences in geo-chemical conditions in aquifers and differences in contact period between groundwater and fluoride-bearing rocks, the fluoride content in groundwater of Indian aquifers varies from < 1 ppm up to 25 ppm. Yet, another factor contributing to excess fluoride in groundwater in rural regions of India is the over-exploitation of groundwater resources for agricultural and drinking water purposes. The quantum of water drawn from the aquifers exceeds aquifer re-charge that aids the concentration of fluoride in the aquifers[2].

Fluoride removal from drinking water in India is usually achieved by the Nalagonda technique and the activated alumina process[6]. The Nalagonda technique was developed by the National Environment Engineering Research Institute (NEERI), Nagpur, after extensive testing of many materials and processes[7]. The Nalgonda technique involves addition of aluminum salts, lime and bleaching powder followed by rapid mixing, flocculation, sedimentation, filtration and disinfection. The dose of aluminum salt increases with increase in the fluoride and alkalinity levels of the raw water. The dose of lime is empirically 1/20th of the dose of aluminum salt. Lime facilitates forming dense floc for rapid settling. Bleaching powder is added to the raw water at the rate of 3 mg/l for disinfection.

The activated alumina was proposed[8,9] for defluoridation of water for domestic use in the 1930s. Since then the activated alumina has become a popular defluoridation method. As the ceramic candle domestic filter is well known in some countries, it has been used as a unit for activated alumina defluoridation.

Discarding the sludge from the Nalgonda process is a serious environmental health problem[10]. The sludge is toxic as it contains the removed fluoride in a concentrated form. In nature the fluoride would be expected to mobilize rapidly due to weathering processes. The free fluoride ion would then be subject to infiltration to underground or rain run off. Similarly the activated alumina filter needs periodic recharge by caustic soda and acid solutions to rejuvenate fluoride-retention capacity of the candle. Recharging the activated alumina filter involves handling of hazardous chemicals and generates fluoride-rich wash. Another major cause for concern with the Nalagonda technique is that if the dose of alum is not adhered to, there is a possibility of excess aluminum contaminating the water[6]. The maximum contamination of aluminum permitted is 0.03 mg to 0.2 mg/litre of water according to the Indian Standards[4], as excess aluminum is suspected to cause Alzheimer's disease.

In addition to the Nalagonda technique and the activated alumina method, magnesium oxide has also been used for fluoride removal from drinking water[11–15]. The mechanism of removal of fluoride ions from water by magnesium oxide is as follows[11,16,17]. Addition of magnesium oxide to fluoride-bearing water results in the hydration of magnesium oxide to magnesium hydroxide as:

$$MgO + H_2O \rightarrow Mg(OH)_2. \quad (1)$$

The magnesium hydroxide formed in reaction (1) combines with fluoride ions to form practically insoluble magnesium fluoride as:

$$2NaF + Mg(OH)_2 \rightarrow MgF_2 + 2NaOH. \quad (2)$$

Precipitation of fluoride ions as insoluble magnesium fluoride lowers the fluoride ion concentration in water. Figure 1 illustrates the amount of fluoride retained at a range of dissolved fluoride concentrations in spiked water samples (2–20 ppm) by varying amounts of magnesium oxide. Figure 1 illustrates that for a given mass of magnesium oxide, the amount of fluoride retained increases with concentration of fluoride ions in the spiked water samples. Further, at a given solution concentration, the amount of fluoride retained by magnesium oxide decreases with increase in solids : solution ratio. Figure 2 illustrates that at any given fluoride solution concentration and solids : solution ratio, magnesium oxide exhibits more than 86% retention efficiency for fluoride ions.

Magnesium oxide in conjunction with calcium oxide (lime) is commonly used for chemical stabilization of soils[18]. The cementitious nature of magnesium oxide in conjunction with calcium oxide provides an environmentally safe route for re-use of fluoride-bearing magnesium oxide sludge in soil-based building materials, such as stabilized soil blocks, tiles, etc. The possible re-use of fluoride-bearing magnesium oxide sludge in environmentally safe modes and the non-toxic nature of magnesium oxide prompted the development of IISc method of de-fluoridation of water using magnesium oxide for domestic purposes.

Though the earlier works[11–15] succeeded in establishing the fluoride-removing ability of magnesium oxide, vital issues necessary for successful field implementation of the method were not addressed. For example, the dosages of magnesium oxide required for treating water containing different fluoride and dissolved salts concentrations were not specified, the issue of lowering the pH of magnesium oxide-treated water within potable water limits was not comprehensively addressed, the optimum conditions for mixing the magnesium oxide–water suspension were not defined. Failure to address the above issues has impeded the commercial success of the magnesium oxide treatment method for fluoride removal from water. The IISc method provides solutions for a range of issues that were not addressed by earlier workers and which are necessary to design an efficient, cost-effective and environment-

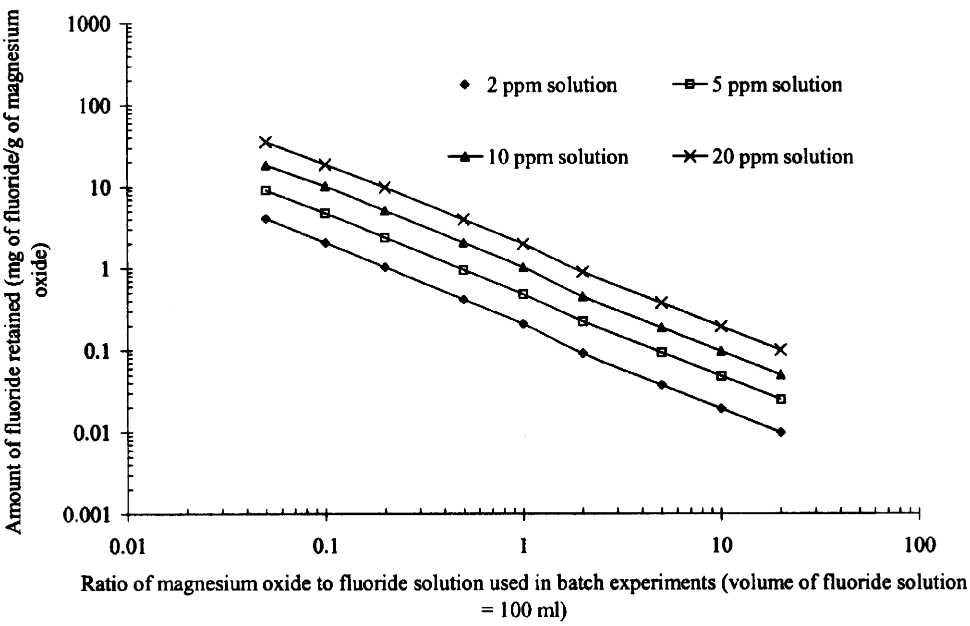

Figure 1. Variation in amount of fluoride retained with variations in weights of magnesium oxide used in batch experiments.

friendly process for fluoride removal from groundwater using magnesium oxide.

IISc method of de-fluoridation of water using magnesium oxide

The method uses magnesium oxide, calcium hydroxide and sodium bisulfate to lower fluoride ion concentrations and pH of fluoride-contaminated water samples to desirable limits[19]. Magnesium oxide removes dissolved fluoride ions from water samples through reactions (1) and (2). Use of magnesium oxide increases the pH of treated water samples between 10 and 11. The pH of the treated water samples is adjusted to desirable limits (6.5 to 8.5) by adding known amounts of sodium bisulfate to magnesium oxide-treated water samples (0.15 to 0.20 g per litre). If the fluoride-contaminated samples contain bicarbonate ions in excess of 200 ppm, these ions interfere with sodium bisulfate used for lowering the pH of magnesium oxide-treated water samples. Laboratory results indicated that for fluoride-contaminated water samples containing bicarbonate ions > 200 ppm, use of 0.3 g calcium oxide + 0.8 g magnesium oxide mix per litre of fluoride-contaminated water (fluoride concentrations 2–5 ppm) is effective in overcoming the bicarbonate interference towards sodium bisulfate.

Table 1 details the chemical compositions of the water samples (both spiked and natural water samples from Kolar District, Karnataka) subjected to fluoride removal by the IISc method. The spiked water samples contained fluoride concentrations of 2 to 5 ppm, total dissolved salts concentration of 260 to 940 ppm and bicarbonates ranging from 100 to 450 ppm. Comparatively, the natural water samples contained fluoride concentrations of 1.8 to 3.5 ppm, total dissolved salts concentration from 390 to 775 ppm and bicarbonates from 215 to 390 ppm. Addition of 0.8 g of magnesium oxide (specified for bicarbonate concentrations < 200 ppm in the natural water) or 0.3 g calcium hydroxide + 0.8 g magnesium oxide (specified for bicarbonate concentrations > 200 ppm in the natural water) per litre of fluoride-bearing water and buffered with sodium bisulfate meets the water quality parameters as specified by the Indian Standards[4] for drinking water (Table 1).

A simple to use domestic defluoridation unit (DDU, Figure 3) is developed to treat 15 litres of fluoride-contaminated water by the IISc method. The principle of the DDU is briefly described. The device comprises two units, each of 20 litres capacity. The upper unit serves as a mixing-cum-sedimentation unit, while the lower unit serves as treated water-collection unit. The upper unit is equipped with a manually operated, geared mechanical stirring device for efficient mixing of magnesium oxide and fluoride contaminated water. Fifteen litres of fluoride-contaminated water is poured in the upper unit. Calcium hydroxide + magnesium oxide mix is added to fluoride-contaminated water and manually stirred for five minutes using the stirring device. The suspension is allowed to stand for 16 h, at the end of which fluoride-bearing sludge settles at the bottom of the container. The clear water is decanted into lower collection unit through flexible connecting pipe fitted with a fine filter to trap any escaping sludge parti-

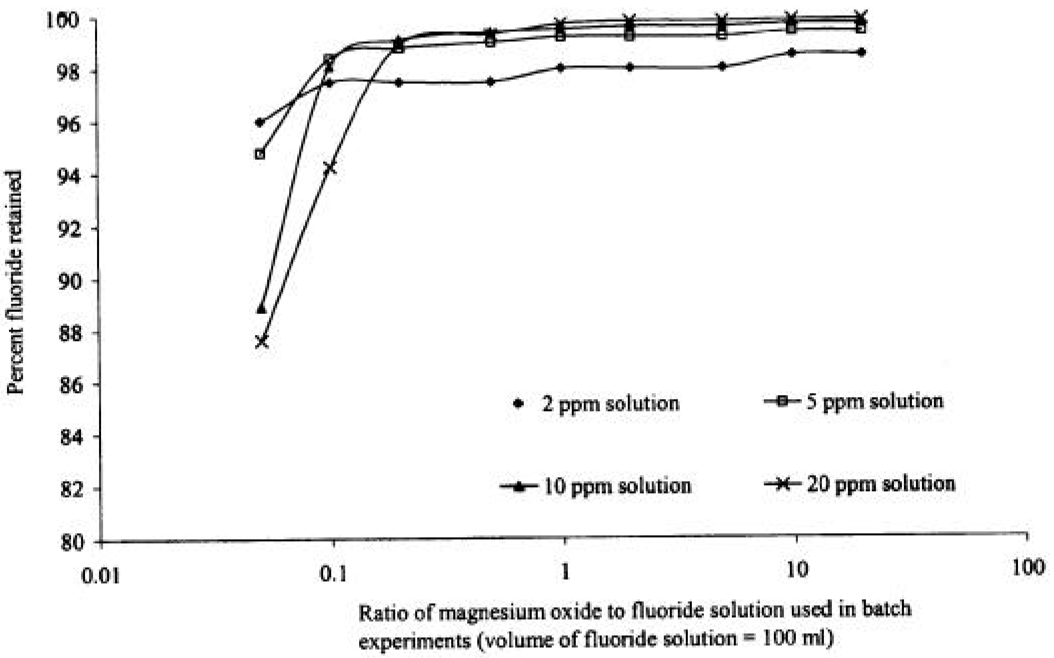

Figure 2. Per cent fluoride retained by magnesium oxide at various fluoride concentrations.

Table 1. Chemical composition of fluoride-contaminated water samples treated with magnesium oxide

	Concentrations of ions in spiked and natural water samples (ppm)		Indian Standards specifications for potable water[4]	
Parameter	Initial concentration	After treatment with magnesium oxide/calcium hydroxide + magnesium oxide and buffered with sodium bisulfate	Desirable limit	Permissible limit
Magnesium	5–20	5–35	30 ppm	100 ppm
Calcium	30–120	8–30	75 ppm	200 ppm
Sodium	40–170	70–200	No limit specified	
Potassium	0–20	0–20	No limit specified	
Fluoride	2–5	0.5–1.2	1 ppm	1.5 ppm
Sulfate	30–150	115–200	200 ppm	400 ppm
Alkalinity as bicarbonates	100–450	50–100	200 ppm	600 ppm
Chloride	50–210	50–210	250 ppm	1000 ppm
Nitrates	0–50	0–50	45 ppm	100 ppm
TDS	250–950	330–800	500 ppm	2000 ppm
Total hardness	95–380	40–220	300 ppm	600 ppm
Electrical conductance	0.4–1.5 mS/cm	0.5–1.25 mS/cm	No limit specified	
pH	8.1–8.5	7–7.5	6.5–8.5	No relaxation

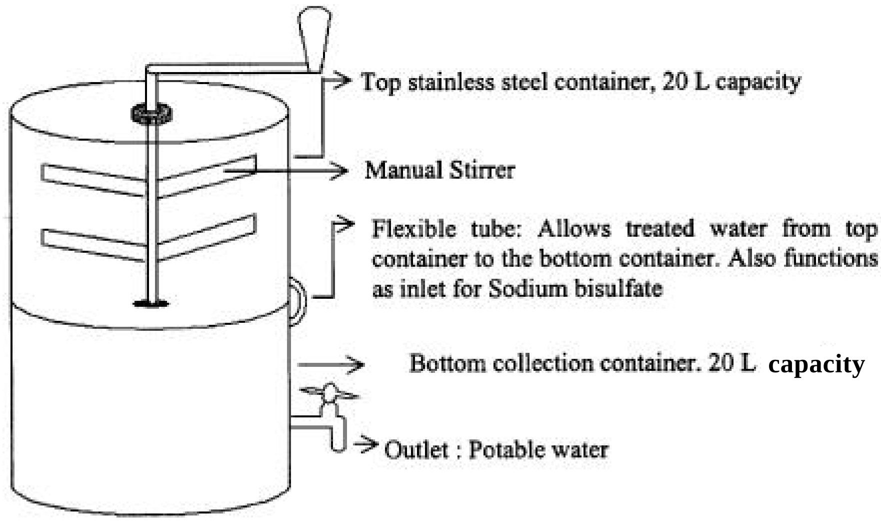

Figure 3. Schematic diagram of domestic defluoridation unit.

cles. Water-soluble sodium bisulfate is dissolved in the lower collection unit and the water is ready for use. The sludge is stored in a concrete lined pit till further use.

The cost of treating 1 litre of fluoride-contaminated water (having fluoride concentrations from 2 to 5 ppm) by the IISc method is 7 paisa/litre. The cost of the DDU is approximately Rs 2000/per unit that may require periodic maintenance expected of any mechanical device. The IISc method can also be scaled up to treat fluoride-contaminated water at community level (500–2000 litres per day). Field trials of this method at individual household levels will soon commence in four villages of Kolar District, Karnataka.

Conclusions

Degradation of water quality creates water scarcity and limits its availability for human use and ecosystem and thereby impacts the optimum management of water resources. Pollution of surface and groundwater resources occurs through point and diffuse sources. Fluoride ions contaminate some Indian aquifers due to geo-chemical conditions and over-exploitation of groundwater resources. Consumption of fluoride-contaminated water (> 1.5 ppm) leads to dental and skeletal fluorosis. The fluorosis problem is severe in India as almost 80% of the rural population depends on untreated groundwater for potable water supplies. A new method to treat fluoride-contaminated water using magnesium oxide has been developed at the Indian Institute of Science. The main advantages of this method are that all chemicals used are non-toxic, the method does not involve any recharge process and thus avoids generation of corrosive and toxic wastes and re-use of fluoride-bearing magnesium oxide sludge in environmentally safe modes is possible.

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