Eawag —
Swiss Federal Institute of
Aquatic Science and Technology

Water Resource Quality (WRQ)

Geogenic Contamination Handbook

Addressing arsenic and fluoride in drinking water

WHO Collaborating Center
for Sanitation and Water
in Developing Countries

eawag
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Cover Photo:

Women collecting fluoride-treated water at the community filter in Wayo Gabriel, Ethiopia, implemented by Eawag, Oromia Self-Help Organization (OSHO) and Swiss Interchurch Aid (HEKS)

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Preface

Groundwater has long been used to provide drinking water to urban and rural populations. The second half of the 20th century has seen an unusually rapid growth in the use of groundwater because of the introduction of mechanised pumping. Without its use, the Millennium Development Target 7c – to halve the number of people without access to safe drinking water by 2015 – would not have been achieved as early as it was, in 2012. However, although groundwater is generally free of pathogens, its chemical quality can be affected by natural or geogenic contaminants leached from the aquifer rocks and sediments. Arsenic and fluoride pose the most serious health threats. To date, an estimated 300 million people worldwide, or roughly 10% of those who use groundwater as a source of drinking water, are known to be exposed to elevated arsenic and fluoride concentrations. With currently a third of the world's population relying on groundwater for drinking purposes, and with increasing pressure on water resources, these numbers are likely to rise.

Although it has been recognised for several decades that drinking water in many regions can be contaminated with arsenic and fluoride, the provision of contaminant-free drinking water has proven to be a great challenge for poor urban and rural communities. Understandably, in some regions, geogenic contamination has taken second place to more pressing health issues. However, the complexity of effective mitigation has also played an important role. Where possible, alternative, contaminant-free water resources have been used to mitigate the deleterious health effects of these geogenic contaminants. However, in many settings where water resources are scarce, water treatment is the only option.

The challenges posed by the need for water treatment are manifold. Not least is the creation of awareness, for both institutions and users. Planning is another challenge for institutions. "Which areas are most at risk?", "What options are available?" and "What are users willing to pay?" are just some of the questions that need to be addressed. Technical issues, such as the choice of the most suitable option, supply chains and maintenance, costs and how the financial burden is to be distributed, are important issues. Last, but certainly not least, is acceptance and use of mitigation options by local communities and individual households.

Over the last five years, an Eawag team of geochemists, social scientists and engineers has been working together with local partners on arsenic mitigation in Bangladesh and fluoride mitigation in the Ethiopian Rift Valley. The tools that they developed and tested are presented here.

This handbook is a practical guide aimed at government and non-government authorities, planning agencies, consultants and engineers. Its aim is to guide users through the procedures of the identification of geogenic contamination and the suitable and locally accepted mitigation options in low- and middle-income countries.

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Abbreviations

AA	activated alumina
As	arsenic
BC	bone char
BCT	Behaviour Change Technique
CP	contact precipitation
DALY	Disability-Adjusted Life Year
eBV	empty bed volume
EDI	Estimated Daily Intake
Eh	redox potential
EC	electrical conductivity
ETB	Ethiopian Birr
F	fluoride
ISE	ion selective electrode
HAP	hydroxyapatite
L	Litre
LCC	Life Cycle Costs
LOAEL	Lowest Observed Adverse Effect Level
mg	milligram
µg	microgram
MCDA	Multi-Criteria Decision Analysis
MFA	Material Flow Analysis
NDC	Nakuru Defluoridation Company
NGO	Non-Governmental Organisation
NOAEL	No Observed Adverse Effect Level
OSHO	Oromo Self-Help Organisation
ppb	parts per billion
ppm	parts per million
PDTI	Provisional Tolerable Daily Intake
QHRA	Quantitative Health Risk Assessment
UNICEF	United Nations Children's Fund
WASH	Water, Sanitation and Health
WHO	World Health Organization
WSP	Water Safety Plan

Summary

This handbook focuses on the requirements of the implementer. Its aim is to provide a concise resource for approaching and handling geogenic contamination (primarily arsenic and fluoride) in groundwater used for drinking and cooking purposes. It provides information on water quality testing, different treatment options and practical guidelines, including draft questionnaires, on the integration of technical, institutional and sociological aspects of the problem. Its aim is to promote the sustainable mitigation of health issues related to drinking water contaminated with arsenic or fluoride.

In some groundwaters, arsenic and fluoride can naturally reach concentrations that are hazardous to human health if geological and geochemical conditions favour the release of these contaminants. The World Health Organization (WHO) has imposed drinking-water guideline values of 10 µg/L for arsenic and 1.5 mg/L for fluoride. When these values are exceeded, there are health risks. Excess uptake of arsenic causes a range of adverse health effects, the most severe of which is cancer. High fluoride concentrations can cause dental fluorosis (tooth discolouration, enamel pitting, early tooth loss) and skeletal fluorosis (joint stiffening and deformation) as well as a range of non-skeletal effects.

Microbiological contamination of surface waters has received far more attention than geogenic contamination of groundwater. This is understandable in view of the immense burden of disease and childhood mortality with which the former is associated. Nevertheless, geogenic contamination affects hundreds of millions of people worldwide and also needs to be brought to the attention of governments. In areas where geogenic contamination is known to exist, large-scale blanket surveys need to be carried out to test every single water source to identify safe and unsafe wells, which then need to be clearly marked. Areas where contamination is suspected but not known need to be screen-tested. Field test kits, though they usually only provide semi-quantitative results, can still give a good first indication of the likelihood of contamination by arsenic and fluoride. More sophisticated analytical methods should be used to validate field test kit results. Exposure to a contaminant can occur via drinking water but also via food and food preparation. A change of diet may need to be considered if food is a major contaminant source. To design suitable mitigation measures, an analysis of contaminant intake is necessary.

Once the presence of a contaminant has been established, suitable mitigation measures need to be implemented. This is a complex challenge. The existence of institutional support and funds will determine the scale of the solution: whether, for example, a large-scale piped water scheme covering a whole region is the answer or a low-tech community-scale solution is a more viable option. For each scale there are several options which will need to be assessed, not only for their technical suitability under a given set of conditions (contamination level, water availability, suppliers, etc.) but also for their acceptance by stakeholders, in particular by the users. It must also be stressed that it may be more cost-effective and sustainable to exploit alternative water resources. In either case, some sort of water treatment is likely to be necessary to ensure both chemical and microbial water safety. We outline a range of technological solutions for arsenic and fluoride removal.

The basis for sustainable solutions is an enabling institutional environment that supports, both in terms of know-how and finances, the coordination and involvement of stakeholders in planning, supply and management. The basis for an enabling environment is political will and government support and a legislative framework that sets the agenda, but also organisational and financial arrangements for implementation. Stakeholder consultation and involvement throughout the implementation process is necessary to ensure commitment and to impart a sense of ownership.

Financing is a critical issue, as we are often asking the very poor to pay for a service, the immediate benefit of which may not seem obvious. Our experience in Ethiopia has shown that fluoride-free water cannot be supplied there without infrastructure subsidies, for example. With or without subsidies, water service providers such as utilities, micro-utilities, water kiosks, water devices, and providers of flasks and tabs have to ensure financial viability. For non-profit organisations, financial viability depends on obtaining access to philanthropic investments. Profit-orientated companies have to ensure that their investments create sufficient revenue to recover the investments and to create an appropriate rate of return. Social businesses have to cover the investment and operational costs, but are more cause-driven than profit-driven.

One aspect that has often been overlooked in the past is consumers' habits. The water supply sector is littered with projects that failed because consumers would not or could not change their behaviour. People need to be persuaded to use a new technology. Targeted campaigns that take people’s preferences into account are likely to be far more successful than those that do not.

The concepts described in this handbook were developed and tested in two major case studies: one on arsenic contamination in Bangladesh and one on fluoride contamination in the Ethiopian Rift Valley.

Introductory remarks

Who is this handbook for?

This handbook is aimed at:

- government officials
- non-government organisations (NGOs)
- planning agencies and consultants
- engineers

working in low- and middle-income countries which are confronted with the problem of geogenic contamination in drinking water. Its focus is on arsenic and fluoride.

It guides users through the health problems associated with arsenic and fluoride intake and the identification of contaminated regions, including the planning of sampling campaigns and available analytical equipment and procedures. The handbook also outlines mitigation strategies, including mitigation options, and socioeconomic strategies required for successful long-term implementation. It provides case-study examples for Ethiopia and Bangladesh.

How to use this handbook

The Geogenic Contamination Handbook is designed as an interactive digital reference and guidance manual. It includes web links (in blue) and file links (in red):

Web links are provided to link to relevant websites or downloadable online documents. For web links to work, a functioning internet connection is necessary.

File links provide access to documents embedded within the handbook pdf file, which can be accessed without an internet connection. **Double-click** on file links to open these documents.

References cited in the text are listed at the end of each chapter. You can click on the citations and jump straight to the reference list.

Also included under "References and further reading" is relevant material that is not necessarily cited in the text, but which may nevertheless give the interested reader more in-depth information on a certain topic.

Because of the many links and online references provided in the pdf, the document loses a lot of its functionality once printed out. We therefore recommend the user to consult the handbook on a computer, as a rule, and to print out small sections of it only when necessary.

A short guide

What aspects do I need to consider for the successful and sustainable mitigation of arsenic- and fluoride-related health effects?

Before mitigation measures are undertaken, priority areas or wells, possible alternative water resources, or even the possibility of alternative sources of contamination from food and food preparation need to be identified. The next step is to consider the institutional framework, financing strategies and consumer commitment and acceptance. Together these aspects provide the basis for sustainable mitigation. (Chapter 1).

Is there geogenic contamination in my region, and what is its extent?

Often, signs of ill health in the population are the first indications of water-related contamination problems. Tell-tale skin lesions, especially on hands and feet, are the visible symptoms of arsenic poisoning (arsenicosis) in addition to less visible symptoms such as cancers and heart disease (Chapter 2). Visible signs of fluorosis are the presence of brown discolouration of the teeth (dental fluorosis) and bone and joint deformation (skeletal fluorosis). Working together with skilled medical staff is essential in pinpointing and correctly diagnosing both arsenicosis and fluorosis.

Searching in the databases of government agencies, universities and private companies for existing water quality data is important to avoid unnecessary (and expensive) sampling campaigns. If no data exist, then water-quality screening for arsenic and fluoride is certainly necessary.

Different field test kits are available to give an indication of contamination, though the results may be only semi-quantitative. For more accurate results, samples should be analysed in a reliable laboratory (Chapter 4).

Is the contaminant taken up only via water, or is food also a contributor?

Even though drinking water makes a major contribution, food can also play a significant role in the daily contaminant intake of a person, particularly where contaminant levels in drinking water are only moderately elevated (Chapter 3). The different food and water pathways and their relative contributions to the total daily contaminant intake can be analysed, for example, by using Material Flow Analysis (Section 9.4). The food component should also be included in a holistic view of mitigation.

Is arsenic/fluoride mitigation supported by governments and institutions?

Long-term implementation is difficult if institutional support is lacking. Before a project is started, a thorough analysis of stakeholder groups and their preferences is necessary if conflict is to be avoided. Prospects for success are much higher if the community is meaningfully involved in all stages and if issues of ownership, gender and equity are taken into account from the very beginning (Chapter 5). The selection of suitable mitigation options will involve the agreement of the different stakeholders; one method for achieving agreement is Multi Criteria Decision Analysis (Section 9.3).

How should my project be funded to ensure sustainability?

The issue of funding is usually at the forefront of water supply and water treatment projects. If funding from external organisations is granted, what happens when this is withdrawn after a few years? Experience shows that in the long term, projects often fail. Therefore, finding suitable funding and having a realistic strategy of how to sustain mitigation options when funding runs out are mandatory before any project is started (Chapter 6).

What mitigation options are suitable?

If alternative, uncontaminated water sources are available, it may be preferable to exploit these rather than to treat contaminated water. It should be pointed out, however, that surface water will also require treatment. Should contaminant removal be necessary, there are different technologies available for different budgets and situations (Chapter 7). Not only technological solutions, but also changes of diet (especially in the case of fluoride) may be effective forms of mitigation. A good diet can hinder the uptake of contaminants by the body and alleviate symptoms (Chapter 3).

How can people's preferences and acceptance of mitigation options be influenced?

If a mitigation option is not accepted by its potential beneficiaries, they are not likely to make use of it. The installation and daily use of a household water treatment filter, for example, requires a direct change in a person's habits and daily routine. Experience has shown that filters are often used for only a short time and then abandoned. By recognising the psychological factors responsible for steering someone's actions, it is possible to plan interventions targeting these factors, ideally resulting in a lasting change in behaviour. Providing technological solutions must be accompanied by "software" to support behavioural change; otherwise there is a high likelihood of failure (Chapter 8).

Do you have any concrete examples?

Elements of the mitigation framework concept (Fig. 1.1) were tested in two major case studies. Working together with Ethiopian partners, the authors tested the institutional support for fluoride removal filters in the Ethiopian Rift Valley, along with the acceptance of these filters by consumers and their technical performance (Section 9.1). In Bangladesh, institutional and consumer preferences for different arsenic remediation options were evaluated (Section 9.2).

1 Introduction

C.Annette Johnson and Anja Bretzler

Water quality has in the past been seen as a secondary issue in a world where, in many regions, the supply of water in sufficient quantities is in itself a major challenge. Focusing on microbial contamination, Millennium Development Target 7c (to halve the number of people without sustainable access to safe drinking water by 2015) has brought the issue of water quality to the forefront. While microbial contamination remains a prime concern, the health of millions of people is also affected by drinking groundwater contaminated by natural, or geogenic, contaminants derived from aquifer rocks. In poor urban and rural settings, the provision of drinking water free of geogenic contamination is proving to be a real challenge. Indeed, in many regions (e.g. in parts of East Africa and the Indian subcontinent) the problem has been recognised for decades, but comparatively little has been undertaken, perhaps partly because geogenic contamination is not at the top of the list of political priorities but also because of the complexity of meeting the challenge of providing contaminant-free drinking water. Avoiding the need for water treatment by providing water from alternative sources is a preferred option, both of government agencies and consumers. However, treatment to remove geogenic contaminants cannot be avoided in all cases. While centralised water treatment may be cost-effective in terms of infrastructure, maintenance and staffing, it is not always feasible, particularly for rural communities. The issues of responsibility and support are far more complex on a community or household level.

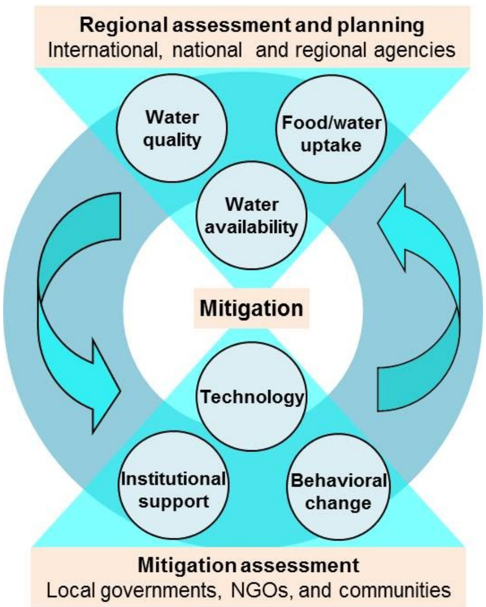

Fig. 1.1 *Framework elements that need to be taken into account when planning strategies for mitigating geogenic contamination (www.wrq.eawag.ch)*

Mitigation strategies and measures addressed either from a national or regional perspective require assessment and planning to identify: i) priority areas; ii) the presence of possible alternative water resources and iii) the possibility of alternative sources of contamination from food and food preparation (Fig. 1.1). On a local scale where water treatment (for example filtration) is being considered, it is necessary to assess the different options not only technically – i.e., in terms of cost, efficiency, simplicity, electricity requirements, availability of materials and know-how – but also in terms of institutional support and local acceptance. The mitigation framework elements shown in Figure 1.1 need to be applied in combination. Figure 1.2 illustrates how the different framework elements are interconnected and how they contribute to making a chosen mitigation option sustainable.

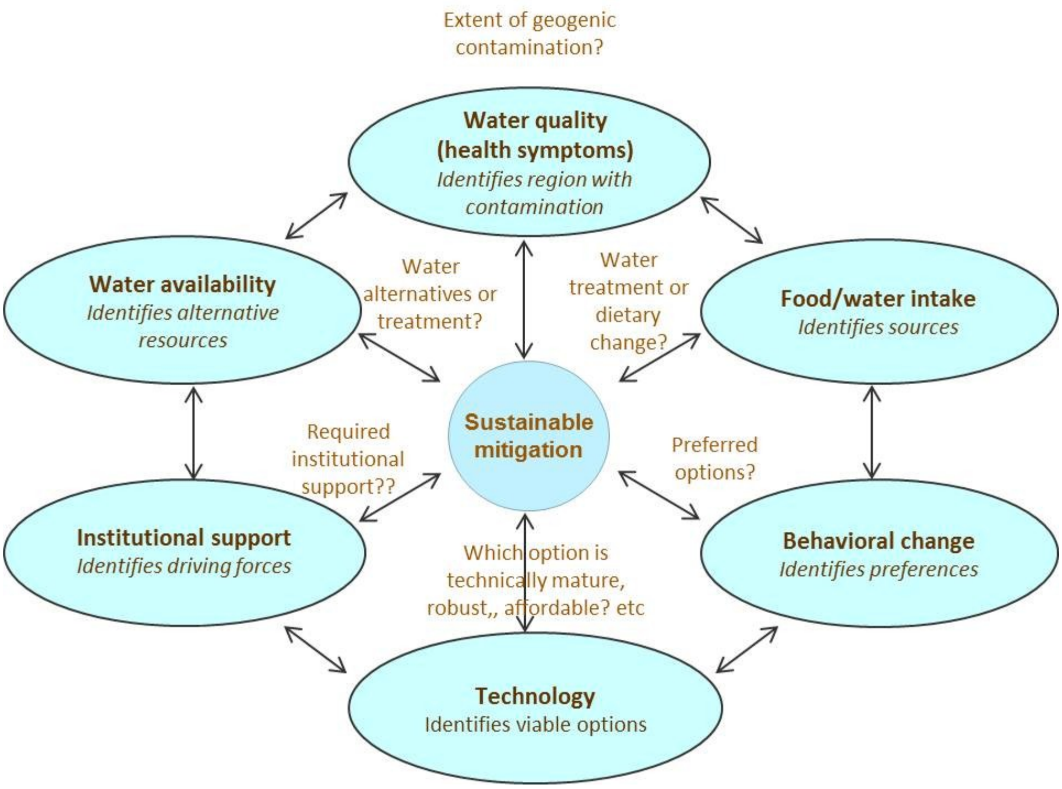

Fig. 1.2 *Schematic representation of the interconnection of the mitigation framework elements and the questions that the mitigation framework addresses*

The importance of an integrated approach to the problem cannot be stressed too much. Below, we outline some key factors that were identified by the participants of GeoGen2013, a conference addressing the challenges associated with attaining a sustainable, safe drinking-water supply free of geogenic contaminants (Johnston et al., 2013; Johnson et al., 2014 and manuscripts therein).

Governance: It is the responsibility of governments to develop a policy framework for managing the health threats posed by geogenic arsenic and fluoride. Moreover, coordination between sectors is required, because geogenic contamination involves both the water and the health sectors. Planning is a very important step, requiring a regional or countrywide perspective that takes demographic changes into account. While different government entities may play key roles in setting norms, delivering services and exercising regulatory oversight, international and local NGOs can sometimes be quicker to try out new approaches. The private sector may also be critical in providing services or goods efficiently, though government regulation is essential.

Technology: Reducing exposure to arsenic and fluoride requires sound, cost-effective technological solutions which are disseminated and maintained in socially responsible ways. Without an “enabling environment”, good technological systems and approaches cannot flourish. When governance is weak, smaller-scale solutions are often sought. The more cost-effective and culturally appropriate the technology is, the more likely it is to be adopted. Efficiency of removal, simplicity in operation and maintenance, and availability of materials (supply chain) are also essential factors.

Society: The social environment plays a critical role, encompassing the culture, education and institutions that play roles in the lives of individuals. It affects attitudes towards perceived health risks and investment in safe water solutions. Cultural norms – which, for example, may prevent women from walking to a communal well – are very important and must be taken into account in the search for safe-water solutions. “Ownership” of a technological solution is critical for its success, as is trust in the technological solution and in the providers. Sustainable approaches incorporate early engagement with community members and usually require long-term support, such as follow-up promotions or technical support in solving problems that lie beyond the capabilities of a local caretaker.

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2 Geogenic contamination

C. Annette Johnson, Richard B. Johnston, Anja Bretzler

Contamination in drinking water, both chemical and microbiological, can originate from a range of sources, most of which are anthropogenic, such as agriculture, industry or human settlements (Fig. 2.1). As the name suggests, geogenic contamination derives from geological sources. It stems from interactions between aquifer rocks and groundwater that lead to the release of substances from the aquifer rock or sediment into the water. Such interactions are always taking place – in fact, rocks and sediments largely control water chemistry – but if a particular substance is released in quantities that are high enough to have a detrimental effect on life forms, then it is termed a geogenic contaminant.

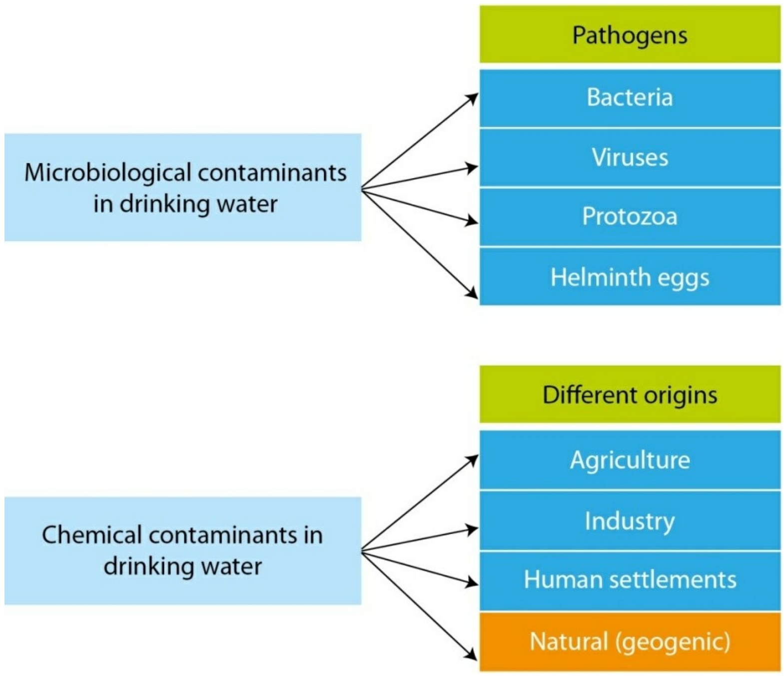

Fig. 2.1 *Overview of contaminant types leading to water- and sanitation-related diseases*

Only a very small number of the 98 naturally occurring elements have the potential to be geogenic contaminants. There are three critical factors:

- their concentration in rocks and sediments,
- their solubility under at least some environmental conditions and
- their presence in soluble form in concentrations that are toxic to humans.

The most common soluble ions in groundwater are sodium (Na^{+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^{-}), bicarbonate (HCO_3^{-}) and sulphate (SO_4^{2-}). While these can make water unpalatable, they do not pose a direct threat to health.

Contamination with dissolved iron (Fe) and manganese (Mn) can occur in groundwaters with little or no oxygen. High levels of these elements are also more of an aesthetic than a health concern, though there is increasing evidence that exposure to manganese in drinking water can cause neurological problems (e.g. Wassermann et al., 2006).

Of all inorganic groundwater contaminants, arsenic (As) and fluoride (F) clearly represent the greatest threat to human health. Many millions of people are affected worldwide. Other elements, such as selenium (as selenate), uranium (carbonated anions), boron and chromium (as chromate), can be important locally but are not as widespread as arsenic and fluoride.

2.1 Arsenic

Occurrence

Arsenic in drinking water is a global threat to health, potentially affecting about 140 million people in at least 70 countries worldwide (Ravenscroft et al., 2009). It is considered by some researchers to have more serious health effects than any other environmental contaminant (Smith and Steinmaus, 2009).

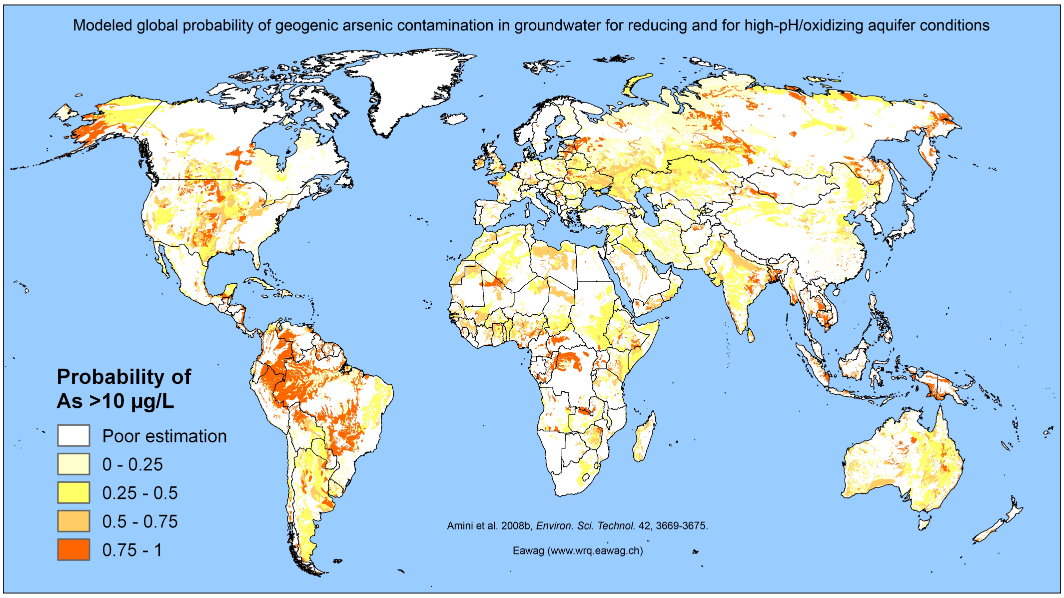

Fig. 2.2 *Modelled global probability of elevated geogenic arsenic concentrations in groundwater (Amini et al., 2008a)*

Drinking water can contain arsenic at concentrations of up to several mg/L, most commonly as the reduced species, As(III) (arsenite), or the oxidised species, As(V) (arsenate). As(III) is uncharged (H_3AsO_3) under ambient pH conditions, and as such, is more mobile than As(V) ($H_2AsO_4^-$ or $HAsO_4^{2-}$). Under most geochemical conditions, arsenic in aquifers remains tightly bound to the sediments, and concentrations of dissolved arsenic in the groundwater remain low. However, two geochemical conditions have been identified under which elevated concentrations of arsenic can be found in the groundwater even when solid-phase concentrations in the sediments are unremarkable: reducing conditions in young alluvial aquifers and arid, high pH oxidising conditions in rocks and/or sediments with relatively low permeability (Smedley and Kinniburgh, 2002). Figure 2.2 shows the modelled probability of the occurrence of geogenic arsenic contamination in groundwater for both of these conditions combined. In addition, geothermal contributions and sulphide oxidation in mine tailings can also lead to elevated arsenic concentrations in groundwater, but these conditions tend to be more localised and have not been included in the model.

Health effects

Arsenic causes a wide range of adverse health effects. The acute toxicity of As(III) is somewhat greater than that of As(V), but because As(V) is reduced to As(III) in the body, the two species can be considered equally toxic.

The first obvious symptoms are often skin lesions (keratosis, melanosis; Fig. 2.3), but other effects can include weakness, diarrhoea, bronchitis, vascular disease and diabetes mellitus (UNICEF/Chinese Ministry of Health, 2004).

Fig. 2.3 *Skin lesions (keratosis, melanosis) indicating arsenic poisoning*

The main health concerns, however, are cancers of the skin or internal organs. In particular, arsenic-related lung and bladder cancers can cause heavy mortality (Argos et al., 2010; Sohel et al., 2009). More recently, arsenic exposure has been linked to cardiac effects such as myocardial infarction (heart attacks) (Yuan et al., 2007). Cardiac risks are elevated within short exposure periods, while cancers can take decades to develop, even long after arsenic exposure has stopped (Fig. 2.4). In addition, arsenic is linked with a range of impacts on children, including reduced birth weight, infant mortality and impaired cognitive development (Smith and Steinmaus, 2009).

Because of the ongoing uncertainty about low-level effects and the difficulties involved in measuring arsenic concentrations below 10 µg/L or in reducing arsenic concentrations to this level, the WHO has set 10 µg/L as a provisional guideline value (WHO, 2011). Many countries have a less strict drinking-water standard of 50 µg/L. The disease burden at these levels can be considerable; Argos et al. (2010) found all-cause mortality levels to be 34% higher in a population exposed to 0.01–50 µg/L arsenic, compared to a control group with <10 µg/L exposure. Those exposed to 150 µg/L or more showed 68% higher all-cause mortality.

There is no effective medical treatment for chronic arsenicosis, except for switching to an arsenic-free drinking-water source. However, palliative care such as application of ointments to cracked skin lesions can ease suffering. Chelation therapy is effective for short-term, acute poisoning, but not for long-term exposure.

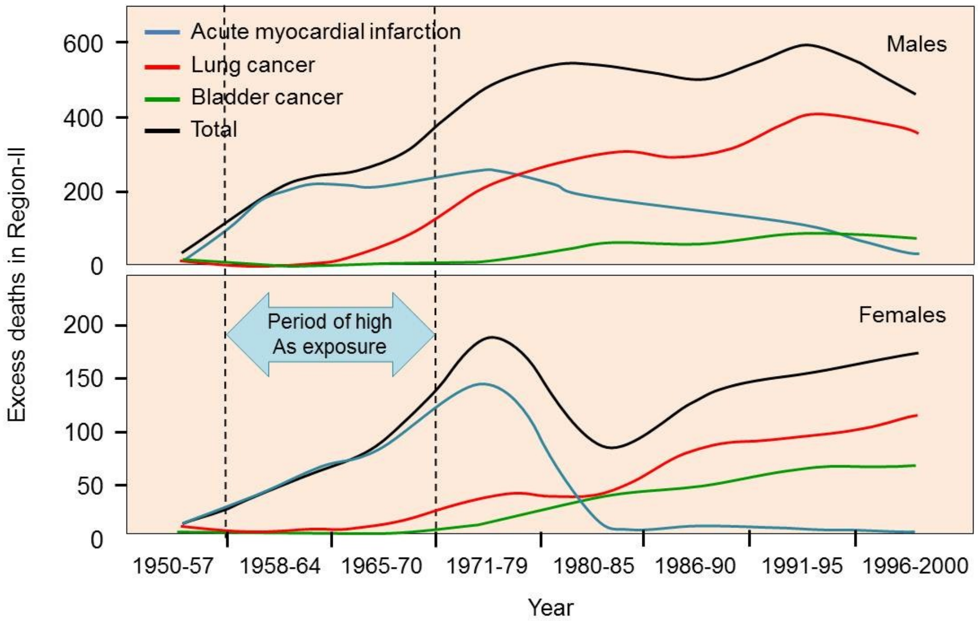

Fig. 2.4 *Latency of cancer and heart disease in northern Chile. Drinking water contained approximately 800 µg/L arsenic from 1958–1971, after which an arsenic removal plant greatly reduced exposure. Source: Redrawn by Ravenscroft et al. (2009) after Yuan et al. (2007)*

2.2 Fluoride

Occurrence

Fluoride is the 13th most abundant element found in the Earth's crust. Its occurrence in natural waters is closely related to the abundance and solubility of fluoride-containing minerals such as fluorite (CaF_2). The fluoride concentrations of most natural waters lie below the WHO guideline value for fluoride in drinking water (1.5 mg/L, WHO, 2011). Nevertheless, elevated fluoride concentrations in groundwater are still a problem in many regions of the world (Fig. 2.5).

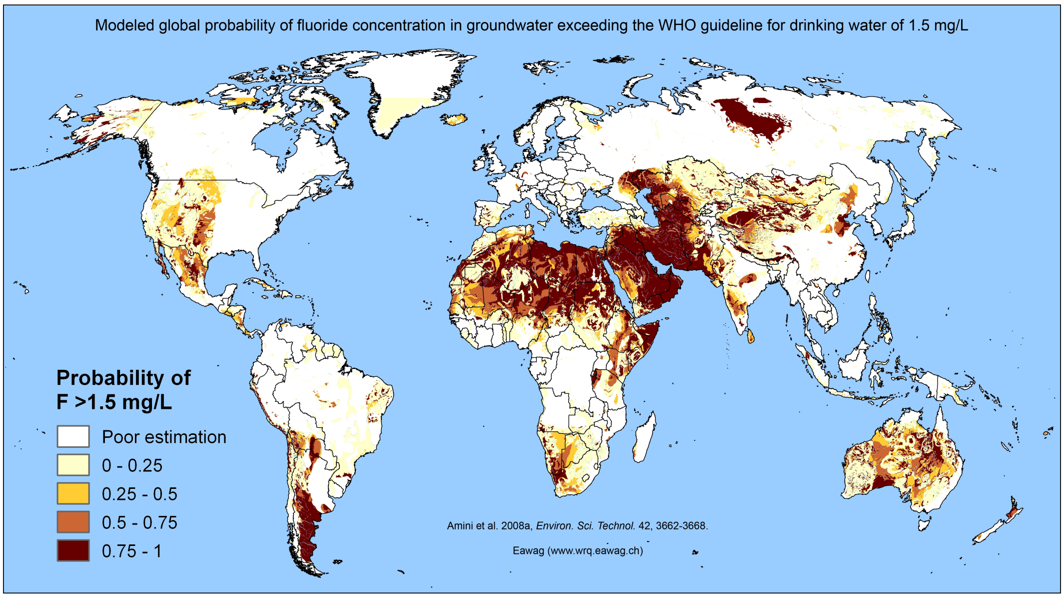

Fig. 2.5 *Modelled probability of fluoride concentrations in groundwater exceeding 1.5 mg/L (Amini et al., 2008b)*

High geogenic fluoride concentrations in groundwater (>1.5 mg/L) are associated with a variety of geological and climatic conditions:

- Granitic basements
- Arid climates
- Alkaline volcanic rocks

Granitic basement aquifers containing a relatively large proportion of high-fluoride minerals, such as micas, apatites or amphiboles, can yield groundwaters with elevated dissolved fluoride concentrations (e.g. in India, Sri Lanka). High fluoride concentrations can also be found in arid climates, where groundwater infiltration and flow rates are slow, and prolonged water-rock reaction times promote leaching of fluoride. Some of the highest fluoride concentrations are found in alkaline volcanic regions, such as the East African Rift Valley, where high-fluoride hyper alkaline volcanic rocks are present and fluoride is furthermore added to groundwater via high-fluoride geothermal solutions (Edmunds and Smedley, 2005).

Low calcium concentrations can also lead to high fluoride concentrations in water, as fluoride is not removed from solution by the precipitation of CaF_2. Such conditions are found, for example, in alkaline groundwaters whose chemistry is dominated by sodium bicarbonate. Also, groundwater associated with granitic rocks tends to contain little calcium.

Health effects

Fluoride has beneficial effects on teeth at low concentrations, but excessive exposure to fluoride can have a number of adverse effects, such as dental and skeletal fluorosis, the severity of which depends on the level and duration of exposure (Gazzano et al., 2010). Worldwide, an estimated 200 million people are at risk of fluorosis. However, incomplete data make precise quantification of the global health burden of fluorosis impossible (Fewtrell, 2006).

The ingestion of moderate amounts of fluoride, including that from drinking water, can lead to structural strengthening of tooth enamel and a lower rate of dental caries. The greatest decline is seen when drinking-water fluoride concentrations lie between 0.7 and 1.2 mg/L (Oszvath, 2009). This has led to the widespread fluoridation of drinking water in countries such as the USA and to the use of fluoridated toothpaste.

Fig. 2.6 *Examples of dental and skeletal fluorosis*

Childhood exposure to fluoride concentrations in drinking water that exceed the WHO guideline limit of 1.5 mg/L can lead to dental fluorosis (Fig. 2.6), a condition characterised by the mottling and pitting of teeth. Dental fluorosis occurs in young children as the tooth enamel is developing (NRC, 2006). Fluoride ingestion after about the age of 8, when adult teeth have been formed (even if they have not yet erupted), will not lead to dental fluorosis.

Adults with dental fluorosis must therefore have been exposed to high fluoride concentrations in their early childhood. Symptoms of mild dental fluorosis are the appearance of white striations or patches on the tooth enamel, while yellow and brown staining, pitting and chipping of the tooth enamel are symptoms of more severe fluorosis. Dental mottling is permanent, though some cosmetic treatment (bleaching, abrasion) can remove some of the visible stains.

Prolonged exposure to high fluoride concentrations over several years increases the risk of developing crippling skeletal fluorosis. This condition is characterised by pain and stiffness in the backbone and joints, accompanied by increased bone density (osteosclerosis). In its later stages, crippling deformities of the spine and joints arise, together with neurological defects, muscle wasting and paralysis (Oszvath, 2009). Studies on occupational and endemic fluorosis have shown that the extent of the symptoms is related to the duration and level of exposure and that skeletal fluorosis is at least partially reversible over a number of years. (e.g. Grandjean, 1982; Krishnamachari, 1986; Susheela and Bhatnagar, 2000). In addition to these more obvious symptoms, there are others grouped under the term "non-skeletal fluorosis". Non-skeletal fluorosis includes a reported decrease in cognitive capacity (measured by IQ tests), lethargy, an impaired ability to concentrate and possibly even the onset of dementia (USRC, 2006). Whether these effects could be due to enzymatic changes or impaired function of the thyroid gland is unclear. Fluoride may also disturb the endocrine system, acting as an inhibitor of secretions from the parathyroid glands, which regulate extracellular calcium and phosphate concentrations. Possible effects on the gastrointestinal, renal, hepatitic and immune systems have also been reported (USRC, 2006). There has been difficulty in proving observed health effects (in scientific studies) to be the result of elevated fluoride intake, and more rigorous epidemiological studies have been recommended.

The WHO guideline value of 1.5 mg/L might not be suitable for hot, arid areas where people have a higher daily water intake (Brouwer et al., 1988). The recommended maximal daily fluoride intake for children younger than 8 years (to prevent dental and skeletal fluorosis) is 0.1 mg/day per kg of body weight (SCSEDRI, 1997, Table 3.3). For adults, a daily intake of 14 mg leads to an excess risk of adverse skeletal fluorosis, and there is evidence for increased risk of an effect on the skeleton at an intake of 6 mg/day (Fawell et al., 2006). Not only drinking water, but also cooking water and fluoride contained in food products can contribute considerably to a person's daily fluoride uptake (Malde et al., 2011). A review of fluoride and nutrition is presented in Chapter 3. Skeletal effects in fluorotic areas may vary in severity depending not only on the daily fluoride uptake, but also on the intake of other essential nutrients important for bone formation, such as calcium, zinc, iron and magnesium. Deficient nutrition will therefore increase the risk of bone deformation when excess fluoride is consumed (Chakma et al., 2000).

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3 Nutritional intake and health risks of arsenic and fluoride

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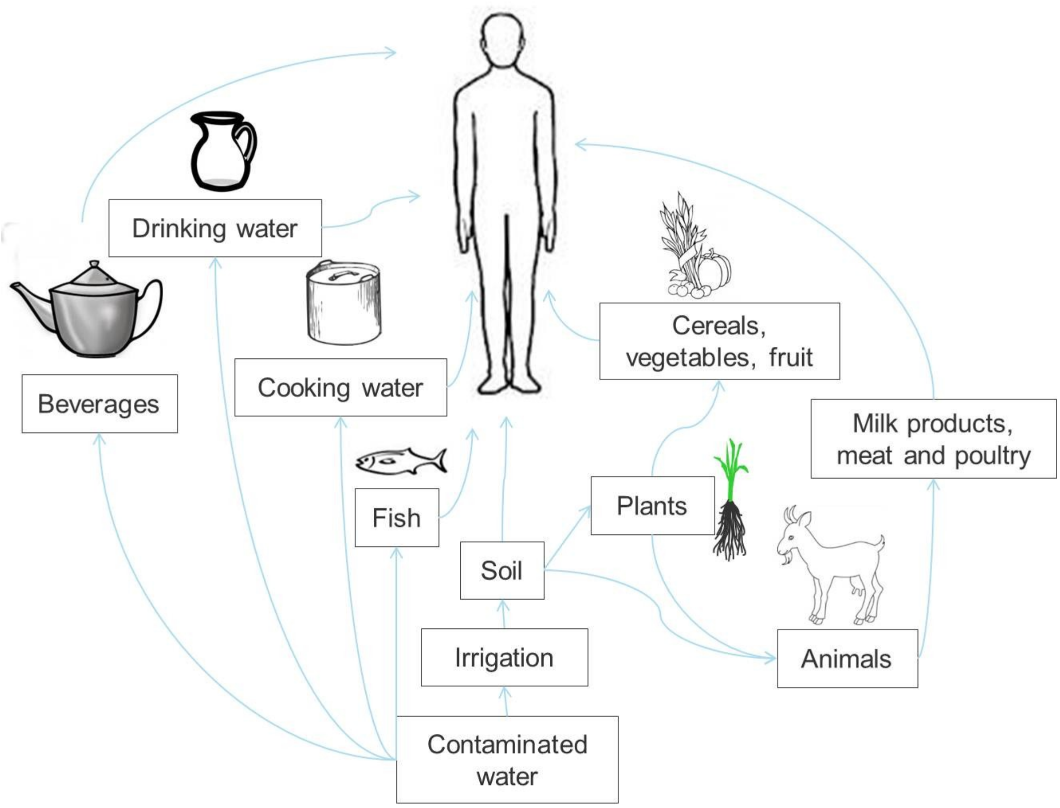

Fig. 3.1 *Different food and water pathways by which contaminants may enter the body*

Uptake via drinking water is only one of the potential pathways by which contaminants enter the human body. Elevated contaminant concentrations may also be found in foodstuffs and beverages or in water used for food preparation (Fig. 3.1). Locally produced cereals and vegetables using contaminated irrigation waters may contain elevated contaminant levels. Medical products or industrial production can also be sources of contamination. Though not an alternative to the provision of safe drinking water where water contamination is high, an understanding of the uptake pathways widens the scope of the mitigation possibilities to include changes in food production and consumption behaviour.

3.1 Arsenic

Overview of arsenic in soils, plants and foodstuffs

Arsenic is ubiquitous in the environment. Whilst uncontaminated soils typically contain less than 10 mg As/kg, concentrations of up to 80 mg As/kg have been reported from areas irrigated with arsenic-contaminated groundwater (Hossain, 2006). The mobility of arsenic in soils and its availability for plant uptake depend strongly on soil redox conditions. In aerated soils, arsenic is present mainly as arsenate (As(V)), which binds strongly to iron oxides. Arsenic concentrations in soil porewater solutions are therefore generally low. By contrast, much higher concentrations of dissolved arsenic are found in flooded soils, where reducing conditions prevail and arsenite (As(III)) is the dominating species. This is related to As(III) binding more weakly to the solid phase, and to iron oxides, its main host phase, being dissolved under reducing conditions. Plants growing in oxic environments, such as most cereal crops and vegetables, are therefore exposed to relatively low concentrations of As(V) in the soil porewater solution. Plants growing in flooded soils, most importantly rice, are by contrast exposed to higher concentrations of dissolved As(III) (Zhao et al., 2010).

Arsenic is a non-essential and toxic element which plants take up via the channels for essential nutrients. Because of its chemical similarity to phosphate, As(V) is taken up via phosphate transporters. As(III) has recently been shown to share the silicate uptake system in rice plants (Zhao et al., 2009). Since arsenic uptake occurs via the root system, plant roots often accumulate more arsenic than shoots, leaves and fruit. In rice plants, the arsenic content decreases in the order roots > stems and leaves > grain, with arsenic content being generally ~10 times lower in grains than in shoots and leaves (Heikens et al., 2007). Irrigation with arsenic-contaminated groundwater has been shown to lead to increased arsenic levels in rice and vegetables (Williams et al., 2006; Ahsan and del Valls, 2011; Table 3.1). Whilst arsenic speciation in terrestrial plants is dominated by inorganic arsenic, fish and other seafood contain mainly arsenobetaine, an organic arsenic species considered to be of no toxicological concern (Zhao et al., 2010). The overall contribution of seafood to inorganic arsenic exposure is therefore very limited (Table 3.1). The inorganic forms of arsenic are orders of magnitude more toxic than organic species (NRC, 1999, 2001).

Human exposure to arsenic via food

Owing to its traditional cultivation in flooded fields, rice contains significantly higher amounts of arsenic than other cereals (Table 3.1). Rice is the staple food of half the world's population. This includes those living in the large river deltas most affected by the geogenic arsenic contamination of South Asia. In rural Bangladesh, for example, adults consume around 0.5 kg dry weight of rice per day, which accounts for ~70% of their calorific intake ((Khan et al., 2009; FAO/WFP, 2008). Assuming a total As content of 0.13 mg As/kg dry weight in the rice, corresponding to the average As content in rice from urban Bangladeshi markets (Table 3.1), the daily consumption of 0.5 kg dry weight of rice leads to the ingestion of 65 µg As per day. The arsenic intake via the consumption of fresh vegetables, 130 g fresh weight for a typical rural Bangladeshi diet, is less than 5 µg As per day (Williams et al. 2006; Table 3.1). If we assume a body weight of 60 kg, the calculated daily ingestion of arsenic via rice translates to a daily intake of 1.08 µg As per kg body weight. This corresponds to around 50% of the provisional tolerable daily intake (PTDI) for inorganic arsenic recommended by the joint WHO/FAO Food commission (WHO, 1989). In As-affected areas in Bangladesh, where the arsenic content in rice can be up to 0.3 mg As/kg, the daily arsenic ingestion via rice can increase to over 100% of PTDI. As ~80% of arsenic in rice from Bangladesh is inorganic, the contribution of rice consumption to the PTDI in the two examples above is critical (Meharg et al., 2009).

The above estimates illustrate two points: a) among food items, rice contributes most strongly to inorganic arsenic exposure in Bangladesh and b) the amount of inorganic arsenic ingested via rice consumption is of the same order of magnitude as the provisional tolerable daily intake (PTDI) of 2.1 mg As/kg body weight recommended by the joint food commission of WHO/FAO in 1989. The recommended limit was recently withdrawn because of new epidemiological data, but a revised, stricter tolerable daily intake value for arsenic has yet to be established (WHO, 2011). This strongly suggests that exposure to arsenic via rice consumption is likely to lead to negative health impacts in the Bangladeshi population. However, as illustrated in the following, exposure via rice consumption is of secondary importance compared to exposure to arsenic via geogenically contaminated drinking water.

Comparison of exposure to arsenic via food and drinking water

The drinking-water limit for arsenic in Bangladesh is 50 µg/L. An adult weighing 60 kg and consuming 3 L of drinking water complying with this limit ingests 2.5 µg As/kg body weight. This alone corresponds to around 120% of the PDTI (Watanabe et al., 2004). In many rural areas of Bangladesh, however, people continue to rely on water with arsenic concentrations well above the national limit. Arsenic exposure via drinking water can thus easily be 2–6 times higher than the exposure calculated here. Wherever people do not have access to drinking water complying with the Bangladeshi guideline value, exposure to inorganic arsenic via drinking water therefore clearly exceeds exposure via food. The most urgent and effective mitigation measure in geogenically contaminated areas is therefore the provision of safe drinking water.

Mitigating exposure to arsenic in food

Various measures can be taken to reduce the arsenic content of food crops, including breeding low-arsenic cultivars, diversifying agriculture towards crops requiring less irrigation input and modifying the growing conditions of water-intensive crops. In particular, growing rice in fields flooded only intermittently or in raised beds with furrow irrigation represents a promising strategy for reducing the arsenic content of rice grain and straw (Duxbury and Panuallah, 2007; Roberts et al., 2011). Since straw is used as cattle feed in Bangladesh and West Bengal, avoiding high arsenic concentrations in rice straw represents an important additional measure limiting the introduction of arsenic into the food chain (Ahsan and del Vals, 2011). A more comprehensive review of mitigation options in crop production can be found in Brammer (2009) and Zhao et al. (2010).

Table 3.1 *Arsenic content of different foodstuffs, expressed as mg As/kg of dry weight (rice) and fresh weight (vegetables and other food items)*

Foodstuff	**Mean** (mg/kg)	n*	**Range** (mg/kg)
Global [1]			
Rice grain	0.15	901	0.01 – 0.82
Europe [2]			
Rice grain	0.14	1122	0 – 1.18
Cereal products (excluding rice)	0.02	1004	0 – 0.89
Vegetables	0.012	2604	0 – 1
Fish and seafood **	2.38	5083	0 – 195
Milk and dairy products	0.0089	3896	0 – 0.66
Meat and meat products	0.0098	9890	0 – 0.98
Eggs	0.0080	1404	0 – 0.182
Bangladesh [3,4]			
Rice grain, urban markets	0.13	144	0.02 – 0.33
Rice grain, farmers' fields	0.192	326	0.04 – 0.27
Rice grain, farmers' fields, As-affected areas	0.347	397	0 – 1.08
Vegetables, farmers' fields	0.0293	144	0.004 – 0.23

n = number of samples analysed.
*The percentage of inorganic arsenic in rice falls in the 30%-90% range (EFSA, 2009). Rice grown in Bangladesh contains an average of 80% of inorganic arsenic (Meharg et al., 2009).
**Fish and other seafood contain the non-toxic organic As compound, arsenobetaine. Inorganic As ranges between 0.03 mg and 0.1 mg As/kg fresh weight (EFSA, 2009).
[1] Meharg et al., 2009
[2] EFSA, 2009
[3] Williams et al., 2006
[4] Zavala and Duxbury, 2008

In terms of food processing/preparation, two simple measures can be taken to reduce As ingestion via rice: a) rice milling and b) boiling rice in excess As-free water and discarding the water after cooking. Both rice milling and cooking rice with excess water are common practices in Bangladesh and West Bengal. Rice milling removes the outer bran layer of the grain where arsenic concentration is particularly high. A drawback of rice milling is that it also leads to the removal of beneficial trace nutrients such as zinc (Zhao et al., 2010) and vitamin B1 (thiamine) (WHO, 1999). Boiling rice in water with low As concentrations lowers grain As content. By contrast, cooking rice with As-contaminated water leads to an increase in grain arsenic and should therefore be avoided (Mondal et al., 2010). Using excess arsenic-free pond water for cooking therefore represents an option for reducing arsenic ingestion via rice consumption.

Since there is no effective medical treatment of arsenicosis, avoiding arsenic intake represents the only way to improve the health status of affected populations. Nevertheless, there is evidence that symptoms of arsenicosis are less pronounced in people with varied diets rich in proteins and vitamins (Milton et al., 2004; Mitra et al., 2004). Selenium deficiency, which is common in Bangladesh, on the other hand, appears to exacerbate arsenicosis (Zwolak and Zaporowska, 2012). Diversifying people's diet to include more vegetables and proteins or the provision of selenium supplements (Sah and Smits, 2012) may thus also contribute to reducing the incidence of As-related symptoms.

3.2 Fluoride

Overview of fluoride in soils, plants and foodstuffs

Fluorine is an abundant element in the Earth's crust, and soil concentrations can range from approximately 100 to over 1000 mg/kg. With its high affinity for electrons fluorine exists as the negatively charged ion, fluoride. Geochemical factors control fluoride solubility, and the resulting reduction in availability, coupled with only a passive plant uptake mechanism, limits food concentrations to at most a few mg/kg (Table 3.2). However, plants grown in fluoride-contaminated soils may accumulate considerable amounts of fluoride, although the amount of fluoride accumulated appears to be very dependent on the species. In general, roots accumulate more fluoride than shoots, leaves and fruit, and it is also thought that in some cases, fluoride accumulation is related to the calcium content of the plant. The high fluoride content in Ethiopian cereal products, in particular teff, could possibly be related to the fluoride-rich soils of the Rift Valley (Table 3.2).

In addition to standard food items, such as those listed in Table 3.2, other products such as toothpaste can make a significant contribution to fluoride intake. Trona, a salt used in the Rift Valley of East Africa for cooking, contains significant amounts of fluoride (100 to 17,900 mg/kg, Nielsen and Dahi, 1995), as does the condiment “black salt” (rock salt), used extensively in Indian cuisine (~ 20,000 mg F/kg, single measurement, Eawag). Another potential source of fluoride intake for young children, soil ingestion, can be excluded in most cases (NRC, 2006).

Table 3.2 Fluoride content of different foodstuffs

Foodstuff	**Content** mg F/kg	**Reference**
Milk and milk products	0.01 – 0.8	Hungary, Germany, USA, China Fawell et al., 2006
Meat and poultry	0.01 – 1.7	
Fish	0.06 – 4 6	
Baked goods and cereals	0.04 – 1.9	
Vegetables	0.01 – 1.3	
Beverages	0.003 – 1.3	
Brewed tea	0.05 – 5.0	
Cereals from the Rift Valley, Ethiopia		
Teff, white, Ethiopia	6.0	Malde et al., 1997
Wheat flour, Ethiopia	4.9	
Maize flour, Ethiopia	1.1	

Fluoride intake standards

Fluoride has both beneficial and adverse effects on human health. In low concentrations, it is known to contribute to the prevention of dental caries; however, in excess amounts, it is toxic (Gazzano et al., 2010; see Section 2.2 for more details). The range between adequate and excess fluoride intake is quite narrow. Standards for fluoride intake have been established for the USA and other industrialised countries (Table 3.3). They stipulate an adequate intake of 0.05 mg F/kg/day, based on the amount necessary to prevent dental caries. Tolerable upper daily intake levels are around 0.1 mg F/kg/day for infants and 0.1–0.14 mg F/kg/day for adults.

Estimates of total daily fluoride intake in selected industrialised countries around the world with fluoride water concentrations up to 1.0 mg/L range from 0.2 to 1.3 mg F/day for children and up to 3 mg F/day for adults. Young children are thought to be particularly at risk of excess fluoride intake. The study estimates that for children aged between 7 and 10, beverages, including water, account for only one third of fluoride uptake, while for adults, beverages, primarily tea, account for two thirds of fluoride intake (Cressey et al., 2009).

Mitigating exposure to fluoride via food

Fluoride metabolism (absorption into and excretion from the body) is influenced by a number of factors, including respiratory and metabolic disorders, altitude of residence, physical activity, nutritional status, composition of diet and genetic predisposition (Buzala and Whitford, 2011). These factors can lead to an acid-base imbalance in the body.

Fluoride absorption in the stomach is pH-dependent. In acidic gastric fluids, fluoride is protonated (< pH 3.4), and the neutral HF species can pass through the lipid bilayer membrane of the stomach a million times more readily than the charged fluoride ion (F^-). Some fluoride absorption (independent of pH) also occurs in the small intestine (Buzala and Whitford, 2011).

Diet has an important influence on fluoride absorption. For example, a vegetarian diet leads to an increase in urinary pH. Calcium in the diet reduces fluoride absorption in the body by the formation of insoluble fluorite (CaF_2). In China, a study in Jiangzi province showed that children that drank milk had a significantly lower dental fluorosis rate than those who did not (Chen et al., 1997).

Table 3.3 *Standards for fluoride intake*

Standard	Intake		Source
Adequate Intake (AI)	0 – 6 months > 6 months 4 – 8 years Adults (male) Adults (female)	0.01 mg/kg/day 0.05 mg/kg/day 1 mg/day 4 mg/day 3 mg/day	Food and Nutrition Board of the USA (SCSEDRI, 1997) (Based on assessment of requirements for caries prevention)
Tolerable Upper intake Level (UL)	0 – 8 years > 8 years	0.1 mg/kg/day 10 mg/day	SCSEDRI, 1997
Tolerable Upper intake Level (UL)	1 – 3 years 4 – 8 years 9 – 14 years >15 years	1.5 mg/day 2.5 mg/day 5 mg/day 7 mg/day	European Food Safety Authority EFSA, 2011
Dental Fluorosis NOAEL* LOAEL**	 0.06 mg/kg/day 0.12 mg/kg/day (8 mg/day for adults)		US Department of Health and Human Services USDHHS, 2003
Skeletal fluorosis NOAEL* LOAEL**	 0.15 mg/kg/day 0.25 mg/kg/day (17.5 mg/day for adults)		

* No Observed Adverse Effect Level
**Lowest Observed Adverse Effect Level (5% of test population)

In India, where fluorosis is endemic, dietary change to lower the intake of fluoride and increase the uptake of calcium, iron, vitamins and antioxidants is recommended (Godfrey et al., 2011). Reversal of skeletal disfigurement caused by fluorosis in young children has been achieved by giving them dietary supplements and switching them to low-fluoride drinking water (NEERI, 2007). It should be pointed out, however, that the diagnosis of skeletal fluorosis requires X-ray analysis, and some bone alterations appear to be permanent (Krishnamachari, 1986). Cortical bone thickening and calcification of muscle insertions and ligaments appear to remain unchanged (Grandjean and Thomsen, 1983).

Fluorosis and dietary assessment and mitigation guides have been developed by the Fluorosis Research and Rural Development Foundation (Susheela, 2000) and the National Environmental Engineering Research Institute (NEERI, 2007). It is recommended that the potential for fluorosis mitigation through dietary changes be explored as an integral part of a fluorosis mitigation strategy.

3.3 Quantitative health risk analysis

Risk assessment is the scientific evaluation of known or potential adverse health effects resulting from human exposure to environmental hazards. One of the more commonly used risk assessment paradigms, the Quantitative Health Risk Analysis (QHRA), is based on the U.S. National Academy of Science in Risk Assessment in the Federal Government: Managing the Process (NAS, 1983), colloquially known as the “Red Book”. In the Red Book, the four steps are:

Hazard identification: The identification of known or potential health hazards associated with a particular agent.

For the QHRA, it is important to identify health effects that are characteristic for the contaminant under consideration. For arsenic, skin lesions and cancers are typical health effects (e.g. Lokuge et al., 2004). For fluoride, dental and skeletal fluorosis are clearly visible health effects (Serap and Buchanan, 2005; Fewtrell et al., 2006).

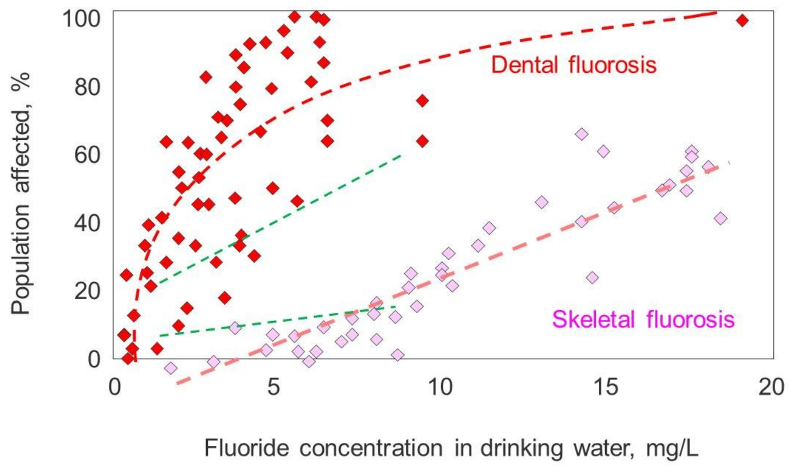

Fig 3.2 *Sketch of dose-response curves for dental and skeletal fluorosis determined by Fewtrell et al. (2006). Superimposed as green dashed lines are the regressions from Bo et al., (2003).*

It should also be noted that though some health effects may not be considered in a QHRA, it does not mean that they are insignificant. For example, there is growing evidence that excess in the intake of both fluoride and arsenic is linked to impaired cognitive development (e.g. Wang et al, 2007; Seraj et al., 2012; Choi et al., 2012).

Dose-response assessment: In this step, the relationship between the dose of the contaminant and the risk of a subsequent health effect is characterised. For arsenic and fluoride, dose-response assessments are based on the relationships between the contaminant concentration in drinking water (and food) and the incidence of a particular health effect.

This step requires measured data. Health effects need to be identified and characterised by health experts and related to the exposure. An example is given in Figure 3.2. Fewtrell et al. (2006) examined the dose-response relationships from 12 publications on dental fluorosis and 4 publications on skeletal fluorosis. They concluded that more data would be required and that it would be important to include nutritional status and fluoride sources in addition to drinking water.

Also shown in Figure 3.2 are the results of a study in Jilin province in China (Bo et al., 2003). The dose-response curves are encouragingly similar. Nevertheless, the nature of the relationship between dose and response remains contentious, and there are calls for more biologically-based risk assessments (Carlson-Lynch et al., 1994; Kitchin and Conolly, 2010).

Great efforts have been made to evaluate the dose-response of arsenic-related diseases. Fewtrell et al. (2005) estimated the risk of developing skin lesions caused by elevated arsenic concentrations in drinking water using data from Bangladesh, Inner Mongolia (China) and West Bengal (India). The evaluation showed that at a drinking-water arsenic concentration of >350 µg/L, the age-adjusted prevalence of skin lesions is around 33%. The evaluation of cancer rates and mortality linked to arsenic exposure has also been the subject of many studies (for example Fig. 3.3) and evaluations (e.g. NRC 1999, 2001, 2014). Dose-response functions have been developed to predict incidence rates from arsenic exposure (usually in drinking water). The functions include available demographic parameters, such as gender and age (e.g. Yu et al., 2003).

The determination of dose-response functions for both arsenic and fluoride is very much a field of development. As new data sets become available, the models will certainly be refined. One important factor is nutritional status, as malnutrition increases the likelihood of disease (NRC, 2001 and references therein). Differences in water consumption and diet, and the speciation of the contaminant in foodstuffs, have also been noted as factors that affect dose-response functions.

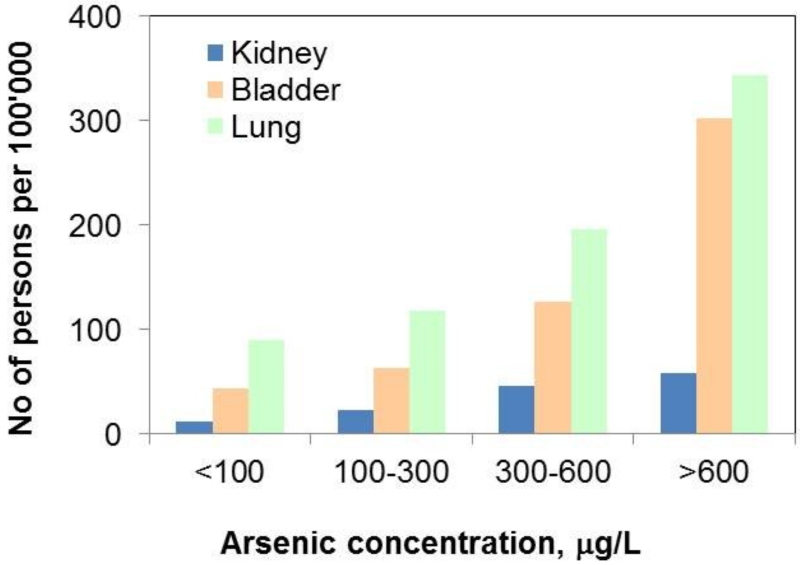

Fig 3.3 *Mortality rates from different cancers as a function of the arsenic concentration in drinking water in the 50–69 age group (men and women) in an endemic area of chronic arsenicosis on the southwest coast of Taiwan from 1973 to 1986 (Chen et al., 1992).*

Exposure assessment: The determination of the size and nature of the population exposed, and the route, amount and duration of the exposure.

The estimated daily intake (EDI) is the sum of all possible inputs, including water and foodstuffs, per unit body weight per unit time. More details can be found, for example, in Phan et al., 2010 or Erdal and Buchanan, 2005. The EDI can be simplified to contaminant intake via water, but ideally it should be demonstrated that other pathways can be excluded. This step is important, because in cases where contaminant concentration in water is not so high, other sources become important. Section 9.4 provides a good example of fluoride intake in Ethiopia.

Risk characterisation: An integration of steps 1–3 to estimate the magnitude of the public health problem, including information uncertainties. The units are the number of people affected, often per 100,000 people.

With a QHRA, it is possible to estimate the number of people that are at risk in a particular population, but how can different health effects (i.e. skin lesions, cancer) be compared? How can death and/or disability be compared? Comparisons of risks on the same scale are a valuable aid in evaluating and planning interventions to improve health. The concept of disease burden is based on the need for such a tool.

Estimation of disease burden

The disease burden can be quantified in terms of Disability Affected Life Years (DALYs), which quantifies the number of years affected or lost due to disease (WHO, 2014).

One DALY can be thought of as one year of healthy life lost, and the overall disease burden can be thought of as a measure of the gap between current health status and ideal health status, where the individual lives to old age free from disease and disability. Fewtrell et al. (2005, 2006) assume a life expectancy of 80 years. The health burden (expressed in DALYs) is the sum of mortality (years of life lost, YLL, and years of life with disability, YLD). Disability levels are weighted (see Table 3.4). The weighting correlates to the degree of disability (WHO, 2014).

DALY = YLL + YLD

where YLL = N x L

N: Number of deaths

L: Standard life expectancy at age of death in years

and YLD = P x DW

P: Number of prevalent cases

DW: Disability weighting

Table 3.4 *Definition of disability weighting (DW) (Murray, 1994)*

Class	Description	Weight
1	Limited ability to perform at least one activity in one of the following areas: Recreation, education, procreation or occupation	0.096
2	Limited ability to perform most activities in one of the areas listed in Class 1	0.220
3	Limited ability to perform activities in two or more of the areas listed in Class 1	0.400
4	Limited ability to perform most activities in all of the areas listed in Class 1	0.600
5	Needs assistance with instrumental activities of daily living such as meal preparation, shopping or housework	0.810
6	Needs assistance with activities of daily living such as eating, personal hygiene or toilet use	0.920

The weighting corresponds to the loss in quality of life. Fewtrell et al. (2006) give dental fluorosis a low weight of 0.0033 that remains constant with age. They base the weight for skeletal fluorosis on that of untreated rheumatoid arthritis with a weight of 0.24 for the age range 40–59 and of 0.5 for those aged 60 or above. A weighting of 0.1–0.2 is given for arsenic-related skin lesions, depending on the length of exposure (Fewtrell et al., 2005).

The DALY can be used to compare different scenarios. For example, DALY estimates have been used to compare the health burden associated with water consumption from different arsenicosis mitigation options in Bangladesh considering both the potential decrease of arsenic intake and the potential increase in microbial contamination (Howard et al., 2006, 2007),

Due to the complexity of the calculations, no examples are given in this handbook. Seriously interested readers should consult the literature and guidelines and tools provided by the WHO on the estimation of the national burden of disease (WHO, 2001, 2014).

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4 Water sampling and analysis

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Human exposure to geogenic contamination occurs primarily through consumption of contaminated water. It is therefore essential to identify contaminated water sources. From an institutional perspective, this implies national surveys that help establish i) if there is any contamination; ii) where the regions of contamination might be and iii) where mitigation activities are most urgently required. For local organisations, the survey may be limited to a region of suspected contamination, with much less technical support.

Sampling and analysis of water is a time-consuming and costly process, and planning is one of the most important steps of any field campaign. Often health symptoms provide the first indication of geogenic contamination (see Chapter 1). The first step is always to evaluate already available information, e.g. government agency reports or academic studies on water quality. Our experience shows that relevant data often exist, but sharing these data can be a problem. Next, it needs to be decided where more information is required, which water quality parameters are essential and which instrumentation for the analysis of As and F is available. Finally, the necessary preparations need to be taken before going into the field. The following sections give an overview of sampling and measuring procedures.

4.1 Basic principles

Both fluoride and arsenic are tasteless, odourless and colourless in water. The only way to detect these contaminants is through chemical analysis. If water-quality data are not already available, a field sampling campaign is necessary to find out if arsenic and fluoride concentrations are above the relevant WHO guidelines (10 µg/L for arsenic and 1.5 mg/L for fluoride) and/or national guidelines. In a first step, only a selection of water sources in areas indicated to be at risk, perhaps by the observation of fluorosis or arsenicosis symptoms in local populations, are screened. It may be possible to prioritise certain geographic areas, which are thought to be more vulnerable to geogenic contamination, for testing.

If the screening confirms elevated fluoride or arsenic levels in even a few water sources, then a more time- and resource-intensive testing of all water sources (blanket testing) should be carried out. This needs to be done because contamination levels can vary greatly over short distances. If the financial resources are available, it may be worthwhile not only to measure arsenic and/or fluoride concentrations, but to undertake a full water analysis (sum parameters, major components, minor components), as this gives a much more complete picture of water chemistry and might yield explanations for the occurrence of geogenic contamination. More details can be found in Section 4.4 at the end of this chapter.

Selection of measurement method

Arsenic and fluoride analyses may be carried out directly in the field using semi-quantitative or quantitative field kits. The samples may also be taken back to a laboratory for analysis. Semi-quantitative field test kits are only recommended to classify wells as above or below an acceptable limit, while quantitative measurements provide information on arsenic or fluoride concentrations. Quantitative measurements allow us to evaluate the health hazard and are essential for mitigation planning.

Field testing versus lab testing

Field test kits have the advantage of providing immediate results in the field, allowing water sources to be marked as safe or unsafe straightaway. They also allow a check to be made for alternative safe water sources in the immediate surroundings of the contaminated well. The possibility of sharing safe sources can be discussed on the spot (keeping in mind that microbial contamination may be a problem). However, field measurements are more prone to human error, as they are performed under suboptimal conditions, and often by different testers.

Laboratory equipment will produce results of superior accuracy and precision to field test kits, if correctly operated and maintained by well-trained and dedicated staff. However, there are three main obstacles to the exclusive use of laboratory methods in large screening exercises (Kinniburgh and Kosmus, 2002):

- The lack of sufficient laboratories of the required quality to process large numbers of samples reliably (though a large sampling campaign might allow long-term capacity building and result in improving laboratory performance).
- The lack of management experience to organise the collection and tracking of samples and reporting of results on a large scale, resulting in the risk of results being misreported.
- Logistical problems associated with the transporting of samples from the field to the laboratory and relaying the results back to the field.

Evidence shows that well-designed and well-implemented arsenic survey programmes using field test kits can be reasonably accurate and comparable to laboratory tests (Rosenboom, 2004; Steinmaus et al., 2006; Jakariya et al., 2007, George et al., 2012; Spear et al., 2006). The same can be expected for fluoride surveys.

Testing campaigns have to be carefully planned:

1 Select sampling sites, measurement method and quality-control plan
2 Train staff involved in sampling procedures, preservation and/or transportation of water samples and handling of analytical equipment
3 Prepare monitoring forms Indeterminate Example_Monitoring-Form

4 Prior to each sampling trip: check and carefully pack equipment.
(Often forgotten: stickers and waterproof pen for labelling, spare batteries, screwdriver for opening battery case, distilled water, pipette, GPS etc.).

Accuracy and precision

Regardless of the equipment used, sample concentrations are obtained by comparing an analytical signal to standards or known samples. While in semi-quantitative methods these may be colour charts, in quantitative methods these will be blanks (distilled or deionised water containing analyte chemicals) and known concentrations. Laboratory analyses of >20 sample batches will usually comprise a blank and standards (between 3 and 8 standards) at the beginning and end of analysis, with one blank and one standard every 10 samples. Ideally, samples will be analysed in duplicate or triplicate. In the field, the number of analytical checks may be reduced (for practical reasons) to one blank and only a few standards at each sampling location. It is therefore recommended to make quality control checks on field kit analyses and to cross-check 5–10% of the water samples with measurements made in reference laboratories (APHA, 2012).

The multiple analysis of the same sample gives a mean. The precision is the scatter around the mean (UNICEF, 2008a; Fig. 4.1). If the results lie close together, the precision is said to be high. However, their accuracy is dependent on how close they are to the “true” value. The accuracy and precision of an analytical procedure will depend on a number of factors, including the skill of the analyst, the proper operation and maintenance of the equipment and the quality of reagents used.

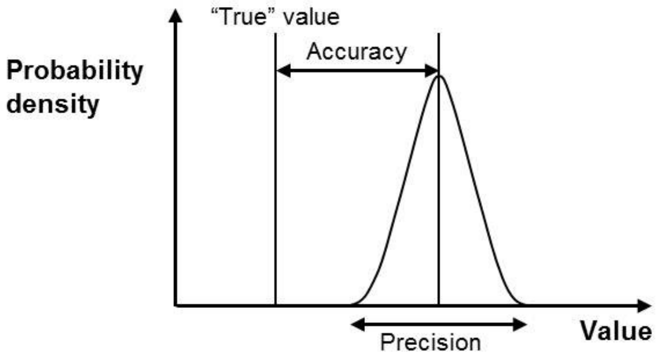

Fig. 4.1 *Difference between accuracy and precision*

For screening, quantitative accuracy may not be essential; if the countrywide drinking-water standard for arsenic is 50 µg/L, a field test kit does not need to be able to distinguish reliably between 200 and 300 µg/L in order to identify the well as contaminated. In India and Bangladesh, arsenic surveys have used field test kits in a semi-quantitative way to classify wells as above or below the acceptable limit of 50 µg/L.

The operation of field test kits is normally easy and explained well in the user manuals of commercially available products. Nevertheless, good training on the use and maintenance of field test kits is a key factor in obtaining accurate measurements. Sophisticated laboratory methods can only be installed and operated by experienced and well-educated laboratory staff.

Some fluoride and arsenic tests might depend on pH or be influenced by competing ions in the water sample. It is important i) to make an in-depth study of user manuals and ii) to consult experts if necessary, to avoid such interferences.

Costs and availability

Analytical costs depend on the number of measurements planned. For instance, the capital costs for an ion-selective electrode (ISE) to measure fluoride is high, so if only few tests are carried out, the cost per sample will be high. However, if many measurements are conducted, the running costs per test are lower for the ISE method than for most of the fluoride field test kits. On the other hand, for arsenic, the costs per measurement are lower for field test kits than for laboratory analyses.

Importing chemicals from abroad can be expensive and complicated, making it preferable to obtain them from a local supplier.

Health and safety

Many of the reagents required for arsenic and fluoride measurements are harmful when in contact with the eyes or skin. They have to be carefully stored during transportation, and safety equipment (gloves and glasses) needs to be worn when handling the chemicals. Children need to be kept away from the work area, and all waste must be taken away from the field and disposed of responsibly.

Another issue related to arsenic field test kits is that they may expose the analyst to unsafe levels of the toxic gas, arsine. One study found that nearly half of the arsine generated during analysis escaped from the reaction vessel (Hussam et al., 1999). Newer kits are better designed, but the analyses still need to be conducted in a well-ventilated area (i.e. outdoors).

The transport of reagents in the cabin or hold of an aeroplane may be prohibited. Cargo companies or postal services are an alternative. Some documentation might be necessary for customs.

Ensuring safety: It is recommended that contaminated water sources be clearly marked (e.g. A red pump spout for contaminated water sources and green spout for uncontaminated water sources (UNICEF, 2008b)), so that it is obvious to local users whether a well is contaminated and that water should not be used for drinking or cooking purposes. Appropriate colours should be determined by consultation with the local population. It is recommended to label the well with its measured As or F concentration, as well as with the date and method of analysis.

4.2 Arsenic sampling and measurement

Inorganic arsenic in groundwater is found in two different oxidation states: As(III) (arsenite) and As(V) (arsenate). There are also organic forms, but these are rare in drinking water. Both As(III) and As(V) are toxic, but the two species behave somewhat differently in the environment. The testing methods described in this manual give total inorganic arsenic concentrations, which are adequate for most general purposes. Specialised techniques are needed to tell whether arsenic is present as arsenite or arsenate.

The detection range of interest is 10 to 50 µg/L (the typical range of national standards for arsenic). Maximum concentrations of naturally occurring arsenic in groundwater can exceed 1000 µg/L.

Sampling and preservation

For both field and laboratory testing, it is important that correct sampling procedures be followed. To ensure that the sample is representative, it should be freshly drawn from the aquifer. The groundwater should be pumped to ensure that at least one well volume of water is removed before collecting a sample. An alternative is to measure dissolved oxygen and/or pH can in the pumped water until the parameters have a constant value, before taking a sample. The acid-washed sampling bottle should be rinsed three times using the pumped water, making sure to keep the lid clean, before the sample is collected for analysis. Depending on the analytical method chosen, the arsenic measurement can be carried out directly on-site at the water source, or as soon as possible back in the laboratory.

If a sample is to be taken back to the laboratory, its volume should suffice for at least 5 arsenic analyses. The sample bottles should be filled to the top. The sample ID should be written on the bottle, or better still, on a label stuck on the bottle, with a waterproof pen BEFORE the sample is taken. A leaky sample bottle can render labels unreadable.

High density polyethylene (HDPE) plastic bottles are recommended. They should be washed with acid (1% HCl) and well rinsed with distilled water (3 times) before use. Water samples should be transported and stored in a cool, dark and clean environment. If the samples are properly preserved, the arsenic measurements will still be reliable even if carried out several months after sampling (This is important when samples are collected for quality checking in a reference laboratory).

To avoid the formation of iron (oxy)hydroxide in the sample (orange colouring commonly associated with groundwater containing iron), which may remove arsenic from solution, the pH of the samples should be reduced to below 2 using acid. Nitric acid is commonly used (hydrochloric acid is another option); the acid should be certified to contain essentially no arsenic. Blank samples (distilled water with and without acidification) should always be tested to ensure that no arsenic is added to the samples along with the acid or the sample bottles. Generally it is sufficient to add 0.2–1% of the filling volume (e.g. 0.2–1 mL acid for a

100 mL sample bottle) of concentrated nitric acid (65%). For safety reasons, it might be advisable to use diluted acid (1:1 or 1:2) in the field.

Water samples can be filtered before acidification (through 0.45 µm filters) to remove any particles that might dissolve arsenic at low pH, which would lead to higher arsenic readings. Filtration increases the precision of the results, as the particulate content is difficult to control. However, if particulate arsenic also contributes significantly to arsenic exposure, then filtering samples will lead to an underestimate of actual exposure. Generally, filtered samples are better for understanding geochemistry, while unfiltered samples are better for public health purposes.

Field test kits

Various arsenic field kits are commercially available (Tables 4.1, 4.2). The most commonly used field test methods rely on the chemical reduction of arsenic present in the sample to arsine gas, which then reacts with other chemicals on a test paper or in an indicator tube to produce a colour with an intensity proportional to the arsenic concentration. The tester then compares the colour with a calibrated colour chart. In some field testing equipment, a digital photometer is used to measure the colour intensity, which eliminates human error.

Bacterial biosensors may offer another alternative for the detection of arsenic contamination in drinking water (Trang et al., 2005). These sensors, which rely on genetically engineered E. coli bacteria that glow when exposed to arsenite, are cheap and easy to use but require some training. The microbiological arsenic test has a great potential in large screening campaigns (see ARSOlux, Table 4.1).

Arsenic analysis in the laboratory

All laboratory analyses must be performed by experienced laboratory staff.

There are various methods of quantifying arsenic concentrations in the laboratory. In order of increasing sophistication (and cost), they are the colorimetric method requiring a (spectro) photometer that uses silver diethyl-dithio-carbamate (SDDC), Anodic Stripping Voltammetry; Graphite Furnace Atomic Absorption Spectrophotometry (GF-AAS); Flame AAS with Hydride Generation apparatus (HG-AAS) and inductively coupled plasma mass spectroscopy (ICP-MS). For a detailed review, see Rasmussen and Andersen (2002).

Table 4.1 *Overview of commercially available semi-quantitative arsenic field test kits (this list does not include all available kits, and is not intended as an endorsement of any of the companies or products listed):*

Industrial Test Systems
(Arsenic Quick™)

Available for low- (5–500 µg/L) and high- (20–3000 µg/L) concentration ranges. The test takes 20 minutes. Contains hazardous chemicals.

Instruction-Leaflet_(LowRange)

Material-Safety-Data-Sheet

Where to buy: www.merck-chemicals.com

Hach
(Arsenic Test Kit)

Hach offers two arsenic test kits. The Arsenic Low Range Test Kit has a range of 10–500 µg/L and is best for samples containing sulphide or arsenic-iron particles. The EZ Arsenic High Range Test Kit has a range of up to 4000 µg/L, comprises fewer steps, and is more economical.

Instruction-Leaflet_(Low-Range)

Where to buy: www.hach.com

Industrial Test Systems
(Arsenic Quick™)

Industrial Test Systems markets a range of different arsenic test kits. The main product, the Quick™ test, has a range of 5–500 µg/L, with a reported reaction time of only 12 minutes.
This kit has been verified by the USEPA's Environmental Technology Verification programme.
Further reading on test kit performance:
George et al., 2012

Documentation

Where to buy: www.sensafe.com

ARSOlux
(Biosensor)

ARSOlux offers a biosensor to determine whether arsenic concentrations (in the chemical form of arsenite) are above or below a chosen calibration value (e.g. 10 µg/L). The pH of the water sample has to be between 6 and 8, and it is necessary to incubate the sample for two hours between 20 and 35°C.

Information-Leaflet

Website: www.arsolux.ufz.de

Other semi-quantitative field test kits

The Asia Arsenic Network, an early player in arsenic testing and kit development, continues to market an inexpensive kit with a range of 20–700 µg/L in Bangladesh. A variation on this kit, measuring arsenic from 10–500 µg/L, was developed by the Environment and Public Health Organization, Nepal.

A joint project between UNICEF and the Rajiv Gandhi National Drinking Water Mission in India has developed specifications for a field kit that does not use the conventional mercuric-bromide paper. Instead, a detector tube is filled with a granular medium coated with a secondary colour reagent that reacts with arsenic and mercuric bromide to produce a pink colour. Following completion of the test, the arsenic concentration (10–110 µg/L) is read directly by measuring the extent of pink colour penetration in the detector tube. Specifications for the kit are available from the Rural Water Supply Network.

UNICEF also supported the development of locally manufactured arsenic test kits in China, Thailand and Vietnam, and in China and Thailand, they are still in use. The Thai kit, developed and marketed by Mahidol University, has a detection range of 5–500 µg/L and is used in Thailand and in other countries in the region.

Table 4.2 *Overview of commercially available quantitative arsenic field test kits (this list does not include all available kits, and it is not intended as an endorsement of any of the companies or products listed):*

Wagtech/Palintest (Digital Arsenator, DigiPAsS) 	The Digital Arsenator detects arsenic within a reported range of 2–100 µg/L. Wagtech also produces a Visual Arsenic Detection Kit, which uses a visual reference colour chart instead of the optical photometer. It has a reported range of 10–500 µg/L. It has been widely used in Bangladesh, Kenya and other countries. Operation-Leaflet_1 Material-Safety-Data-Sheet_(Sachets) Material-Safety-Data-Sheet_(Tablets) Where to buy: www.wagtech.com, www.palintest.com
Merck (Spectroquant®, Nova 60A) 	Merck sells a digital photometer arsenic kit (Spectroquant®) with a reported range of 1–100 µg/L. The Merck photometers are typically used in a laboratory setting, but one model (Nova 60A) comes with a battery pack and can be used as a portable instrument. Operation-Manual Material-Safety-Data-Sheet Where to buy: www.merck-chemicals.com

4.3 Fluoride sampling and measurement

Fluoride concentrations in drinking water normally range from below 0.1 mg/L up to 10 mg/L, but can in some cases reach 20 mg/L or more. At fluoride concentrations of >20 mg F/L, the water is often saline and therefore not used for drinking or cooking. The WHO guideline value (and that of many national standards) is 1.5 mg/L, so quantification in this range is critical.

Fluoride measurement methods can be divided into colorimetric/photometric methods (semi-quantitative and quantitative) and potentiometric methods (using an ion-selective electrode, ISE). More sophisticated methods (e.g. ion chromatography, IC) do not deliver more accurate results than a carefully calibrated ISE and are not discussed in this manual (basic information on IC can be found in Fawell et al., (2006)).

Sampling and preservation

For both field and laboratory testing, it is important that correct sampling procedures be followed. To ensure that the sample is representative, it should be freshly drawn from the aquifer. The groundwater should be pumped to ensure that at least one well volume of water is removed before collecting a sample. An alternative is to measure dissolved oxygen and/or pH can in the pumped water until the parameters have a constant value before taking a sample. The sampling bottle should be rinsed three times using the pumped water, making sure to keep the lid clean, before the sample is collected for analysis. Depending on the analytical method chosen, the fluoride measurement can be carried out directly on-site at the water source, or as soon as possible back in the laboratory.

If a sample is to be taken back to the laboratory, its volume should suffice for at least 5 fluoride analyses. The sample bottles should be filled to the top. The sample ID should be written on the bottle, or better still, on a label stuck on the bottle, with a waterproof pen BEFORE the sample is taken. A leaky sample bottle can render labels unreadable.

Plastic bottles are recommended, as glass bottles can easily break. Water samples should be transported and stored in a cool, dark and clean environment. If the samples are properly preserved, the fluoride measurements will still be reliable even if carried out several months after sampling (This is important when samples are collected for quality checking in a reference laboratory). However, it is better to analyse the samples as soon as possible, because some fluoride might precipitate in the presence of other ions.

Field test kits

A large number of fluoride field kits based on colorimetric techniques are commercially available (Tables 4.3, 4.4). The final colour of a test paper or a water sample is either compared visually with a colour scale (semi-quantitative) or more precisely against standard measurements using a photometer (quantitative). The colouring reagent SPADNS (1,8-

dihydroxy-2-(4-sulfophenylazo)naphthalene-3,6-disulfonic acid) is commonly used as a reagent for fluoride determination.

The ease of operation of the photometers makes them attractive for organisations without well-trained laboratory staff. Some photometers are designed for field use. A drawback of all fluoride field test kits is the low upper detection limit; water samples often have to be diluted, increasing the risk of miscalculation.

Table 4.3 *Overview of commercially available semi-quantitative fluoride field test kits (this list does not include all available kits, and it is not intended as an endorsement of any of the companies or products listed):*

Kyoritsu (Pack Test Fluoride) 	Measuring range up to 8 mg/L (though quite imprecise for concentrations above 3 mg/L). Dilution of the water samples might be necessary (distilled water is required). Measuring time is 10 minutes. Instruction-Leaflet Where to buy: www.kyoritsu-lab.co.jp
Macherey-Nagel (Fluoride Test) 	Measuring range up to 100 mg/L, though the accuracy is not very high. Measuring time is 5–7 minutes. The test kit contains hydrochloric acid but in a concentration that does not have to be declared as hazardous. Instruction-Leaflet Material-Safety-Data-Sheet Where to buy: www.mn-net.com
Merck (Aquamerck® Fluoride Test) 	Detection range from 0.15–0.8 mg/L. Due to the low upper detection limit, dilution of the water samples is always necessary (distilled water is required). The test takes 12 minutes. Contains hazardous chemicals. Instruction-Leaflet Material-Safety-Data-Sheet Where to buy: www.merck-chemicals.com

Other semi-quantitative field test kits

Two field test kits are available in India; however, it might not be possible to ship these to other countries. The Orlab test kit (www.orlabindia.com) and the test kit are developed by the National Chemical Laboratory in Pune and are distributed by the Chem-In Corporation (www.indiamart.com/chemincorporation/).

Fluoride analysis in the laboratory

Ion-selective electrodes (ISE) are widely used for fluoride analyses. TISAB (total ionic strength adjustment buffer) is added to the diluted or undiluted water sample, which is stirred during the measurement. The electropotential is measured with an ion-selective electrode. This analytical method requires more laboratory experience than a photometric method.

Table 4.4 *List of commercially available quantitative fluoride field test kits (this list does not include all available kits, and it is not intended as an endorsement of any of the companies or products listed):*

Hach (Fluoride Pocket Colorimeter) 	Hach offers a simple-to-use photometer for qualitative fluoride measurements using SPADNS reagent. The measuring range is 0.1–2 mg/L. The water sample often has to be diluted (distilled water is required). The SPADNS solution is hazardous. Please note that phosphate ions may interfere with measurements. Hach sells SPADNS either in small glass ampoules or in 1 L bottles. This method is practical, as the water can be directly sucked into the ampoules. On the other hand the ampoules are more expensive, are breakable and are bulky to transport. Operation-Manual Where to buy: www.hach.com
Wagtech/Palintest (Photometer 7100) 	The Photometer 7100 from Wagtech/Palintest can be used for measuring fluoride as well as other water-“quality” parameters. For fluoride, the measurement range is 0.1–1.5 mg/L. The water sample often has to be diluted (distilled water is required). Operation-Manual Reagents Material-Safety-Data-Sheet Where to buy: www.wagtech.com, www.palintest.com

The fluoride electrode has to be calibrated before use. The preparation of 3–8 standards with fluoride concentrations ranging between 0.05 mg/L and 2 mg/L is recommended. Dilution will be necessary if concentrations exceed 2 mg/L, so that sample concentrations lie within the calibrated range. Please note that high concentrations of dissolved aluminium in the sample can interfere with the ISE fluoride analysis. Suppliers of ISE provide manuals with information on calibration. A list of some suppliers and operation manuals is provided below:

- Hach (www.hach.com) Operation-Manual
- Metrohm (www.metrohm.com) Operation-Manual
- Mettler (www.mt.com) Operation-Manual
- Thermo Orion (www.thermo.com) Operation-Manual

4.4 Detailed water analyses

The planning of a water survey can be restricted to the measurement of arsenic and fluoride concentrations, but measuring further parameters may be helpful:

- To identify other contaminants that may be present
- To interpret the causes of geogenic contamination
- To physically and chemically characterise the groundwater

A comprehensive analysis of water composition can be costly, as extensive laboratory analysis is involved. The usefulness of the information must therefore be weighed against the cost. Sometimes a parameter that was not initially considered may later become important. The most important parameters are presented here to aid the reader to decide which water-quality parameters to include in a survey.

The composition of groundwater is affected by a combination of processes (Appelo and Postma, 1993) including:

- Weathering, dissolution and precipitation of minerals
- Evaporation and evapotranspiration
- Decay of organic matter
- Selective uptake of ions by vegetation, e.g. potassium and phosphate
- Mixing and dilution
- Ion exchange

All these processes in combination affect ion concentrations in solution, i.e. water composition. In-depth hydrogeological studies would be necessary to fully understand water composition, but in the context of this handbook, it is sufficient to capture the waters that are characteristic for geogenic contamination. Here we focus on sum parameters (Table 4.5), major components (Table 4.6), redox parameters (Table 4.7) and minor components and contaminants (Table 4.8).

The sum parameters pH, Eh (redox potential) and EC (electrical conductivity) can be measured with portable instruments in the field and give a general indication of water quality (Table 4.5). Redox potential, and the related parameter, dissolved oxygen, are liable to atmospheric contamination, making it very important to avoid contact between samples and air.

Major ion chemistry, together with a knowledge of sum parameters, provides an understanding of the type of water that the measurement of the sum parameters alone does not provide. Some examples are:

- The chemical composition of a groundwater with a pH value of 7 to 8 and with calcium as the predominant cation may be controlled by the mineral calcite ($CaCO_3$). In the presence of calcium, elevated concentrations of fluoride would not be expected.
- The chemical composition of a groundwater with a pH value of around 5 to 6 and a low ion content may indicate a crystalline rock environment, for example, granite. Fluoride content could be elevated.
- A neutral to alkaline groundwater (pH range 7 to 8 or above) with high ion content is indicative of arid conditions. High evaporation rates can lead to an increase in salinity (particularly $NaHCO_3$). Under these conditions, calcite ($CaCO_3$) tends to be insoluble, resulting in a low calcium content. Depending on the composition of the source rock, geogenic contaminants might be present.

Table 4.5 *Description of sum parameters*

Parameter	Description
pH	pH is a measure of the activity of free protons (H+) in solution. It is a number on a logarithmic scale from 0 to 14, on which a value of 7 represents neutrality. Values of pH <7 indicate increasing acidity, while values of pH >7 indicate increasing alkalinity. Each unit of change represents a tenfold change in H+ activity. The definition of pH is: $pH = -\log \{H+\}$ where {H+} is the activity of protons in moles per litre (mol/L).
Electrochemical potential (Eh) Unit: mV	Eh is a measure of the reducing/oxidising (redox) state of the water. Eh values in natural waters can range from -400 mV (highly reducing) to +800 mV (highly oxidising). Positive Eh values indicate oxidising conditions with dissolved oxygen present. Negative values indicate that conditions are reducing (low in dissolved oxygen) and predominated by reduced chemical species, such as Mn(II) and NH4+ in mildly reducing conditions and dissolved iron (Fe(II)), sulphide (S(-II)) and methane (CH4) under highly reducing conditions. Arsenic is often found in highly reducing environments. The measurement of Eh in the field can be very imprecise. A more reliable alternative is to determine dissolved oxygen content (and concentrations of reduced species). Dissolved oxygen can be measured potentiometrically with an electrode.

Parameter	Description
Electrical conductivity (EC) Unit: mS/cm, µS/cm	EC is a measure of Total Dissolved Solids (TDS). The approximate relationship between EC and TDS is EC (mS/cm) ≈ TDS (mg/L) / 640 A high electrical conductivity therefore indicates high ion concentrations. EC values in drinking water usually range from 0.05 to 0.5 mS/cm or ≈30–320 mg/L TDS. Fluoride is often found in groundwater in arid climates and can be associated with high EC.

A groundwater with negative redox potential or no measureable oxygen may contain reduced species (Table 4.7) irrespective of the major ions present. An elevated dissolved organic carbon content might be expected. Under these conditions, soluble reduced arsenic might be present.

The quality of the measurements can be verified by comparing the sum of the cations with the sum of the anions. As aqueous solutions cannot be charged, the two should be equal ("charge balance"). If the calculation shows an excess positive or negative charge (i.e. too few cations or anions), this indicates that the analysis is incorrect or that a parameter is missing. Care has to be taken during the calculation that the units are the same. For example, all units should be measured in milligrams per litre (mg/L). For the charge balance, values then need to be converted to mmol/L by dividing the values in milligrams per litre (mg/L) by the molecular weight of the respective ions. The final step is to multiply the millimolar concentration by the respective charge (z) of the ion, which gives the milli-equivalents of charge per litre (meq/L) for a particular ion. The total charge of the cations and anions is obtained by summing the meq/L as shown below:

$$\Sigma \text{ cations (meq/L)} = \Sigma \text{ cation concentration (mmol/L)} \times z \text{ (charge)}$$

$$\Sigma \text{ anions (meq/L)} = \Sigma \text{ anion concentration (mmol/L)} \times z \text{ (charge)}$$

Mole units

One mole is equal to 6.02×10^{23} atoms or molecules of a chemical substance. This number is derived from the number of atoms in 12 grams of carbon (^{12}C).

The mole is widely used in chemistry instead of units of mass or volume, because it is a convenient way to express the number of atoms, molecules or other units of reactants or products in chemical reactions. For example, one mole of calcium (Ca^{2+}) will react with 2 moles of fluoride (F^-) to form one mole of fluorite (CaF_2).

The values represent the equivalents of charge of cations and anions, which – as stated before – should be equal. Agreement to within 10% is excellent. If values differ by more than 20%, the samples must be re-analysed or a missing factor sought. Organic acids can make a significant contribution to the anionic charge in surface and contaminated waters.

NOTE: The ion balance is usually limited to the major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, Table 4.6). For most groundwater samples, this is sufficient.

The redox potential is of particular significance in arsenic-contaminated waters, as arsenic is a redox-sensitive element. The measurements of Eh can be substantiated by measuring the concentrations of redox-sensitive species (Table 4.7). The cause of reducing conditions is generally the oxidation of organic carbon (as may be found in young organic-rich sediments) by microbes. The microbes use different oxidising agents in a specific order: oxygen, nitrate, manganese oxides, then iron oxides and sulphate. These are themselves reduced.

Table 4.6 *Major ions found in water samples*

Cations		**Anions**	
Sodium	Na^+	Chloride	Cl^-
Potassium	K^+	Sulphate	SO_4^{2-}
Magnesium	Mg^{2+}	Bicarbonate	HCO_3^-
Calcium	Ca^{2+}		
Also (representing influence from agricultural activities and the mineralisation of organic carbon):			
Ammonium	NH4+	Nitrate	NO_3^-
		Phosphate	PO_4^{3-}
Optional			
Borate	BO_3^{3-}	Borate can be associated with volcanic rocks and hydrothermal activity	
Aluminium	Al_3^+	Solubility limited in neutral pH by the precipitation of $Al(OH)_3$ (solid)	
Silicic acid	H_4SiO_4	Solubility limited to a maximum of 28 mg/L by precipitation of H_4SiO_4 (solid)	

Total organic carbon (TOC) or dissolved organic carbon (DOC) content can be an indicator of these processes. Oxic groundwater generally contains ≤ 2 mg DOC/L. It should also be noted that dissolved ammonium (NH_4^+) is often associated with biodegradation processes and may result from the microbial reduction of nitrate.

Table 4.7 *Redox species*

Order	Parameter	Description	
1	reduced manganese	Mn^{2+}	Solutions that only contain manganese are generally not reducing enough to release reduced arsenic. Arsenic is generally found in association with reduced iron, but not sulphide (as insoluble arsenic-sulphides are formed). These species are oxidised rapidly in the presence of oxygen and are unstable. Appropriate sampling and preservation procedures must be followed.
2	reduced iron	Fe^{2+}	
3	sulphide	S^{2-}	

Table 4.8 *Minor and potential contaminant species*

Ions	Most frequent chemical form	Description
Possible geogenic contaminants		
Fluoride	F^-	These species may sometimes be found in high concentrations where arid conditions coincide with rocks/sediments containing elevated contaminant concentrations. These species are negatively charged and their solubility controlled by calcium. In sodic waters dominated by $NaHCO_3$ with low calcium content, these species can be soluble. (Note that arsenic is present in oxidised form). It is more common to find elevated fluoride, borate and perhaps arsenate and uranyl concentrations.
Arsenate	AsO_4^{3-}	
Uranyl	UO_2^{2+}	
Borate	BO_3^{3-}	
Molybdate	MoO_4^{2-}	
Selenate	SeO_4^{2-}	
Vanadate	VO_4^{3-}	
Arsenite	$As(OH)_3$	This reduced arsenic species is soluble.
Chromate	CrO_4^{2+}	Chromate is derived from the oxidation of chromium released from ultramafic rocks.
Heavy metals		
Copper	Cu^{2+}	These heavy metals are generally associated with anthropogenic activities such as mining, industrial activities, airborne contamination to soils etc. Other than in very acidic conditions (e.g. acid mine drainage) their solubility is limited to the low microgram per litre range.
Lead	Pb^{2+}	
Cadmium	Cd^{2+}	
Zinc	Zn^{2+}	
Mercury	Hg^+	

The choice of trace metals and metalloids to analyse is dependent on the type of geogenic contamination (Table 4.8).

- For reducing conditions where groundwater may be contaminated with arsenic, it is sufficient to quantify arsenic and possibly iron, manganese and sulphide (noting that sulphide would indicate the absence of arsenic). Arsenic is one of the very few elements (including manganese and iron) that is more soluble in reduced form than in its oxidised state.
- Where fluoride might be expected, usually under oxidising conditions, the analysis of further potential contaminants, including arsenic and uranium, would be beneficial.

Sampling and the preservation of the water samples for the determination of minor and contaminant species should follow guidelines provided by the laboratory (APHA, 2012). The measured values are assessed by comparing them with the WHO Drinking-Water Guideline values or with national standards where applicable.

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5 Institutional settings and enabling environments

Christoph Lüthi and Hong Yang

This chapter deals with the role of the institutional framework and stakeholder engagement to ensure the success of projects. Evidence from several decades of experience with water supply and water resources management shows that two of the most important reasons for project failure are the lack of coordination and of proper stakeholder involvement in the planning, supply and management of water resources. A sound institutional framework depends upon knowledge availability, sound political decision-making and legal and regulatory frameworks. This chapter will therefore provide:

- an overview of why working towards enabling environments is important;
- an outline of how to conduct a stakeholder assessment;
- guidance on how to initiate and sustain community engagement; and
- an explanation of how to work towards inclusive institutional environments that guarantee sustainable water resources management and equitable service delivery.

5.1 Fostering an enabling environment

«The enabling environment is the term used to describe the broader system within which individuals and organizations function and one that facilitates or hampers their existence and performance. This level of capacity is not easy to grasp tangibly, but is central to the understanding of capacity issues. They determine the 'rules of the game' for interaction between and among organizations. Capacities at the level of the enabling environment include policies, legislation, power relations and social norms, all of which govern the mandates, priorities, modes of operation and civic engagement across different parts of society.» (UNDP, 2008)

An enabling environment creates an atmosphere that allows a flourishing and sustainable water sector where people have dependable and adequate services. Without an enabling environment, managers in a water sector struggle on a day-to-day basis just to provide intermittent services that barely, if at all, meet minimal quality standards. People lack access to water, the economy is held back and the environment suffers. The following key features are prerequisites of a sound institutional framework or "enabling environment" (Fig. 5.1):

Political will and government support: Elected and accountable local governments and authorities that demonstrate political will are a precondition for successful service delivery. Strengthening governance and improving civic participation are key prerequisites of the effective development of civic infrastructure (the "demand side" of governance).

→ *Build rapport with decision-makers and encourage them to be accountable and to act in a transparent fashion.*

Institutional arrangements: In many countries, there is no clear distinction between regulation and service provision. A sustainable and equitable service delivery can only be guaranteed by a sound institutional set-up. This requires a clear distinction between: (i) independent institutions responsible for performing monitoring and evaluation (usually at the district or provincial level) and (ii) service provision at the local level (including operation and maintenance).

→ *Define the interface between local community involvement, user groups, non-governmental organisations and the local authority or utility.*

Legal framework: The technical norms and standards that influence the types and levels of service which are put in place are important. Problems that need to be overcome here are regulatory inconsistencies, lack of regulations and unrealistic standards. A further issue in many countries is poor enforcement of existing regulations.

→ *Make sure your project is in line with national and municipal policies and by-laws.*

Knowledge and Skills: The capacity to provide services effectively and efficiently is the backbone of sustainable service provision. The skills base available in each context will define how well policies and strategies can be implemented. This will include both public (local authority) staff, but also private-sector and NGO stakeholders, who also have their roles to play.

→ *Identify capacity gaps, particularly at municipal and community levels, then fill the gaps with tailored training courses, on-the-job training, exposure visits, etc.*

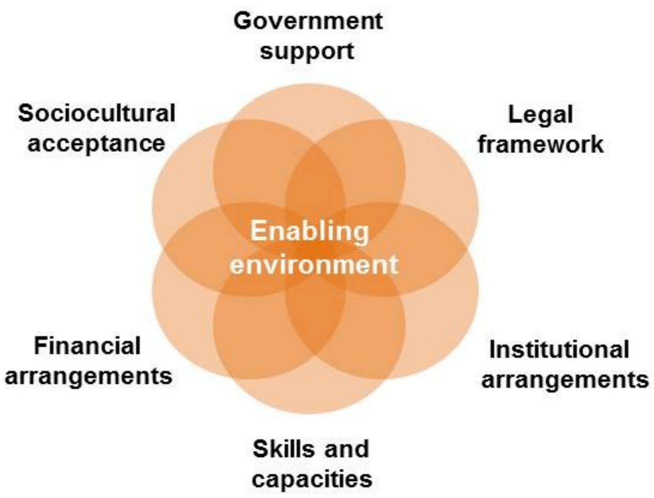

Fig. 5.1 Depiction of the six elements of an enabling environment (Source: Lüthi et al, 2011)

Financial arrangements: An enabling financial environment ensures that an intervention is economically sustainable in the long run by introducing user fees and, where appropriate, targeted subsidies.

→ *Financial contributions and investments are required from users, from government agencies and from the private sector. Here the key is to increase the capacity and willingness of beneficiaries to generate funds.*

Sociocultural factors: Awareness of and respect for the local sociocultural landscape, especially in traditional rural contexts, is crucial. Neglect of sociocultural factors and failure to ensure that solutions are socioculturally embedded are two of the most common reasons for past failures.

→ *Identify behaviours and prevailing sociocultural norms through surveys or market research (see Chapter 8 on behaviour change).*

A more in-depth discussion on working towards enabling environments can be found on pages 49–65 of the CLUES guidelines (www.sandec.ch/clues).

5.2 Carrying out stakeholder assessments

A stakeholder assessment forms the basis for understanding the institutional and organisational setting. With this knowledge, an enabling environment can be fostered. The aim of a stakeholder assessment is to understand the opinions and attitudes of different stakeholders about something (an action, a project). Such information is important to highlight public concerns and values, which should be incorporated when later trying to find an acceptable and sustainable solution to the problem. As a first step, possible stakeholders need to be identified. These may belong to one or more groups:

- Key stakeholders have significant influence upon or importance within an action, e.g. government agencies and officials, donors, policy makers or some influential NGOs.
- Primary stakeholders are those ultimately affected, either positively or negatively, by an action, e.g. households and end users.
- Risky stakeholders are persons or organisations who have low importance or interest, but who can indirectly influence an action or who are indirectly affected by an action, e.g. researchers.
- Low-priority stakeholders have low importance, interest or influence, but could become primary stakeholders if their interest was awakened.

Stakeholders' interests in and influence on a project may be visualised in a diagram to demonstrate differences in opinion and influence. Many techniques for stakeholder mapping exist. Here we present a simple Influence-Importance matrix (Fig. 5.2), in which stakeholders are mapped according to their importance or interest and influence over a decision. Conducting stakeholder assessments requires trained experts and moderators – make sure you have the necessary expertise. More details are available in the SSWM Toolbox.

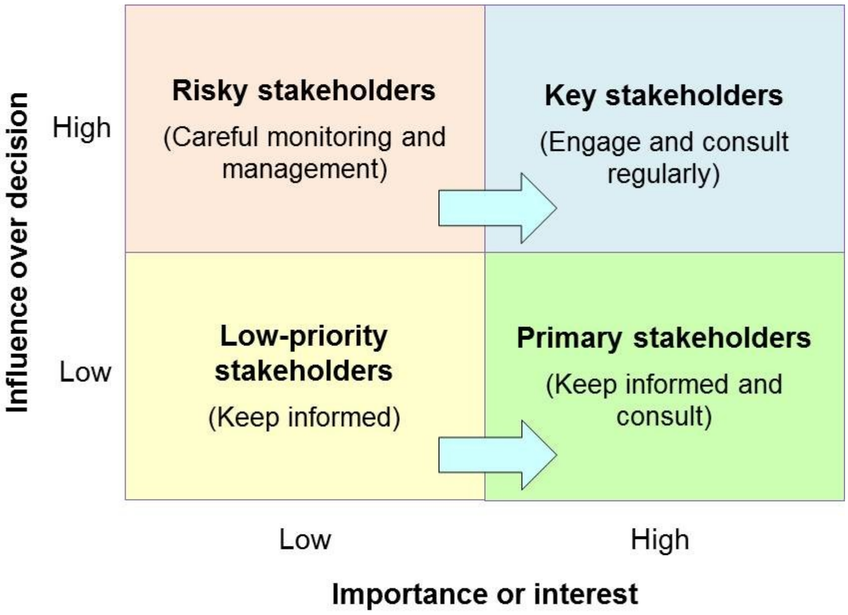

Fig. 5.2 *Stakeholder matrix, in which different groups or individuals are mapped according to their importance and influence. The blue arrows indicate the desired changes in stakeholder status.*

Advanced tools for stakeholder assessment

Willingness-to-Pay Analysis (WTP)

Finding out how much end-users are willing to pay for a water service is critical for setting water tariffs and determining how high demand for the service is. Many different methods for carrying out willingness-to-pay evaluations exist, and if done correctly, very useful information can be gained. WTP is a complex analysis and may not be appropriate in institutionally weak settings. It requires:

- A large investment in time and effort
- People with expertise in economics
- Well-trained interviewers who can avoid initiating bias amongst those surveyed

It is debatable whether people should be asked how much they are willing to spend for a product or service that they do not yet know. A detailed description on how to conduct WTP surveys for water services can be found in Wedgwood and Samson (2003).

Multi-Criteria Decision Analysis (MCDA)

MCDA is a technique for comparing different options (e.g. products or services) and eliciting stakeholder preferences. It identifies the measures and options that have the broadest acceptance and which defuse conflict among stakeholders. The technique can be used to identify a single most preferred option, to rank options or to distinguish acceptable from unacceptable possibilities. It is a complex exercise that needs accurate input data and may be difficult to complete successfully in institutionally weak environments. A “light” version can be a very useful exercise in decision-making workshops to initiate discussion between stakeholder groups and to elicit their preferences, as has been shown by Osterwalder et al. (2014).

The individual steps of an MCDA, using fluoride mitigation options as an example, are outlined in Chapter 9.3.

5.3 Ensuring effective participation

It is widely acknowledged that stakeholder participation is a linchpin for the catalysis of change and makes people active participants in their own development. Community participation primarily seeks to achieve sustainable services for the poor and transparency and accountability throughout the process. Good partnerships and participatory programmes begin when actors come together to achieve a common goal based on agreed priorities. The following arguments are advanced when making the case for community participation:

- **Ownership:** By giving affected communities a real say in decision-making through active consultation, communities gain ownership of the development process.
- **Greater efficiency and effectiveness:** Both national governments and development agencies see community contributions as a means to achieve project goals (e.g. mobilising funds or contribution of “sweat equity”)
- **Better design:** Participation during the planning stage will lead to a more appropriate design and technology – especially at the user interface.
- **Social change and empowerment:** Involving beneficiary communities in mobilisation, planning and project design creates a sense of ownership over the outcomes, and thus social capital is gained. This can lead to new forms of social partnership and “empowered communities” (Lüthi and Kraemer, 2012).

Engaging proactively with communities has the potential to help foster social capital formation in communities. Non-tangible community assets such as trust, networks and behaviour change are an important asset for poor communities that lead to greater empowerment. Communicative planning tools that enable “real” community participation include community surveys, focus group discussions, community meetings and participatory mapping exercises. These tools and participatory approaches assist in forming community-based organisations or user groups that ensure sustained use and correct water treatment procedures over time. A detailed overview of useful communicative planning tools is provided in the following file links from the CLUES Toolbox:

T2_Interview-Methods
T3_Participatory-Assessment-Methods
T4_Organising-Meetings,_Events_and_Workshops

Community engagement approaches may work better in some places than in others. Past experience shows that community involvement does not necessarily lead to sustainable services and can go wrong. The three most common problems are:

1. Elite capture and social control resulting from power inequalities between different community segments;
2. Financial mismanagement by community groups, which leads to mistrust and internal conflict; and
3. Top-down mode of project delivery by local authorities, resulting from inexperience in the design and delivery of community engagement strategies.

It is therefore becoming widely recognised that sustainability of services can only be achieved through ongoing financial and technical support to communities by external bodies – usually by local authorities or NGOs (WSUP, 2013).

If done correctly, investing in the “social capital” of communities can lead to empowerment and strengthening of capacity at community levels. But this is not free of charge. Any project that aims to achieve sustainable community engagement should devote roughly 15% to 20% of the overall planning and implementation costs to ensure effective community participation (Lüthi and Kraemer, 2012).

5.4 Fostering inclusive institutional environments

Working towards inclusive institutional environments is very context-specific, so that any solution will need to be adapted to the local context. This means investigating different options for long-term service sustainability involving community-managed, utility-managed or co-managed operations. The following points should be kept in mind when initiating a project for mitigating geogenic contamination:

- Community-based approaches that are well connected to external service providers can help foster social capital formation in communities. Recent sector experience shows that non-tangible social capital (e.g. trust or social networks) is an important asset in poor communities.
- Provide continuous communication with the communities, involving various media. For example, conducting study tours, targeted communication campaigns or focus group workshops will help build momentum and ensure the smooth planning and implementation of a project. By giving a voice to citizens and local organisations,

social accountability mechanisms are introduced and the accountability of local authorities strengthened.

- Aim for co-management partnerships that provide a clear division of responsibilities between (i) day-to-day operation, maintenance and minor repairs which can easily be managed and carried out by a community-based organisation and (ii) more sophisticated maintenance and major repairs/spare parts which must be provided by professional service providers or operators.
- Ensure that non-technical support is also part of the package. This entails two main items: (i) support to professionalise community-based organisations and (ii) addressing behavioural change issues that are closely linked to the correct and sustained use of novel technology and water treatment procedures. A successful framework for implementing behaviour change is presented in Chapter 8.

References and further reading

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WSUP, Water and Sanitation for the Urban Poor (2013) Getting communities engaged in water and sanitation projects: Participatory design and consumer feedback. WSUP Topic Brief 07. www.wsup.com/sharing/TopicBrief7.htm

Links with further information

Community-Led Urban Environmental Sanitation Planning published by Eawag in partnership with UN-HABITAT and WSSCC: www.sandec.ch/clues

The Sustainable Sanitation and Water Management Toolbox: www.sswm.info

6 Financial viability for drinking-water services

Heiko Gebauer and Caroline Saul

Drinking-water services often fail for the low-income segment living close to the poverty line – not only in terms of quantity and quality, but also in terms of affordability and accessibility (Anderson and Markides, 2007; WHO, 2012; Massa, 2012; Gebauer and Saul, 2014). The low-income segment often suffers from a "poverty penalty", where the least privileged pay more for drinking water than their richer counterparts. The low-income segment does not benefit from subsidies for water provision, or it simply lacks access to adequate water quality and quantity. Arguably, improving access to and affordability of sufficient quantity and quality of drinking water should be guaranteed for people living close to the poverty line.

The financing of water services remains a major concern. Typical key and follow-up questions are:

- How can I finance the production, distribution and marketing of water treatment options? Where can I get funding from? Can I apply for funds from the government? Can I get access to philanthropic money? Is patient capital available? Do I have to invest my own money?
- What types of cost do I have to cover? How can I identify the necessary costs? What would be a good cost ratio between investment and operational costs?
- How can I ensure that people pay for water services? How do I collect payments from the users?

Philanthropy and donation-based aid programs can make an important impact on the quality and quantity of water services, but they are inherently not economically sustainable. Once the financial resources have been invested in one location, there are often no finances remaining to transfer the water service programmes to another location (up-scaling) or provide for the continued operation and maintenance of the initial site.. On one hand, financial viability means that water providers should at least break even – or even attain profitability and a competitive rate of return. This would enable organisations to re-invest in the extension of water services. Non-profit organisations and social businesses providing water services may pass on all savings and profits to their members or may use them to expand their scale and scope of water services. On the other hand, subsidies might be necessary to facilitate the development and use of water services.

The next few sections discuss the key issues on financial viability for water services. Our basic rationale is that financial viability can only be ensured if the water service providers cover the investment and operational costs and are able to manage a certain contribution paid by the consumers for water services. The discussion is divided into two parts. First, we describe financial options for the water service providers. Second, we highlight ways for water service providers to ensure that the consumer pays for the services provided. It should be noted that the following sections mostly include examples of the treatment of microbially contaminated water, as there is great activity in this field and because the financial issues are independent of the type of contamination.

6.1 Financial options for water service providers

There are different types of water service providers:

- Utilities can be private or public. They manage water treatment units and centralised water networks.
- Micro-utilities are owned by communities. They manage small-scale water treatment units and a decentralised water network.
- Water kiosks are booths that sell drinking water (usually treated). They may also deliver water directly to households.
- Providers of treatment devices for household use.
- Providers of disinfectant products, such as chlorine tabs that are used for water disinfection.

All these providers can use different financial options to invest in water service provision. The financial option depends on the type of organisation (Fig. 6.1) providing the water services. There are three general types of organisation.

1 **Profit-orientated businesses:** Profit-orientated businesses recover their investment and operational costs, generate revenues with the water services and maximise their profits. Typical examples are multinational enterprises such as Unilever, which sells its Pureit Water Filter to generate profit, or smaller firms such as the Indian Sarvajal or the WeConnex, that sell water treatment equipment for profit.

2 **Non-profit organisations:** Non-profit organisations do not recover the investments and operational costs. Instead they rely on donors and aid finances to cover these costs. See NWP/IRC (2009) for a listing of donors financing water services. A typical example would be A Vision for Clean Water, which finances Kanchan arsenic removal filters through donations. Publicly owned utilities also act as non-profit organisations using a mix of user fees and tax revenues to manage water services. They still aim to recover investment costs and generate enough profit to cover operation and maintenance costs.

3 **Social businesses:** Social businesses borrow elements from profit-orientated businesses and non-profit organisations. Social businesses have to cover the investment and operational costs, but they are more cause- than profit-driven. A typical illustration would be the Naandi Foundation, which sets up water kiosks in

rural India. Costs are recovered by selling 20 litres of water. In addition, some of the investment costs are covered by subsidies. . Another illustration of a social business is OSHO (Oromo Self-Help Organisation), which receives funding to install community-based water systems and generates revenues by selling the filter material to treat the water.

All three types of organisation have to consider their investment and operational costs. Investment costs include all necessary costs to purchase the water treatment equipment and distribution infrastructure. In the case of the Naandi Foundation, investment costs can be as much as $10,000 for a water kiosk. Investment costs for individual household treatment options are much lower, for example Unilever's Pureit water filter can be purchased for as low as $40. Operational costs include the costs for operating and maintaining the water treatment equipment

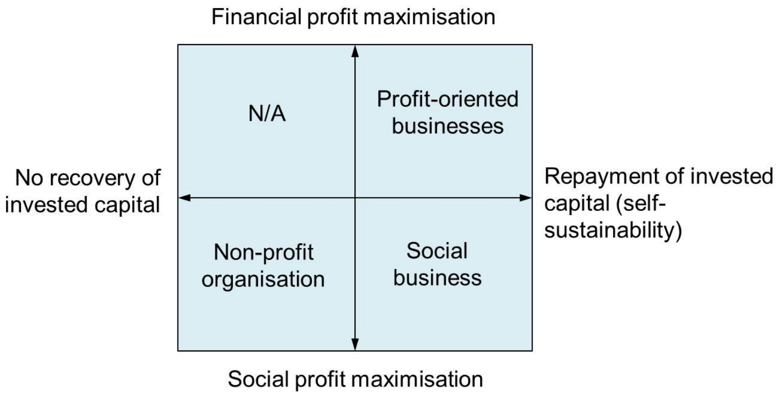

Fig. 6.1 *The orientation of different types*

Operational costs cover a variety of expenditures, such as operator labour costs, repair costs, electricity costs, costs for filter media and so on. Organisations often refer to life-cycle costs (LCC). LCC analysis is a method for assessing the total cost of ownership of water treatment equipment. LCC analysis takes into account all the costs of designing, acquiring, owning, and disposing of water treatment equipment. Acquisition costs refer to the investment costs, while ownership costs are close to operational costs.

Profit-orientated firms, social businesses and non-profit organisations can source the necessary capital through philanthropy, as investment capital or patient capital.

Philanthropy: Philanthropic activity can be described as caring for, nurturing, developing and enhancing "what it is to be human" on both the benefactors' side (by identifying and exercising their values in giving and volunteering) and beneficiaries' side (by benefitting). In water service provision, philanthropy is usually associated with private donations and corporate philanthropy. The most typical philanthropic activities are private initiatives, for public good, focusing on quality of life. Each private donation is supplemented by a philanthropic investment by Procter&Gamble. Philanthropy and donation-based aid programmes can make an important impact, but they are inherently not economically sustainable. Once the financial resources are used in serving one community, region or country, there are no funds remaining to transfer the water service programme to another location. Investment capital and patient capital offer attractive alternatives, because they can be economically more sustainable.

Investment capital: Investment capital is money that is invested in a profit-orientated firm. The investment is recovered through revenues generated by the firm over several years. Revenues are expected not only to cover the initial investments, but should also generate a competitive rate of return. Investment capital is used for the initial set-up or expansion, rather than for day-to-day operations (operational costs).

Patient capital: Patient capital has a long-term perspective and has gained importance with the rise of social businesses. Patient capital investors are willing to forgo maximum financial returns for social impact. Patient capital has greater tolerance for risk than traditional investment capital, and longer time horizons for returns are expected. As illustrated in Figure 6.2, patient capital is not philanthropy. It is an investment intended to achieve below market-rate returns (or internal rates of return). Patient capital maximises social impact and catalyses the creation of water markets. On the spectrum of capital available to non-profit organisations, social businesses and profit-maximising firms, patient capital combines traditional venture capital, philanthropy, development aid and foreign direct investment. Patient capital is invested in water entrepreneurs that are starting companies and organisations that provide water services.

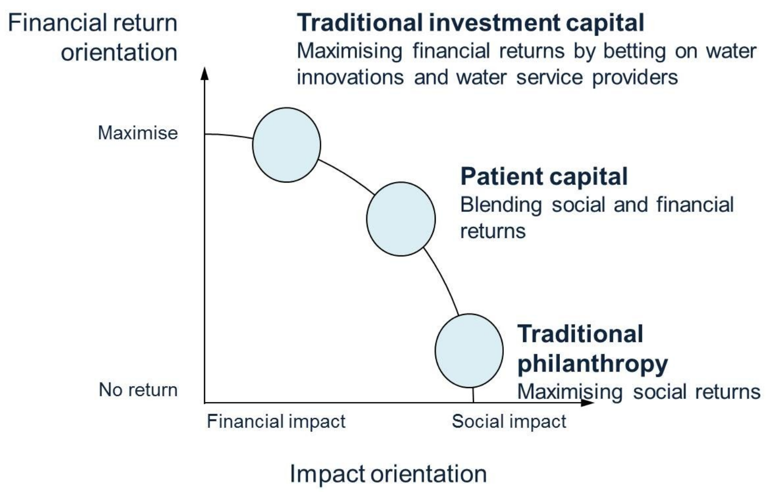

Fig. 6.2 The orientation of different investment types

6.2 Contributions to water services

In addition to charging a water tariff, there are additional options for upholding revenues while increasing the population that is served including: (1) mobile payment systems, (2) micro-credits and (3) consumer subsidies.

Mobile payments systems: Water service providers should explore the opportunities arising from mobile payment systems. Mobile payment systems can significantly reduce transaction costs. Customers can pay very small amounts, which suits the volatile and complex cash flows in the low-income segment, where customers frequently receive their income on a daily rather than weekly or monthly basis. Mobile payment systems also help to reduce collection costs and payment defaults.

Micro-credit: Micro-credit is a component of microfinance, or banking for the “unbanked”, which facilitates access to small loans, often in the form of group lending. They are used in various ways. The Indian company Sarvajal uses microcredit to enable entrepreneurs to finance the initial investments required for entering franchising agreements. Entrepreneurs can receive a loan, which enables them to start a Sarvajal water kiosk. Unilever enters partnerships with microfinance institutes to propose small loans to self-help group members for the purchase of water filters. The Water Initiative promotes more expensive and effective filters through leasing models. Micro-credit contributes to financial viability in at least two ways. First, water service providers can partner with microfinance institutes so that community members can borrow money for buying filters or disinfection products. Microfinance institutes lend the money to community groups, which know more about the loan takers (community members) than outsiders, such as official banks or water service providers. Partnerships with microfinance institutes enable the water service providers to transfer some of the screening and monitoring costs. Secondly, while water service providers typically cannot impose either financial or non-financial sanctions on people who default on a loan, community members who might belong to the same village or who are neighbors, relatives or friends might be able to impose effective social pressure on each other at low cost.

Subsidies: Here we are referring to consumers needing subsidies to be able to afford safe water. Subsidies can come from local, regional or national governments. The poorest of the poor in particular may need targeted financial support to purchase water filters or reduced water tariffs. Managing such subsidies does, of course, bring its own challenges. To target the poorest of the poor, it is important to identify the various household income levels and to discriminate between them to avoid an unfair distribution of subsidies (Easterly 2005). Tiered payments can be privately and sensitively managed, using electronic payment methods, such as prepaid cards or mobile payments.

6.3 Summary

Water service providers, such as utilities, micro-utilities, water kiosks,sellers of water treatment devices and the providers of chemical treatment options such as flasks and tabs, have to ensure that they remain financially viable. For non-profit organisations, financial viability depends on getting access to philanthropic investments. Profit-orientated companies have to ensure that their investments create sufficient revenue to recover the investments and to create an appropriate rate of return. Social businesses rely on patient capital, which offers a more long-term perspective, focuses on social impact and aims at a low rate of return. Profit-orientated companies and social businesses need to ensure that that the consumers pay for the services provided. Subsidies for the very poor, mobile payment systems and micro-credits are promising ways to tackle these challenges. Table 6.1 summarises the answers to our key questions:

Table 6.1 *Answers to key questions on the financing of water services*

How can I finance the production, distribution and marketing of water treatment options? Where can I get the money from? Do I have to invest my own money?
The answers to these questions depend on the type of organisation: • Non-profit organisations finance water services from external sources, such as donors or government. • Social businesses finance water services through patient capital and contributions from consumers (water users). • Profit-orientated organisations have to invest their own money and expect a financial return on their investments with a certain interest rate. New investments are financed through these revenues. All these types of organisations can also receive subsidies from the government. Such subsidies should specifically target the poorest of the poor.
What types of cost do I have to cover, and how can these be identified? What would be a good cost ratio between investment and operational costs?
• Important costs are investment and operational costs. • LCC-analysis (life-cycle cost analysis) is most suitable for identifying these investment and operational costs. Good cost ratios between investment and operational costs are 10:1 to 5:1.
How can I ensure that people pay for water services? How do I get the money from the users?
• Mobile payment systems and pay-per-use approaches are most suitable to motivate people to pay for water services. • Micro-credit for financing water services help consumers to avoid up-front investments.

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Yunus M., Moingeon B., Lehmann-Ortega L. (2010) Building social business models: Lessons from the Grameen experience. Long Range Planning 43(2–3), 308–325.

Links with further information

Water service providers

Access to Safe Water for the Base of the Pyramid (Report) http://hystra.com/safe-water/

Safe Water at the Base of the Pyramid (Booklet) http://static.squarespace.com/static/51bef39fe4b010d205f84a92/t/51f23b56e4b05adf4a8ee570/1374829398315/Access_to_Safe_Water_for_the_BoP_FULL_REPORT.pdf

Financing WASH services

Financial Sustainability of WASH Services (SSWM Toolbox) www.sswm.info/category/planning-process-tools/programming-and-planning-frameworks/frameworks-and-approaches/sani-9

Various publications on financing WASH services (Trémolet Consulting) www.tremolet.com/publications

Patient capital

Patient capital http://en.wikipedia.org/wiki/Patient_capital

Acumen makes investments that generate both social and financial returns http://acumen.org/investments/investment-model/

Investment and operating costs

Operating cost http://en.wikipedia.org/wiki/Operating_cost

Life-Cycle Costs (LCCs)

Life-cycle cost approach www.ircwash.org/resources/briefing-note-1a-life-cycle-costs-approach-costing-sustainable-service

Mobile payment systems and financial services in developing countries

Mobile Water Payment Innovations in Urban Africa (Report) www.gsma.com/mobilefordevelopment/wp-content/uploads/2012/03/Mobile-Water-Payment-Innovations-in-Urban-Africa.pdf

Trends in Mobile Payments in Developing and Advanced Economies www.rba.gov.au/publications/bulletin/2013/mar/8.html

The mobile financial services development report 2011 http:\\www3.weforum.org/docs/WEF_MFSD_Report_2011.pdf

The Economist: “The Bank of SMS” www.economist.com/blogs/graphicdetail/2012/04/daily-chart-12

7 Mitigation options

Richard B. Johnston, Anja Bretzler, Lars Osterwalder, Stephan J. Hug, Michael Berg, C. Annette Johnson

It can be very difficult to determine the best technological approach for providing water free of arsenic and fluoride. Often people think first of contaminant removal technologies, but it may be more cost-effective and sustainable to exploit alternative water resources. In either case, some sort of water treatment is likely to be necessary to ensure both chemical and microbial water safety. A wide range of technological options are available at different scales: in professionally managed centralised plants, in small community-scale systems or at the household level. Each of these scales has advantages and disadvantages, and the most suitable solution is determined by the local context (Table 7.1).

Introducing a new technology is a complex process, which should be participatory, involving all stakeholders from the outset. The institutional framework, legislation, funding, support and long-term financing needs to be determined (Chapters 5 and 6), as is promoting safe water use among the affected population and facilitating behaviour change (Chapter 8). Insufficient operation and maintenance (O&M) can quickly lead to technological failure, so these aspects need to also be planned and considered before the technology is installed. The Operation and Maintenance Network gives useful tools and information on this issue. Detailed information on the whole process of supporting sectors in scaling up WASH technology is presented in the Technology Applicability Framework (TAF) of the WASHTech project.

Water Safety Plans

Water Safety Plans (WSP) can provide a systematic means to address and manage health-related water risks. They provide a practical framework to implement a systematic, risk-based approach to most effectively ensure consistent supplies of safe drinking water. The WSP approach requires that hazards and associated risks be identified in the entire water supply chain, from catchment to point of use, and it gives a framework for the prioritisation and management of those hazards and risks (Bartram et al., 2009; WHO, 2012; WHO/IWA, 2013). WHO and its partner organisations, including the International Water Association (IWA), actively support the WSP approach. Several tools exist to assist in the development and implementation of WSPs (WHO 2012; WHO/IWA 2013).

WHO (2012) Water safety planning for small community water supplies: step-by-step risk management guidance for drinking-water supplies in small communities. World Health Organization, Geneva, Switzerland.

WHO/IWA (2013) Water safety plan quality assurance tool. World Health Organization, Geneva, Switzerland.

Table 7.1 Drinking-water treatment at different scales

Scale	Advantages	Disadvantages
Centralised 	• Process parameters can be controlled and optimised. • There may be economies of scale, but these are counterbalanced by increasing costs of large distribution systems.	• Requires large capital investments and incurs significant recurring costs. • Requires trained personnel and constant operation and maintenance. • Difficult to extend to areas of low population density. • Risk of low community inputs and support. • Potential of microbial contamination during distribution and collection.
Community scale 	• Processes can be regulated and optimised better than at household scale. • Relatively inexpensive. • Demand-responsive: can be designed for local needs. • With community leadership and support, sustainability may be greater.	• Processes cannot be regulated and optimised to the same extent as in centralised schemes. • Limited capacity for operation and maintenance. • Potential of microbial contamination during distribution and collection.
Household 	• Takes advantage of existing water supply infrastructure (e.g. boreholes). • Allows targeting of people most at need. • Relatively easy and inexpensive to implement.	• Systems may not be operated correctly. • Lifetime of chemical removal filters is difficult to predict, so it is hard to know when replacement is needed. • Effective replacement requires supply chain and motivation. • Routine monitoring is a challenge. • Some populations can easily be excluded due to lack of information or financial resources.

Difficult questions to answer:

- Which water resource should be developed? Is it better to remove the chemical or to find a chemically safe resource?
- Which technology is best suited for water treatment in this particular setting?
- On which scale can this technology best be applied?

Answers should be based on the combined understanding of available water resources, institutional setting (Chapter 5), financing strategies (Chapter 6) and acceptability (Chapter 8). Those responsible for water supply often have to make choices between these different approaches without a solid evidence base and sometimes without a clear method for taking decisions. A list of factors for the comparative evaluation of technologies is given below (Fig. 7.1).

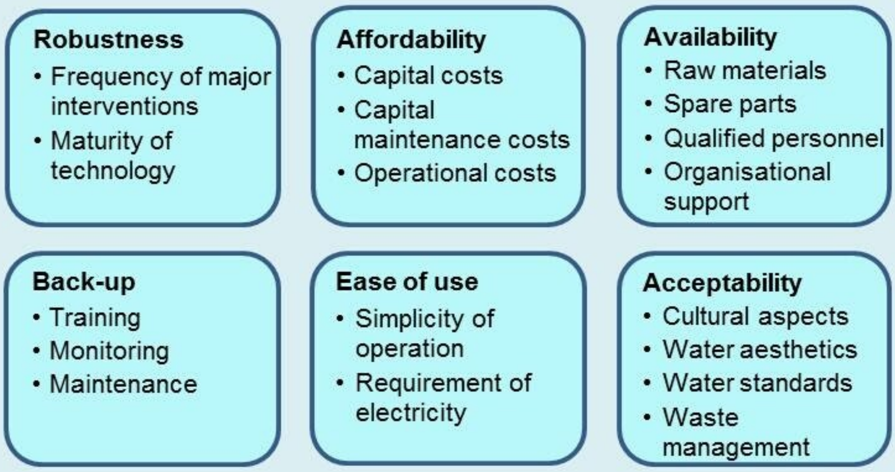

Fig. 7.1 *Selected criteria for technology evaluation*

Note: The choice of technology heavily depends on local conditions. A filtration technology may be suitable for water with low contamination, whereas the same technology may be too expensive for highly contaminated water. In another region, salinity or industrial contamination may require the use of alternative water resources etc.

Water treatment: A fundamental difference between arsenic and fluoride

In geogenically contaminated water, arsenic concentrations can range from >10 to around 500 µg/L, while fluoride concentrations can be orders of magnitude higher, generally ranging from >1.5 to 20 mg/L.

Filtration is a frequently used water-treatment technology. Since fluoride concentrations are so much higher than arsenic concentrations, more frequent regeneration and replacement of filter material is necessary, and the water treatment costs are subsequently higher.

7.1 Exploiting alternative water resources

The provision of drinking water from alternative sources that are not contaminated with arsenic and fluoride has proven to be a popular mitigation option. In Bangladesh, for example, "well switching" is most commonly used for mitigation of arsenic contamination. The underlying reason for this is the difficulty, in terms of acceptance, supply, monitoring, maintenance and overall cost, in establishing technologies to remove contaminants. Therefore, before efforts are made to treat contaminated water, it is worthwhile to determine whether alternative water resources are available.

Resource availability is a question of scale and thus of institutional engagement:

Regional-scale solutions may be sought by government agencies that need to provide water not only for drinking, but also for agriculture and industry. This may include the provision of piped drinking water derived from surface water or groundwater.

Many water resource tools of differing degrees of sophistication have been developed to support planning and implementation. One central theme is Integrated Water Resources Management (IWRM), a planning and implementation tool for managing water resources for different uses, including agriculture, industry, personal use, recreation and ecosystem protection. See the website of the Global Water Partnership (GWP and UN Water) for more information and downloadable resources.

Local-scale solutions may include rainwater harvesting, making use of uncontaminated groundwater from different locations in the aquifer by "well switching" or the treatment of local surface-water resources, such as rivers, lakes or ponds.

Here the focus is on ensuring that microbial contamination does not replace geogenic contamination as a health problem, since groundwater is often selected as a replacement for microbially contaminated surface waters. Water storage is another important issue. Infrastructure is required to collect, treat and deliver drinking water to consumers. "Household Water Treatment and Safe Storage" is a strategy for making surface-water sources safe in resource-poor settings (see section below). Numerous texts provide guidance on the exploitation of surface water, groundwater and rainwater for drinking; see the References section for a small selection.

Surface water

Surface water is the water found in rivers and lakes. Surface water is replenished naturally by precipitation and is "lost" naturally through discharge to the seas and oceans, by evapotranspiration, by evaporation and by sub-surface seepage. Although the only natural input to any surface-water system is precipitation within its watershed, the total quantity of water in that system at any given time is also dependent on many other factors. These factors include storage capacity in lakes, wetlands and artificial reservoirs, the permeability of the soil beneath these storage bodies, the runoff characteristics of the land in the watershed, the timing of the precipitation and its interaction with groundwater, and local evaporation rates. All of these factors also affect the proportions of water lost.

Although surface water is seldom contaminated by arsenic and fluoride, it nearly always requires treatment to improve the microbial water quality. Pathogens differ in their susceptibility to various treatments. For example, Cryptosporidium cysts may be retained by filters but are resistant to chlorination; the opposite is true of many viruses. Furthermore, all treatment systems are subject to occasional failures which may not be recognised by the operators. The key to developing a robust and reliable system for providing safe water is to implement multiple barriers for pathogen control. Different pathogens can be removed in different stages, according to their particular weaknesses, resulting in water of progressively higher quality. The multiple-barrier approach protects against the transmission of pathogens in the event that one barrier should fail. A typical multiple-barrier system for treating surface water might include sedimentation, some type of filtration (multi-stage filtration, slow sand filtration or coagulation followed by rapid filtration) and disinfection.

Numerous texts provide guidance on the design of treatment plants that can be used for conventional drinking-water treatment. An excellent starting point, available for free download on the internet, is the "Small community water supplies" (IRC, 2002). The IRC in 2006 also produced a detailed report on multi-stage filtration (IRC, 2006).

Groundwater

Groundwater is water that fills the cracks and spaces between underground rocks and sediments. Underground rocks and sediments that hold substantial amounts of water are called aquifers – these can gain water from, or lose water to, surface water bodies. Sometimes it is useful to make a distinction between shallow aquifers that are closely associated with surface water and deep aquifers that are isolated from the surface, containing what is sometimes called "fossil water".

A critical factor in the use of groundwater is that abstraction rates need to be lower than replenishment rates. In arid climates, replenishment rates may be very low. This results in a lowering of the groundwater table.

Because of natural filtration through sediments, groundwater is typically of a much higher microbial quality than surface water. However, groundwater is not necessarily free from pathogens: especially where aquifers are near the surface and water tables are high, sediments contain little silt and clay and on-site sanitation is widely practised, groundwater is vulnerable to contamination. While groundwater is often distributed and consumed without treatment, safety disinfection (e.g. chlorination) would be recommended in such settings (ARGOSS, 2001).

Since aquifers by their nature allow long contact periods between pore waters and rocks and sediments, groundwater frequently has higher levels of dissolved minerals than does surface water or rainwater. Under the right geochemical conditions, different elements can reach undesirable levels in groundwater. This manual describes contamination with fluoride and arsenic in detail, but other elements commonly found in groundwater can include sodium and chloride (major components of salinity), calcium and magnesium (which make up hardness), and iron and manganese (metals which can stain materials and give an unpleasant taste to water).

Removal of salinity and hardness is complicated and relatively expensive. However, simple sand filters can be optimised to remove iron and manganese, as described in Hartmann (2001).

Even though groundwater extracted from one aquifer may be contaminated with arsenic or fluoride, other aquifers (deeper or shallower) in the same area may provide completely uncontaminated water. This could be due to differences in the mineralogy of the aquifer material or changes in dissolved oxygen concentrations, which can influence the mobility of redox-sensitive contaminants such as arsenic. A classic example of this is the widespread geogenic arsenic contamination in deltaic areas of Bangladesh. Here, shallow wells in young sediments under reducing conditions yield very high arsenic concentrations, whereas deep tube wells usually provide water with a completely different chemistry, with little arsenic (Hug et al., 2011).

A vast number of technologies exist for the abstraction of groundwater. These are described in a range of resources and manuals. A good overview of water-lifting devices is given in WHO/IRC (2003) and Baumann (2000). In addition, UNESCO has produced several documents describing groundwater resources. Particularly useful are “Groundwater resources of the world and their use” (UNESCO/IHP, 2004) and “Non-renewable groundwater resources: A guidebook on socially-sustainable management for water policy makers” (UNESCO, 2006).

Rainwater

Rainwater is the ultimate source of all drinking water in the long term, since it replenishes both surface water and groundwater. Rainwater can also be captured directly and used as drinking water. However, rainwater is highly variable in its spatial and temporal distribution, so the use of rainwater for drinking often requires significant storage or distribution capacity. Whether rainwater harvesting is viable in a certain region depends very much on the yearly amount and distribution of rainfall. Rainwater is a main drinking-water source for relatively few people, but in some settings on ocean shores or islands, it can be the only source of drinking water.

Rainwater is free from pathogens, at least until it reaches the ground, and except in some urban areas, is of excellent chemical quality. When properly collected and stored, rainwater can provide a safe and acceptable source of drinking water for at least part of the year. Rooftop water harvesting has been extensively researched by the Development Technology Unit of the University of Warwick, which has produced an excellent handbook on the topic of “Roofwater harvesting: A handbook for practitioners” (Thomas et al., 2007). A wealth of additional information on rainwater harvesting can be found at the SSWM portal: Rainwater Harvesting (Rural).

Household water treatment and safe storage

Regardless of its source, drinking water can easily become contaminated with pathogens through unhygienic distribution, collection, handling and storage (Wright, et al., 2004). One approach to minimising the adverse health impacts of such contamination is to promote microbial treatment at the household level, or Household Water Treatment, combined with safe storage (HWTS).

A growing body of evidence demonstrates that the use of HWTS methods improves the microbial quality of household water and reduces the burden of diarrhoeal disease in users (Fewtrell et al., 2005; Clasen et al., 2007; Waddington and Snilstveit 2009). Several HWTS methods have been proven to improve drinking-water quality significantly, both in the laboratory and in field trials in developing countries (Clasen et al., 2007; WHO, 2011). These HWTS methods include filtration, chemical disinfection, disinfection with heat (boiling, pasteurisation) and the use of flocculants and/or disinfectants. The role of the International Network on Household Water Treatment and Safe Storage (the “Network”) is in part to coordinate the effective implementation of such options. The Network, established in 2003 by WHO, and as of 2011 co-hosted by WHO and UNICEF, includes over 100 international, governmental and non-governmental organisations, private sector entities and university research departments that are actively involved in household water treatment and safe storage policy, research, implementation, monitoring and evaluation.

Additional resources can be found in the WHO/UNICEF toolkit (WHO/UNICEF 2012) and at the SSWM portal (Sustainable Sanitation and Water Management Toolbox).

7.2 Arsenic treatment technologies

Technologies for arsenic removal rely on basic physical and chemical processes that are summarised in the following sections. More details can be found in the scientific literature and more information and references in one of the several reviews of arsenic removal technologies (e.g. Mohan and Pittman, 2007).

The review here focuses on decentralised (community or household) arsenic removal methods. Particular emphasis is on technologies which have been validated through independent verification programmes (Johnston, 2002; USEPA, 2005). The following chapters present and summarise the principal steps and procedures for arsenic removal.

Pre-treatment (oxidation)

Arsenic in groundwater is mainly present in two oxidation states, As(III) and As(V), depending on the environmental conditions in the aquifer. Most arsenic removal technologies are most effective at removing As(V) (arsenate), since As(III) (arsenite) is predominantly non-charged below pH 9.2. Therefore, many treatment systems include an oxidation step to convert arsenite to arsenate. Oxidation alone does not remove arsenic from solution; it must be coupled with a removal process such as coagulation/precipitation, adsorption or ion exchange.

Air oxidation

Atmospheric oxygen is readily available as an oxidising agent; however, the kinetics of air oxidation of arsenic are very slow (taking weeks), and the reaction needs to be catalysed. Metals such as iron or manganese, which are naturally present in groundwaters, catalyse the oxidation of As(III), but oxidation is normally not complete without additional oxidants or the repeated addition of Fe(II).

Chlorine

Chlorine is widely available and is a rapid and effective oxidant for arsenite. Dosing can be difficult, since locally available chlorine can be of uncertain quality in developing countries. When enough chlorine is added for effective disinfection of water from microbial contamination, arsenite oxidation is normally complete. Doses generally range from 1.0 to 5.0 mg/L, with the goal of approximately 0.5 mg/L residual chlorine to provide protection against microbial contamination after treatment.

Manganese compounds

Potassium permanganate (MnVII) effectively oxidises As(III), along with Fe(II) and Mn(II). Filtration of water through a bed of solid Mn(IV) oxides can rapidly oxidise arsenite to arsenate without the need for adding a liquid or gas oxidant. Oxidation is efficient over a wide range of pH and does not release excessive manganese into solution.

Other more advanced oxidants (e.g. ozone, ultraviolet lamps) are not considered here, as they are difficult to use in developing countries.

Adsorption and ion exchange

Ion exchange is a reversible chemical reaction between an insoluble solid and a solution during which ions may be interchanged. The ions can be relatively easily exchanged. Adsorption, on the other hand, involves the formation of a bond between a dissolved ion and the solid-phase surface. These bonds are not so easily broken. Various solid materials have a strong affinity for dissolved arsenic. Arsenic is strongly attracted to sorption sites on the surfaces of these solids, and is effectively removed from solution.

Ion exchange resins

Ion exchange is a physico-chemical process by which an ion in the solid phase is exchanged for an ion in the feed water. The solid phase is typically a synthetic resin which has been chosen to preferentially adsorb the particular contaminant of concern. To accomplish this exchange of ions, feed water is continuously passed through a bed of ion-exchange resin beads in a down-flow or up-flow mode until the resin is exhausted. A good example is the READ-F ion exchange filter (Fig. 7.2).

Fig. 7.2 *READ-F household ion-exchange filter used in Bangladesh (see also document on "Verified Arsenic Removal Technologies in Bangladesh")*

Most commonly, the resins are composed of a matrix of polystyrene cross-linked with divinylbenzene. Charged functional groups are attached to the matrix by covalent bonding. These functional groups determine the resin's affinity to certain ions such as arsenate. Conventional sulphate-selective resins are particularly suited for arsenate removal. Nitrate-selective resins also remove arsenic, but arsenic breakthrough occurs earlier (USEPA, 2003c). Only arsenate can be removed using ion-exchange filters, as arsenite is not charged. A pre-oxidation step might therefore be necessary.

Arsenic removal: Various strong-base anion exchange resins are commercially available which can effectively remove arsenate from solution, producing effluent with less than 1 µg/L arsenic (Clifford, 1999). Arsenate removal is relatively independent of pH and influent concentration. On the other hand, competing anions, especially sulphate, can have a strong effect. In low-sulphate waters, ion-exchange resins can easily remove over 95% of arsenate and treat from several hundred to over a thousand bed volumes, before arsenic breakthrough occurs. However, when sulphate is present and saturates the exchange sites, it can lead to desorption of large amounts of exchanged arsenate – so-called "arsenic dumping". Accordingly, the USEPA recommends that ion-exchange resins only be used for low-sulphate waters (USEPA, 2000b).

Regeneration: Exhaustion occurs when all sites on the resin beads have been filled by contaminant ions. At this point, the bed is regenerated by rinsing the column with a regenerant, a concentrated solution of the ions initially exchanged from the resin. The number of bed volumes that can be treated before exhaustion varies with resin type and influent water quality (USEPA, 2000b). Ion-exchange resins are easily regenerated by flushing with concentrated salt solutions (1.0 M NaCl is commonly used). Brine can be reused 20–30 times, in spite of increasingly concentrated arsenic levels in the regenerant. Spent regenerant is loaded with arsenic and needs to be treated or disposed of safely (USEPA, 2000d).

A hybrid anion exchanger (HAIX) containing hydrous ferric oxide has been used to remove arsenic from drinking water in West Bengal for 10 years now. The initial investment in this material appears to be offset by the long filter life. Please see German et al. (2014) for further details.

Advantages

- High adsorption capacity
- Commercially available
- Regeneration possible

Disadvantages

- Moderately expensive
- Risk of "arsenic dumping" of waters with high sulphate concentrations
- Interference from sulphate and total dissolved solids
- Water rich in Fe and Mn might require pre-treatment to prevent filter clogging
- Regeneration produces arsenic-rich brine

Activated alumina

Activated alumina (AA) is a commercially available granular form of aluminium oxide which can be used as a filter medium to remove a range of contaminants from water, including arsenic. The contaminant ions are exchanged with the surface hydroxides on the alumina. When adsorption sites on the AA surface become filled, the bed must be regenerated. Activated alumina has a much higher affinity for As(V) than for As(III). Therefore, depending on the prevalence of As(III), filtration might need to be preceded by an oxidation.

Arsenic removal: The arsenic adsorption capacity of AA (mg As/g AA) varies significantly with water pH and influent arsenic concentrations and speciation. Arsenate removal capacity is highest within a narrow range of solution pH from 5.5 to 6.0, in which the alumina surfaces are protonated, and in which other anions are not concentrated enough to compete with arsenic (USEPA, 2000b). In large systems, pH adjustment is often applied to optimise treatment.

Regeneration: Regeneration of AA beds is usually accomplished using a strong basic solution of concentrated NaOH. Arsenic is more difficult to remove during regeneration than other ions such as fluoride. Therefore, higher base concentrations are used, typically, 4% sodium hydroxide. After regeneration with strong base, the AA medium must be neutralised using strong acid (e.g. 2% sulphuric acid). Arsenic-rich wastes must be processed before disposal (USEPA, 2001).

Advantages

- High arsenic removal efficiency
- Commercially available
- Regeneration possible
- Tested in community and household application

Disadvantages

- Moderately expensive
- Strong acid and base needed for regeneration
- Arsenic-rich waste produced
- Optimal arsenic removal within a limited pH range

Iron-based solids

Iron, especially in the ferric state (Fe(III)), has a strong affinity for arsenic. It also has an affinity for other ions. Phosphate, arsenate and silicate bind equally strongly, followed by negatively charged ions (Balistrieri and Chao, 1990; Hsu et al., 2008; Hug, 2014):

phosphate = arsenate ≈ silicate > (bi)carbonate > humic acid >fluoride > sulphate > chloride

This sequence indicates that arsenic will compete for binding sites with phosphate and silicate, but not with ions such as fluoride, sulphate or chloride.

Fig. 7.3 *SIDKO community arsenic removal filter installed in Bangladesh*

Granular iron-based media have been developed relatively recently for arsenic removal (e.g. Driehaus et al., 1998). Several commercial iron-based materials are available, including granular ferric hydroxide (e.g. AdsorpAs®, see SIDKO filter, Fig. 7.3). Iron-based solids can effectively remove arsenate, arsenite and phosphate from water. Before the water is passed over the active medium, it is aerated and pre-filtered to oxidise and remove iron flocs (USEPA, 2003b).

Sands coated with iron oxides have been synthesised by various researchers and tested for their arsenic removal capacity. UNESCO-IHE has developed a household filter which uses coated sand from Dutch iron removal plants (Petrusevski et al., 2008).

Advantages

- High arsenic removal efficiency
- Works well over a broad range of pH
- Removes both As(V) and As(III): pre-oxidation may not be needed
- Commercially available
- Tested in community and household application

Disadvantages

- Moderately expensive
- Regeneration is possible but usually not done
- Arsenic-rich waste produced

Zero-valent (metallic) iron

When metallic, or zero-valent, iron corrodes, it produces dissolved ferrous iron (Fe(II)). The ferrous iron reacts with oxygen to form ferric iron (Fe(III)) that precipitates as iron hydroxide ($Fe(OH)_3$), which acts as a sorbent for arsenic. Reactive oxygen species produced during iron corrosion also oxidise As(III) to the more strongly sorbing As(V) (Leupin and Hug, 2005). A household filter (the_SONO_filter, Fig. 7.4) has been developed which makes use of metallic iron to remove arsenic from drinking water in Bangladesh (Hussam and Munir 2007). This filter consists of two buckets placed on top of each other, with the top bucket containing sand, iron filings and brick chips and the bottom bucket containing sand, charcoal and brick chips. It has been verified through the BETV-SAM programme (see document on Verified_Arsenic_Removal_Technologies_in_Bangladesh).

Fig. 7.4 *SONO filter using metallic iron for arsenic adsorption*

Advantages

- High arsenic removal efficiency
- Continuous generation of ferric adsorption sites prolongs filter lifetime
- Removes both As(V) and As(III)
- Relatively inexpensive

Disadvantages

- Iron corrosion may lead to clogging and low filtration rates
- Limited field experience, mainly in household filters
- Limited commercial availability
- Arsenic-rich waste produced

Choice of filter medium

The choice of filter medium is primarily related to its use.

- Ion exchangers and granular ferric oxides, though relatively expensive, remove arsenic quickly and can be used for high throughput situations providing that As(III) has been oxidised.
- Filters using metallic iron, which also oxidises As(III), are less expensive and need to be run slowly and are more suited to household or community filters with limited water volumes.

Precipitation, co-precipitation and coagulation

Precipitation methods reduce dissolved arsenic concentrations by the precipitation of low-solubility solid minerals such as calcium arsenate. But these cannot normally lower arsenic to drinking-water limits. Co-precipitation refers to the precipitation of solid particles in the arsenic-containing water – normally aluminium or iron (hydr)oxides – that can sorb and incorporate arsenic.

Coagulation is the clumping of fine particles in solution to larger ones that can settle. Metal salts, such as alum, ferric chloride or ferric sulphate, are widely used coagulants to remove arsenic from drinking water (USEPA 2000a). These salts initially dissolve upon addition to water and then rapidly form fine precipitated flocs of metal hydroxides. These flocs coagulate and settle out of solution, scavenging many dissolved and particulate materials in the process. Vigorous stirring is required immediately after coagulant addition to ensure uniform mixing. Once the coagulant is dispersed, slow mixing allows the flocs to collide and grow (flocculate) without breaking up. Much of the floc matter will settle by gravity, but filtration is essential to remove small particles which can remain in suspension, as these can contain significant amounts of arsenic. If water is soft and of low alkalinity, it may be necessary to increase alkalinity (e.g. by adding lime addition) to ensure good floc formation.

Alum ($Al_2(SO_4)_3$) is effective for removing As(V) but ineffective for As(III), so pre-oxidation is often necessary. Alum has a narrow effective range, from pH 5–7; if the pH is above 7, removal may be improved by adding acid to lower the pH. Typical doses are 10 to 50 mg alum per litre.

Ferric (Fe(III)) salts (e.g. $FeCl_3$ and $Fe_2(SO_4)_3$) coagulate best between pH 5 and pH 8. Typical doses are 5 to 50 mg/L ferric salts. Ferric salts can remove both As(III) and As(V), but As(V) is retained more strongly, so pre-oxidation is often carried out.

Ferrous (Fe(II)) salts (e.g. $FeSO_4$) can also be used to remove arsenic, but oxygen (in air) and time are required to let the Fe(II) oxidise to Fe(III), which forms the arsenic-sorbing Fe(III) (hydr)oxide particles. At pH 7, it takes 1–4 hours for Fe(II) to oxidise completely to Fe(III) and to precipitate. Less time is required at a higher pH. During the oxidation of Fe(II) to Fe(III) by oxygen from air, a part of the As(III) is also oxidised to As(V), so the overall removal of As(III) with Fe(II) is better than with Fe(III), if no additional oxidant is used (Roberts et al., 2004). Groundwater often contains naturally dissolved Fe(II). If the natural concentration of Fe(II) is high (>15 mg/L), then this Fe(II) alone might be sufficient to remove the arsenic.

Coagulation also improves turbidity and colour and can also reduce levels of organic matter, bacteria, iron, manganese and fluoride, depending on operating conditions. If concentrations of phosphate or silicate in the source water are high, coagulation may be less effective.

Coagulation is operationally complex and is more commonly practised in centralised water-treatment plants. Chile has been removing arsenic from drinking water by coagulation for a long time – in 1970, the world's first arsenic removal plant was constructed along the

Toconce River. Since then, numerous plants have been built in Chile, most of which use ferric chloride coagulation with chlorine pre-oxidation (Sancha, 2006).

Some household coagulation systems have been developed, typically using an upper bucket for coagulation and flocculation and a lower bucket with filter material (e.g. charcoal and sand) for the removal of suspended solids, including metal (oxy)hydroxide particles containing arsenic (e.g. Cheng et al., 2004).
The performance of the Shawdesh_Aqua_Filter, a two-bucket system using ferric sulphate, was verified in the Bangladeshi BETV-SAM project (see "Verification Programmes" below).

Electrocoagulation, in which aluminium or iron flocs are produced by passing a current through metal plates in contact with the water to be treated, is an emerging technology. Electrocoagulation offers certain advantages over conventional treatment with salts: removal of As(III) may be superior due to at least partial oxidation, the need for chemical supply and addition is greatly reduced and sludge volumes are smaller (e.g. Kumar et al. 2004; Emamjomeh and Sivakumar 2009a). As electrocoagulation is a relatively new approach for the removal of arsenic (and fluoride), current research is focusing on optimising the many design factors which can influence treatment efficiency and cost (Addy et al., 2011).

Common to all (co)precipitation techniques are:

Disposal: The use of coagulants produces arsenic-rich sludge which needs to be safely disposed of, away from drinking-water sources (USEPA, 2000d). Wastes may be thrown into latrines that are well separated from drinking-water wells. However, centralised landfilling is probably the best disposal route.

Costs: Coagulation using metal salts requires simple chemicals that are readily available and cost-effective. Filter material generally consists of sand and charcoal, materials which are also cheap and easy to obtain.

Advantages

- Relatively inexpensive
- Simple chemical reagents, widely available
- Usually applied in batch treatment; effectiveness should remain constant over time (i.e. no "breakthrough" or saturation issues)

Disadvantages

- Requires rigorous and time-consuming operation and maintenance
- Usually requires pre-oxidation
- Generates arsenic-rich sludge
- Phosphate and silicate may reduce arsenic removal rates
- Treatment adds ions (sulphate, chloride) to the water, which may affect its taste
- Limited optimal pH range
- Limited field experience with electrocoagulation, processes not yet optimised

Co-precipitation with naturally occurring iron

High dissolved iron concentrations in groundwater pumped from anoxic aquifers can be utilised to remove arsenic. When the iron to arsenic mass ratio is greater than 40–50 (Meng et al., 2001), oxidation and filtration of iron will generally reduce arsenic to acceptable levels (USEPA, 2000c; USEPA, 2006). If groundwater also contains high phosphate concentrations, the iron:arsenic ratio should be even higher (Hug et al., 2008). If this criterion is met, then the system can function from its first use.

In Vietnam, household sand filters are commonly used for iron removal. An upper chamber is filled with locally available sand, while a lower chamber serves to store the filtered water. Groundwater pumped from a tube well trickles through the sand filter into the underlying storage tank (Fig. 7.5). Arsenic removal is governed by the precipitation of iron (hydr)oxides, which form a coating on the surface of the sand grains. Arsenic is then absorbed by the iron (hydr)oxides and remains immobilised under oxic conditions. The efficiency of the method is dependent on the concentration of the naturally occurring iron, as well as on the concentration of competing ions (especially with phosphate >2 mg/L) (Luzi et al., 2004; Roberts, 2004). Fe/As ratios of ≥50 or ≥250 are required to ensure arsenic removal to concentrations below 50 or 10 µg/L, respectively. In Vietnam, where 93% of tube wells contain >1 mg/L iron and <2 mg/L phosphate, the sand filters' median arsenic removal efficiency was 91%. Estimates for Bangladesh indicate that a median residual level of 25 µg/L arsenic could be reached in 84% of the contaminated groundwaters (Berg et al., 2006).

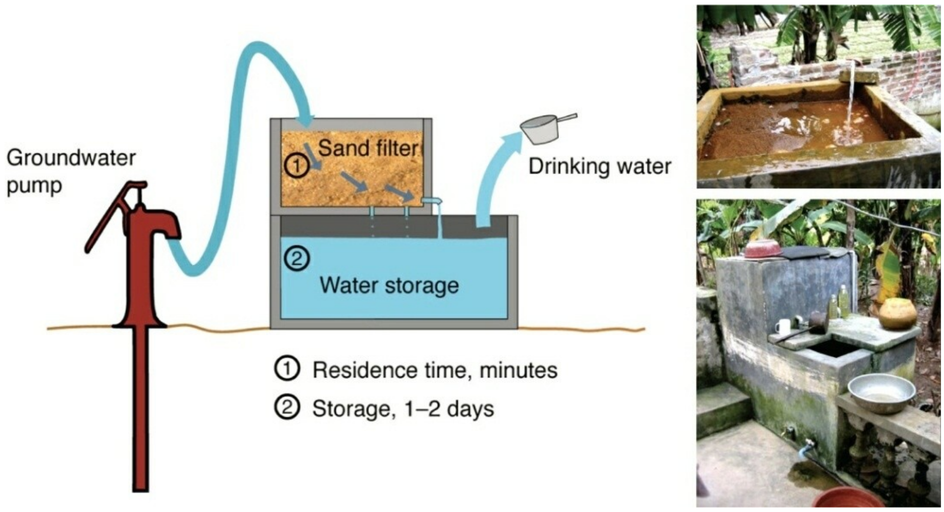

Fig. 7.5 *Sand filter for arsenic removal in Vietnam*

Advantages

- Relatively inexpensive
- Achievable using locally available materials
- No consumables or regeneration needed
- Efficiency improves with time, as ferric iron accumulates in sand filter
- Taste and appearance of water is markedly improved through iron removal

Disadvantages

- Arsenic removal is limited, requires high Fe/As ratio
- Poor performance where phosphate concentrations are high
- Lack of standard design parameters can lead to inefficient "homemade" systems
- Stored water may be vulnerable to faecal contamination

Membrane methods

Selectively permeable synthetic membranes can remove a variety of contaminants, including arsenic. Reverse osmosis and nanofiltration are two membrane technologies suitable for arsenic removal, operating with membrane pore sizes of less than 0.01 micron, which is sufficient to remove metal ions. These membranes need to be operated with pressure gradients ranging from about 3 to 10 bar (Johnston et al., 2002).

Membrane techniques require that inflowing water be of relatively high quality to prevent membrane fouling, meaning that a preceding filtration step is often necessary. Arsenic removal is possible over a wide pH range.

The percentage of treated water that can be produced from the feed water is known as the recovery. In municipal systems, recovery can be up to 85% for nanofiltration and 30–85% for reverse osmosis. In household systems, this value is typically significantly lower (e.g. 10–25%), which can be seen as a disadvantage, as a large amount of raw water is needed to produce the desired amount of treated water (USEPA, 2003a).

Advantages

- Additional removal of other chemical contaminants and pathogens
- Arsenic removal over a wide pH range

Disadvantages

- Complex and maintenance-intensive process
- Membrane fouling needing pre-treatment and chemical cleaning
- Operation at high pressures
- Low recovery rate
- High capital and operating costs

Reverse osmosis for contaminant removal is described in more detail in Section 7.3.

Verification programmes

The performance of a number of commercial technologies for arsenic removal has been independently verified by different agencies.

The USEPA, through its Environmental Technology Verification programme, has evaluated twelve commercial arsenic removal systems, in cooperation with NSF International Technologies (USEPA, 2007) include coagulation/filtration, ion exchange, adsorption onto iron-based solids or iron-modified activated alumina, and reverse osmosis.

In Bangladesh, the project Bangladesh Environmental Technology Verification – Support to Arsenic Mitigation (BETV-SAM) evaluated fifteen technologies between 2005 and 2009. Six of the technologies were issued verification statements and have been certified for sale in Bangladesh. These six technologies are briefly profiled in the file, Verified_Arsenic_Removal_Technologies_in_Bangladesh.

More detailed reports on the six technologies can be downloaded:

- Shawdesh_Aqua_Filter
- Nelima_Filter
- MAGC/Alcan_Filter
- READ-F_Filter
- SONO_Filter
- SIDKO_Filter

In addition to the six technologies described above, the BETV-SAM project tested a further seven technologies but denied them verification.

Four of the verified technologies (MAGC/Alcan, READ-F, SONO, and SIDKO) were distributed at scale for the purpose of a social assessment through the Deployment of Arsenic Removal Technologies (DART) project. Experiences with these filters are described in detail by Hanchett and Khan (2009).

7.3 Fluoride treatment technologies

A range of technologies are available for the removal of fluoride from drinking water. These can be divided into three categories based on the underlying fluoride-removal process:

- Adsorption (Filter Materials)
- Precipitation and Coagulation
- Membrane Methods

In the following section, we profile the technologies that are suitable for application at household and community scale for decentralised systems in developing countries. We focus on technologies that have already been implemented in the field. Many other technologies exist that have been tested in the laboratory but have not yet proved successful in the field or were never pursued beyond laboratory experiments. It is important to remember the following:

→ The ideal technology, suited for all types of conditions, does not exist!

The particular challenge for fluoride-removal technologies is the fluoride concentration in contaminated waters, which is roughly 50–150 times higher than arsenic concentration in arsenic-contaminated waters. This particularly affects the costs of the adsorption and precipitation/coagulation methods, as more filter materials, chemicals and/or maintenance are required.

The choice of the most suitable technology will be influenced by a range of factors, such as the fluoride concentrations in the input water, the funds available for implementation, operation and maintenance requirements, the local availability of raw materials and whether the technology is accepted by the targeted end users. Cost issues are usually at the forefront when decisions concerning the selection of a technology are made. The life cycle costs that will need to be considered (e.g. capital expenditures, maintenance expenditures etc.) are described in more detail in IRC (2011) and on the WASHCost website. Readers interested in technologies that are mentioned here may also consult several reviews on defluoridation methods, for example Fawell et al. (2006), Ayoob et al. (2008), Mohapatra et al. (2009), KEBS (2010), Bhatnagar et al. (2011) and Jagtap et al. (2012).

Adsorption (filter materials)

A widely used method for the removal of fluoride is to pass the contaminated water through a filter bed that retains the fluoride. The binding of fluoride to the surface of granular filter materials is an adsorptive process. In developing countries, most filter materials that have a high affinity for fluoride are aluminium- or calcium-phosphate-based. On the following pages, we describe two commonly used materials: activated alumina and bone char.

Activated alumina

Activated alumina (AA) is a commercially available granular form of aluminium oxide (Al_2O_3) that can be used as a filter medium to remove a range of contaminants, including fluoride, from water (Fig. 7.6).

In contact with water, the surface of the AA becomes hydrated and forms $Al(OH)_3$ with surface hydroxide groups (≡Al-OH). Negatively charged ions can replace the hydroxide (OH^-) ion, as shown for fluoride below:

$$\equiv Al\text{-}OH + F^- \rightarrow \equiv Al\text{-}F + OH^-$$

The strength of binding with the sites is reported by Amy et al. (2000) to be:

$$OH^- > H_2AsO_4^- > F- > SO_4^{2-} > HCO_3^- > Cl^- > NO_3^-$$

This means that while hydroxide binds most strongly, the binding strength of fluoride is stronger than most ions in drinking water. Therefore there will be little competition from these ions.

The highest removal capacities using AA are achieved within the narrow pH range of 5.5–6, when the attraction of fluoride ions to the AA surface is at its greatest and interference with competing ions is minimised. At higher pH values, the fluoride removal capacity is significantly lower, and fluoride breakthrough occurs earlier (Rubel and Woolsley, 1979). Activated alumina is used in industrialised countries in municipal plants, but also in developing countries at community and household scales (see e.g. Venkobachar et al., 1997; Daw, 2004).

Fig. 7.6 *One type of activated alumina: Compalox (Albemarle®)*

Production: Activated alumina is a commercially available product.

Fluoride Removal Efficiency: AA is highly efficient in reducing fluoride concentrations in treated water to levels below 0.3 mg/L. Fluoride removal of 85–95% can be achieved in well-maintained systems running at optimum conditions (Pickard and Bari, 2004). However, filter function is dependent on input-water quality and especially its pH. AA fluoride uptake capacity is at a maximum between pH 5.5 and pH 6, and it decreases considerably with increasing pH values. Waters with high alkalinity and high pH therefore need to be acidified before they are passed over the AA bed. There are many different types of activated alumina with different uptake capacities on the market.

Regeneration and re-use: When the AA is exhausted, it needs to be regenerated. (The filter material may also be replaced, but regeneration is generally more cost-effective.) Regeneration is typically done by passing a sodium hydroxide solution (1–4%) over the AA bed, followed by rinsing with clean water. This results in caustic waste water rich in total dissolved solids, aluminium and fluoride, which needs treatment to remove these ions before disposal. The filter is then reactivated using sulphuric acid or CO_2 gas, followed by flushing with water until the bed is at a pH of ~6.

The fluoride removal capacity appears to be lower after each regeneration cycle. Complete replacement of the filter material is generally necessary after 3–5 regeneration cycles (e.g. Chauhan et al., 2007; Fawell et al., 2006), while application in South Africa has shown AA media to still be efficient after 6 or more regeneration cycles (Schoemann, 2009). A step-by-step documentation on activated alumina regeneration as carried out in villages in India is given in the UNICEF (2004) Report, “Regeneration Manual for Activated Alumina used in Domestic Defluoridation Units”.

Costs: The initial costs of the filter material are generally relatively high, though efficient regeneration may bring down overall costs considerably. However, it may be necessary to establish a “regeneration centre” at a central location where spent media from household and community filters can be brought for regeneration.

Advantages

- High fluoride uptake capacity (at pH 5.5–6)
- Filter medium can be regenerated

Disadvantages

- Skilled operator needed for supervision of plant (community filter) and for regeneration
- Expensive filter material, not cost-effective if not regenerated
- Pre-treatment necessary if pH of input water is too high

Bone char

The charring and crushing of animal bones produces a granular material that has been used successfully in several countries (e.g. Kenya, Ethiopia, Thailand) as a filter material to remove excess fluoride from drinking water. The removal of fluoride from water by bone char (BC) is an adsorptive process, allowing the exchange of fluoride ions with hydroxide ions (OH^-) at the surface of the main mineral constituent of BC (the hydroxyapatite, $Ca_5(PO_4)_3OH$), releasing OH^- into solution:

$$Ca_5(PO_4)_3OH + F^- \leftrightarrow Ca_5(PO_4)_3F + OH^-$$

Bone char filters can be implemented at both community and household scale (Fig. 7.7). Raw water is fed into columns or filters and is allowed to percolate through the system. Once the 1.5 mg/L fluoride threshold has been reached in the filter outlet, the material needs to be regenerated or replaced.

Filter Material Production: The bone material needs to be largely free of flesh before it is charred. The charring is carried out in a kiln in a low-oxygen atmosphere at a temperature of 300 to 500°C for approximately 10 days, to produce bone char with the highest fluoride removal capacity with no organic remains (CDN, 2007). If the temperature is too high, the hydroxyapatite contained in bones changes to another mineral, and the resulting bone char has a significantly reduced uptake capacity. The desired product should be grey in colour. A soot-coloured product indicates the presence of organic material, and a white-coloured product indicates that the temperature was too high.

After charring, the bones are crushed to size fractions between 0.4 and 4 mm, which are washed with a solution of sodium hydroxide (6 g/L, pH 13) to remove remaining organic substances. The bones are then rinsed with water and acidified with CO_2 gas or sulphuric acid.

In Ethiopia and Kenya, large kilns capable of charring several tonnes of bone per batch are used. In Thailand, small household furnaces have been tested in which householders can produce their own bone char (Smittakorn et al., 2010). Generally, in small-scale production, it may be harder to maintain quality control of the bone char produced than in larger, standardised processes.

Note: Production requires skill and may take some time to perfect. Should a faulty batch containing residual organic substances, taint the water to be used, it is probable that the trust of users will be irrevocably destroyed.

Fluoride Removal Efficiency: The fluoride uptake capacity of the filter material depends on the quality of the bone char and particle size. The smaller the particles, the higher their uptake capacity (Mjengera and Mkongo, 2002). Implementation in Kenya has shown that BC filters can reduce fluoride concentration from over 6 mg/L to less than 0.1 mg/L after filtration, with a fluoride uptake capacity of ~1.2 mg/g determined in both field and laboratory studies (Mutheki et al., 2011).

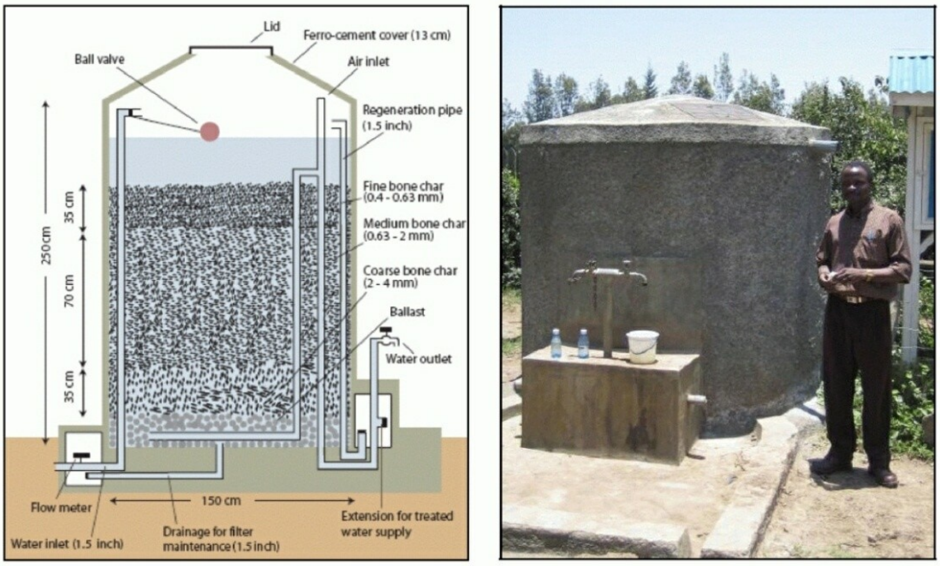

Fig. 7.7 Community BC filter used in Kenya by the Nakuru Defluoridation Company (NDC)

Regeneration: Once the WHO drinking-water standard for fluoride (1.5 mg/L) or a national standard has been reached in the treated water, the filter material needs to be replaced or regenerated. Regeneration is typically done by passing a sodium hydroxide solution (0.25%–1%) through the BC bed, followed by rinsing with clean water. This results in caustic waste water rich in total dissolved solids and fluoride, which needs either to be neutralised or strongly diluted. The filter is then reactivated using CO_2 gas or sulphuric acid followed by flushing with water until the effluent has a pH of ~6. The fluoride removal capacity is lower after each regeneration cycle.

The caustic waste can be treated with $CaCl_2$ or $Ca(OH)_2$ (lime) to produce a highly insoluble solid CaF_2 precipitate, which needs to be disposed of safely.

Costs: Production of bone char is intensive in terms of infrastructure and labour. These costs and the cost of raw bones are the main contributors to the total costs.

Advantages

- Bones as raw material are locally available at relatively low cost
- Filtered water is neutral in taste and colour (if the BC has been correctly produced)
- Relatively short contact time required (around 30 minutes)
- Regeneration possible

Disadvantages

- Initial investments and experience needed for setting up bone char production (building of kiln etc.)
- The use of animal bones as a filter material may not be acceptable in some regions for religious or cultural reasons
- Use of low quality bone char with a high organic content might result in the treated water having an unacceptable taste
- Relatively low fluoride uptake capacity (around 1.2 mg/L), which can necessitate frequent filter media replacement and lead to high transportation costs

Synthetic “bone char”: HAP

Bone char essentially consists of hydroxyapatite (“HAP”, $Ca_5(PO_4)3OH$). This material can also be produced synthetically using simple raw materials (lime and phosphoric acid). Laboratory studies have shown that synthetic HAP can have a clearly higher fluoride uptake capacity than BC. Synthetic HAP is already used for fluoride removal in Germany and Italy and was used in the past in the USA. Recently, the Nakuru Defluoridation Company in Kenya and Oromo Self-Help Organization in Ethiopia have started producing HAP which is now tested in the field.

Uptake capacities of filter materials

The uptake capacity of a filter material is important, because it provides information on how long a filter material will last. The maximum uptake capacity is attained when all available sites are occupied and occurs only at high dissolved arsenic or fluoride concentrations. At lower dissolved concentrations, the amount that is sorbed is proportional to the amount in solution:

$$K_d = C_{solid}/C_{solution}$$

where K_d is the distribution coefficient, and C_{solid} and $C_{solution}$ are the solid-phase and dissolved fluoride or arsenic concentrations, respectively.

Thus the uptake capacity will be high at higher inflow concentrations. The uptake capacity is also influenced by solution pH, contact time and temperature.

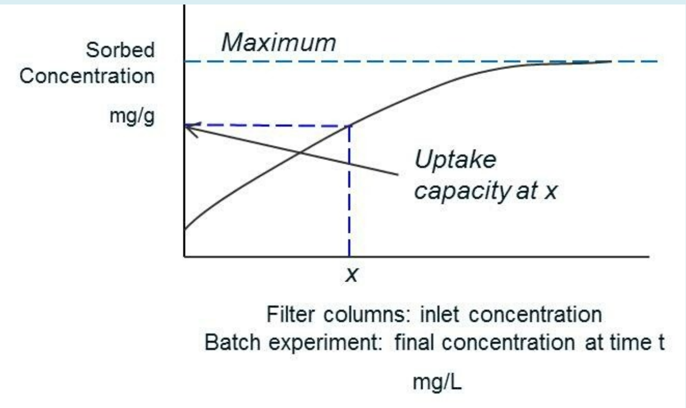

Fig. 7.8 *An adsorption isotherm for fluoride*

!! Handling acids and bases !!

The regeneration of filter materials is usually carried out using sodium hydroxide and concentrated acids, such as sulphuric acid, for neutralisation. The handling and storage of such chemicals requires occupational health training and skills development, careful supervision and strict enforcement of rules and regulations.

Guidelines

Wear safety goggles to avoid permanent damage of the eyes when working with acids and bases.

Wear suitable clothing that will protect you against spilled chemicals. Hard-soled, covered footwear must be worn at all times.

Wear gloves to protect your hands.

In case of spills, wash chemicals from skin straightaway.

i) Wash your hands and face quickly and thoroughly whenever they come into contact with a chemical.

ii) If you receive a chemical burn from an acid or base, immediately wash the burned area with large quantities of water.

iii) Chemicals spilled over a large part of the body require immediate action. Remove all contaminated clothing and rinse with water. Do not use creams or lotions, but get immediate medical attention.

Note: If you wear contact lenses, they must be removed for effective cleansing. It is better to wear glasses in case of a spill.

Work in well-ventilated surroundings to avoid inhaling of toxic fumes. Acid fumes in particular can cause permanent damage to the lungs.

Always pour concentrated acids into dilute solutions or water and **never** the other way round. Heat is generated by the mixing process, and by controlling the amount of acid in the mixture, you can prevent the temperature from rising too much. Quick mixing can cause the mixture to boil and splash the surroundings.

Further Reading

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Precipitation and coagulation

Fluoride can be removed from solution by precipitation and coagulation processes, followed by the settling (or flotation) of the precipitates. This usually involves the addition of chemicals that act as precipitating agents. Established techniques involving precipitation or coagulation include the Nakuru technique, the Nalgonda technique and electrocoagulation.

Contact precipitation (the Nakuru Technique)

The contact precipitation technique works by adding calcium (Ca) and phosphate (PO_4) compounds to untreated water, with fluoride concentrations being reduced by both sorption and precipitation reactions when the fluoride comes into contact with hydroxyapatites, e.g. bone char.

One method, implemented in Tanzania, is to add $CaCl_2$ and NaH_2PO_4 to the water. These dissolve, releasing Ca and PO_4. The resulting solution is then passed through a bone char bed (Dahi, 1996). It is relatively high in maintenance, as frequent addition of chemicals is required.

Fig. 7.9 *Calcium phosphate pellets that are used in combination with bone char in fluoride removal filters ("Nakuru Technique")*

To combat this drawback, another contact precipitation approach has been developed and successfully implemented by the Nakuru Defluoridation Company (formerly the Water Quality Group of the Catholic Diocese of Nakuru (CDN WQ)) in Kenya, involving the production of calcium phosphate pellets, which slowly release Ca and PO_4 when in contact with water (Fig. 7.9). This technology is known as the Nakuru Technique. The water passes through a pellet and BC mixture (3:1 ratio) and then through a bone char bed. The Nakuru Technique has successfully been implemented in fluoride removal filters in Kenya and Ethiopia (Fig. 7.10). In the following paragraphs, we will describe this method in more detail.

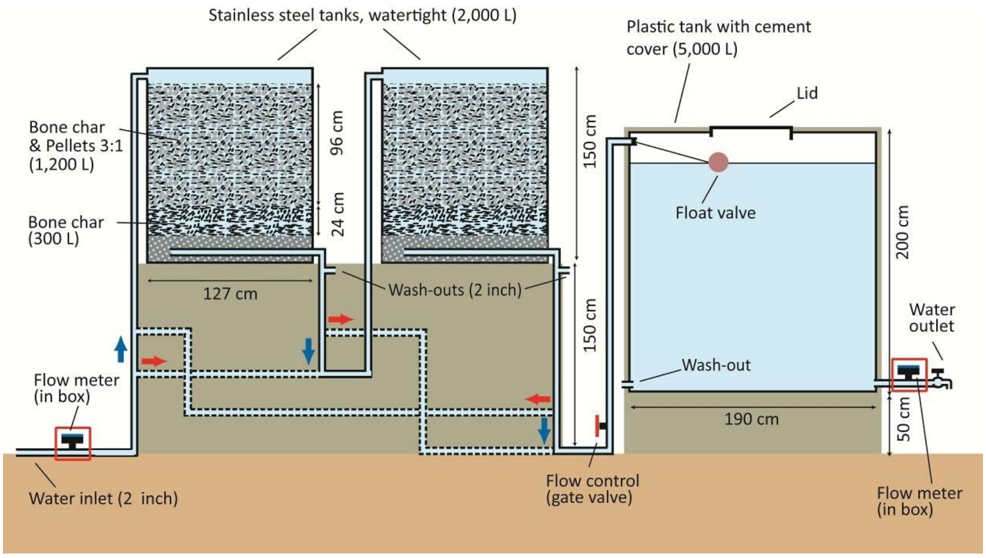

Fig. 7.10 *Design of a Nakuru Technique filter implemented in the Ethiopian Rift Valley by Eawag and Oromia Self-Help Organisation (OSHO)*

Filter Material Production: To the authors' knowledge, Ca-PO_4 pellets for use in fluoride removal filters are currently only produced by NDC in Kenya. Pellets are produced in a cement mixer using $Ca(OH)_2$, Kynofos21 (a commercially available Ca-PO_4 mixture sold as animal feed) and bone dust as raw materials. Subsequent curing, washing and drying steps follow. Readers that are interested in more details should contact the Nakuru Defluoridation Company Ltd. for details on bone char production, see the “Bone Char” section in this document.

Fluoride Removal Efficiency: Monitoring has shown that the fluoride uptake capacity of a bone char filter can be increased up to threefold, to 2–4 mg/L, when Ca-PO_4 pellets are added (Korir et al., 2009; Mutheki et al., 2011) (see Fig. 7.11). The fluoride removal efficiency of the Nakuru Technique is highly dependent on the flow rate. The filters have to be designed in a way that allows the water to stay in contact with the filter medium for a long time (at least 3 hours).

Regeneration and Disposal: Regeneration of contact precipitation filter material is not possible. It therefore needs to be replaced when the pellets are exhausted and fluoride breakthrough occurs (>1.5 mg/L). Whether spent filter material could be valuable as a phosphate fertiliser to increase crop yields is still being investigated. Preliminary research has shown that spent filter material has a lower fluoride content than commercially available fertilisers and similar phosphate availability (Hukari, 2011).

Costs: A clear advantage over regular bone char systems is that the filter medium lasts longer, thereby reducing replacement and transportation requirements. On the other hand, the pellet costs depend highly on the cost of the calcium phosphate used for its production. If phosphate prices increase in future, the costs for pellet production will rise as well. The filter material costs (without regeneration for BC) for treating water with an initial fluoride content of 5 mg/L in Kenya are currently estimated at around 2.5 USD/m³ for CP and 4.2 USD/m³ for BC (Mutheki et al., 2011).

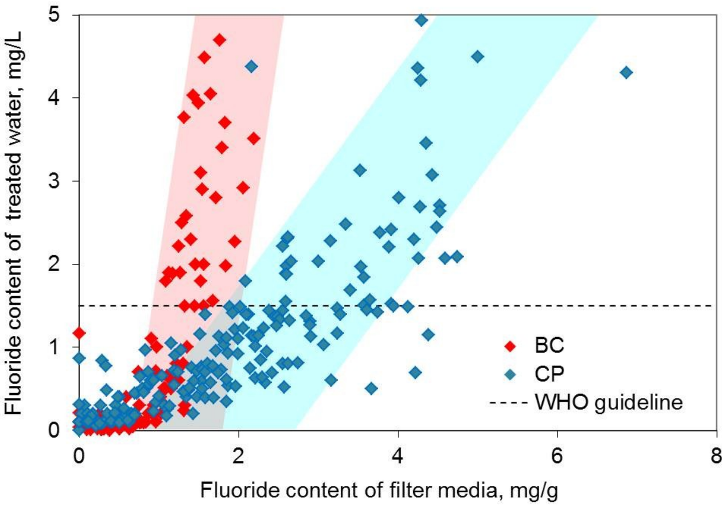

Fig. 7.11 Fluoride uptake as a function from field tests in Ethiopia and Kenya. Shaded areas show ranges for BC and CP obtained from laboratory tests done at NDC (Kenya) and Eawag (Switzerland) (Johnson et al., 2011)

Advantages

- Prolonged lifespan of filter material in comparison to filters containing only bone char
- Non-toxic raw materials
- Research suggests that the spent medium can be reused as fertiliser

Disadvantages

- Regeneration of the filter medium is not possible
- Fluoride removal efficiency is highly dependent on the flow rate, which makes its application in household filters difficult
- Pellets used in the Nakuru Technique are not widely available commercially, as they are currently produced only by NDC in Kenya
- Skill and experience are needed for pellet and bone char production
- Kynofos21 (calcium phosphate raw material) might not be available locally and would have to be imported, or a local alternative found

Nalgonda technique

The removal of fluoride using alum as a coagulant was first proposed in the United States in the 1930s. It was later adapted by the National Environmental Engineering Research Institute (NEERI) in India in the 1970s and named the "Nalgonda Technique" (Nawlakhe et al., 1975, Fig. 7.12). It is a coagulation-flocculation method that requires alum (aluminium sulphate, $Al_2(SO_4)_3$) and lime (calcium hydroxide, $Ca(OH)_2$):

$$Al_2(SO_4)_3 + 3Ca(OH)_2 \rightarrow 2Al(OH)_3 + 3Ca^{2+} + 3SO_4^{2-}$$

Alum is first dissolved and is then added to the untreated water, forming aluminium hydroxide flocs. Fluoride binds to these flocs, which are left to settle.

The dose of chemicals required depends on the quality of the raw water. Although rough dose rates exist based on theoretical models and field trials (Lyengar, 2000; UNICEF, 2008; Fawell et al., 2006), these cannot be taken as standard in every case. Field trials will therefore be necessary to determine the correct dose.

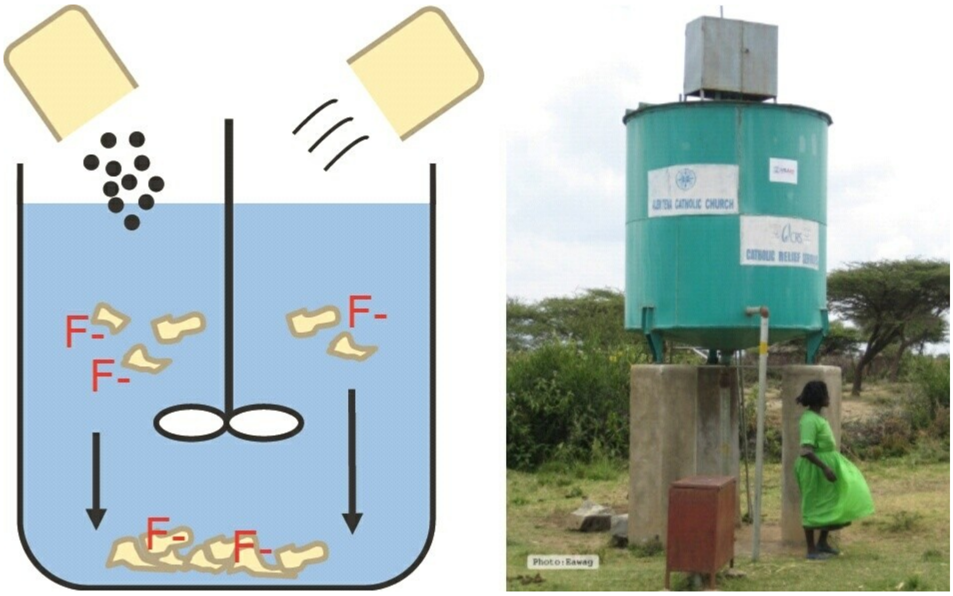

Fig. 7.12 ***Left:*** *Principle of Nalgonda technique (left): Alum and lime are added to the high fluoride water, the mixture is stirred and precipitates containing fluoride settle as sludge to the bottom of the solution*
Right: *Community Nalgonda Unit installed by the Catholic Relief Service in the Ethiopian Rift Valley*

Fluoride Removal Efficiency: The Nalgonda technique may be insufficient to reduce F- values to below 1.5 mg/L when alkalinity and fluoride values in the untreated water are high. Use of the Nalgonda technique in Tanzania only reduced fluoride concentrations to 2.1–3 mg/L in water initially containing between 8 and 12 mg/L fluoride (Dahi et al., 1996).

Fluoride and alkalinity levels in raw water need to be monitored frequently, as the chemical dosage needs to be adjusted according to the quality of the inlet water.

Disposal: Fluoride- and aluminium-rich sludge is produced, which needs to be disposed of safely, out of reach of children and animals and away from drinking-water sources, preferably landfilled. Disposal in latrines is possible if these are well separated from groundwater resources.

Costs: The chemicals needed (alum and lime) are relatively cheap and readily available in most countries, making the Nalgonda technique an inexpensive fluoride removal method if conditions are such that fluoride guidelines are met. Additional costs for a generator need to be taken into account for community units which require an electrical stirrer.

Advantages

- Chemicals readily available in most countries
- Relatively inexpensive in comparison to other technologies

Disadvantages
- Insufficient fluoride removal efficiency when concentrations in raw water are high
- The method is labour intensive and requires rigorous and time-consuming operation and maintenance
- Some community filter units require power for the electrical stirrer
- Electrical stirrers include movable parts, which are prone to mechanical failure
- Perceived taste of the treated water may be affected by high sulphate concentrations (~ 600 mg/L)
- Large amounts of waste are produced that are often deposited onsite

Electrocoagulation

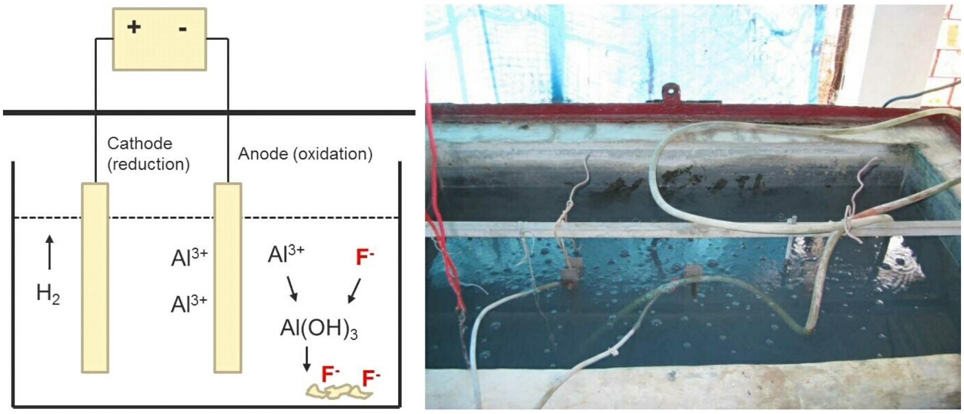

Fig. 7.13 *Schematic principle of electrocoagulation (left) and EC community plant operated by NEERI, India (right)*

The electrocoagulation (EC) method has been used to remove fluoride and other ions from industrial wastewaters for some time (e.g. Shen et al., 2003; Hu et al., 2008) and is now increasingly receiving attention as a suitable technology for fluoride removal from drinking water in developing countries. This technology lies at the intersection of three more fundamental technologies: electrochemistry, coagulation and precipitation.

The method utilises metal (e.g. aluminium) plates that act as anode and cathode. When a potential is applied to the electrodes, a current flows and Al^{3+} is released at the anode and reacts with water at neutral pH to form precipitate of $Al(OH)_3$, a compound which has a high affinity for fluoride (Fig. 7.13). The resulting $Al(OH)_3$-F flocs settle at the bottom of the solution and can be removed as sludge.

Fluoride Removal Efficiency: Fluoride removal efficiency depends on the initial fluoride concentration, the initial pH of the influent water and the current density (Emamjomeh and Sivakumar, 2009b; Gwala et al., 2011; Ghosh et al., 2008; Zuo et al., 2008; Zhao et al., 2011). The optimum pH for fluoride removal lies between 6 and 7. Laboratory studies have shown that fluoride concentrations can be lowered from 15 mg/L to below 1.5 mg/L within 40 min (Gwala et al., 2011; Mameri et al., 1998). Field implementation in India has accomplished fluoride removal from 4.5 mg/L to below 1 mg/L within 2 hours using solar energy as an electricity source (Gwala et al., 2011).

Disposal of Waste: The fluoride- and aluminium-rich sludge settling at the surface needs to be removed and disposed of safely, out of reach of children and animals and away from drinking-water sources. Disposal in latrines is possible if these are well separated from groundwater resources. Another possibility may be to stabilise sludge in cement or bricks.

Costs: Electrocoagulation uses simple and readily available materials (e.g. aluminium plating). An electricity source is needed (solar panels or a generator), which can result in high initial costs and, in the case of a generator, high operational costs as well.

Advantages

- High fluoride removal efficiency (at pH 6–7)
- Simple system, no moving parts
- No hazardous chemicals used (unless pH adjustment with acid needed)
- Relatively small amounts of sludge generated

Disadvantages

- High SO_4^{2-} concentrations in raw water can inhibit fluoride removal
- Aluminium levels in treated water may exceed the level recommended by WHO level (200 µg/L)
- Energy source needed (e.g. solar energy)
- pH may need to be controlled
- Requires relatively skilled staff

Membrane methods

Membranes with fine pores can be used to separate contaminants from water physically. As the fluoride ion is very small, most membranes are not fine enough to retain it. Reverse osmosis is a technique utilising very fine membranes coupled with high pressures to remove fluoride from drinking water efficiently.

Reverse osmosis

Reverse osmosis utilises a synthetic, semipermeable membrane, which allows the passage of water but not of ions or larger molecules. In principle, during the process of osmosis, water molecules move through the membrane along a concentration gradient from a high to a low dissolved salt concentration. The opposite effect is desired in the reverse osmosis process: pressure is applied on the membrane to overcome the osmotic pressure and to force water molecules from the concentrated solution to the fresh water side (Fig. 7.14). Reverse osmosis is widely applied for desalination and water purification purposes, including the removal of fluoride. More information on the principle of reverse osmosis and other membrane methods can be found in a range of documents, including Elimelech and Phillip (2011), Greenlee et al. (2009), Mulder (2000), Pontié et al. (2006) and Shannon et al. (2008).

Compared to other technologies for fluoride removal, reverse osmosis has the advantage that it removes not only fluoride but also ions in general (brackish water) and pathogens (viruses, bacteria, protozoa). There are two major limitations of the reverse osmosis technology:

1 High energy requirements;
2 Membrane fouling.

Membrane fouling occurs when suspended particulate matter, colloids, bacteria and organic material are deposited on the surface of the membrane. To control fouling, a pre-filtration step or conventional pre-treatment (e.g. coagulation and disinfection) may be needed to remove the particulate, colloidal and dissolved organic matter causing the fouling. Chemical cleaning is used to restore the permeability of the fouled membranes. During reverse osmosis filtration, feed water is recirculated, and only a certain percentage (around 20–50% , depending on the system used) of the raw water ends up as treated water (permeate), the rest being waste. Reverse osmosis therefore has a high water demand and should not be used in areas of known water scarcity.

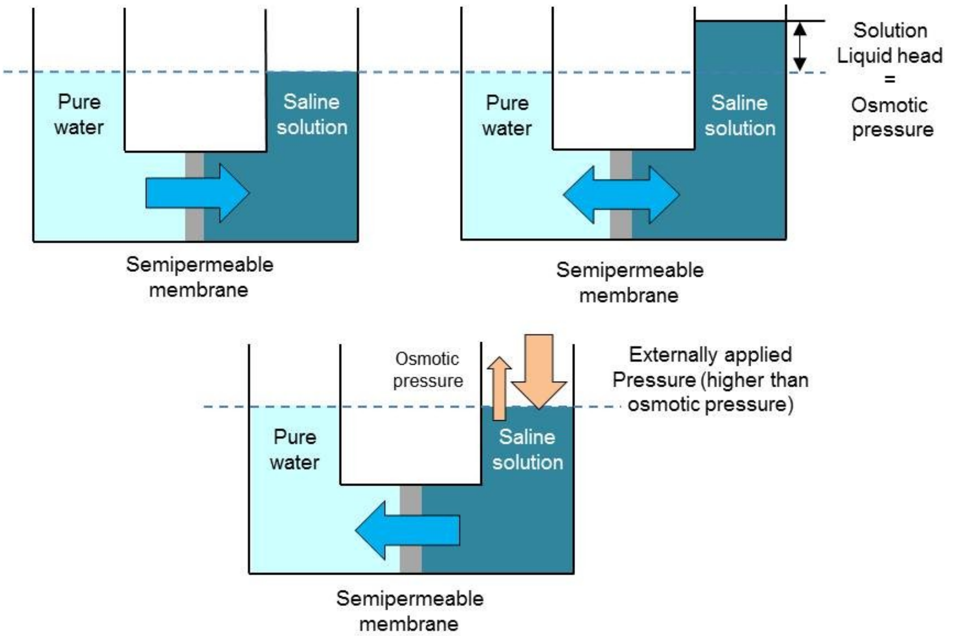

Fig. 7.14 Principle of reverse osmosis

Fluoride Removal Efficiency: Reverse osmosis can remove fluoride almost completely. Treated water can be deficient in minerals serving as essential micronutrients to humans and generally needs to undergo remineralisation before distribution.

Costs: Reverse osmosis is a high-tech process needing skilled operators. Capital and operational costs are high. It is an energy-intensive technology, requiring the generation of high pressures. Electricity costs can therefore be substantial.

Advantages

- Efficient fluoride removal
- Reduction in salinity
- Additional removal of chemical contaminants and pathogens

Disadvantages

- Complex and high maintenance process
- Membrane fouling needing pre-treatment and chemical cleaning
- High energy consumption
- High water use
- Cost-intensive

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Links to alternative water resources information

International Network on Household Water Treatment and Safe Storage. www.who.int/water_sanitation_health/water-quality/household/household-water-network/en/

Operation & Maintenance Network: www.operationandmaintenance.net

Rural Water Supply Network (RWSN): www.rural-water-supply.net

Samsamwater: www.samsamwater.com/library.php

SSWM Toolbox: www.sswm.info/category/implementation-tools/water-purification/hardware/point-use-water-treatment/hwts

Technology Applicability Framework (TAF): www.washtechnologies.net/en

8 A guide to behaviour change

Hans-Joachim Mosler, Alexandra C. Huber, Jennifer Inauen, Robert Tobias

Fig. 8.1 *Woman collecting water from an arsenic-contaminated tubewell in Bangladesh*

It is not sufficient to provide people at risk of consuming contaminated water with safe water facilities. For various reasons, they might not use these facilities properly or regularly, or they might not use them at all. Consumers have to be motivated to use them. They will change their habits if they, for example, are convinced of the positive health effects of these filters, like the taste of the water, perceive the price as reasonable, think that others approve, think that it does not require too much additional effort etc..

The key to persuading people to change their behavioural habits and to use a safe water source is to understand their motivations. Once we understand these, we can carry out targeted campaigns to change their behavioural habits. This process is called “behaviour change”. This is an evolving field and it is important to note that the dignity, participation and choice of the participants should always be respected. Furthermore such techniques should be applied only when viable and sustainable solutions (e.g., for the provision of safe water) are available and with active support and participation of responsible institutions.

A general procedure for **behaviour change** consists of 9 steps:

1 Define the target population and the desired behaviour (i.e. continual use of a safe-water source).
2 Obtain an impression of the conditions that favour or hinder this behaviour.
3 Catalogue all possible factors that determine the behaviour.
4 Develop a questionnaire to measure the importance of behavioural factors.
5 Conduct a representative survey (baseline survey).
6 Use the survey results to determine the factors that steer the target behaviour.
7 Define and design campaigns (interventions) to change peoples' perceptions of these factors.
8 Define suitable communication channels.
9 Evaluate the effectiveness of the behaviour change techniques and their long-term effects.

Training courses and guideline

Behaviour change is a crucial step in the mitigation of the geogenic contamination of drinking water and other water-, sanitation- and hygiene-related issues. It requires skills and time. People and institutions interested in applying this approach are strongly recommended to participate in Eawag training courses courses and to make use of the guideline 'Systematic Behaviour Change in Water Sanitation and Hygiene. A practical guide using the RANAS approach' which can be retrieved from http://www.eawag.ch/en/department/ess/empirical-focus/environmental-and-health-psychology-ehpsy/.

8.1 Define target population and behaviour

So that human and financial resources are not wasted, it is important to define **who** exactly should change **which** behaviour.

Note that at this point, the technically and institutionally most suitable option(s) should already have been determined, and the aim is to define which behaviours potential users need to adopt or change in order to install, use and maintain these options.

Target population

Defining the target population is crucial. Different actions will be required depending on whether the behaviour that needs to be tackled is that of children, men, women or adults of both sexes. The target individuals are the ones who make the decisions. For example:

- The head of the household is the target individual if he/she decides where a young daughter collects the drinking water.

- The landlord is the target individual if he/she has to give permission to the tenants to dig an additional tubewell if the one they are using is contaminated.
- If people share a facility, then the group needs to take the decision for change. The whole community may be involved in this process.

The main questions that need to be answered are:

- Who are the decision-makers? E.g. head of household, a housewife, community leader, religious leader, head of neighbourhood union etc.
- Who are the people who perform the target behaviour? Are they the women, girls or men or a group of people?

Target behaviour

Defining exactly the behaviour to be changed is a crucial first step in the behaviour change process. In order to do this, it is necessary to take a closer look at the daily routine of the potential water users. Important questions that should be asked are:

- Which safe-water option should be used? E.g. a community filter, a household filter or a neighbouring well?
- What tasks does use of the safe-water option require? E.g. fetching water from a public community filter, regularly filling a private household filter or contacting a neighbour to use his/her well?
- Which new habits are crucial for the target population? E.g. is it important that women also cook with safe water, and do they do so, or is the safe water only intended for drinking?

What we want to achieve is a change in habits. The most important outcome is to build up a long-term habitual change in behaviour in the majority of the target population in favour of the safe drinking-water option.

Step 1: Tasks

→ Interviews with experts and/or
→ Interviews with local partners and/or
→ Interviews with community and opinion leaders
→ Focus group discussion

Example

A rural village in Ethiopia has elevated fluoride concentrations in all its accessible water sources. To prevent the intake of excess fluoride, a fluoride removal community filter was installed. The filter is located in the centre of the village next to the main raw water source. The community can now purchase water from the new community filter. However, the treated water is more expensive than the unsafe raw water. The price was set by the local water committee to assure financial sustainability for the filter. After the filter was installed, the research team held interviews with their local partner NGO to complete step 1. The target behaviour was identified as fetching water from the community filter, which was not very different from the alternative behaviour, fetching water from an unsafe well. Both are public and require the effort of carrying water to the home. Through the interviews, the research team also found out that the decision-makers are the heads of the households (mainly men) but that the ones who perform the task are mainly women and younger girls.

Note: The examples provided in the boxes are fictional but are based on the experience gained in several projects carried out by the authors.

Fig. 8.2 *Young woman fetching water at the community filter, Ethiopia*

8.2 Gain a first impression of conditions that favour or hinder the target behaviour

In this second step, a small number of the target population are questioned in depth about their daily routines. We are interested in finding out what motivates them to perform certain tasks related to the target behaviour. For example, they may be asked about the effort of collecting water, about costs, or about cultural habits such as the importance of what others do or how important it is to serve guests safe, uncontaminated water. It is also important to understand the behaviour under different situational conditions. For example, do people have to access safe water in the fields or at school?

In addition to the interviews, the daily routines of randomly selected households are observed to find out when and where people perform the behaviour (or do not). For example, when is a household filter filled, and which incidents hinder the filling?

Step 2: Tasks

→ In-depth interviews with a small number of the target population
→ Observation of randomly selected households during a whole day

Example

The research team conducted in-depth interviews with five different households and spent a whole day observing five women who are responsible for fetching water. From the interviews, the research team learned that culturally, it is very common to have guests for a coffee ceremony. So this would be an important moment to use filtered water instead of raw water. Because of this finding, the research team decided to consider the importance of having guests and serving them safe water as a possible factor favouring the targeted behaviour.

Fig. 8.3 *Coffee ceremony in a rural household in Ethiopia*

8.3 Catalogue all possible behavioural determinants

Having gained a superficial understanding of daily routines and the underlying motivations of, and influences on, actions related to the target behaviour, the next task is to start preparing an in-depth quantitative questionnaire (this section and Sections 8.4, 8.5 and 8.6) to better understand the motivations in psychological terms.

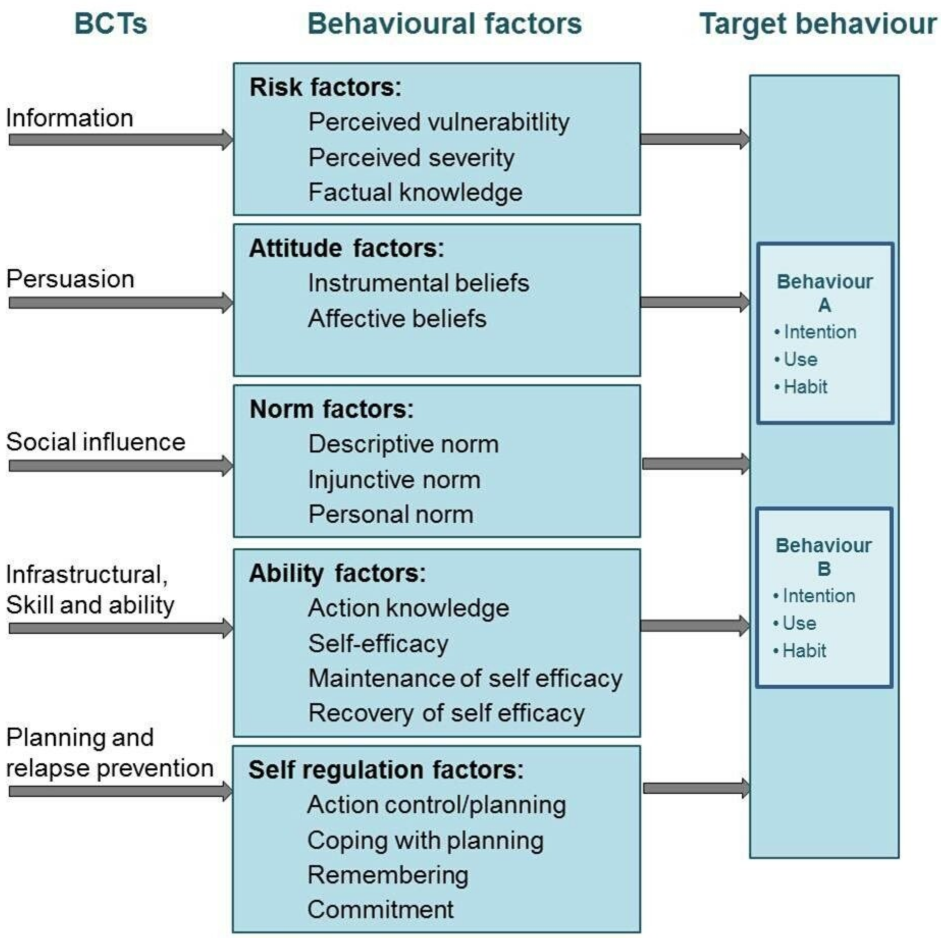

Fig. 8.4 *The RANAS Model (Risk, Attitudes, Norms, Abilities and Self-Regulation) of behaviour change. It shows the target behaviours, the factors that affect behaviour and behaviour change techniques (BCTs)*

Several theories of health psychology can be used to explain health behaviour; e.g. the Theory of Planned Behaviour (Ajzen et al., 2007) and the Health Action Process Approach (Schwarzer, 2008). These have been adapted to the RANAS Model (Risk, Attitudes, Norms, Abilities, and Self-regulation (Mosler, 2012). This model is divided into three distinct components (Fig. 8.4, right to left): (i) the target behaviours; (ii) factor blocks that group the behavioural factors that represent similar issues; and (iii) interventions that represent the corresponding behaviour change techniques (BCTs).

Target behaviours and alternatives

It is important to assess old and new habits or "behaviours". This means, for example, assessing both the new safe drinking-water option (Behaviour A) and the drinking-water option(s) in current use (Behaviour B). In each case, the intention, use and habit need to be part of the survey, and these points must be addressed in the list of "behavioural determinants" described below.

Behavioural factors and intervention strategies

The five groups of factors are defined below.

Risk factors are the perceived vulnerability of contracting an illness, its perceived severity and factual knowledge about the possibilities of being affected by a potential contamination.

Intervention**:** Information and education are used to increase awareness.

Attitudinal factors consist of instrumental beliefs, which relate to the perceived advantages/disadvantages and costs/benefits of the new or alternative behaviour (A or B, Fig. 8.4). Affective beliefs refer to feelings arising when thinking about the behaviour.

Intervention: Positive attitudes can be induced by persuasion. The idea here is to highlight benefits of the new behaviour.

Normative factors represent different social influences. Descriptive norms are what a person perceives as "what everyone does". Injunctive norms are what an individual perceives as behaviour approved of or disapproved of by others. Personal norms are personal standards; i.e., what should be done. The influence of peer pressure is represented in these factors.

Intervention: Norms can be changed by obtaining approval from opinion leaders, which may be traditional leaders, women's groups etc.

Ability factors represent firstly the knowledge about what to do (action knowledge), secondly the confidence in how to organise and manage the behaviour (self-efficacy), and lastly the confidence in one's ability to deal with possible barriers (maintenance self-efficacy, recovery self-efficacy).

Intervention: Interventions include changes in infrastructure to make the new behaviour easier or more convenient. They also include support in organising and managing confidence in the new behaviour.

Self-regulation factors Planning interventions help to translate goals into actions to get people started, to prevent distraction and to help them to avoid fall-back into old habits. Coping planning helps people to overcome conflicting goals and possible barriers to the desired behaviour. The commitment to perform a behaviour can be enhanced by making a contract with the person in which she or he obliges her- or himself to perform the behaviour (self-commitment).

Intervention: Goals are translated into actions by planning and by anticipating barriers and making plans for how to overcome these.

Step 3: Tasks

- → Carefully read this section and familiarise yourself with the behavioural determinants
- → If necessary, add more behavioural determinants to the model

Example

The research team noticed that one possible factor was missing in the RANAS model to explain their target behaviour. As was found out during the in-depth interviews and the observations (step 2), having guests for a coffee ceremony is something that had to be surveyed. That is why a new factor was added to the norm factor block of the behaviour change model: the importance of serving filtered water to guests (guest norm).

The RANAS model was used to encourage behaviour change in several case studies: solar water disinfection in Bolivia (Heri and Mosler, 2008) and in Zimbabwe (Kraemer and Mosler, 2010); hygiene behaviour in Kenya (Graf et al., 2008); the use of arsenic-free deep tubewells in Bangladesh (Mosler et al., 2010); and the consumption of fluoride-free water in rural Ethiopia (Huber et al., 2012).

8.4 Develop a questionnaire to measure behavioural factors

A questionnaire, aimed at measuring the behavioural factors identified in the previous section, is now developed. The factors and example questions used for their quantification are listed in Table 8.1. This is a crucial step that requires much time and effort.

Table 8.1 *Example questions about drinking arsenic-contaminated water versus arsenic-safe water. The factors are specific psychological terms.*

	Factor	**Item example** [response scale]
1	Vulnerability	How high or low do you feel are the chances that you will get arsenicosis when drinking unsafe water? [very low to very high: -4 – +4]

	Factor	Item example [response scale]
2	Severity	If you were to contract arsenicosis, how severe do you think the impact on your life would be? [not severe to very severe: 0 – 4]
3	Factual knowledge	How do you contract arsenicosis by drinking unsafe water? [open-ended]
4	Instrumental beliefs	Do you think that using arsenic-safe water is time-consuming (expensive/healthy/hard work)? [not at all to very much: 0 – 4]
5	Affective beliefs	How much do you like or dislike arsenic-safe disinfected water? [dislike to like very much: -4 – 4]
6	Descriptive norm	How many of your relatives drink arsenic-safe water? [almost nobody to almost all: 0 – 4]
7	Injunctive norm	Do you think that, overall, people who are important to you approve or disapprove that you drink arsenic-safe water? [nearly all disapprove to nearly all approve: -4 to +4]
8	Personal norm	Do you feel a strong personal obligation to consume arsenic-safe water? [Not at all to very much: -4 – 4]
9	Action knowledge	What can be done to avoid arsenicosis and its harmful effects? [Multiple choice answers: 0 for wrong answer, 1 = right answer]
10	Self-efficacy	Are you sure that you can consume as much arsenic-safe water as you need within the next month? [very unsure to very sure: 0 – 4]
11	Maintenance self-efficacy	How confident are you that you can freely consume arsenic-safe water, even if your relatives continue to consume raw water? [not confident at all to very confident: 0 – 4]
12	Recovery self-efficacy	Imagine you have stopped drinking arsenic-safe water for several days. How confident are you that you would be able to start drinking arsenic-safe water again? [not confident at all to very confident: 0 – 4]
13	Action control (planning)	Do you have a plan of when during the day to start collecting arsenic-safe water? [no detailed plan at all to very detailed plan: 0 – 4]
14	Coping planning	Have you made a plan of what to do when you are hindered in collecting arsenic-safe water? [no detailed plan at all to very detailed plan: 0 – 4]

	Factor	Item example [response scale]
15	Remembering / Forgetting	How often do you forget to collect arsenic-safe water? [never to almost always: 0 – 4]
16	Commitment	How committed do you feel to drinking arsenic-safe water? [not at all to very much: 0 – 4]
Behavioural questions		
17	Intention	How strongly do you intend to always drink arsenic-safe water? [not at all to very strongly: 0 – 4]
18	Behaviour	What is the percentage of arsenic-safe drinking water of your total daily water consumption? [%]
19	Habit	Do you go to collect your arsenic-safe water automatically? [not automatically at all to very automatically: 0 – 4]

The questions have to be adapted and developed for each topic and, particularly, for each local condition. They have to be clearly understood by the target population. It is therefore necessary to work closely with local persons. If the investigator does not speak the local language, the items have to be carefully translated into the local language and retranslated back to the original language to unveil translation problems. Finally, the items need to be introduced into a standardised questionnaire and be brought into a meaningful sequence.

Step 4: Tasks

- → Look at the example baseline questionnaires (Tools 1 and 2) and adapt the questions to your target behaviour and target population
- → If necessary, add more questions regarding other behavioural determinants you added to the model
- → Translate and retranslate your questionnaire

Tools

Tool_1: Example baseline questionnaire on fluoride-contaminated water in Ethiopia

Tool_2: Example baseline questionnaire on arsenic-contaminated water in Bangladesh

Example

The example baseline questionnaire for fluoride in Ethiopia is found in Tool 1. We added additional questions to cover the new factor, guest norm. These questions addressed the issue of how important it is for the person being questioned to serve filtered water to their guests and what their guests would think of them if they served raw water instead.

The questionnaire was drawn up in English and then translated into the two languages of the target population in Wayo Gabriel – Amharic and Oromifa – and was retranslated into English. Translation errors were found and corrected.

8.5 Conduct a representative baseline survey

The next step is to conduct the first survey to obtain a general understanding of the situation. This is called the baseline survey. It is important to interview a large sample of the population in order to obtain a representative perspective on the attitudes and behaviour of the population and to identify important subgroups. The following rule of thumb can be applied to determine the minimum number of households to be interviewed: If the number of all households in a village or region is less than or around 200, then 20% of the households should be interviewed; otherwise 10% of the households should be sufficiently representative. It should be noted that once chosen, the same selected group (or panel) of individuals are surveyed in all further surveys and interventions in order to follow their behaviour over time. It should also be noted that for reasons of comparison, different BCTs will be carried out in separate regions, and one control group is also required. Thus, there will be a minimum of two regions. It is also possible to test different BCTs sequentially with one test group, but it should be kept in mind that the BCT “history” will affect outcomes.

Fig. 8.5 *Training interviewers, Bangladesh*

The first vital preparation task is to conduct a thorough interviewer training course, at which interviewers learn how to conduct interviews and how to explain the questions in ways that are understandable to the local population, and then rehearse these interviews. Interviewers need to learn about basic health behaviour theory, facts about the particular contamination (arsenic or fluoride) and safe water options.

The next task is to test the questionnaire. Each interviewer conducts two interviews, the aim of which is to identify questions that cannot be clearly understood or that do not show any variance (i.e. that were answered the same way by all respondents). The identified items need to be reworded or omitted.

The final task is to randomly select households, as the target population is usually too large to conduct interviews with everyone. The selection cannot be left up to the interviewers, because a bias in the results would probably arise (e.g. by selecting only the closest households). Random selection of the respondents (those providing answers to the questionnaire) from a list of the total population would be ideal (e.g. by tossing a coin). If such a list is not available, the random-route method can be applied: the interviewers are sent to randomly selected road intersections that are evenly distributed over the whole study area. From there, they select the households according to a fixed plan (e.g. every third house).

Fig. 8.6 *Interview with a woman responsible for fetching water, Ethiopia*

Step 5: Tasks

- → Recruit a team of local interviewers
- → Train the interviewer team in how to approach households and in interviewing techniques
- → Test your questionnaire in the field (on approx. 20–30 households)
- → Get information on population figures in your project villages
- → Randomly select households for interviews
- → Conduct the baseline survey

Example

In the Ethiopian case study (Tool_1), eight local college students were chosen after a test and personal interview. These students were then trained for four days. The training included: information about the project, fluoride, fluorosis and its prevention; how to approach households; how to handle rejections and difficult situations; interviewing techniques; and questionnaire. After the training, the questionnaire was tested in the field on 20 households. We were informed by the regional office and the community leader that approximately 320 households belong to our project village. The team decided to approach 100 households for interview (as sufficient funds were available). The random route procedure was introduced, and interviewers approached every third household on their route.

8.6 Determine the factors steering the target behaviour

The next step is to determine which factors are most decisive for different behaviours. We can do this based on either basic estimates or statistical analysis. The latter is better but requires some skills in statistics. Basic estimates can be made on paper or with a simple calculation program (e.g. Excel), while the statistical calculation requires a statistics program (e.g. SPSS).

Dividing the sample into non-performers and performers

For a basic estimate, we first have to differentiate between non-performers and performers of the target behaviour. If the behaviour is performed for 0% or for 100% of the time, then the distinction is easy, but values usually range between 0% and 100%. It is therefore necessary to define cut-off values. For example, if there is only an improvement in health when 90% of the drinking water consumed is contaminant-free, then people consuming less than 90% contaminant-free water would be considered as low performers and people consuming 90% or more contaminant-free water as high performers.

Calculate means

Next, we calculate the mean for each behavioural factor for both groups (non-performers and performers). The greater the difference between the means of the two groups, the more important the factor is. Note that for this step, it is important that all variables be on the same scale (e.g. from 0 to 4).

For statistically more reliable results, we recommend regression analysis, but this might require expert support (for a short description, see Mosler, 2012).

Step 6: Tasks

- → Look at the example Excel sheet to understand the procedure
- → Take your data and perform the steps described above

Tools

Tool_3: Example Excel Sheet for calculating means

Example

Our example case is found in Tool_3. For fluoride, it is essential that the total water consumption (drinking and cooking) of a household is fluoride-free. We therefore defined performers as people who consume 100% fluoride-free water and non-performers as people who consume less than 100% of fluoride-free water. We found 50 households to be performers and 50 households to be non-performers (remember, this is a fictional example). For these two groups, we calculated the means of all factors from the RANAS model (including our new factor, “guest norm”). In Tool 3, only 5 factors are shown. Calculating the means of both groups for each factor and then looking at the difference between the two means, we found that the two groups differ most in the descriptive norm (“what others normally do”) and commitment towards using the community filter. These two behavioural factors will be most important in steering target behaviour.

8.7 Define and design interventions to change significant behavioural factors

We now know which behavioural factors are most significant and can now apply the Behaviour Change Techniques (BCTs) that correspond to these. In the following paragraphs, each behaviour change technique is described in detail, and examples from different projects are given. The BCTs are based on Albarracin et al. (2005), Michie et al. (2008), Abraham (2011) and Mosler (2012).

Information BCTs to address risk factors

Information and education are BCTs. Risk perceptions can be influenced by information which people can use to gain an understanding of the health threat.

Presentation of facts / knowledge transfer: Verbal presentation, pictures and/or videos are common techniques used to communicate the circumstances under which a disease can be contracted.

Personal risk information: Individualised messages may focus on cumulative risk effects and on presenting qualitative and quantitative examples to each person individually. It can also be useful to request people to appraise their own susceptibility; this may lead to a discussion of their invulnerability beliefs.

Fig. 8.7 *Women's educational workshop, Ethiopia*

Showing scenarios: Presenting situations in the everyday life of the person where she or he can contract the disease is powerful, scenario-based risk information.

Fear arousal: Graphic illustration of pain, distress, bodily disabilities or even death are more effective in arousing fear than theoretical arguments.

Persuasive BCTs to address attitudinal factors

Instrumental beliefs can be changed by persuasive interventions with strong arguments or peripheral cues.

Persuasive arguments: These use causal explanations, explain technical functionality, present novel and important information and are of high positive expectancy value.

Persuasive peripheral cues: Examples of such cues are competence, sympathy, credibility, fame, publicity and the length and number of arguments in the message.

Talking to others: A person is subject to the self-persuasion they need to generate or reuse arguments in favour of the new behaviour.

Affective persuasion: The new "healthy behaviour" is promoted to be pleasant or joyful, and aversion is associated with the "unhealthy behaviour".

Norm BCTs to address normative factors

BCTs targeting norms aim to change normative beliefs about other people's behaviour and their appreciation of the new behaviour.

Highlighting norms: This BCT focusses on a still infrequent but desired behaviour using positive messages – how others will think well of you. Injunctive normative messages, about how others will disapprove of your behaviour, are also effective, while a message that an undesired behaviour is regrettably frequent (descriptive norm) is counter-effective.

Informing about others' approval/disapproval: Knowing that other people who are considered important (e.g. traditional leaders) support the desired behaviour or disapprove of the unhealthy behaviour is an important motivator to comply.

Public commitment: People make public their commitment to a favourable behaviour, thus showing to others that there are people who perform the new behaviour.

Anticipated regret: People are brought to imagine the concerns and regret they would feel after performing undesired behaviours which are not consistent with their personal norms of living healthily.

Infrastructural, skill and ability BCTs to address ability factors

Infrastructural, skill and ability BCTs help people to gain confidence in their ability to perform a behaviour.

Setting up infrastructure: Having access to the necessary infrastructure (e.g. vessels for water collection, filters for filtering water etc.) is a precondition for performing the behaviour. The infrastructure can be provided externally (e.g. community filters, neighbouring wells) or privately by the household itself, perhaps with some external help (e.g. household filters).

Guided practice: The target behaviour is demonstrated, instructed and enacted, and feedback is given.

Financial resources: Financial support may be given directly to the persons and may be coupled to the condition that some effort be made to obtain some financial resources for remaining costs.

Social help: Neighbours, friends, acquaintances or relatives encourage and support the person with material help and practical advice.

Provide instruction: Skills can be enhanced by conveying know-how.

Modelling: Persons who perform the behaviour and who are perceived as competent and successful serve as role models.

Reattribution of past successes and failures: Self-efficacy is fostered if failures are not attributed to the persons themselves but to adverse circumstances; successes, in contrast, are attributed to the person.

Coping with barriers: Self-efficacy can be improved by identifying barriers to the new behaviour and seeing how these could be overcome.

Coping with relapse: Risky situations, in which a person might fall back into the old behaviour patterns, can be counteracted by planning coping responses and by practicing these responses until they become automatic.

Fig. 8.8 *Public commitment at a women's workshop, Bangladesh*

Planning & relapse prevention BCTs to address self-regulation factors

The focus here is on self-regulation.

Daily routine planning: Planning fosters action control as the person is prompted to plan exactly when to perform the desired behaviour in the course of daily life. Discussions are held with the person about how (and when and where) to integrate the new behaviour into her/his daily routine.

Outcome feedback: Feedback is given on the effects (e.g. on health) that result from the desired behaviour, or the person herself/himself checks for these effects (self-feedback).

Contingency management: The person builds her/his own incentive system so that she/he is rewarded each time the desired behaviour is performed.

Stimulus control: Coping planning can be carried out by removing reminders or cues to engage in old behaviours and adding cues or reminders to engage in the new behaviour.

Prompts: These are cues or reminders that trigger the behaviour in the right situation.

Commitment: Individuals are stimulated to formulate when, where, and how they intend to achieve their goals.

Step 7: Tasks

→ Take your calculation from step 6 and identify which of your behavioural factors has the strongest intervention potential (the biggest difference in means between groups)

→ Link your behavioural factors with the strongest potential to the list above and identify possible BCTs for influencing that factor

→ After identifying possible BCTs, check the examples provided and decide whether these would be applicable in your case, or design new BCTs using the explanations in this section

Examples for BCT designs:

- Design_1: Information BCT loudspeaker rickshaw in Bangladesh
- Design_2: Persuasive BCT in Ethiopia
- Design_3: Knowledge transfer BCT in Ethiopia
- Design_4: Risk information BCT in Bangladesh
- Design_5: Public commitment BCT in Ethiopia
- Design_6: Pledging BCT in Bangladesh
- Design_7 : Coping planning BCT in Bangladesh
- Design_8: Daily routine planning BCT in Ethiopia
- Design_9: Implementation intention BCT in Bangladesh

Example

We have found that the most promising factors to be addressed when attempting to change people's behaviour are the descriptive and commitment norms. That means that we could apply two interventions. Here we focus on the public commitment BCT.

In order to compare the effect of our BCT, we divide our sample into two groups: an intervention group and a control group. The intervention group is made up of 25 randomly selected households that are 100% users of the fluoride-free water source and 25 households who are defined as non-performers (i.e., those who do not use, or only partially use, the safe-water source). All other households are assigned to the control group (and do not receive a BCT).

8.8 Define suitable communication channels

The behavioural interventions have to be brought to the target population in the most effective way. The communication channels can be impersonal (via mass media) or personal. By talking to people (interpersonal communication) we can better address motivations specific to each individual. Many investigations have shown that interpersonal channels are more effective, but more people can be reached with mass media (Albarracin et al., 2005; Mosler and Martens, 2008; Tamas et al., 2009). The choice of whether to use impersonal or personal communication channels will depend on the potential access to mass media, on financial resources and on what kind of channel people are accustomed to. In the following paragraphs, the different channels are briefly described.

Mass media

Mass media can be divided into print media (newspapers, brochures and leaflets), audiovisual media (radio, television or loudspeaker systems on cars) and the internet. In the following, some of the most important uses of the channels are outlined. For an example of a mass media communication channel, see **Design 1**.

Informative report: Information is disseminated about a disease is contracted and what kind of behaviour can prevent this.

Mass media role modelling: The people are given advice from experts using role-model stories of community members who are perceived as attractive and similar in lifestyle to themselves, to increase the adoption of new behaviours.

Entertainment-education: Portrayals of popular role models and reinforcements in various formats, such as soap operas, popular music, films and comic books.

Behavioural journalism: Potential models are interviewed with questions designed to elicit informative reasons for adopting the new behaviour, on skills used or acquired in adopting the behaviour, and the perceived positive outcomes.

Fig. 8.9 Mass media campaign with loudspeaker rickshaw, Bangladesh

Interpersonal channels

Using interpersonal channels means that one or more persons communicate messages to a single person or a group of people.

Community meetings: BCTs can be introduced with messages or demonstrations, in a show, quiz or theatre play, open to all community members.

Home visits with promoters: Promoters can be hired and trained for door-to-door promotion of the new behaviour.

Opinion leaders: Persons open to innovation, who are of high social status within a social system (community), can be trained as voluntary social workers to promote the new behaviour within their social network.

Peer-to-peer communication: People are persuaded to do word-of-mouth advertising by talking positively about the new behaviour.

From teachers to children to parents: Teachers are instructed to educate their pupils in behaviour change, and then the pupils transfer the information to their parents.

Small-group training: The new behaviour is introduced and demonstrated to a small group, and the pros and cons of the new behaviour are discussed.

Mobilising social networks: Group members are linked to new networks, for example mentor programmes, buddy systems and self-help groups, that practise the new behaviour.

Fig. 8.10 *Interpersonal communication: a health promoter talking to the head of a household, Ethiopia*

For many interventions (BCTs), both communication channels can be used. However, interpersonal channels are more effective for communicating some BCTs (Table 8.2). For examples of interpersonal channels, see **Designs 2 to 9**.

Table 8.2 *BCTs that are best communicated through interpersonal channels*

BCT categories	BCTs
Information	Personal risk information Showing scenarios
Norm	Anticipated regret
Infrastructure, skill and ability	Reattribution of past successes and failures Coping with barriers Coping with relapse
Planning and relapse prevention	Outcome feedback Contingency management Stimulus control Prompts Planning the daily routine Commitment

Step 8: Tasks

- → Check the table above (Table 8.2) to see how your planned BCTs can best be communicated
- → Check on financial and human resources and talk to local partners to determine what communication channels are available
- → Implement your BCTs

Example

As we are working in a rather small village, we can reach our target population through interpersonal channels. Having checked our resources, we decide to employ health extension workers from the village to deliver our public commitment intervention (blue flags to highlight which and how many households are already consuming 100% fluoride-free waters) (see **Design 8**).

For ethical reasons, the control group receives the most effective intervention at the end of the field test after the final survey.

8.9 Evaluate the effectiveness of the BCTs and their long-term effects

With this evaluation, we aim to determine how effectively the BCTs have changed behaviour. There may be several consecutive intervention campaigns in one area, and each must be evaluated with an intermediate survey after 1–2 months. A final survey is conducted 6–12 months after the last intermediate survey. During this 6–12 month period, there should be no interviews or interventions in the project area.

An alternative is to carry out BCTs in different areas, including one control area. In such a case, exactly the same questions need to be posed in all surveys in order to analyse how behavioural factors change over time as a result of interventions. Additional questions should be included to check whether the BCTs were delivered as intended. Did the targeted group participate in BCTs? Did people like or dislike the BCTs? What can they remember about the BCTs?

The effectiveness of the BCTs is evaluated by comparing the change in behaviour of groups who received a BCT with groups who did not. The analysis shows whether the targeted behavioural factors were actually changed or not and provides information on how the campaign should be modified.

The final survey is vital in order to evaluate the long-term effects of BCTs. This questionnaire should specifically focus on assessing whether and why people have stopped performing the target behaviour. This information is important for further relapse prevention, so that new or more BCTs can be designed.

Fig. 8.11 *Interviewing a woman responsible for water treatment, Bangladesh*

Step 9: Tasks

→ Tool_4: Intermediate questionnaire, Ethiopia

→ Tool_5: Intermediate questionnaire, Bangladesh

→ Tool_6: Final questionnaire, Ethiopia

→ Tool_7: Final questionnaire, Bangladesh

→ Tool_8: Example Excel sheet for calculating intervention effects

Tasks

→ After the implementation of the BCTs, wait for 1–2 months

→ Prepare your intermediate questionnaire by adding appropriate questions about the BCTs to your baseline questionnaire

→ Conduct the intermediate survey to evaluate the intervention effects

→ After the last survey, wait for 6–12 months and make sure that during this period, there are no activities taking place in the project area

→ Prepare your final questionnaire by adding appropriate questions about the reasons for stopping the target behaviour to your intermediate questionnaire.

→ Conduct your final survey to evaluate the long-term effects of BCTs and design new BCTs for relapse prevention

→ Calculate the short- and long-term effects of BCTs with the help of Tool 8

Example

First we check whether our public commitment BCT had a positive effect on changing the commitment. Using Tool_8 (Sheet 2 in the Excel file) we can now see how people changed their behaviour over time. The group who received a public commitment BCT used more filtered water themselves, perceived an increase in the use of filtered water by others and felt themselves to be more committed. The findings for the control group were similar but less marked. This result is not surprising, given the fact that both groups were living in the same village. The fact that people in the village committed themselves in public to use the community filter must have had an effect on their descriptive norm (what others normally do).

Ten months after the intermediate survey, we conducted our final survey to evaluate the long-term effects of our BCT. The data that we collected can be seen in Tool_8 (Sheet 3). There we added an extra column for entering the data from the final survey. If we now calculate the differences between the means from the final and the intermediate survey we can see the long-term effects in both groups. In our example, we find that the behaviour of the public-commitment-BCT group had stabilised, while that of the control group had decreased over time.

These results indicate that if the new behaviour is not promoted, the initial increase in the use of a new technology can lapse with time.

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9 Case studies and applications

9.1 Implementation of defluoridation filters in Ethiopia

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Background

It is estimated that more than 8 million people live in fluoride-affected areas in Ethiopia (Rango et al., 2012 and references therein). The main sources of fluoride are basaltic rocks, which have both elevated fluoride content and low soluble calcium concentrations. In the Ethiopian Rift Valley, over 40% of deep and shallow wells are contaminated, and fluoride levels are often significantly higher than the present international WHO guideline value of 1.5 mg/L (Tekle-Haimanot et al., 2006). As a result, dental and skeletal fluorosis is widespread among the population of the Rift Valley. The mitigation of this health problem has been hampered mainly by the lack of suitable, inexpensive removal methods and technical support. A switch to treated surface waters for drinking is being discussed, but it is accepted that fluoride removal systems for rural communities are required, at least until longer-term solutions can be put in place. Therefore, in 2009, in collaboration with Addis Ababa University, Eawag launched the research project, “Optimization and acceptance of fluoride removal options in rural Ethiopia”, funded by the Swiss National Science Foundation and the Swiss Agency for Development and Cooperation.

Aim

The aim of the project was to combine technical and social research with field implementation to find a suitable and acceptable solution for the problem of fluoride contamination in drinking water in rural Ethiopia:

- To compare and optimise the removal efficiency of two different filter materials in the laboratory and subsequently to test the performance of these technologies in the field
- To assess the personal, social and situational factors that influence the continuous use of fluoride removal systems by the rural population
- To investigate the institutional settings and identify stakeholders’ interests and preferences for the implementation of fluoride removal
- To investigate fluoride uptake pathways via food and water
- To strengthen the institutional capacity for research and implementation in Ethiopia

Intensive interaction between physical and social sciences was indispensable in this project, because even the best technical solution is useless when it is not accepted by the population. Another important goal of this collaborative project was capacity building and human resource development in Ethiopia. It included a south-south knowledge transfer between Kenya and Ethiopia that was aimed at strengthening the research capacity of Addis Ababa University. The participation of NGOs consolidated the ties between research and implementation. Furthermore, the results should be applicable not only to Ethiopia but also to other fluorosis-affected developing countries.

Partners

Addis Ababa University (AAU): Main research partner of Eawag. The Chemistry Department developed an aluminium-based filter medium (AO). The institutional analysis of the Ethiopian water sector was conducted through the Department of Political Science and International Relations.

Nakuru Defluoridation Company Limited (NDC): Producer of high-quality bone char and calcium phosphate pellets in Nakuru, Kenya. Eawag and NDC have been working jointly on optimising the Nakuru Technique since 2006. NDC provided bone char and pellets to the research project.

Oromia Self-Help Organization (OSHO): Local NGO and field implementation partner of Eawag. Since 2007, OSHO has been introducing bone char household filters funded by Swiss Interchurch Aid (HEKS), with technical support from Eawag and NDC.

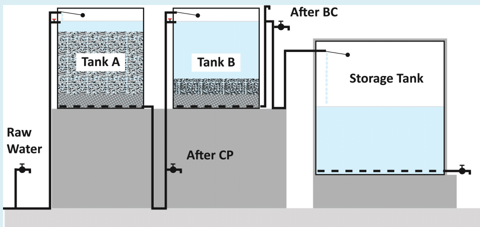
National Fluorosis Mitigation Project Office (NFMPO): The office is currently located at the Ministry of Water and Energy and took up work in 2009. Information was exchanged regularly with other project partners.

Key stakeholders that were involved in the project included water offices at national, regional, zone and district levels, development partners interested in fluoride mitigation, Ethiopian research institutions, water committees and beneficiaries in the project villages. A number of workshops with stakeholder participation were held during the course of the project to strengthen stakeholder involvement in decision-making and to disseminate results.

Integrative approach

Two community fluoride removal filters were constructed in the Ethiopian Rift Valley for detailed field testing, one using the Nakuru Technique (Section 5.3) and one using aluminium (hydr)oxide (“AO”, a filter media developed by Addis Ababa University). The filter sites were selected during a workshop in Addis Ababa in November 2009, in consultation with representatives from regional, zone and district (woreda) water offices. For the sake of convenience, only the results from the community filter using the Nakuru Techniques in Wayo Gabriel village are discussed in this chapter (see Fig. 9.1).

A separate meeting was held with the local water committee, village administrators and a district representative to set the tariff for treated water in time for the opening of the filter. The water committee is an elected group of people from the village responsible for managing a water scheme. Individuals usually have to pay for drinking water in the Ethiopian Rift Valley, so paying for water was not a new concept. The intention was to set a water tariff that covered the operator's salary plus more than 50% of the costs during filter media replacement during the three-year project, and to explore the potential of 100% medium-cost coverage in collaboration with OSHO for the long term.



Community Filter using the Nakuru Technique

(Inauguration in May 2010)

Wayo Gabriel, Dugda Woreda, Oromia Region
(approximately 320 households)

Connected to a small piped water supply system with a fluoride concentration of 3 mg/L

Water tariff: 0.50 ETB (about USD 0.03) per 20 L jerrycan

Tank A is filled with 900 L calcium phosphate pellets mixed with 300 L bone char, and tank B with 300 L bone char*. All are imported from NDC, Kenya.

* The bone char layer is placed in Tank B for research purposes. For normal operation, all material is first placed in one tank. The second one would be filled when the fluoride level exceeds the desired fluoride level in the first tank.

Fig. 9.1 *Technical details of the community filter in Wayo Gabriel*

The filter design was adapted from the one-tank systems used by NDC in Kenya to a more sophisticated version that guarantees optimal utilisation of the filter medium. The system consists of two filtration tanks in series (2 m^3 each), of which either can be used as the main tank (first) or the polishing tank (second). When fluoride breakthrough occurs, the filter medium in the main tank is replaced and the flow reversed (the main tank with the fresh filter medium then becomes the polishing tank, and vice versa). A storage tank for the treated water (5 m^3) allows a slow and continuous water flow, while providing sufficient reserves for times of greater demand. (From previous laboratory experiments, it is known that the fluoride uptake capacity of the Nakuru Technique increases with reduced flow rates). The system is sufficiently simple to handle, so that the operator, usually someone from the village, does not need special skills except for some basic training. The operator is also in charge of collecting the water fee from the users.

The different components of the integrated study are shown in Figure 9.2.

Fluoride uptake through food and water

To determine the amounts of fluoride ingested through food and water, interviews were conducted with 20 families on their daily diet over the previous seven days and on recipes for the most common dishes. Based on this information, the most commonly consumed food ingredients were collected in nine households around Wayo Gabriel and analysed for their fluoride content. The selected households collected drinking and cooking water from three different water sources with fluoride concentrations of 0.75 mg/L (average of water treated at the community filter 0–1.5 mg/L), 3 mg/L and 10 mg/L. Using the information from the interviews and the results from the analysis to estimate mean daily consumption, the mean daily fluoride uptake through food and water was calculated.

Filter performance

Data on the quality and consumption of the treated water were collected in order to analyse the fluoride removal performance of the filter and to guarantee safe drinking water for the consumers. Weekly measurements of fluoride concentrations were conducted and water meter readings taken to find out how much water had been consumed. On a monthly basis (and more frequently during the first few months), water samples were taken from all four sample taps (raw and treated water after Tank A and after Tank B), and a complete chemical analysis was carried out. Fluoride measurements were generally conducted every week.

Behavioural change

In both villages with community filters, a baseline survey to determine the psychological factors that influence the desired behaviour (using fluoride-free water for drinking and cooking) was conducted using structured questionnaires in 100 randomly selected households in each village. Three different behavioural change campaigns (interventions) were then undertaken to promote the use of the filtered water.

Surveys were conducted after each intervention and at the end of the 18-month promotion period. A team of ten local college students were recruited and trained to conduct the interviews. The duration of one interview was, on average, one hour per household; the questionnaires were translated into Amharic and Oromifa.

Institutional analysis

This task was performed in four steps.

Step 1: Stakeholders involved in fluoride mitigation in Ethiopia were identified through literature review and contacts with experts in the field.

Step 2: Seventy end-users in the field (35 of them in Wayo Gabriel) were interviewed personally by the PhD student about affordability and access to safe drinking water, using semi-quantitative questionnaires.

Step 3: Representatives from water offices at different levels, development partners and members of the National Fluorosis Mitigation Technical Advisory Committee were selected and interviewed, using a qualitative questionnaire, about sustainability, preferences, opportunities and the threats of different fluoride mitigation options.

Step 4: A Multi-criteria Decision Analysis (Section 9.3) was carried out during the final project workshop to compare stakeholders' preferences which referred to different fluoride removal technologies.

Cost and Affordability

One of the most important aspects that needs to be addressed in order to achieve sustainable and successful fluoride mitigation in Ethiopia is the issue of cost. When donor funding runs out, can the costs of fluoride removal still be covered? Within this case study, an analysis of the expenditures that need to be taken into account when installing and managing a fluoride removal filter was carried out. More details about the individual cost components can be found in IRC (2011).

Capital Expenditure (CapEx): These are the funds that need to be invested in fixed assets, such as filter tanks and pipes, in initial awareness raising campaigns and in training operators, in the water committee and the district water office. CapEx can pose a significant investment at the start of a project.

Capital Maintenance Expenditure (CapMEx): Occasional cost of renewing (replacing, rehabilitating, refurbishing) essential parts of the system (e.g. filter material) in order to ensure that services continue at the same level of performance that was first delivered.

Operation and Minor Maintenance Expenditure (OpEx): Cost of daily operation and light maintenance (e.g. power, salary of operator). OpEx does not include costs of major repairs.

Expenditure on Direct Support: Pre- and post-construction support activities directed at local stakeholders and users. This could include monitoring, technical advice, administrative or organisational support, conflict resolution, capital maintenance, training and refresher courses, the provision of information and resource mobilisation.

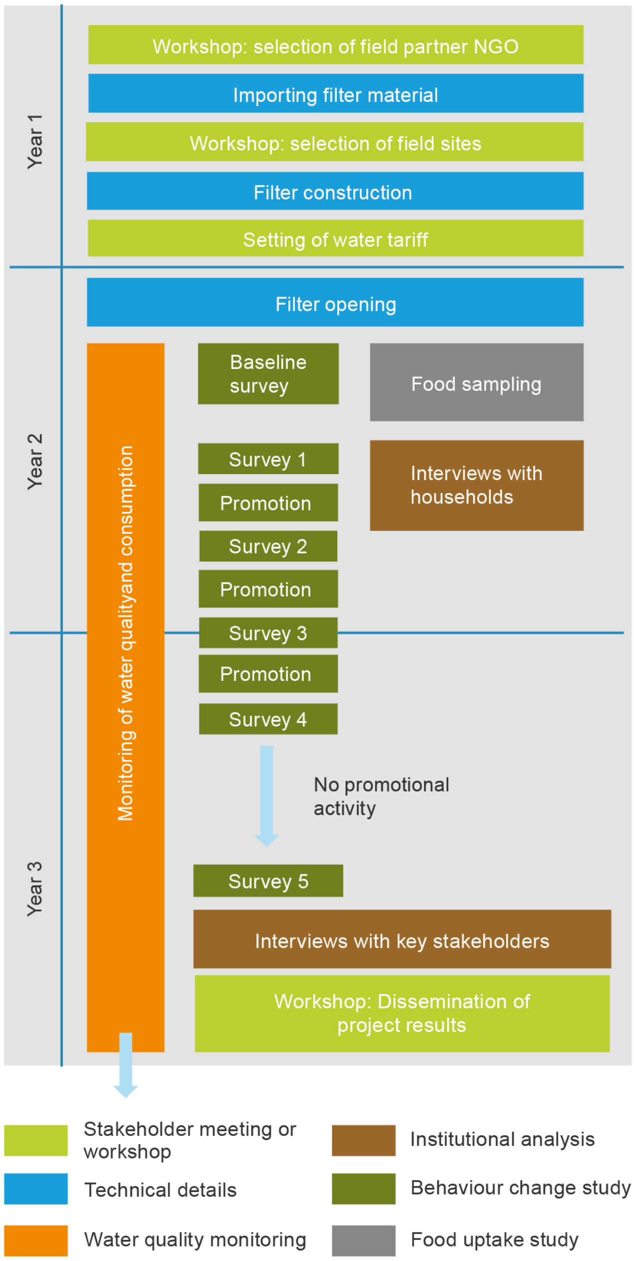


Fig. 9.2 *Project planning overview*

Results

Fluoride uptake through food and water

The total average fluoride intake of an adult consuming treated water for drinking and cooking from the community filter was estimated to be around 6 mg/day. (For comparison, the daily fluoride intake of an adult consuming water with 10 mg/L is 25 mg/day.) This is close to the tolerable upper intake level (Table 3.3).

Filter performance

The Nakuru Technique community filter was not saturated at the end of the research project, mainly due to an initially low water consumption. Based on the experience of NDC in Kenya, it was expected that the filter could treat at least another 750 to 1000 m^3 until fluoride breakthrough, if not more, because of the improved design compared to the NDC filters. Nevertheless, the field test in Ethiopia revealed two major challenges remaining for this optimised and more sophisticated filter design:

Slow and continuous flow: The stainless steel tanks could not be pressurised as planned because of leaks in the lid seal. Instead, the operator needed to turn the main water line on and off manually. As a result, water passed rapidly through the filter tanks for only a few hours instead of the intended slow and continuous flow over 24 hours. This is the reason for the fluoride level fluctuation after tank A (see Fig. 9.3). Nevertheless, the bone char layer was still able to remove all remaining fluoride.

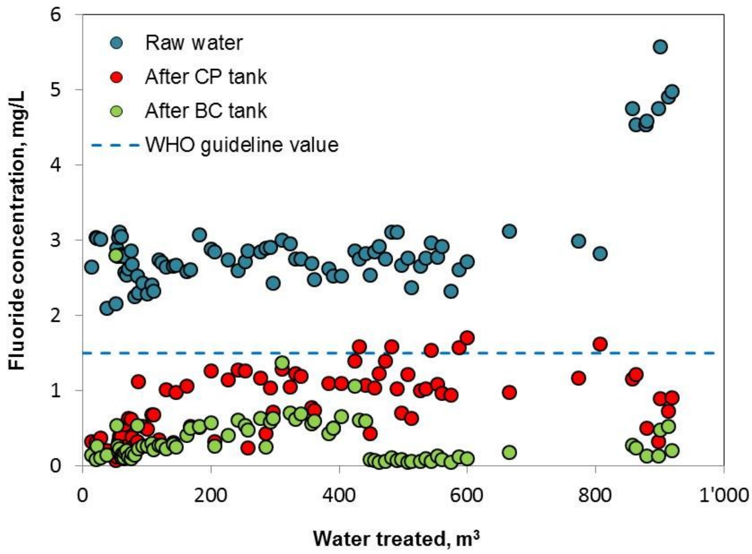


Fig. 9.3 *Results of fluoride monitoring from 20.05.2010 to 28.02.2013 in the Nakuru Technique filter. CP: contact precipitation ("Nakuru Technique"), BC: bone char. At around 800 m3, the concentrations of fluoride and salts in the raw water rises.*

Two interchangeable filter tanks: The operation proved to be more complicated than expected. After 50 m^3 of water had been treated, a wrong valve was opened, and raw water bypassed the system. After this incident, another valve was not completely closed, and some water passed only through tank A but not through tank B. This was noticed and rectified after 450 m^3 of water had been treated.

These problems were finally resolved by installing float valves in the two filter tanks to control the water flow automatically. A detailed operation manual for the filter is being developed in participation with OSHO, district water officers and community filter operators.

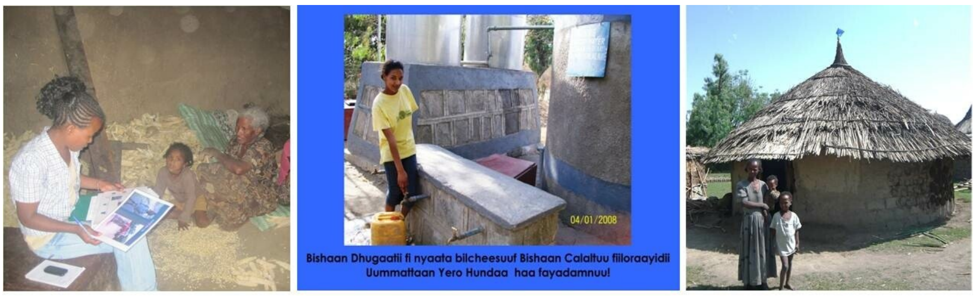
Behaviour change

The baseline survey in Wayo Gabriel revealed that the consumption of fluoride-free water was hindered mainly by (i) high perceived costs but also by (ii) perceived taste, (iii) perceived ability and (iv) commitment (Section 8.3, Huber and Mosler, 2012; Huber et al., 2012). Furthermore, the behaviour of others had a strong influence on individual households (people who think that many others are also collecting water from the community filter are more likely to collect water from the same source themselves). Based on this understanding of psychological factors, the following interventions were conducted to increase the consumption of fluoride-free water and to keep consumption sustainably high (Huber et al., 2014; Fig. 9.4):

Phase 1: Persuasion campaign. Households were visited by a health promoter who was trained in persuasion techniques to tackle perceived costs (determined by the baseline survey to be an important factor) and perceived vulnerability (conventional wisdom holds that raising awareness about the severity of health effects may stimulate behaviour change).

Phase 2: Photo promotion. People that fetched water at the community filter had their picture taken, and they received these with a reminder slogan added below the picture (Fig. 9.4). The promotion aimed to motivate new users to try filtered water and to help people (with the picture as a reminder) to remember fetching water at the community filter.

Phase 3: Flag promotion. Households were again visited by promoters and asked to commit themselves to consume only fluoride-free water in the future. A blue flag was installed on the household's roof to make their commitment public. The aim of this was to increase people's commitment and at the same time, to inform other villagers that the people in that particular household were consuming treated water.



Persuasion *Photo promotion* *Flag promotion*

Fig. 9.4 *Behaviour change interventions*

An increase in fluoride-free water consumption by people who had received the photo reminder and had put it up on the wall where it was visible was observed in Phase 2. The flag promotion in Phase 3 resulted in an increased average fluoride-free consumption of all households in the area. People who had committed themselves and had a flag on their roof increased consumption significantly more than others. However, an increase in fluoride-free water consumption was also observed by those who had not received the commitment intervention. They probably saw the flags all over the village and therefore realised that many of their neighbours were using fluoride filtered water.

After a 6-month break during which no surveys or interventions were carried out, the long-term effectiveness of the behaviour-change activities was evaluated. Most photos and flags were still in place, and all of the households that had switched to the consumption of fluoride-free water were still buying this water. The overall consumption was still high, even though people without any intervention slightly decreased their consumption. In general, it can be concluded that the promotion strategies were very successful in increasing and maintaining the consumption of fluoride-free water within the community, with the exception of the "conventional wisdom" intervention targeting awareness of the risk of contracting fluorosis.

Institutional analysis

Figure 9.5 shows stakeholders that were identified as being active in fluoride mitigation in Ethiopia. Many are supportive, and a few stakeholders are neutral or unsupportive. The National Fluorosis Mitigation Project Office (NFMPO) was found to have established a reasonable basis for coordination and communication between different stakeholders. An important point to be addressed in the near future is the location of the NFMPO; i.e. whether it should be embedded in the existing institutional structure of the Ministry of Water and Energy (MoWE) or whether it should be set up independently in a research institute or a university. There are several organisations that could become more involved. Of these, the Ministries of Health and Education would be important partners.

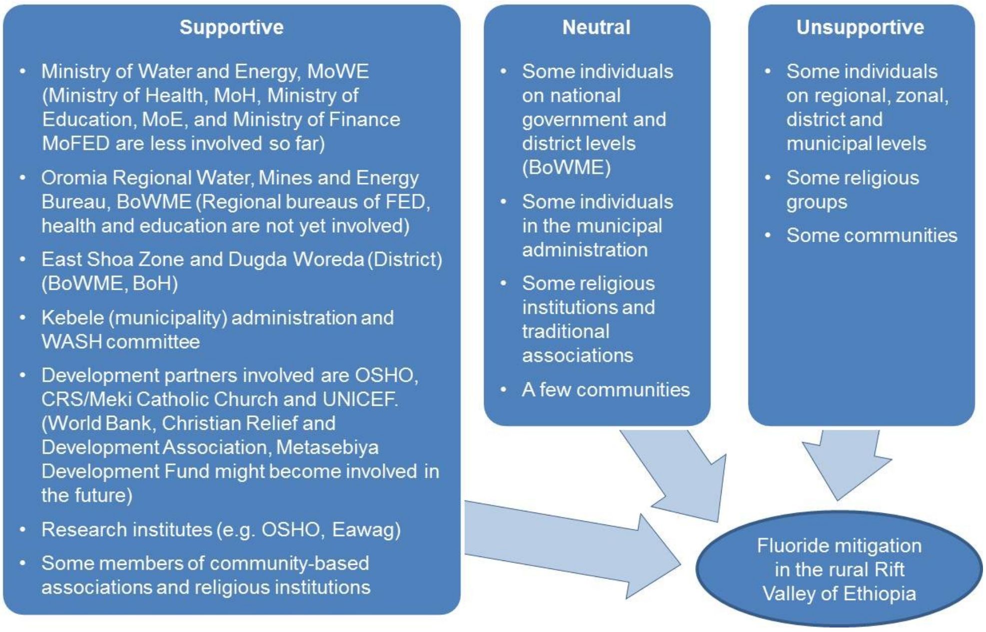


Fig. 9.5 *Map of stakeholders involved in fluoride mitigation in the Ethiopian Rift Valley*

Cost and affordability analysis

Under the current situation, when all types of costs are considered, rural communities in Ethiopia are not (yet) able to afford fluoride removal activities without significant subsidies from other sources such as governments or NGOs. This is especially the case when fluoride concentrations in the raw water are high, and the filter material needs frequent replacement or regeneration. There is a remaining need for fluoride mitigation options to be developed or adapted in order to achieve higher cost-effectiveness. Organisations that are implementing fluoride removal units need to assess carefully the willingness and ability of stakeholders (beneficiaries, government, NGOs) to cover certain types of costs sustainably. Cost indicators should be included in the monitoring procedure.

Conclusions

The results of the intake analysis show that a high percentage of fluoride is taken up via water used for drinking and cooking. If fluoride-contaminated water is treated with a removal technique, a significant reduction in the risk of developing skeletal fluorosis can be expected. The Nakuru Technique fluoride removal community filter in Wayo Gabriel can reduce fluoride concentrations to below the WHO guideline of 1.5 mg/L, although the fluoride uptake capacity should be increased further to make the system more cost-effective (and reach 100% cost coverage by the local community). The adapted filter design could contribute to achieving this goal, but only if the operation is carried out properly. It was shown that the Nakuru Technique is well accepted by consumers. This contradicts previous studies that stated that bone char is generally culturally not acceptable in Ethiopia. It was also shown that simply providing a filter is not sufficient; in Wayo Gabriel, it was only after well-designed promotional campaigns that the majority of consumers used fluoride-free water for drinking and cooking purposes. However, fluoride exposure through food remained at levels high enough to cause dental, and possibly also skeletal, fluorosis. While reducing fluoride exposure through water is necessary to mitigate fluorosis, it is not sufficient. The results of the Ethiopian case study were communicated to the major stakeholders during a two-day workshop in April 2012 in Addis Ababa.

Recommendations

- More focus on the “software” components. Capacity building for local authorities and NGOs in effectively promoting behaviour change in communities, combined with close monitoring of the consumption of fluoride-free water.
- Close monitoring and documentation of newly installed fluoride removal options during the first few years to further optimise filter design and to obtain information on real filter performance and costs.
- Reduction in the overall costs of defluoridating drinking and cooking water. This could include optimising the production of the filter media, regeneration or reuse in agriculture and testing of newly developed, low-cost filter media in the field.
- Increased involvement of health authorities in fluoride mitigation by supporting a combination of fluoride removal with microbiological drinking-water treatment, sanitation and hygiene promotion. Health impact studies could complement further fluorosis mitigation activities.
- Food intake represents a significant source of fluoride exposure. Strategies need to be developed to reduce fluoride exposure through foodstuffs through changes in either agricultural or cooking practices.

9.2 Assessing stakeholder preferences in Bangladesh

Richard B. Johnston, Stephan J. Hug, Jennifer Inauen, Nasreen Khan, Hans-Joachim Mosler, Hong Yang, C. Annette Johnson

Background

Widespread arsenic contamination of shallow (<150 m) and some deep tubewells was first identified in 2000 (BGS/DPHE, 2001). Of the total population of 125 million in Bangladesh, it was estimated that 57 million were exposed to arsenic concentrations above the WHO provisional guideline value of 10 µg/L, while 35 million were consuming water with concentrations above the Bangladesh Drinking Water Standard of 50 µg/L. Early mitigation efforts focused on technologies such as pond sand filters and hand-dug wells, but these options are more vulnerable to faecal contamination. It was estimated that in comparison to shallow tubewells, deep tubewells were predicted to cause a much lower burden of disease (Howard el., 2006). Deep tubewells were not prioritised in the 2004 national policy and implementation plan because of concerns that deep tubewells might not be free of arsenic in some regions, or that abstraction of deep groundwater could induce downward transport of arsenic from contaminated shallow aquifers. While deep groundwater in certain regions (notably parts of Jessore, Satkhira and the Sylhet Basin) can contain arsenic under specific geological conditions, the last decade has shown that deep tubewells are geochemically stable and that the feared draw-down does not occur as long as large volumes of water for irrigation purposes are not abstracted from deep aquifers. These results have given impetus to the already preferred deep tubewell mitigation option. As the capital costs of drilling deep tubewells are high, subventions were necessary. Government programmes contribute 90% of the installation costs.

A second national survey in 2009 found that exposure to 10 µg/L may have been reduced by roughly a quarter (although this just keeps up with population growth) and that exposure to higher concentrations (>200 µg/L) may have been reduced even further (UNICEF/BBS, 2011). As tubewells have a limited lifetime, new wells are continually being drilled, though arsenic is not always monitored (van Geen et al, 2014).

Ensuring that tens of millions of people exposed to arsenic have access to and use safe water is an extremely complex and expensive task, and though progress has been made, there is still a long way to go. The work presented here is based on Johnston et al. (2014).

Aim

The aim of the project was to learn from the experience gained in Bangladesh. Specifically, the aims were:

- To obtain an understanding of existing institutional support for arsenic mitigation

- To elicit households' willingness to pay for obtaining arsenic-free drinking water and the factors influencing their willingness to pay
- To assess personal, social, and situational factors that influence the continuous use of arsenic-free drinking water by the rural population
- To determine which factors would best convince householders to use arsenic-free water sources
- To determine the technical factors that limit the use of deep tubewells and how these can be addressed

Partners

Department of Public Health and Engineering (DPHE) of the Government of Bangladesh. Within the Ministry of Local Government, Rural Cooperatives and Development, DPHE is the lead agency responsible for provision of drinking-water and wastewater management in the country excepting the municipal corporations (Dhaka & Chittagong) and a number of urban pourashavas. DPHE has worked with Eawag on a survey of deep tubewells in a village in Munshiganj.

UNICEF Bangladesh has been one of the leading agencies responding to the arsenic threat facing Bangladesh. Results of a field survey by Eawag's environmental psychologist team to determine the driving psychological factors that cause people to adopt (or not) new arsenic-safe sources of drinking water have been adopted in UNICEF's arsenic communication strategy. Our team members also coordinated with UNICEF Bangladesh on interpretation of nation-wide drinking water quality surveys.

Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh (Prof A.B.M. Badruzzaman, Prof M. Ashraf Ali). BUET is the country's leading engineering research institute. We have worked together on safe installation of arsenic-free wells in arsenic-affected areas, and on removal of arsenic, iron and manganese from drinking-water.

Dr Kazi Matin Uddin Ahmed, Department of Geology, University of Dhaka is a global expert on arsenic contamination of groundwater. We work together in assessing the quality of groundwater in different geological units, not only in terms of arsenic but other chemical parameters including iron, manganese, and salinity.

Dhaka Community Hospital Trust (DCH Trust): The trust-owned private, self-financed and non-profit organization was established in 1988. Its goal is to provide an integrated and sustainable health care delivery system at an affordable cost in both the urban and rural areas of Bangladesh. Besides basic health care services, the trust is largely involved in disaster management, arsenic mitigation, safe water supply and community based development programs. The DCH Trust provided logistic support and staff for the institutional field survey in 2010.

Procedures

The studies were carried out during the same time period, between spring 2005 and autumn 2011, at sites that were most appropriate for individual investigations.

Analysis of institutions governing mitigation activities

The institutional study required preparation to obtain an overview of the institutional setting. Problem scoping and site selection were carried out in the following steps:

Step 1: An overview of national and local governmental and non-governmental organisations, policies, regulations, plans, goals and funding (and funding sources) in dealing with geogenic contamination, as well as available mitigation options and the status of their implementation, were obtained by reviewing the relevant literature and by holding discussions with experts in the field.

Step 2: Governmental, non-governmental and international organisations and experts were contacted through local project partners and personal connections to pave the way for taking further steps.

Step 3: Representative sites with different mitigation measures and levels of geogenic contamination, as well as different natural and socioeconomic conditions, were selected.

Two structured face-to-face questionnaire surveys were developed and conducted to obtain the opinions at the institutional and household levels on various aspects of arsenic mitigation in Bangladesh.

Institutional stakeholder surveys were performed in Munshiganj, Comilla and Pabna districts. A stakeholder survey was conducted targeting officials from central and local government, NGOs, and donors involved in arsenic mitigation (Khan and Yang, 2014). The background to the questionnaires and the type of questions asked is outlined below and are also given in Schmeer (1999) and GTZ (2007).

Institutional survey of stakeholders who can affect actions and outcomes

Structured or semi-structured face-to-face interviews should be held with representatives from:

- Central government
- Local government
- NGOs (central and local levels)
- International agencies
- Donor agencies
- Research institutes

The information to be sought through the interviews should include the following:

- Stakeholders' preferences and interests with regard to different mitigation measures
- Financial resources of organisations involved in mitigation activities (implementation, operation and maintenance of mitigation facilities; e.g. arsenic removal filters)
- Role of different stakeholders in mitigation activities and their influence on these activities;
- Interests and conflicts between different stakeholders.

Understanding the institutional setup at different levels and the interaction between these levels:

- Which institutions/authorities play what roles in managing water resource quality?
- Which are the specific laws, rules or regulations that define these roles (principles, norms, rules, procedures)?

Understanding the available means of execution and enforcement of laws, rules and regulations:

- What laws, rules and regulations exist to assist in the execution, implementation and enforcement of mitigation measures? (There may be none.)
- What means (mechanisms, procedures) are available and have been put in place to enable monitoring and control of compliance to be assessed?

Understanding the forms of governance:

- Are any methods of participatory governance specified?
- What are the participatory governance realities? How is governance organised? Who participates?

Understanding the reality of implementing and enforcing the laws, rules and regulations:

- How well are the laws, rules and regulations implemented and enforced?
- What informal practices exist?

The following example questionnaire is an abbreviated version of the one used for interviewing stakeholders about arsenic mitigation strategies in Bangladesh on the organisational level.

Example: Stakeholder_questionnaire_for_a_survey_at_organisational/policy-level

A householder survey was carried out to determine preferences and willingness to pay for arsenic-free drinking water, as these are critical factors for the success of any mitigation option. The survey was conducted in 13 arsenic-affected rural villages from Sirajdikhan, Sujanagar, Ishwardi and Laksham upazilas (sub-districts). Six hundred and fifty household respondents were asked about their current and preferred water sources and usage practices, awareness of arsenic contamination and medical costs related to arsenicosis, as well as their willingness to pay for or contribute to a new alternative water source, namely, deep tubewells (Khan et al., 2014; Khan and Yang, 2014). This is an important issue, because the financing and successful implementation of a mitigation measure may be dependent on the financial contribution of the users. There are a number of approaches for eliciting willingness to pay. The Contingent Valuation Method (CVM) is one of these. This method emerged in the 1960s and has become widely used since the 1990s. More details on conducting willingness-to-pay surveys can be found, for example, in Wedgwood and Sansom, 2003. An outline of the background to the questionnaires and the type of questions asked is given below.

Local community and household surveys (primary stakeholders)

A structured or semi-structured survey eliciting detailed information relating to:

- Household's sociodemographic characteristics
- Ownership and sources of the drinking-water supply
- Possession of resources, income and expenditure
- Knowledge and awareness of, and local rules and practices for, managing geogenic contamination in drinking water
- Perceptions of the health risks of geogenic contaminants in drinking water
- The cost of treating the associated illness
- End-user willingness to pay (WTP) for the cost of installation and the operation and maintenance (O&M) costs of various mitigation options.

The questionnaire needs to be pre-tested on pilot sites before a full-scale field survey is conducted. The sample size for the full-scale household survey should be over 300 to allow robust statistical analysis of the data.

The following example questionnaire is an abbreviated version of a questionnaire used for interviewing households on arsenic mitigation strategies in Bangladesh.

Example: Questionnaire_for_household_surveys

Behaviour change

A series of surveys of the inhabitants of six arsenic-affected districts – Munshiganj, Comilla, Satkhira, Khulna, Bagerhat and Brahmanbaria – was conducted. In all study locations, the people had access to one (or two) of eight arsenic-safe options: dug wells, pond sand filters, piped water supply, household arsenic removal filters, community arsenic removal filters, household rainwater harvesting, deep tubewells or the possibility of the sharing of safe shallow wells. All mitigation options had been installed by the DPHE, UNICEF or local governments.

The purpose was to investigate the acceptance and use of available arsenic-safe water options (Inauen et al., 2013a), including the psychological factors leading to their use (Inauen et al., 2013b; Mosler et al., 2012), and to test behaviour change interventions intended to increase their use (Inauen and Mosler, 2013; Inauen et al., 2013c). The procedures are described in Chapter 8.

Technical study

The aim of the technical study was to determine at what depth the water was safe to drink and what measures could be taken to ensure that the right depth had been reached during drilling (Hug et al., 2011). The study site, Munshiganj district near Sreenagar town (a 2.5 by 2.5 km^2 area), which lies 30 km south of Dhaka and 5 km north of the Ganges River, was selected because over 85% of shallow tubewells in the Mushiganj district are affected by arsenic concentrations >50 mg/L.

Fig. 9.6 *Drilling a deep tubewell*

In 3 surveys from 2005 to 2010, samples were collected from existing shallow and deep tubewells, monitoring wells (5–210 m depth) and newly installed deep tubewells. Electrical conductivity (EC), pH and dissolved O_2 were measured in freshly pumped water with a multi-parameter sensor. Filtered (0.2 µm, nylon) and unfiltered samples were collected into pre-acidified (0.15 mL 2M HCl) polypropylene vials (4 mL) for the analysis of cations (major ions (charges omitted): Na, K, Mg and Ca; minor ions: Mn(II), Fe(II), As_{tot} etc.). For the determination of total organic carbon (TOC), unfiltered samples were collected in pre-acidified (0.2 mL 5M HCl) polypropylene vials (30 mL). For Cl, SO_4, NH_4 (charges omitted) and alkalinity measurements, samples were collected untreated in 50 mL or 100 mL polypropylene bottles. The samples were placed in a refrigerator on the day of sampling and cooled to 4–8 °C until analysis.

A survey involving around 200 deep wells was conducted by Eawag in collaboration with UNICEF and the University of Dhaka in the sub-district of Monoharganj (Comilla). The purpose of the survey was to assess the water quality with regard to salinity and to arsenic, manganese and other elements, and to find the best depth for the installation of new deep tubewells. The preliminary results were used as a basis for the installation of deep tubewells in this region by UNICEF and by private donors (e.g. Rotary). Surveys were also conducted on taste and odour, with the purpose of determining acceptable limits for salinity and the concentrations of metal(loid) ions.

Results

Institutional analysis

The results presented here are based on Khan and Yang (2014) and Khan et al. (2014).

Stakeholders from all different types of organisations stated that their major roles were to provide arsenic-safe water and to increase awareness of arsenic contamination and exposure among the rural population. The majority (63%) felt that one of their major achievements had been to increase awareness of arsenic contamination among the rural population, and that as a result of increased awareness, demand for deep tubewells and other alternative arsenic-safe water options had increased. Other major achievements revealed by the stakeholders included the provision of assistance for health-care services related to arsenicosis problems (32%) and introducing and ensuring safe water options (27%).

Surveys at both the institutional and household levels clearly identified deep tubewells and piped water systems as the most preferred options for avoiding arsenic exposure through drinking water. Institutional stakeholders rated deep tubewells as being “highly suitable” (89%) as a long-term safe water option, followed by piped water systems (68%). Rainwater harvesting was also identified as a popular and suitable option in coastal areas of Bangladesh, where groundwater salinity restricts water supply through either deep tubewells or piped water systems. However, household arsenic removal filters were identified as being a “not suitable” option by a majority of institutional stakeholders (63%), and the household-level survey found that less than 10% of households interviewed expressed their preferences for household filters as a safe water option. None of the other water options (pond sand filters, dug wells, rainwater harvesting) were significantly favoured by institutional stakeholders, and overall, 50% of the respondents considered other water options as being “not at all suitable” and only 10% considered any other water options as “highly suitable”. Last but not least, the majority of the institutional stakeholders (68%) strongly preferred a community-based safe water option over individual household options.

On average, institutional stakeholders estimated that 50 BDT/month (range 10–250 BDT/month) until full recovery of installation cost was made would be reasonable. These estimates matched well with household responses: Overall, three quarters of the household respondents were willing to pay 25 (32%) or 50 (42%) BDT for monthly operation and maintenance costs. Household survey results indicated that study households were generally willing to pay up to 5% of their disposable average annual household income for a one-time investment (capital cost) towards construction of a deep tubewell to receive arsenic-free drinking water (Khan et al., 2014). This low value reflects the fact that in the rural villages in Bangladesh, the concept of “paying for water” has not been completely developed, because households can still obtain water without payment. Stakeholders stressed that regular awareness programs would help to develop the concept of “paying for water” in the rural community.

The great majority of the institutional stakeholders (90%) agreed that end-users should be willing to walk (WTW) a certain distance for water, while only 10% believed that end-users should not walk at all for water. Most believed that 0–250 m and 10–30 min per trip were a reasonable distance and time for water collection, without unduly impairing the ability of women (traditionally responsible for water collection in Bangladesh) to manage efficiently their other household work. However, stakeholders also mentioned that religious and cultural issues are also principal factors restricting people's WTW for water. As for cultural factors, in some areas of rural Bangladesh, the women and girls are not encouraged to travel far outside the family home (bari). This can pose a barrier to the collection of water from public sources.

When asked the reasons for the relatively slow progress in arsenic mitigation, the most common response identified by 32% of institutional stakeholders was the lack of responsibility and accountability. Insufficient funding, lack of coordination and shortage of skilled manpower were all considered as major limiting factors by about 25% of the stakeholders. They particularly mentioned the locally elected upazila parishad (sub-district councils), whose responsibility it is to identify and mitigate arsenic contamination in drinking water. The stakeholders were of the opinion that greater decision-making power (37%) along with increased funding and the allocation and retention of trained manpower (74%) would strengthen capacity at the local government level and hence result in better performance.

Most institutional stakeholders also believed that lack of accountability (32%) and commitment (11%) from both providers and end-users, as well as a lack of coordination between organisations (26%), were the key factors resulting in unsustainable arsenic mitigation. Stakeholders were of the opinion that for sustainable, effective arsenic mitigation by the upazila parishad, the effectiveness of existing arsenic coordination committees was crucial and that this could be enhanced by organising regular meetings and involving experienced people regardless of their political affiliation. Stakeholders also agreed that arsenic mitigation should use a combination of different options suitable to different parts of Bangladesh, and therefore a single blanket mitigation option for the whole country would not be sustainable.

Behaviour change

The study of eight arsenic-safe water options showed that overall, only 62% of households with access to a safe water option (N = 1268) actually use it (Inauen et al., 2013a). The study also revealed great discrepancies between user rates for the different water options. The most used options were piped water, followed by community arsenic-removal filters, well-sharing, deep tubewells, dug wells, pond sand filters and rainwater harvesting systems (Fig. 9.7). Clearly, if more people would use the options which are accessible to them, the public health burden would be reduced.

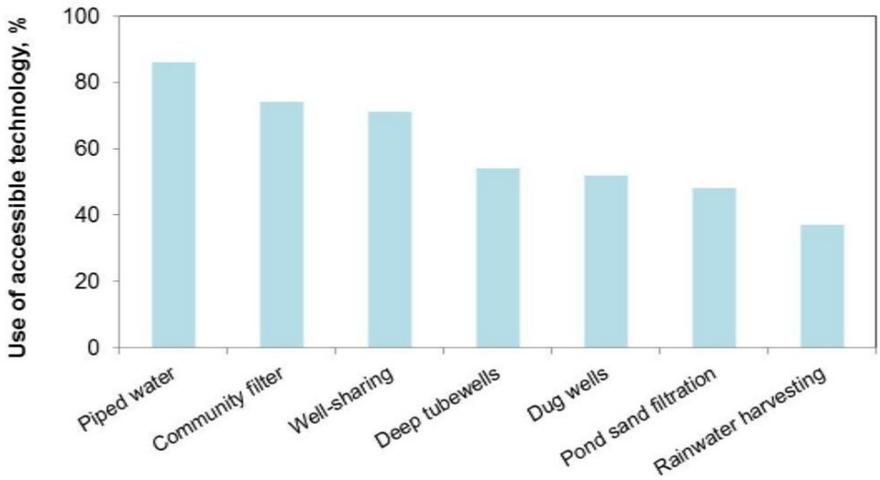


Fig. 9.7 *Use of accessible arsenic-free water sources. Household filters were not included, as the data were unreliable (50% of those who should have had a filter refused to be interviewed).*

Psychological factors determined from the RANAS model of behaviour change (risk, attitudes, norms, abilities, self-regulation) (Mosler, 2012) are an aid to better understanding the reasons why some options are preferred over others (Inauen et al., 2013a). A piped water supply was most popular in terms of taste and temperature preferences, followed by strong social norms (i.e. that many relatives and friends are in favour of using arsenic-safe water sources, and that they are also using them), high confidence in their ability to obtain as much arsenic-safe water as needed (i.e., self-efficacy, Bandura, 1997) and high commitment (i.e. a personal desire, Inauen et al., 2013c) to consuming piped water. Interestingly, deep tubewells also enjoy a high degree of acceptance, despite only moderate user rates. This may be due to the fact that collecting water from deep tubewells has been reported as time-consuming, which may have led to lower commitment (Inauen et al., 2013c). Households with access to neighbours' tubewells only reported below average social norms for using them and low commitment, perhaps also because users are dependent on their neighbours' consent. At the other end of the spectrum, dug wells were perceived as time-consuming and were associated with taste and odour issues.

The next step was to analyse the survey data to forecast the most promising promotion campaigns. Self-efficacy and the descriptive norm (i.e. how many other people use arsenic-safe water options, Cialdini, 2003), emerged as the most important factors to explain the use of arsenic-safe tubewells (Inauen et al., 2013b). Further important factors were instrumental attitudes (i.e. the perception of water collection as time-consuming and hard work) and the injunctive norm (i.e. what one thinks that others think should be done, Schultz et al., 2007). This was applicable to all arsenic-safe water options included in the study. Summarising, these studies indicated that more committed persons, who perceive safe water collection as "normal" and have higher confidence in their abilities to collect safe water, find safe water collection less time-consuming and less of an effort, and those who feel they have more approval from others when they collect arsenic-safe water are more likely to use arsenic-safe water options.

Fig. 9.8 Illustrations of risk information (left) and prompts (right)

Given their general acceptance, deep tubewells were chosen for promotional campaigns to overcome the issues of distance and lack of commitment. To increase commitment, the most promising factor of deep tubewell use, they developed reminders, implementation intentions (simple plans of when, where and how to obtain arsenic-free water, Gollwitzer, 1999) and public commitment (sometimes termed "pledging", Fig. 8.8), and combined them with risk information (Fig. 9.8, Inauen et al., 2013c, Gollwitzer, 1999).

The results of a randomised controlled trial revealed that evidence-based behaviour change techniques increased the behaviour change effect by 50% compared to simple information provision (Inauen et al., 2013c). But also less "spontaneously" accepted and used arsenic-safe water options can be promoted by targeting any of the psychological factors identified above. For well-sharing, for example, the commitment-enhancing behaviour change techniques described above increased the number of users by up to 66% (Inauen and Mosler, 2013).

Technical

The analyses of water from shallow and deep tubewells in the tested area of Sreenagar, Munshiganj, identified three types of groundwater currently used for drinking:

- Shallow water from 20 to 100 m: dark-grey sediments with high As concentrations (100–1000 µg/L), intermediate to high Fe (2–11 mg/L), intermediate Mn (0.2–1 mg/L) and relatively low electrical conductivity (EC) (400–900 µS/cm), dominated by Ca–Mg–HCO_3.
- Water from 140 to 180 m: light-grey sediments with low As (<10 µg/L), intermediate Mn (0.2–1 mg/L), intermediate Fe (1–5 mg/L) and intermediate EC (1200–1800 µS/cm), dominated by Ca–Mg–HCO_3-Na-Cl.
- Deep water from 190 to 240 m: brown sediments with low As (<10 µg/L), high Mn (2–5 mg/L), low Fe (<3 mg/L) and high EC (2000–3000 µS/cm), dominated by Ca–Mg–Na–Cl with high Ca and Cl concentrations.

Drillers have traditionally used the transition from grey to brown sediments as an indicator of the depth from which safe drinking water can be obtained. However, in most of the tubewells in the study area below 190 m, the Mn concentrations exceed the WHO limit of 0.4 mg Mn/L (WHO, 2011) by a factor of 2–5, and the water tastes noticeably saline. Based on these findings of this small survey of deep tubewells, a depth range of 150–180 m with light grey sediments is recommended for the construction of new wells.

The finding of an "intermediate depth" at which water which is safe not only with regard to arsenic but also with regard to salinity and manganese is echoed by Hossain et al. (2012), who found good quality groundwater at 120 m in Chandpur, one of the most highly arsenic-affected areas in the country. Groundwater from this depth contained moderate levels of iron (2–4 mg/L), but iron in the region is also common in shallow groundwater (~10 mg/L), and locals are accustomed to the metallic taste.

The surveys in Monoharganj have shown that the concentrations of arsenic, manganese and salinity as a function of depth are locally highly variable and that the best depth for water extraction should be determined in each community in which a larger number of deep tubewells are planned. Finding a depth with acceptable water can be difficult in some locations, and newly installed deep tubewells often deliver water that is too saline or that contains high manganese concentrations. Methods are being developed that allow drillers to test the water quality during the drilling process and to install well screens at the optimal depth.

More generally, high salinity in deep tubewells is also common in parts of the coastal zone as well as in the Sylhet basin, and manganese concentrations frequently exceed both the government limit of 0.1 mg/L and the WHO health-based value (WHO, 2011) in central and northern Bangladesh (UNICEF/BBS, 2011). Owners have reported damaged pumps that apparently corroded more quickly due to high salinity.

Conclusions

These studies have shown that there is considerable agreement between the wishes of the institutional stakeholders and rural householders with respect to the preferred mitigation options, namely, piped water and deep tubewells. Further, there is agreement between institutional stakeholders and householders about cost. However, the institutional stakeholders were of the opinion that a distance of 0–250 m (or 10–30 min) per trip was acceptable, whereas householders perceived water collection as time-consuming and hard work.

These studies also showed that there would be significant potential for reducing the number of people exposed to arsenic if householders used the safe-water options available to them. They also showed that information alone would not be enough to change people's habits. Evidence-based behaviour change techniques to increase commitment would be required.

With respect to deep tubewells in the Sreenagar district, it was found that, although free of arsenic, water taken at depth can be saline and contain unacceptably high manganese concentrations. Water taken from intermediate depths (140–180 m) fulfilled the quality requirements. Further, pumping tests showed that the deeper aquifer was to a large extent separated from the upper aquifer, so that the abstraction of small amounts of water for drinking using hand pumps can be deemed safe as long as wells are periodically tested.

Recommendations

The institutional stakeholders identified a lack of capacity at the level of the locally elected sub-district councils (upazila parishad). They also mentioned a lack of accountability and coordination between organisations. These appear to be good starting points to improve mitigation outcomes.

The role of awareness creation appears to the institutional stakeholders to be an important factor in reducing exposure to arsenic, while the results of the behavioural change study indicate that the introduction of simple behaviour change techniques to "empower" the local population to make use of existing facilities, particularly well-sharing and deep tubewells, could make a significant difference to the number of people at risk.

With respect to deep tubewells, it must be remembered that groundwater quality is spatially highly variable and that safe zones within the deep (or intermediate) aquifer are site-specific. It is therefore recommended that in areas where deep tubewells are to be installed, safe depth zones should be identified by surveying existing deep tubewells and, if possible, by the installing of a small number of monitoring wells, which could also serve as sources of drinking water. Maps can be very useful.

9.3 Multi-criteria decision analysis to evaluate fluoride-removal options in Ethiopia

Hong Yang, Lars Osterwalder, Richard B. Johnston, C. Annette Johnson

Background

Multi-Criteria Decision Analysis (MCDA) is a technique for comparing and evaluating different options (or measures) in order to identify options with the broadest acceptance, or to rank options or to distinguish acceptable from unacceptable options.

In a workshop, stakeholders with different perspectives (e.g. regional government agencies and householders) select criteria important to them which they can use to compare different options. A list of criteria is then made that all stakeholders can accept, and then the options are valuated with the help of the criteria. The list is interactive and facilitates transparent and participatory assessment. MCDA can foster collaboration and learning in a situation in which a diversity of interests are openly represented.

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

The MAVT procedure consists of following steps:

1 Establishing the decision context
2 Identifying the options
3 Identifying objectives and criteria
4 Scoring
5 Weighting
6 Obtaining an overall value
7 Calculating values
8 Examining the results

Here we illustrate the MAVT procedure used in a workshop to evaluate different fluoride removal technologies in Ethiopia. See Osterwalder et al. (2014) for a description of MAVT procedure and technical information presented at the workshop.

The purpose of the workshop was to bring the different stakeholders together to discuss fluoride-removal options for drinking water and what factors, particularly cost, need to be considered when selecting a method for implementation.

Procedure

Step 1. Establishing the decision context

Information is needed by decision-makers as a basis for deciding among alternatives. The decision context determines to some degree what information is required. The decision context is governed by policy, administrative and technical issues and the social context. Stakeholders and other key players who should be involved in the decision context need to be identified, as does the extent of their participation in the analysis. Not all stakeholders need to participate physically in the MCDA, but their values should be represented by one or more key players who do participate. The decision context is decided on at the beginning; e.g. "Sustainable fluoride-free water solutions for rural households in Ethiopia".

On 27th April 2012, a one-day stakeholder MAVT workshop was held in Addis Ababa with around 40 representatives from the federal government, regional governments, non-governmental organisations and academia. The aim was to assess fluoride-removal technologies appropriate for rural Ethiopia.

Workshop participants were asked to evaluate the technologies for each of three scenarios (Table 9.1) with different fluoride concentrations, water consumption and water scarcity. In addition, the acceptance of bone char filter material and water salinity were considered. In plenary discussion, stakeholder groups evaluated the different options for the three scenarios using the MAVT approach. Because of time constraints, the research team preselected technologies and criteria based on interviews with 10 institutional stakeholders held early in 2012. Background information for each technology, for example, costs and technological requirements, were also collated in preparation for the workshop.

Table 9.1 *Parameters of the three scenarios*

Variable	Case 1	Case 2	Case 3
Water consumption per unit (L/day)	3,000	7,500	15,000
Fluoride concentration in raw water (mg/L)	5	10	10
Acceptance of bone char	95%	100%	95%
Acceptance of slightly salty water	100%	95%	95%
Water scarcity	yes	no	no

Step 2. Identifying the options

The options within the decision context need to be selected.

The five technologies illustrated in Figure 9.9 were selected for the MAVT exercise. Provision of fluoride-free water was excluded because, although it is the long-term option of choice for the National Fluorosis Mitigation Project Office (NFMPO) of the Ministry of Water and Energy in Ethiopia, in the short term, it is fluoride-removal options that are needed. Technologies that have been implemented in other countries (e.g. electrocoagulation; Gwala et al., 2010) or which are under development in Ethiopia (e.g. aluminium oxide; Shimelis et al., 2005) were not considered here, as the stakeholders present at the 2012 workshop thought it would be premature to include them. An important criterion for the selection of technologies for the stakeholders was maturity.

AA Filtration with granulated alumina.
BC Filtration with charred, crushed and washed animal bones filter material.
CP Filtration with BC and calcium phosphate pellets (to increase filter life).
NT Co-precipitation by addition of alum and lime to water, rapid stirring followed by setting.
RO Filtration through membrane.

Fig. 9.9 *Selected fluoride removal technologies*

Step 3. Identifying the objectives and criteria

To be able to rate and compare the different safe water options, a number of criteria need to be agreed on. These could, for example, be the costs involved, their technical performance, their accessibility to all in the community or the lifespan of technologies or machinery involved.

Three objectives with which to compare the different options – reliability, acceptability and affordability – were identified together with measurable criteria (Table 9.2).

Table 9.2 *Criteria selected in Step 3 for the assessment of fluoride-removal technologies in Ethiopia*

Objectives	No.	Criteria
High reliability (technical)	1	Simplicity of operation
	2	Electricity requirement
	3	Frequency of major repairs and/or replacements
	4	Local availability of raw materials and spare parts
High acceptability (social, political, environmental)	5	Cultural acceptance
	6	Water aesthetics
	7	Drinking-water standards
	8	Waste management
High affordability (financial)	9	Capital costs
	10	Capital maintenance costs
	11	Operational costs
	12	Total costs

Step 4. Scoring

The next step is to determine values for the criteria and to give them comparative scores. Each evaluation needs to be turned into a score. Normally, the scale extends from 0 to 1, 10 or 100. This is necessary in order to be able to combine different types of values, for example numerical values and qualitative ratings (poor, medium, good). More detail on scoring can be found in the MCDA manual of the Department of Communities and Local Government (2009).

As an example, criteria attributes and scores are shown for Case 1 (Table 9.3). In the case study presented here, the stakeholders strongly objected to the 0 value for the minimum score and weight. We therefore assigned the scale from 1 to 10 for both score and weight. The sensitivity analysis indicated that this scale range did not alter the final ranking of different options. The background to criteria attributes and scores is given in Osterwalder et al. (2014). It should be noted that some attributes are location-specific, while others are not.

Exclusion factors also needed to be considered, as not all technologies are suitable for all settings. These were:

- if the total cost of producing treated water were to exceed 100 ETB/m^3
- if less than 70% of the target population were to accept the technology, either for cultural or religious reasons or because of taste
- if fluoride concentrations < 1.5 mg/L could not be achieved
- if major interventions were to be necessary less than every 60 days
- if the technology were to produce a high volume of contaminated, non-potable water in a water-scarce area. This applied primarily to RO.

Table 9.3 *Criteria attributes and scores for the reliability objective for Case 1 (Step 4). In Case 1, RO is excluded because of water scarcity.*

Objective	**Reliability**			
Criteria	Operation simplicity	Electricity requirement	Frequency of major interventions	Local availability of raw materials and spare parts
Criteria attributes				
Units	-	Yes/No	Days	Points
AA	Easy	No	431	6.7
BC	Easy	No	204	10.0
CP	Medium	No	480	6.7
NT	Medium	Yes	513	10.0
RO	Difficult	Yes	90	0.0
Criteria scores				
AA	10	10	7	0
BC	10	10	0	10
CP	0	10	9	0
NT	0	0	10	10
RO	n.a.	n.a.	n.a.	n.a.

Step 5 Weighting the criteria

Stakeholders assign weights to each of the criteria to reflect their relative importance for the decision. Usually, different stakeholder groups will have different opinions on the importance of the various criteria and will therefore assign weights differently.

In this example, we are using weights on a scale from 1 to 10. The most important criteria will therefore be assigned a weight of 10 and the least important a weight of 1, with the remaining criteria weighted in between.

Table 9.4 *Weighting of criteria by the different stakeholders (most important = 10)*

Criteria	Federal Gov.	Local Gov.	NGOs	Acad.	Arithmetic mean
Local availability	10	10	10	9	9.7
Simplicity of operation	10	10	10	6	8.9
Drinking-water standards	10	6	8	10	8.5
Cultural acceptance	9	6	6	8	7.2
Water aesthetics	7	4	8	9	7.0
Operational costs	5	10	6	4	6.4
Frequency of major interventions	6	0	10	8	5.9
Total costs	8	8	4	3	5.8
Waste management	6	0	8	7	5.2
Capital maintenance costs	5	6	6	2	4.8
Capital costs	7	8	2	1	4.5

The results of criteria weighting revealed that the local availability of raw materials and simplicity of operation are major points of concern. Further, a majority of the stakeholders put a high priority on the fact that the Ethiopian national guideline needs to be met, and the treated water needs to be accepted by the consumer. Different stakeholder groups prioritised different criteria in different ways (Table 9.4). Participants from central government authorities considered capital costs more important, while the representatives of local governments put a higher priority on operational costs, reflecting the fact that the central government often pays for construction, leaving local governments to supervise operation and management. Academics and, to a lesser extent, NGOs and development partners, tended to place a higher priority on aesthetics and a lower priority on costs, perhaps reflecting concerns about sustained use.

Step 6. Obtaining an overall value

The scores for each criterion are multiplied by the given weights to gain one final, overall value for each mitigation option. This can be mathematically expressed as

$$V(A) = \Sigma w_i \cdot v_i (a_i)$$

In the above equation, the scores given for each *criterion* ($v_i (a_i)$) *are multiplied by their given* weights (w_i)*, and these weighted scores are then summed up to gain the final, over*all value V(A) for mitigation option A.

Step 7. Examining the results

The results can be examined to determine the ranking of options.

The results of the MAVT study are given in Table 9.5 and Figure 9.10. In Case 1, high costs and water scarcity resulted in the exclusion of RO. In Case 2, the high fluoride content was the cause of the elimination of BC, as the filter material would have to be replaced too often. In cases 2 and 3, NT was excluded because the WHO guideline value of 1.5 mg/L could not be achieved. Because of the relatively high water requirements and elevated fluoride concentrations, filtration was not suitable, leaving only RO as the remaining option.

Table 9.5 *Ranking of preferred options using the average weighting for Case 1*

	Case 1	**Case 2**	**Case 3**
Ranked options	BC AA NT CP	CP AA RO	RO
Excluded options	RO	BC and NT	AA, BC, CP and NT

Figure 9.10 shows stakeholder preferences for Case 1. There was a large degree of agreement among the different stakeholder groups. All favoured filtration with BC or AA and gave filtration using CP and NT the lowest rankings.

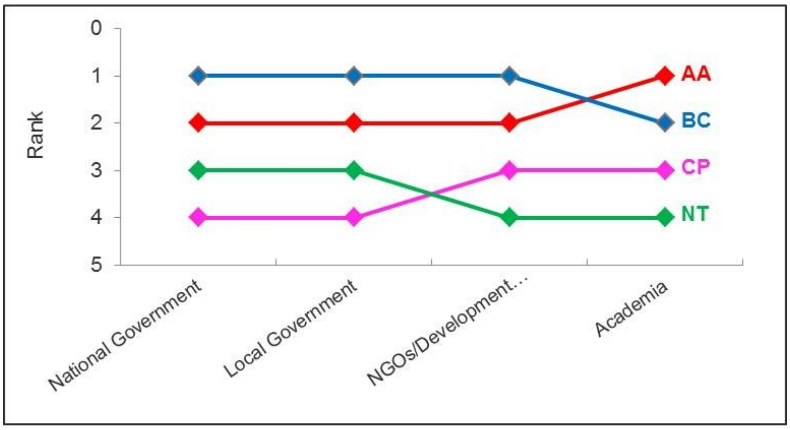


Fig. 9.10 *Stakeholder preferences for Case 1*

Step 8. Sensitivity analysis

The calculated results of an MCDA may be sensitive to changes in the scores and weights assigned to the options and criteria. Even small changes in weighting or scoring may lead to a completely different option being the "preferred option". In projects that attract public interest, the choice of weights may also be controversial. A sensitivity analysis can highlight these kinds of problems and provide a means for examining the extent to which vagueness about the inputs, or disagreements between stakeholders, makes a difference to the final results. The MCDA manual of the Department of Communities and Local Government (2009) describes details on how to undertake a sensitivity analysis.

Conclusions and feedback

Although there was a little scepticism at the beginning of the workshop, all agreed at the end of the day that the workshop had been very useful. First and foremost, the participants were of the opinion that it had been useful to have quantitative data that allowed them to discuss and compare different options objectively. Secondly, the participants valued being able to see for themselves that there is no single, most preferable technical solution for fluoride removal in Ethiopia and that the selection of a technology depends on location-specific parameters and on the relative importance put on different criteria by the stakeholders involved. Thirdly, it was interesting for all to note that there was good agreement between stakeholders in the selection of options. The necessity of examining different financing strategies also became clearer through the separation of costs (into capital, capital maintenance and operational costs).

In the absence of an MAVT, different sets of stakeholders tend to prioritise one option, perhaps because their organisation is promoting it. Other stakeholders may exclude one option by considering only one single criterion, sometimes without the support of empirical evidence, e.g. "reverse osmosis is too expensive" or "bone char is not acceptable to consumers". The MAVT exercise helped to provide a more objective view of the different options. Stakeholder groups could argue for different weightings for different criteria, but not for specific technologies.

Ideally, the MAVT procedure should be repeated with all stakeholders, as more information on existing technologies, or on new ones, including fluoride-avoidance options, becomes available. The methodology can easily be expanded to include more information about conditions specific to a particular location.

9.4 Evaluating fluoride intake via food and water using a Material Flow Analysis

Hans-Peter Bader, Ruth Scheidegger

In the Ethiopian Rift Valley, 41% of all the sources of drinking water have fluoride concentrations exceeding the World Health Organization guideline value of 1.5 mg/L and dental and skeletal fluorosis is widespread (Tekle-Haimanot et al., 2006). In an effort to mitigate disease related to fluoride intake, water treatment options are being sought and tested (see Section 9.1 for an example). As listed in Table 3.3 (Chapter 3), the daily maximum fluoride intake is around 1.5 mg for infants and 10 mg for adults. From these figures, it is clear how easily these limits can be reached by drinking contaminated water. However, there is also a fluoride input via food and food preparation (using contaminated water for cooking).

In order to make daily intake estimates, it is necessary to know, firstly, the pathways along which substances can be taken up by the body. These pathways may be, for example, via beverages, food, inhalation (air), medication or personal care products (pathway analysis). Secondly, we need to quantify the amount of the substance of concern per pathway. Material Flow Analysis (MFA) is very helpful in this.

MFA is a method designed to account systematically for the material, substance and energy use of a defined system. Based on an economic input–output analysis (Leontief, 1936), MFAs were originally developed in the chemical engineering sector for process optimisation. In the mid-1980s, these methods were further developed by Baccini and Brunner (1991) to account for the material, substance and energy flows in whole regions. The MFA was extended by Baccini and Bader (1996) to yield Mathematical Material Flow Analysis, which incorporated modelling concepts to provide a systematic description and simulation of substance flows through a defined system. In the past two decades, this method has been applied to many problems in different fields and on different scales (for an overview, see Schaffner et al., 2009).

The procedure consists of four steps:

1 Model approach
2 System analysis
3 Data collection and calibration
4 Simulation, including sensitivity analysis

The MFA procedure

The MFA procedure is shown in the following four subsections using the example of fluoride intake by children in the Ethiopian Rift Valley, based on the work of Malde et al (2011).

Model approach

The model approach used in our example is the so-called "consumption recipe model". It is based on a knowledge of nutrient or contaminant concentrations in beverages and foodstuffs and on the average daily consumption of these beverages and foodstuffs, either alone or as ingredients in different dishes. For a more detailed description of the model, see Malde et al. (2011).

System analysis

In the first step, we need to define the system to be modelled. Our example comprises the preparation of food and its consumption by a child. These two activities are defined as "processes" and are represented by boxes within the system boundary. In Figure 9.11, the processes are termed kitchen and child.

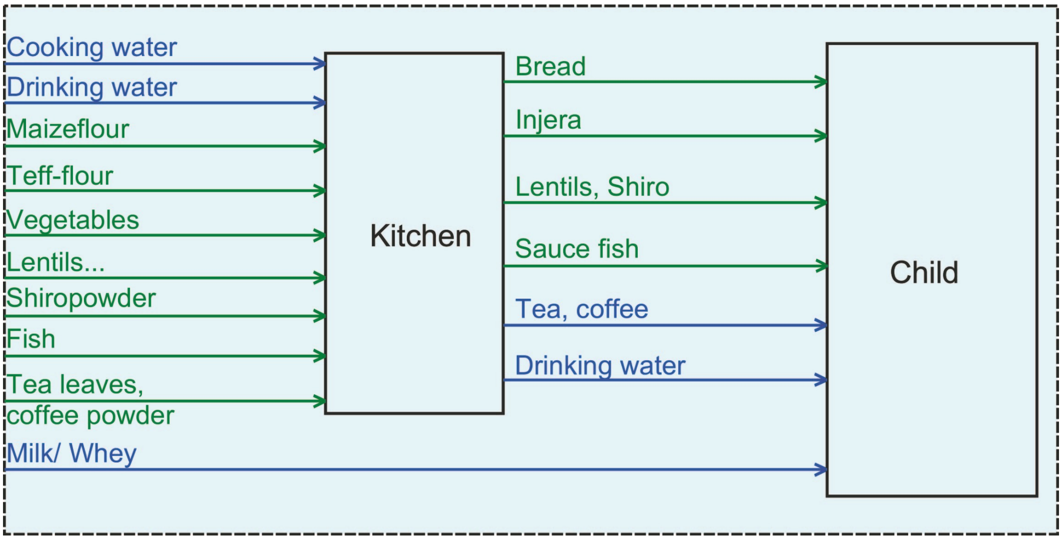


Fig. 9.11 *System analysis of the intake of fluoride through food and beverages by a child in Ethiopia. Blue lines represent beverages and green lines food. For simplicity, all drinking water, even if it not used to prepare coffee or tea, is considered to pass through the process, "kitchen". Shiro powder is a mix of chickpea powder.*

The next step is to determine the pathways by which the intake of fluoride occurs. Of the possible pathways (inhalation, medication and cosmetics, beverages and food), only beverages and food are relevant in the Ethiopian Rift Valley, as there are no factories there emitting fluoride into the air, and little medication, toothpaste or cosmetics are used. In our example, two groups of intake pathways can be identified: (i) Ingredients used in cooking, such as water, vegetables, fish, etc., and (ii) Products that are directly consumed (i.e., milk and whey). The ingredients of a typical meal are shown in Figure 9.12.

Fig. 9.12 *Gomen (Ethiopian greens) (left), different types of lentils and beans (middle) and traditional dishes served on injera (traditional Ethiopian "bread") (right)*

Data collection and calibration

In order to run the model described above, the following data are needed:

- The daily consumption of food and beverages
- Recipes
- Fluoride concentrations in the ingredients used
- Fluoride concentrations in prepared dishes (using the duplicate method)

Possible data sources are: field studies, literature, interviews with experts, estimates and surveys (questionnaire_about_diet, questionnaire_about_recipes). Clearly the data must be checked carefully and compared with data from other sources, if available. The full data set for the case described above is presented in Malde et al. (2011) and references therein. Using this data set, all flows of fluoride shown in Figure 9.11 were calculated.

The model was calibrated by comparing the total fluoride intake calculated from the sum of the beverages and food consumed per child each day with measured intake of fluoride in dishes sampled using the duplicate method (see Malde et al., 2003, 2004).

In the duplicate method of dietary assessment, a duplicate portion of all food and drink consumed throughout the day is prepared. The identical portions are weighed and recorded. The duplicate portion is taken to the laboratory, where it is chemically analysed. Sometimes, multiple days of assessment may be combined into a single composite and then be homogenised before analysis.

http://dapa-toolkit.mrc.ac.uk

Simulation and results

The calibrated model was used in two scenarios:

- Village A with a water source fluoride at a concentration of 2 mg/L and
- Village B with a water source fluoride at a concentration of 14 mg/L

The following calculations were made:

1. The average total fluoride intake per child per day.
2. The comparison of food, food preparation and beverages to the total fluoride intake.
3. The contribution of each item to the total fluoride intake.

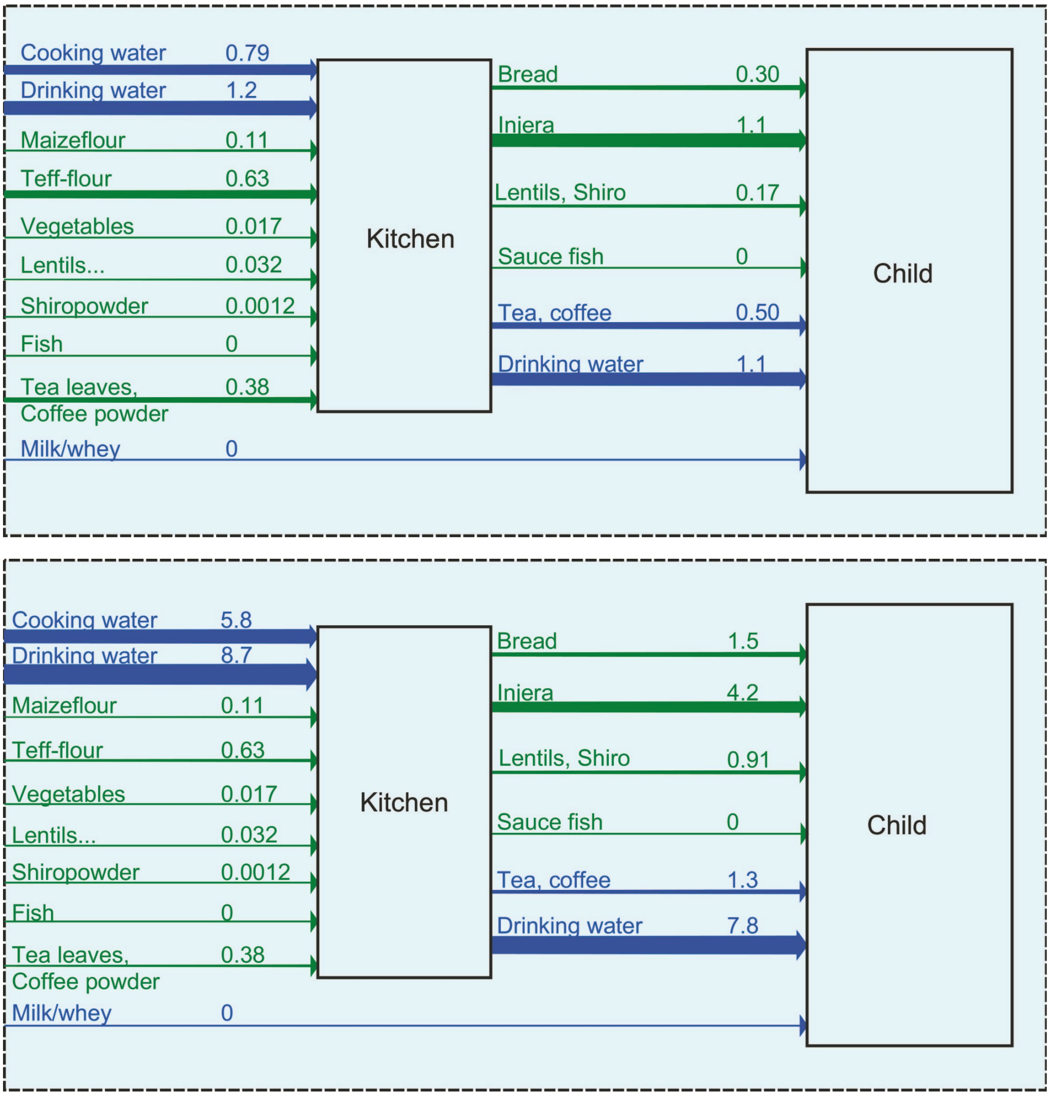


Fig. 9.13 *Simplified flow diagrams summarising the flows of fluoride in food and water for Village A (top) and Village B (bottom). The units are mg F per child per day.*

The simulated fluoride flows for village A are shown in Figure 9.13 (top). From the total intake of 3.2 mg F/day per child, 38% comes from drinking water, 25% from water used for cooking and the remaining 37% from the food. The situation in village B is different (see Fig. 9.13 bottom). Here, 56% of the total intake (16 mg/day per child) comes from drinking water and 37% from the water used for cooking. Only 7% of the total intake comes from food. Next to water used for drinking and cooking, teff flour and tea are significant sources of fluoride.

Obviously a child living in village B has a very high fluoride intake, but the fluoride intake of a child living in village A is also too high. Given that the recommended maximum daily fluoride intake for children below 8 years of age is 0.1 mg/day per kg of body weight, and assuming that a three-year old child weighs about 13 kg, the child's daily intake should not be above 1.3 mg/day (SCSEDR, 1997).

Table 9.6 *Scenarios for the use of filtered water in Villages A and B*

Village	**Total intake mg F/(child and day)**				
	Current situation	Drinking water concentration reduced		Drinking & cooking water concentration reduced	
		1.5 mg F/L	0 mg F/L	1.5 mg F/L	0 mg F/L
A	3.2	2.8	2.0	2.7	1.6
B	15.7	7.9	7.0	2.7	1.6

The model can now be used to simulate the effect on the average total daily fluoride intake of children if the fluoride concentration in drinking and cooking water were to be reduced to 1.5 or 0 mg F/L. The results are presented in Table 9.6. The results show quite clearly that a reduction of the fluoride concentrations in drinking and cooking water to 1.5 mg/L does not sufficiently reduce the average total daily intake of fluoride by children to the recommended maximum. The content of the water needs to be lowered further, preferably towards 0 mg F/L, since the food ingredients themselves already contain about 1.2 mg F. For more details and the results of further scenarios, see Malde et. al (2011).

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