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
aquatic research

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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

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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.

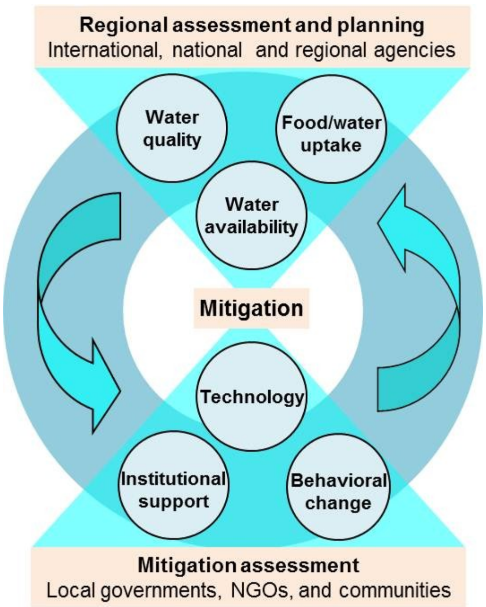

Fig. 1.1 *Framework elements that need to be taken into account when planning strategies for mitigating geogenic contamination (www.wrq.eawag.ch)*

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.

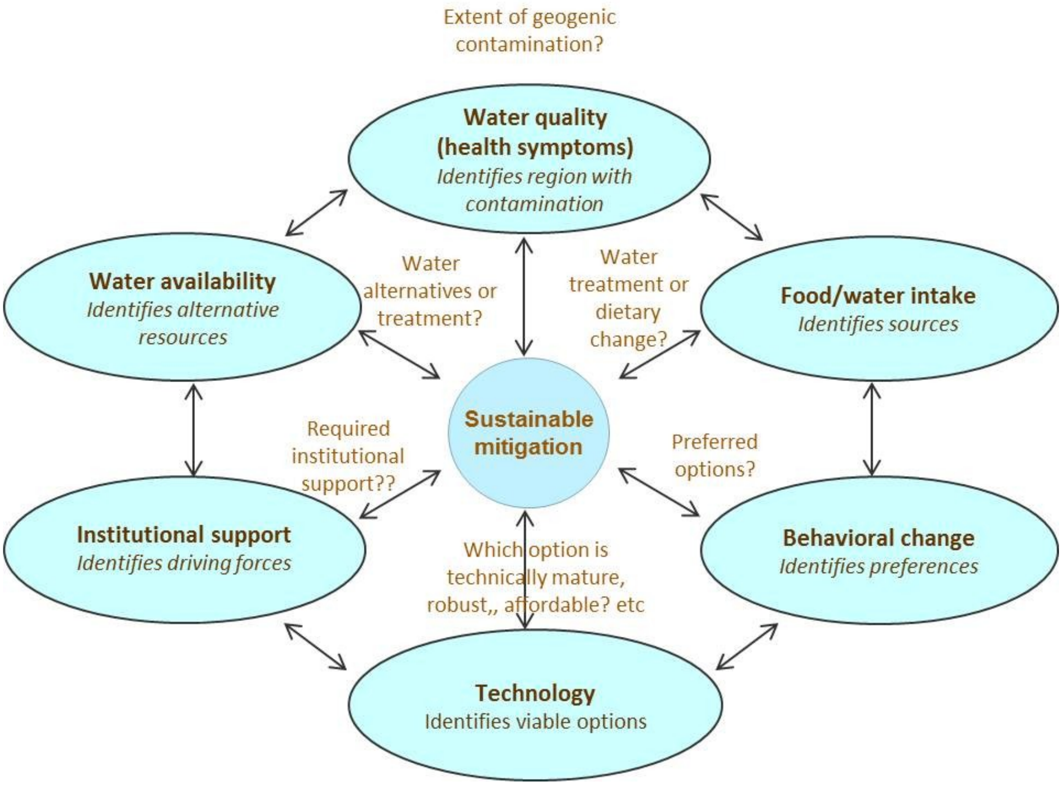

Fig. 1.2 *Schematic representation of the interconnection of the mitigation framework elements and the questions that the mitigation framework addresses*

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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