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Safe Drinking-water from Desalination

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Abbreviations

BTEX	benzene, toluene, ethylbenzene, xylenes
CT	product of disinfectant concentration (C) and contact time (T)
CVD	cardiovascular disease
MF	microfiltration
NF	nanofiltration
NOM	natural organic matter
RO	reverse osmosis
WHO	World Health Organization
WSH	Water, Sanitation, Hygiene and Health
WSP	water safety plan

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1. Introduction

Desalination is increasingly being used to provide drinking-water under conditions of freshwater scarcity. Water scarcity is estimated to affect one in three people on every continent of the globe, and almost one fifth of the world's population live in areas where water is physically scarce. This situation is expected to worsen as competing needs for water intensify along with population growth, urbanization, climate change impacts and increases in household and industrial uses.

Desalination may be applied to waters of varying levels of salinity, such as brackish groundwater, estuarine water or seawater; in some regions, it forms the primary source of drinking-water. At its origins, desalination technology was primarily thermal, by flash distillation, but as a result of technological advances, membranes have become a more cost-effective alternative that is increasingly being selected for new systems. Many thermal plants remain in use.

Saline sources are different from freshwater sources in that they always require a substantive treatment step. However, while the desalination process usually provides a significant barrier to both pathogens and chemical contaminants, this barrier is not necessarily absolute, and a number of issues could potentially have an impact on public health. Some of these are similar to the challenges encountered in most piped water systems, but others, such as those related to stabilizing and remineralizing the water to prevent it from being excessively aggressive, are different and therefore must be addressed within the context of a site-specific health risk management plan (see section 2 below).

This document aims to:

- highlight the principal health risks related to different desalination processes;
- provide guidance on appropriate risk assessment and risk management procedures in order to ensure the safety of desalinated drinking-water.

The document introduces the concept of water safety plans (WSPs) for desalination systems, provides an overview of potential hazards in source water and describes microbial and chemical risks and other key issues associated with treatment, remineralization, storage and distribution. More detailed information is presented in a series of annexes.

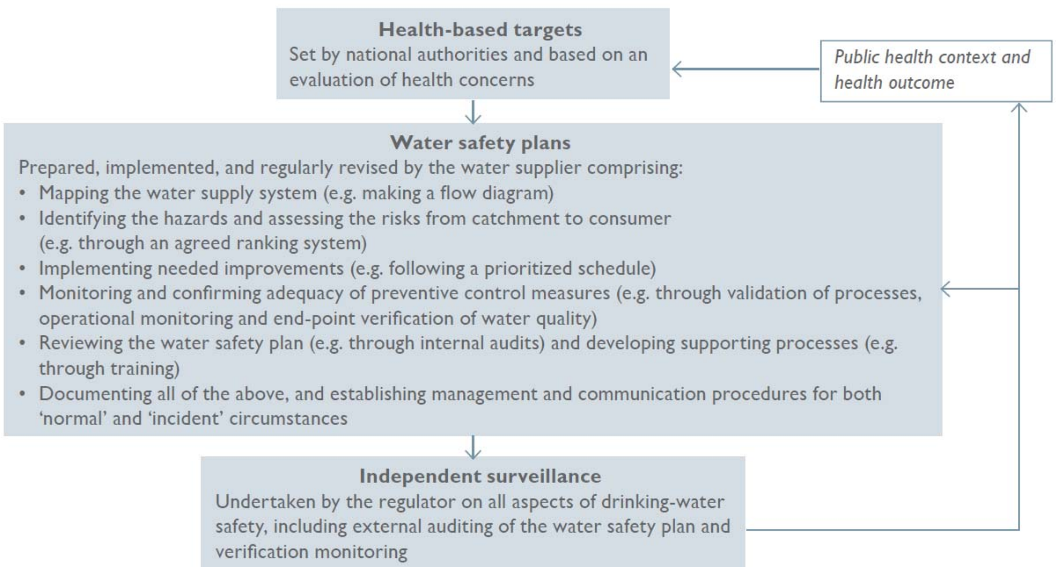
The document will be of use to health authorities, water quality regulators, operators of desalination plants and others interested in water quality and health issues.

A comprehensive examination of technical and water quality issues pertaining to desalination, such as environmental impacts, engineering considerations and equipment and processes for different desalination technologies, is provided in *Desalination technology: health and environmental impacts* (Cotruvo et al., 2010).

2. Desalination and water safety plans

As with any drinking-water supply, the development of a WSP is an essential first step in the provision of safe drinking-water (Figure 1). For any new system, development of a WSP should be initiated at the planning phase and carried through as the plant is built and commissioned. For existing plants, WSPs are equally important, as they help to identify potential risks and available barriers in their systems and support the introduction of a preventive risk management approach to problems that could have an impact on the quantity and quality of water supplied.

Figure 1. Framework for safe drinking-water (WHO, 2011)



A WSP maps the water supply system from catchment to tap to facilitate a thorough understanding of the system, including all its steps and stages, identifies the hazards that may be introduced at each stage and determines the risks associated with those hazards. Hazards are physical, microbial and chemical contaminants that could have an impact on health or adversely affect the acceptability (e.g. taste and odour) of the water to consumers. Hazards may also be substances or circumstances that threaten the operation of the desalination plant. The risks may be the potential for a particular hazard to reach the consumer in numbers (pathogens) or concentrations (chemicals) that will result in illness or the water becoming unacceptable. This may include the risk of exceeding the current drinking-water standards in a given country. In addition to technical considerations, a WSP also entails essential management components, such as training, maintaining records, documentation and periodic review of operating procedures to enhance the operation and management of the water supply system. Table 1 illustrates the key elements of a WSP for desalination.

Table 1. Elements of a water safety plan for desalination

Component	Action
Description of the system, including the water source and sources of hazards.	Thoroughly understand and document the system from the source to the tap.
Assess the risks of hazards reaching consumers in numbers or concentrations of concern, and ensure that steps are in place to mitigate the risks.	Determine the pathogens or chemicals that could be introduced at each stage, and ensure that barriers or operational procedures are in place to reduce the risks to meet health-based targets.
Ensure that the barriers are working efficiently at all times, and develop procedures for responding when efficiency starts to fall.	Develop operational monitoring to demonstrate that processes are working efficiently and an alert system to warn upon a decrease in effectiveness. Develop management procedures to ensure that all of the procedures are followed.
Verification that the WSP is working adequately and that a safe and acceptable supply of drinking-water is delivered.	Analyse key indicators of water quality and safety, and assess against appropriate standards and guidelines.
Develop supporting programmes.	Activities in such programmes are tailored to the specific needs and priorities of the water supply system and may vary from consumer education and community engagement to workforce training programmes.
Periodically review the WSP, and update the WSP in the wake of problems or emergencies.	Ensure that operation and management procedures are kept up to date and revised to incorporate lessons learnt.

Specific hazards and risks are considered in the following sections. Hazards may be present in source waters or may arise during treatment or other drinking-water production processes, during distribution and in consumer premises. Once the hazards have been identified, the associated risks need to be mitigated by removing or reducing their influx into the source using specific treatment barriers and sound operation and management procedures. A key step is operational monitoring of processes or barriers to ensure that they are working optimally at all times. However, all monitoring should be used to provide information that can be applied to ensure the proper management of the system and safe water quality. The WSP will also include procedures to ensure that chemicals and materials used in the system comply with requirements and will not introduce hazards. Appropriate emergency plans that would cover all aspects of the system, from a contamination incident in the raw water source to a breakdown in treatment and distribution (e.g. in final disinfection or damage to the distribution system), are also important components. In addition, WSPs for desalination systems should take into account the process of remineralization or stabilizing the treated water before distribution.

Detailed information on WSPs can be found in the World Health Organization's (WHO) *Guidelines for drinking-water quality* (WHO, 2011) and supporting WHO guidance documents, such as the *Water safety plan manual: step-by-step risk management for drinking-water suppliers* (WHO, 2009).

3. Source water and potential hazards

Source water for desalination can be marine or brackish surface water or highly mineralized groundwater. By definition, this water has a significant content of naturally occurring inorganic ions, and the objective of treatment is to reduce the concentration of, or remove, these substances. These naturally occurring substances include some that would be of potential concern if present in sufficient concentrations after treatment. Like all surface water sources and some groundwater sources, there can be contamination by pathogenic viruses, bacteria and parasites and by a variety of chemical contaminants from human activities.

There are notable differences between freshwater sources and brackish or saline sources. In particular, the survival of many microbial pathogens is significantly reduced in saline waters, especially in combination with a high level of solar radiation. However, some pathogens, such as *Vibrio cholerae*, do survive well in saline waters. There are also many marine algae that can produce toxins of concern to human health. These issues are covered in detail in *Desalination technology: health and environmental impacts* (Cotruvo et al., 2010).

Chemical constituents of interest include boron (borate), bromide, iodide, sodium and potassium; they may require additional actions for removal (boron) or are present in such concentrations as to leave significant residues. While natural organic matter (NOM) varies significantly, there are a number of organic substances, coming from both natural and anthropogenic sources, that are of particular interest. Individual and groups of chemicals that are of concern for desalination processes are considered in more detail in Annex 1.

Understanding the hazards that are likely to be present in the source water is a critical condition for the proper design of the desalination process; it highlights the need for pretreatment steps and the removal of contaminants in treatment or the need for additional treatment barriers. In the case of potential problems from contaminants, either chemical or microbial, the first step in reducing the associated risks is to try to prevent or reduce inputs at source. In some cases, this may be possible; in other cases, siting of the raw water intake may help to minimize the intake of contaminants into the desalination plant. However, thermal plants, in particular, are often co-located with power plants, and there may be limited options in terms of suitable locations for the intake. Where source water quality is highly variable, some form of monitoring will help to provide information in managing water abstraction to minimize the intake of constituents or contaminants. For example, some estuarine-based desalination plants abstract water only at a particular tide level to reduce the salinity in the source water and the concentrations of possible anthropogenic contaminants. In addition, knowledge of potential contaminants is important in preparing emergency plans to protect source water quality (e.g. to deal with oil spills in oil-producing regions).

4. Desalination processes

The desalination process is primarily intended to remove natural ionic contaminants, but some substances are not as well removed as others. For example, boron, which can be present in significant concentrations in saline waters, is not well removed by reverse osmosis (RO). While most systems remove a significant proportion of microbial pathogens, in some circumstances, there is a significant potential for some pathogen transfer. Electrodialysis reversal systems do not provide any barrier against pathogens, and electrodialysis reversal is, therefore, rarely considered to serve as the main treatment barrier for drinking-water production.

In addition, a number of chemical treatments are used to prepare and maintain the desalination systems, and procedures must be established to ensure that the associated compounds do not reach final water in unacceptable concentrations. These processes and the chemicals used are considered in detail in Cotruvo et al. (2010). Cleaning of membranes is fundamental for optimal treatment performance and the quality of water coming from the membranes. When cleaning agents are applied, either online or offline, these chemicals can be present in the system at high concentrations that could negatively affect treated water quality. Therefore, the membranes should be properly flushed before installation and before the system goes back online, and the flushing solution should be disposed of suitably as waste. Pretreatment of the waste will be necessary, and it is important that this waste stream be disposed of properly so that it does not contaminate either source waters or waters that might be used for blending with desalinated water.

Materials such as piping and contact surfaces in treatment systems and processes that come into contact with drinking-water need to be assessed to ensure that no harmful chemicals or substances in these materials are introduced that could cause WHO guideline values to be exceeded, pose a hazard to health or have an impact on the acceptability of the final water. Procedures ensuring compliance are an important component of the WSP.

4.1 Pretreatment

Pretreatment of the source water after the intake is normally designed to remove contaminants that will interfere with the desalination process by, for example, scale formation or membrane fouling. This treatment can include coagulation and filtration or membrane filtration processes that will remove particulate and organic matter, including a significant reduction of NOM, although seawater is generally low in NOM. A disinfectant such as chlorine is normally applied to minimize fouling and reduce the risk of pathogens carrying over to the product water.

Humic and fulvic acids and other related substances that constitute NOM can react with chlorine (and other disinfectants) to produce a wide range of halogenated and oxidation by-products. In the presence of the high bromide concentrations found in seawater and many brackish waters, the bromide is oxidized to bromine or hypobromite, which will take part in the halogenation reactions and produce organobromine products as the predominant by-products. Data from studies on the chlorination of seawater show that the disinfection by-products are dominated by brominated trihalomethanes, particularly bromoform and, to a lesser extent, dibromochloromethane. The WHO *Guidelines for drinking-water quality* consider these substances in detail, and guideline values have been established for them. There may also be small quantities of iodinated trihalomethanes present, which may have an impact on taste, but there are no guideline values for these substances; there are limited data on their presence in disinfected fresh water (Plewa et al., 2004) and some data on their occurrence in disinfected water with high salt content (Richardson et al., 2003). The levels of other potential chlorination by-products, such as the haloacetic acids, will be a function of the precursors present. Again, either distillation or membranes will remove most of these disinfection by-products as well as their precursors, although a proportion of the smaller or more volatile molecules may pass through treatment.

Organonitrogen compounds, particularly *N*-nitrosodimethylamine and other nitrosamines (e.g. nitrosodiethylamine), may form during chloramination if the appropriate secondary amines are present in the source water or possibly in coagulants. Numerous *N*-chloroamine and *N*-chloroamide compounds are undoubtedly formed at very low concentrations, but there are limited data on their occurrence and toxicology. The body of data on the formation of *N*-nitroso compounds during drinking-water distribution is limited but increasing; there appear to be no data, however, on their presence in desalinated water. There is evidence of the formation of nitrosamines in chlorinated wastewater, where there will also be ammonia and secondary amines present. Thus, where chlorinated sewage effluents are likely to have an impact on the raw water, there may be potential for these compounds to volatilize and be carried over into the desalinated product water. *N*-Nitrosodimethylamine is known to be poorly removed by RO membranes because of its low molecular weight, and it is often treated by advanced oxidation processes in water reuse schemes.

Where hypochlorite is produced by electrolytic generation from seawater or brine with a high bromide level, this will lead to the formation of bromate. Because it is ionic, bromate is not likely to pass through membranes and would not be expected to carry over in thermal systems. Where hypochlorite is allowed to age, there is potential for the formation and build-up of chlorate, which can be well removed by either distillation or membranes. The presence of chlorate in finished water would usually be due to post-treatment chlorination.

4.2 Treatment

The efficiency of desalination plants in removing or inactivating microbial contaminants can be assessed by examining the expected performance and factors affecting the quality of each stream or combined final treated water. The potential for survival of microorganisms depends upon the capability and operating conditions of each process unit for their removal or inactivation. Evaluation should include any pretreatment processes, the water produced by membrane processes or the water resulting from thermal treatment processes.

Membranes need to be protected from particulates to prevent clogging and fouling, and so particulate removal processes are employed, while oxidants and biocides may be employed to prevent fouling of the RO membranes. Although these pretreatments are not necessarily employed to reduce the numbers of waterborne pathogens, they will have an impact on numbers, particularly through particle removal.

Pretreatments include the use of membranes for microfiltration (MF) and nanofiltration (NF) to prepare the water for the subsequent desalination process. MF and NF have a substantial capacity to physically remove a large proportion of particulate-associated microorganisms as well as some dissolved solids. They can effectively remove at least 6 logs of microorganisms according to their pore size distribution, but the actual removal should be validated before application as a pretreatment (LeChevallier & Kwok-Keung, 2004).

A vital part of the WSP is the introduction of procedures to monitor that treatment is operating effectively and efficiently. For membrane systems, the barrier function depends on the integrity of the membranes. Integrity testing of the membranes is therefore crucial, as breaches can lead to the passage of pathogens into the processed water. The efficiency of different desalination technologies to remove pathogens is discussed in Annex 2.

There is the possibility that a number of volatile organic contaminants, including those present in raw water and those resulting from disinfection, could carry over to the product water in thermal distillation processes. There is a need to understand under what circumstances this will take place and to confirm that those types of substances are adequately removed.

Membranes provide a barrier to most chemical compounds, although not always a complete barrier. The propensity of boron (as borate or boric acid) and also arsenite to pass through membranes raises the question as to what other anions and small neutral organic molecules will pass through membranes. There is a need for more specific data from actual desalination facilities and for specific types of membranes. This would constitute investigative monitoring either in a pilot plant or retrospectively in an operational plant.

Flash distillation desalination plants are often sited beside coastal power plants, and an additional potential concern, for which there appear to be no firm data, is the use of hydrazine in power plants as an oxygen scavenger. Although hydrazine itself is no longer used, alternatives appear to break down to hydrazine. Where these compounds are used, it is important that there be no potential to transfer, through steam leaks, into the desalination stream.

4.3 Post-treatment

Post-treatment consists of disinfection and conditioning (i.e. blending and remineralization) to reduce the aggressive nature of the treated water. Both processes are key considerations for desalination and have the potential to introduce microbial and chemical contaminants into the water They are considered in greater detail in the following sections.

5. Disinfection

Desalinated waters constitute a relatively easy disinfection challenge because of their low total organic carbon and particle content, low microbial loads and minimal oxidant demand after desalination treatments. Turbidity is not likely to affect chemical disinfectant performance, as turbidity values of desalinated water are low. Post-treatment (e.g. with lime) can cause an increase of inorganic turbidity that would not interfere with disinfection by chlorine. The target levels of inactivation for pathogens remaining in desalinated waters can readily be achieved by appropriate disinfection processes, discussed in the WHO *Guidelines for drinking-water quality* (WHO, 2011). Once the target levels of disinfection have been achieved, it is good practice to maintain an appropriate level of residual disinfectant in the product water during distribution.

Issues to be considered as specific to the disinfection of desalinated water are:

- the potential passage of viruses through some RO membranes, which may require adequate virus inactivation downstream of RO. For CT values (the product of disinfectant concentration and contact time) for the inactivation of viruses, see Tables 2 and 3 (Cotruvo et al., 2010);
- the potential loss of integrity of membranes, which could lead to the passage of pathogens into the process water.

Table 2. CT values for inactivation of viruses

	CT value (mg·min/l)		
Disinfectant	**2 log**	**3 log**	**4 log**
Chlorine[a]	3	4	6
Chloramine[b]	643	1067	1491
Chlorine dioxide[c]	4.2	12.8	25.1

[a] Based on 10 °C, pH 6–9, free chlorine residual of 0.2–0.5 mg/l.
[b] Based on 10 °C, pH 8.
[c] Based on 10 °C, pH 6–9.
Source: CT values from USEPA (1991).

Table 3. CT values for inactivation of viruses using chloramines

Temperature (°C)	CT value (mg·min/l)		
	2 log	3 log	4 log
5	857	1423	1988
10	643	1067	1491
15	428	712	994
20	321	534	746
25	214	356	497

Source: CT values from USEPA (1991).

These issues can be addressed in most cases by applying effective post-desalination disinfection using chlorine-based or alternative disinfection processes (ultraviolet light, ozone, etc.) as an additional barrier to reduce the possible risks. Preventive measures and procedures, as advocated by the WSP approach, should be undertaken to ensure that high levels of chemical contaminants are not introduced during this process (e.g. limits on bromate in electrolytically generated hypochlorite and appropriate storage of hypochlorite solution to prevent formation of high levels of chlorate). Because of the low NOM content of desalinated water, organic by-products are usually present in low concentrations only, although the use of ozone may lead to bromate formation.

6. Blending and remineralization

Desalinated water is low in minerals and is poorly buffered. It is usually aggressive to cementitious and metallic materials used in storage, distribution and plumbing and requires conditioning to address this problem. Blending desalinated water with source water or partially treated water is a common practice, and the addition of minerals to achieve a balanced mineral content in desalinated water is increasingly being adopted. This latter approach may also be used to make a contribution to the mineral intake of consumers in regions where traditional sources of water have contained significant levels of minerals. Remineralization is considered in detail in Annex 3, and blending is considered further below.

6.1 Blending source water with desalinated water

The quality of the source water used for blending is particularly important to the evaluation of the microbial risk of the blended water if there will be mixing of incompletely treated water with desalinated water prior to distribution. The amount of water used for blending may vary from less than 1% to 10% and can include partially treated seawater and untreated groundwater. This potential short-circuiting of the main treatment process should not allow pathogens and other undesirable microorganisms to be introduced into the finished desalinated water. This water should, therefore, be considered as source water and adequately treated to ensure that it is safe. In addition, there should be specific minimum requirements for disinfection and particle removal and monitoring methods for appropriate performance surrogates (Cotruvo et al., 2010; WHO, 2011). Requirements for treatment performance to remove the bacteria, viruses and protozoan parasites should also be designed according to the level of contamination of the raw water used for blending. Similar considerations regarding the formation of by-products in the blending water apply as discussed under pretreatment processes (see section 4.1). There are currently WHO guideline values for several disinfection by-products. Generally, the NOM content in finished water is very low, and the contribution of NOM from the blending water will not normally be significant, and so the yield of by-products from final disinfection would be expected to be low. Chlorine used for disinfection that is generated from brine with high bromide levels may contain significant levels of bromate that could exceed the WHO bromate guideline value for drinking-water. Effective procedures should, therefore, be included in the WSP to ensure that this does not happen.

Seawater as a source of water for blending has both advantages and disadvantages, particularly in terms of corrosion and taste if the blending levels exceed about 1%. In addition, bromide would likely continue to react with residual disinfectants during storage and distribution. Blending with seawater will result in the addition of sodium and some potassium, calcium, magnesium, chlorides and other salts to drinking-water. Therefore, consideration should be given to the natural minerals present and whether these will result in finished water not meeting the WHO guideline values or having unacceptable taste. There is also an issue with regard to potential anthropogenic pollutants from a range of sources that need to be considered on a local basis, whenever any external and potentially minimally treated source is used. It is, therefore, important to take into account potential pollution sources and threats in the WSP and introduce appropriate barriers to minimize the risks from any hazards identified.

In addition, other corrosion-inhibiting chemicals, primarily silicates, orthophosphate or polyphosphate, may be added to the water. Such chemicals are widely used in many parts of the world and are not of direct consequence to health. However, it is important that they be of a suitable quality for addition to drinking-water and that there are no contaminants of concern, particularly those covered in the WHO *Guidelines for drinking-water quality* (WHO, 2011), that would make a significant contribution to the concentrations of such contaminants in drinking-water. It is also important that they be verified to be always of an appropriate quality. Approval systems for chemicals that specify the quality and acceptable levels of contaminants are available. The development of guidance on how such systems can and should operate is under consideration in the ongoing work for the WHO *Guidelines for drinking-water quality*. Where remineralization is practised, it is also important to ensure that the minerals added are of an appropriate quality and do not introduce contaminants that adversely affect water quality.

7. Storage and distribution of processed water

Desalinated water usually undergoes storage prior to or during distribution, and the problems encountered during storage and distribution are similar to those encountered for other supplies derived from fresh water. These relate to the potential introduction of contaminants, both microbial and chemical, the problem of corrosion of materials and the potential for materials and corrosion products to affect water quality, and the growth of pathogenic and potential nuisance organisms. Similar to most drinking-water supplies, there is often a requirement for blending with existing drinking-water streams.

7.1 Microbial quality

The challenge of maintaining microbial water quality during storage and distribution is not specific to desalinated water. Microorganisms will grow during distribution, especially in the absence of an effective residual disinfectant and at the high water temperatures often encountered. A broad spectrum of microbial species, such as *Legionella*, *Aeromonas*, *Pseudomonas*, *Burkholderia pseudomallei* and atypical mycobacteria, some of which include strains that are opportunistic pathogens, can be present in distributed waters. The routes of transmission of these bacteria include inhalation and contact (bathing), with infections occurring in the respiratory tract, in skin lesions or in the brain (Craun & Calderon, 2001). There is no evidence of an association of any of these organisms with gastrointestinal infection through ingestion of drinking-water (Ainsworth et al., 2004), but *Legionella* can grow to significant numbers at temperatures of 25–50 °C. Where temperatures in hot or cold water distribution systems cannot be maintained outside the range of 25–50 °C, greater attention to disinfection and operating measures aimed at limiting the development of biofilms is required. Accumulation of sludge, scale, rust, algae or slime deposits in water distribution systems supports the growth of *Legionella* spp., as does stagnant water (Lin et al., 1998). Systems that are kept clean and flowing are less likely to support excess growth of *Legionella* spp. Care should also be taken to select plumbing materials that do not support microbial growth and the development of biofilms. Further guidance is available in the WHO *Guidelines for drinking-water quality* (WHO, 2011) and in *Health aspects of plumbing* (WHO/WPC, 2006).

Non-pathogenic organisms will grow during distribution, and these contribute to the heterotrophic plate count. The development of heterotrophic plate counts during distribution is no longer considered a significant health risk per se, but its value as an indicator of water quality and treatment efficacy has been reiterated (WHO, 2003). However, such organisms can contribute to problems of acceptability.

The maintenance of water quality during storage and distribution depends on a number of factors, including:

- the amount of biodegradable organic matter available and trace nutrients to support the growth of bacteria;

- balancing the water to reduce corrosion of iron from iron pipes and corrosion sediment;
- the availability and nature of attachment surfaces, in particular the pipe and reservoir surfaces, and the presence of corrosion;
- the maintenance of a disinfectant residual;
- the maintenance of integrity in the pipes and reservoirs;
- the growth conditions, such as system retention time, hydraulic conditions and temperature.

The WHO documents *Safe piped water: managing microbial water quality in piped distribution systems* (Ainsworth et al., 2004) and *Health aspects of plumbing* (WHO/WPC, 2006) set risk management and risk reduction frameworks to limit the health risk associated with the distribution of piped water, and these guidelines also apply to desalinated water. Those water quality concerns should be considered in light of the potential for microbial regrowth.

High water temperatures will limit the maintenance of an effective disinfectant residual throughout the distribution system as a result of the increased chemical reactivity of the disinfectant. The use of chloramines constitutes an advantageous alternative to free chlorine in distribution systems with long retention times and operating at elevated ambient or system temperature. Chloramines also seem to be more effective at limiting *Legionella* growth in domestic plumbing; however, nitrification can occur from chloramines when *Nitrosomonas* bacteria and suitable conditions (pH, temperature, dissolved oxygen level) are present.

7.2 Chemical quality

Desalinated water is initially more corrosive than many other drinking-water sources, and it is important, as indicated above, that the water be stabilized to minimize its corrosive effect on pipes and fittings used in distribution and plumbing systems in buildings. Where tankers are used for distribution, the potential for corrosion of the water tanks must be considered. The requirement is that corrosion should not give rise to levels of metals that exceed the WHO guideline values or result in unacceptable appearance or taste or lead to physical damage to surfaces in contact with water. These can include metals from primary distribution and storage, particularly iron, and from plumbing and fittings in buildings, including lead, copper and sometimes nickel. Iron is a common cause of discoloured water that significantly reduces the aesthetic acceptability of the water for both drinking and household uses. Water that is low in pH can also corrode cement- or concrete-lined pipes or storage reservoirs. In many cases, a range of coatings and materials will be used to coat pipes or storage reservoirs, or storage tanks in buildings, in order to protect against corrosion. It is important that these materials be certified as safe for use with potable water. As indicated above, approval schemes have an important part to play in ensuring their safety and reducing the potential impact on consumer acceptability. There is a particular consideration in the approval of materials, as in many of these circumstances they will be used at elevated temperatures, which can exacerbate leaching of component metals.

Establishing procedures for managing the distribution system is an important part of the WSP. These include mapping the storage and distribution system and identifying any points where there is potential for ingress of microbial and chemical contaminants that could have an impact on water quality, acceptability and health. These procedures should also consider operational management of the water system to avoid surges or sudden disturbances that could dislodge sediments. In a number of countries, desalinated water may be distributed in tankers to consumer premises where the water is stored again. Transfer points make up part of the distribution system, but they potentially introduce vulnerable points where contamination can occur. It is, therefore, important that the WSP also covers this aspect of distribution, with appropriate procedures to ensure that the water does not deteriorate prior to being used for drinking or food preparation.

7.3 Issues with blending desalinated water with other sources of treated drinking-water

Blending of desalinated water with groundwater or potable water from other sources is often a means of increasing the reliability and flexibility of water supply. This practice does not raise any special issues for desalinated water with regard to microbiological quality. Blending water from different sources does, however, have quality implications. Special care should be taken regarding the potential for changes in the taste and mineral characteristics of the water to prevent adverse impacts on consumer perception of quality, especially if blending is intermittent and the blending ratio is highly dynamic. Taylor et al. (2006) provided an excellent review of issues to take into consideration and results from an extensive pilot study of the impact of blending water treated by RO with potable water from groundwater and surface water in various pipe materials. It is of special relevance to maintain conditions aimed at minimizing iron, lead and copper release (selection of disinfectant and dosage adjustment) and to control nitrification when chloramines are used as the secondary disinfectant.

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Annex 1: Chemicals of concern for desalination processes

Boron and borate

Most of the inorganic components will be significantly removed in the desalination process, either thermal desalination or RO desalination, although some sodium chloride and bromide may be present in the treated water from membrane plants and possibly from some older distillation plants. In terms of key contaminants of direct interest for health and the environment, the most important is probably boron, which can be of significance in RO plants, as the rejection ratio of boron-containing anions (probably mostly as borate) is less than that for most other inorganics.

In the fourth edition of the WHO *Guidelines for drinking-water quality*, the health-based guideline value for boron (borate) in drinking-water is 2.4 mg/l (WHO, 2011). This value represents a revision from earlier values and is based upon a review of the toxicological data and studies in areas with high background exposures. Although boron is an essential element for plant growth, it is herbicidal at higher levels, and some plants are sensitive at 0.5 mg/l. The latter is the principal issue for residual boron—that is, its effect as a herbicide if present in sufficient amounts in irrigation water, particularly in areas where rainfall is so low as to not cause sufficient leaching of salts from soils. Acceptable boron concentrations in desalinated water in areas where desalinated water has significant applications for irrigation may best be determined by authorities on a case-by-case basis, reflecting costs, end uses, climate and agricultural activity in the area.

Bromide and bromate

Bromide is initially present in seawater in relatively large amounts (~80 mg/l in some regions), so even high (e.g. >95%) percentage removals will allow some bromide, on the order of 1 mg/l to several milligrams per litre, to be present in the finished water. The concentrations of bromide in desalinated water will be approximately proportional to the chloride concentration because of similar removal mechanisms for these analogous anions. Inorganic bromide is also present in many fresh waters, especially groundwaters and coastal aquifers affected by seawater intrusion, at up to milligram per litre levels. FAO/WHO (1988) developed an acceptable daily intake for bromide of 1 mg/kg body weight; assuming a 60 kg adult drinking 2 litres of water per day with a 20% allocation of the acceptable daily intake to drinking-water could give a health-based reference value in the range of 6 mg/l. A similar conclusion is recommended in the fourth edition of the WHO *Guidelines for drinking-water quality* (WHO, 2011).

If ozonation or other similar oxidation processes are applied to waters with sufficient residual bromide under appropriate conditions, bromate will be formed at concentrations that will likely exceed the current WHO guideline value of 10 µg/l (WHO, 2011). Packaged waters produced by bottling distributed desalinated waters derived from high-bromide source water are often treated by ozonation prior to bottling. This would increase the bromate levels in the bottled water beyond the concentrations in the original distributed water if residual bromide is present. Production of chlorine by electrolysis of seawater will also produce large amounts of bromate. Bromate is carcinogenic in rats and mice in lifetime tests under high-dose conditions, with cancers in the kidney, thyroid and testes being observed, although there are no data available for humans (WHO, 2005a). However, there are strong indications that small amounts of bromate are metabolized and detoxified following ingestion before they can reach the target cells (Bull & Cotruvo, 2006). This was not considered in the process of developing the current WHO guideline value (WHO, 2011), but the next WHO review of the guideline value will take into account ongoing studies that will generate a physiologically based pharmacokinetic model and enable a revised risk assessment for ingestion in drinking-water. As such, the current guideline value probably overestimates the potential risk at low, environmentally relevant exposures.

Sodium and potassium

Sodium concentrations in seawater are in the range of 10 000–15 000 mg/l, depending upon the location. Sodium is an essential nutrient, and there is no health-based WHO guideline value for sodium, which is normally present in relatively low concentrations in drinking-waters derived from freshwater sources. The taste threshold is in the region of 200–250 mg/l, depending upon the associated anions. Daily dietary intake may approach 10 000 mg/day for some individuals, which is well above the required daily intake. Sodium is essential for adequate functioning of human physiology, although the requirement of infants for sodium is lower than that for children and adults, and high sodium intake may lead to hypernatraemia. This is a problem for bottle-fed infants and is the reason why sodium levels in infant formulas have been reduced significantly over time. There have been concerns expressed about the contribution of sodium intake to increasing hypertension across populations. A number of WHO Member States are concerned about the overall intake of salt from all sources, but particularly food, which is the major source of sodium intake, and are seeking to persuade their populations to decrease salt intake. In contrast, hyponatraemia can be a serious, including fatal, acute risk if significant perspiration causes high loss of sodium and there is inadequate sodium intake from the total diet. It is probable that the presence of some sodium in drinking-water in very warm climates might be beneficial for persons engaging in heavy physical activity.

Usually, seawater, brackish water and many fresh waters also contain potassium. Potassium concentrations in seawater are in the region of 450 mg/l, but about 98% of the potassium is removed in the desalination process. Potassium is also an essential nutrient, and the recommended daily dietary requirement is more than 3000 mg/day. There is currently no specific WHO guideline value for potassium; residual concentrations in desalinated water are expected to be small and well below any significant contribution to recommended daily dietary intakes.

Magnesium and calcium

Magnesium and calcium are essential nutrients and are present in seawaters at concentrations of about 1200–1700 mg/l and 400–500 mg/l, respectively. They are the principal defining components of "hard water". They are very efficiently removed by desalination, including NF, but may be added back to finished water by some processes used to stabilize the water and reduce corrosive potential, as discussed in Annex 3.

Organic chemicals found naturally in source waters

Naturally occurring chemicals include NOM, such as humic and fulvic acids, and the by-products of algal and seaweed growth, where this growth occurs to a significant extent. Such chemicals can include substances that can cause taste and odour in the final water, such as geosmin from cyanobacteria, particularly in brackish water; and a range of toxins from a variety of different organisms, including cyanobacteria and dinoflagellates, that can form significant blooms, although these are usually intermittent in nature. Only one of these potential contaminants, the cyanotoxin microcystin-LR, which arises from freshwater cyanobacterial blooms, has a WHO guideline value (provisional) of 1 µg/l (WHO, 2011). Desalination processes will significantly control algal toxins.

The nature of the natural organic molecules is such that most of them have sufficiently high molecular weights or low volatilities that they would not be expected to carry over in thermal desalination processes, although the potential for some carryover by steam distillation remains a possibility. Volatile organics are usually vented as part of the distillation process. The carryover would be expected to be small, but for substances such as geosmin, which has an odour threshold measured in nanograms per litre, this could still be of concern for the potential acceptability of the final product. Most of the organic molecules are relatively large (e.g. greater than ~200 daltons) and would be expected to be excluded by membranes used in desalination; for example, two of the main marine toxins, saxitoxin and domoic acid, have been shown to be rejected by membranes used in desalination (N. Voutchkov, personal communication, 2006). However, low molecular weight polar compounds might require further study in that regard. Solvent-type low molecular weight neutral organics can pass through membranes to a significant degree.

There is also a significant potential for anthropogenic contamination of source waters, particularly seawater and estuarine waters, as a consequence of discharges from sewage treatment plants and from industry. The contaminants present at a particular site will depend on both the industrial and shipping activities that are present in the wastewater catchment or that discharge directly to sea and the size of the population served. Many of the substances that can reach source waters are covered in the WHO *Guidelines for drinking-water quality* (WHO, 2011) and in an associated document, *Chemical safety of drinking-water: assessing priorities for risk management* (Thompson et al., 2007). A number of potential contaminants reaching drinking-water supplies from upstream wastewater discharges, such as pharmaceuticals and hormones, have attracted significant media attention;

however, these have been largely shown not to cross desalination membranes (McGuire Environmental Consultants Inc., 2005). The great majority of those molecules would not be expected to be present in the distillate from thermal processes, but there is a potential issue regarding public perception. Providing reassurance of the adequacy of the barriers to the consuming public would be an important step in a WSP. There is also a significant potential for contamination by petroleum hydrocarbons, particularly in regions where there is substantial oil extraction activity. There is the possibility that more volatile substances may be carried over into product water in thermal distillation processes; these include benzene, toluene, ethylbenzene and xylenes (the BTEX compounds) and solvents such as chloroform, carbon tetrachloride, trichloroethene and tetrachloroethene. These processes are designed to vent those gases during processing, but it is important to confirm that those types of substances are being adequately removed. There may also be potential for those substances, if present in sufficient quantities, to dissolve in RO membranes, migrate through the membranes and thus appear in finished waters. Although there are health-based drinking-water guideline values for all of these substances, the primary issue regarding the BTEX compounds (except for benzene) is the potential for them to cause unacceptable taste and odour at concentrations much lower than the health-based guideline values (WHO, 2011). Prevention of source water contamination is the best method to prevent contamination of finished waters. The assessment of potential hazards and risks from pollutants will require an evaluation of the sources and types of pollutant in the local circumstances.

There have also been suggestions of contamination by metals, particularly mercury, in regions of oil production. Data on actual concentrations in feedwaters are very limited; however, there is an existing guideline value for inorganic mercury of 6 µg/l (WHO, 2011). Mercury also occurs in the form of organomercury compounds, but these substances are hydrophobic, and the main concern relates to accumulation in aquatic organisms rather than in the drinking-water.

Annex 2: Efficiency of desalination processes for removing pathogens

Reverse osmosis

RO has been shown to remove bacteria and larger pathogens and all or a large fraction of viruses (Gagliardo et al., 1997; Adham et al., 1998a; van der Hoek et al., 2000). High-quality RO processes are good treatment barriers to pathogens if properly selected and maintained.

WHO provides guidance on target removals for bacteria, viruses and protozoa, removals that are achieved by typical and enhanced water treatment processes (WHO, 2011). Removal of viruses by RO membranes may vary significantly and is a function of the membrane itself as well as its condition and the integrity of the entire system, including seals. Removals ranging from 2.7 to more than 6.8 logs, depending on the type of RO membrane, have been reported at bench scale using MS2 bacteriophage as the model virus, and Adham et al. (1998b) suggested that the selection of membranes is an important factor in determining virus removal. Kitis et al. (2002, 2003) reported removals of MS2 ranging from 5 logs for a dual-element unit to more than 6.8 logs for a multistage unit. In pilot-scale studies conducted to investigate the potential of integrated ultrafiltration and NF membrane systems for the removal of various microorganisms, including viruses, protozoa (*Cryptosporidium* oocysts and *Giardia* cysts), bacterial spores (*Clostridium perfringens*) and bacteriophage (MS2 and PRD-1), Lovins et al. (1999) observed removals, including those resulting from pretreatment, ranging from 6.1 to 10.1 logs. This shows that membrane treatment exceeds the microbial removal attained by other combinations of process units, such as coagulation, filtration and disinfection of surface water.

Integrity of the RO system

Although RO constitutes an excellent barrier to microorganisms, the maintenance of that barrier depends on the integrity of the system. Breaches of integrity in the membranes or the O-rings could lead to the passage of pathogens into the process water and must be monitored by integrity testing. Building on bench-scale studies done by Colvin et al. (2000), Kitis et al. (2002) critically compared three integrity testing methodologies at pilot scale. They investigated the ability of these tests to quantify virus removal (MS2 bacteriophage) in single-element and two-stage configurations and to determine the changes in virus removal capability when systems are subject to different types of membrane and gasket compromising and fouling. These authors concluded that the loss of membrane integrity decreased virus removal from 5.3 to 2.3 logs when the compromised unit was placed in the lead position and from 5.3 to 4.2 logs when the compromised unit was in the trailing position. Fouling appeared to limit the impact of imperfections by a combination of cake formation and pinhole filling. Cracking of the O-rings did not lead to significant decreases in the removals of MS2 or indicators, and the location of the damage influenced the extent of the small decrease in performance.

Effective methods to measure the integrity of RO membranes should be used to achieve target removals (WHO, 2011). Currently, conductivity measurements are utilized, but the sensitivity limits their application to about 2 logs of removal.

Bacteria have been found in permeate samples of NF and RO effluent, and they can proliferate in discharge lines. This does not mean that pathogens are not rejected, but rather that sterile conditions cannot be maintained (Taylor & Jacobs, 1996). As bacteria have been shown to traverse through membrane defects, membranes cannot be considered as completely effective for disinfection and are commonly succeeded by a disinfection step.

Thermal processes

When thermal processes are used for desalination, microbial inactivation will be controlled by the temperature attained and the time the water remains at that temperature. Typical temperatures to ensure the inactivation of vegetative cells by humid heat vary from 50 °C to 60 °C when maintained for 5–30 minutes to achieve pretreatment . Spores, endospores and other resistant forms are more resistant to heat and require higher temperatures (70–100 °C) held for longer periods of time. Most vegetative pathogens are inactivated under flash pretreatment conditions (temperature of 72 °C for 15 seconds). The condensate is unlikely to contain pathogens after the distillation process because of the killing impact of heat and because pathogens are unlikely to be entrained. However, reduced pressures are used in some desalination processes to reduce the boiling point and reduce energy demand. Temperatures as low as 50 °C may be utilized (USBR, 2003) and might not achieve the required inactivation targets.

Annex 3: Remineralization

In a number of cases, water is remineralized to reduce its corrosive potential during transmission and distribution. Under these circumstances, it is appropriate to consider whether the methods used, such as percolation through limestone, can also increase the concentrations of important nutritional minerals, particularly calcium and magnesium, in the drinking-water. While diet remains the principal source of nutrients and minerals, drinking-water may provide supplemental amounts that could be important for some people.

WHO expert consultations on calcium and magnesium in drinking-water (WHO, 2005b, 2006; Cotruvo, 2006) concluded that there was evidence of dietary deficiency of both calcium and magnesium in many parts of the world. This would be particularly acute in developing countries and in women, as well as in some sectors of the population, such as the elderly, who are also at highest risk of mortality from ischaemic heart disease. Hard water and particularly magnesium, a component of hardness, have been negatively (i.e. beneficially) associated with these conditions in a number of epidemiological studies. Although uncertainties about this association remain, in circumstances where a supply is moving from a source that has significant levels of calcium and magnesium to low-mineral desalinated water, it would be appropriate to consider remineralizing with calcium and magnesium salts. Additionally, calcium intake may reduce osteoporosis risk, and magnesium deficiency may also be associated with metabolic syndrome, indicating a prediabetic condition. However, any decision should be taken in conjunction with health and nutrition authorities in the light of total dietary intakes of nutrient minerals. Blending with 1% seawater provides about 15 mg of magnesium per litre and about 5 mg of calcium per litre to the finished water. It is appropriate for WHO and other organizations to continue to consider the importance of calcium and magnesium for protection against ischaemic heart disease and to determine the optimum levels of calcium and magnesium and the importance of the calcium to magnesium ratio, in order to provide guidance as to the optimum levels of addition, if appropriate. In particular, there are significant considerations with regard to both cost–benefit in particular circumstances and public perception.

Low fluoride intake is also a potential consideration with regard to loss of fluoride from bone and reduced incidence of dental caries. A recommendation of a WHO working group was for a minimum fluoride concentration of 0.2 mg/l, but this recommendation may require examination and confirmatory studies (WHO, 2005b). The recommended WHO guideline value for fluoride is 1.5 mg/l, but the optimal value is usually in the range of 0.5–1 mg/l, based upon average ambient temperatures and water consumption patterns. The appropriate value provides a balance between the benefits of fluoridation of drinking-water and minimizing the occurrence of dental fluorosis. However, use of the guideline value to develop local standards should take into account climate and water consumption, because this value is associated with an intake of 2 litres of drinking-water per day. This is also a consideration with regard to artificial fluoridation used to protect against dental caries, where this is a significant problem or there is a significant risk that cannot be addressed through other means (WHO, 2005b, 2006). Whether to add fluoride to finished water for dental health is a function of the status of tooth decay incidence in the location, diet (sugar consumption levels) and the ready availability and use of dental care in the area throughout the population. These can be determined by appropriate studies in the area.

With regard to sodium levels in the final water, this requires specific consideration of potentially sensitive populations, such as bottle-fed infants.

Calcium, magnesium and cardiovascular disease

This issue was examined in detail in three scientific meetings that were generated by this desalination guidance development process. The first was a meeting of experts assembled by WHO in Rome in 2003. The experts' task was to examine the potential health consequences of long-term consumption of water that had been "manufactured" or "modified" to add or delete minerals. Specifically, this was applied to the consumption of desalinated seawater and brackish water, as well as some membrane-treated fresh waters, and their optimal reconstitution from the health perspective. The latter is economically important, because desalinated waters require stabilization by some form of remineralization, often with calcium carbonate (limestone), to control their corrosive effects on pipes and fixtures while in storage and in transit to consumers. The expert group concluded, among other things, that, on balance, epidemiological studies indicated that consumption of hard water, and particularly magnesium, is associated with a somewhat lowered risk of certain types of cardiovascular disease (CVD) (WHO, 2005b). It also concluded that only a few minerals in natural waters had sufficient concentrations and distribution to expect that drinking-water might sometimes be a significant supplement to dietary intake. These included calcium, magnesium, selenium, fluoride, copper and zinc. It recommended that a detailed state-of-the-art review should be conducted prior to consideration of the matter in the WHO *Guidelines for drinking-water quality*.

That report led to the symposium entitled *Health aspects of calcium and magnesium in drinking-water* (Cotruvo, 2006) and a subsequent WHO expert meeting (WHO, 2006) on the subject. The symposium presented information that large portions of the population are deficient in calcium and magnesium and that water could make important contributions of calcium and magnesium to the daily diet in individuals who had low intakes from other sources. For desalinated water, remineralization methods that include addition of calcium and magnesium are more desirable, because they also contribute nutrient minerals. Seawater blending also adds back magnesium and calcium.

Finally, WHO organized a meeting of experts to further assess drinking-water-related epidemiological, clinical and mechanistic studies that involved calcium or magnesium or hard water that contains calcium and sometimes magnesium (WHO, 2006). A large number of studies have investigated the potential health effects of drinking-water hardness. Most of these have been ecological studies and have found an inverse (beneficial) relationship between water hardness and mortality from CVD. The best correlations were usually with magnesium. Inherent weaknesses in the ecological study design limit the conclusions that can be drawn from these studies. Analytical case–control and cohort studies are more useful than ecological studies for investigating cause-and-effect relationships. Seven case–control studies and two cohort studies of acceptable quality investigating the relationship between calcium or magnesium and CVD or mortality from CVD were identified in the literature. Of the case–control studies, one addressed the association between calcium and acute myocardial infarction and three the association between calcium and death from CVD. None found a positive or inverse correlation between calcium and either morbidity or mortality. Two examined the relationship between magnesium and acute myocardial infarction, finding no association. Five examined the relationship between magnesium and mortality from CVD; although some failed to yield statistically significant results, collectively they showed similar trends of reduced mortality from CVD as magnesium concentrations in water increased. Statistically significant benefits (where observed) generally occurred at magnesium concentrations of about 10 mg/l and greater. The cohort studies examined the relationship between water hardness (rather than calcium or magnesium content) and CVD or mortality from CVD and found no association (WHO, 2006).

The overall conclusion based on identified case–control and cohort studies was that there is no evidence of an association between water hardness or calcium and acute myocardial infarction or deaths from CVD (acute myocardial infarction, stroke and hypertension). There does not appear to be an association between drinking-water magnesium and myocardial infarction. However, the studies do show a negative association (i.e. protective effect) between CVD mortality and drinking-water magnesium. Although this association does not necessarily demonstrate causality, it is consistent with the well-known effects of magnesium on cardiovascular function.

Dietary supplementation

The geographic distribution of the nutrients in source waters used for drinking-water production will be varied and inconsistent, so an appropriate diet should be the principal source of nutrients. In general, drinking-water should not be relied upon as a major contributor of significant trace nutrients to daily intake. However, drinking-water can provide supplementation to dietary intakes in some locations. Dietary supplementation is widely practised for general benefit (e.g. vitamin D in milk, vitamin C in drinks, iron and B vitamins and folic acid in bread and other foods). The only beneficial substances added to drinking-water in some areas are fluoride with the intent of strengthening dental enamel and reducing the incidence of tooth decay (dental caries), ferric iron–ethylenediaminetetraacetic acid complex in some dietary iron-deficient areas and possibly iodine in some areas with high incidence of goitre in the Russian Federation.

WHO states that there is clear evidence that long-term exposure to an optimal level of fluoride results in diminishing levels of caries in both child and adult populations and that fluoride is being widely used on a global scale, with much benefit (WHO, 2006). However, good dental care, use of fluoride toothpaste and low sugar consumption are also important dental health factors. Water fluoridation is controversial in some quarters but generally believed by the dental community and many public health officials to be beneficial and without demonstrable risk. Water fluoridation is a matter of national policy. Seawater is naturally low in fluoride, and the fluoride is further depleted by the desalination process. Optimal fluoridation of the desalinated water can be a significant contributor to daily intake and can reduce the incidence of dental caries in some populations, just as it does with fluoridated fresh waters.

Consumption of low-mineral water

There have been suggestions that drinking-water with a very low mineral content (low total dissolved solids) can have a number of adverse effects on humans, particularly on the gastrointestinal tract, even with a diet that provides an adequate level of essential minerals (Kozisek, 2005). However, this hypothesis remains controversial in many quarters. In order to resolve this controversy, there is a need to investigate this subject in more detail to determine its significance in a wide range of circumstances, such as those encountered with desalinated and other potentially low-mineral manufactured waters.

Desalination has been used in some parts of the world for many decades, and this experience potentially provides a basis for total diet and water epidemiological studies of various health outcomes, including CVD, osteoporosis and metabolic syndrome. Such studies, if properly controlled and with proper consideration of potential confounding factors, would be of considerable value in ensuring the safety of desalinated water. WHO is recommending that before-and-after studies of acute CVD mortality should be conducted in drinking-water supplies that are undergoing changes in calcium and magnesium content .

Desalinated water may be used for irrigation, and, as indicated above, high levels of boron may be toxic to some crops. Suitability for irrigation may also be affected by the low concentration of ions, such as calcium and magnesium, which are also important for plant growth (Yermiyahu et al., 2007). Consideration of specific conditions is, therefore, required if desalinated water is to be used for irrigation, even when this may be on small-scale gardens, which may still be an important source of crops at the village or household level.