Rolling Revision of the
WHO Guidelines for Drinking-Water Quality

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Desalination Guidelines Development for Drinking Water: Background

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Introduction

More than 11,000 desalination plants are in operation throughout the world producing more than 20 million cubic meters (roughly six billion gallons) of water per day. About 63% of the capacity exists in West Asia and the Middle East. North America has about 11% and North Africa and Europe account for about 7% each of capacity. Plant sizes and designs range from more than 500,000 m^3/day to 20 to 100 m^3/day.

Most desalination plants use sea water or brackish water as their sources. It appears that comprehensive performance, operating and product quality specifications have evolved virtually on a site-by-site basis relative to source and the specific end product water use. Most drinking water applications outside of North America use World Health Organization Drinking Water Guidelines in some way as quality specifications. WHO Drinking Water Guidelines cover a broad spectrum of contaminants from inorganic and synthetic organic chemicals, disinfection byproducts, microbial indicators and radionuclides. They are aimed at typical drinking water sources and technologies. Because desalination is applied to non-typical source waters, and often uses non-typical technologies, existing WHO Guidelines may not fully cover the unique factors that can be encountered during production and distribution of desalinated water.

Drinking water production

Drinking water production processes can be divided into three broad categories each of which will impact the quality of the finished water received by the consumer.

I. Source Water Quality

II. Treatment Technology

III. Distribution

In the case of desalination operations some of the factors and issues that distinguish them from most typical drinking water operations are as follows:

Source Water Quality (Tables I, II)

- Total Dissolved Solids in the range for 40,000 ppm
- High levels of specific metals and salts including sodium, calcium, magnesium, bromides, iodides, sulfates, chlorides
- Total Organic Carbon type
- Petroleum contamination potential
- Microbial contaminants and other organisms

Treatment

- RO membranes and distillation
- Leachates from system components
- Pretreatment and anti fouling additives
- Disinfection byproducts
- Blending with source waters

Distribution

- Corrosion control additives
- Corrosion products
- Bacterial Regrowth

Other issues of interest include:

- System components that can contribute chemicals to the water as direct additives or indirectly from surface contact.
- Whether any risks are imparted from consumption of low TDS water either from general reduced mineralization or reduced dietary consumption of specific minerals.
- Environmental impacts of desalination operations and brine disposal.
- Performance of specific technologies particularly for microbial control
- Bacterial regrowth during distribution in warm/hot climates
- Whether microorganisms unique to saline waters may not be removed by the desalination process or post disinfection.
- Monitoring of source water, process performance, furnished water and distributed water to assure consistent quality at the consumer's tap.
- Whether additional water quality guidelines specific to desalination are needed.
- Whether short-term Health Advisory guidelines would be needed to deal with short-term excursions from chronic guidelines caused by system upsets.
- Whether membrane water softening (including home applications) should be included as a subtopic in this WHO assessment.

TABLE I

Major Elements of Seawater

Element	**Concentration (mg/l)**	**Element**	**Concentration (mg/l)**
Oxygen	8.57 x 10+5	Molybdenum	0.01
Hydrogen	1.08 x 10+5	Zinc	0.01
Chlorine	19000	Nickel	0.0054
Sodium	10500	Arsenic	0.003
Magnesium	1350	Copper	0.003
Sulfur	885	Tin	0.003
Calcium	400	Uranium	0.003
Potassium	380	Chromium	0.0003
Bromine	65	Krypton	0.0025
Carbon	28	Manganese	0.002
Strontium	8.1	Vanadium	0.001
Boron	4.6	Titanium	0.001
Silicon	3	Cesium	0.0005
Fluoride	1.3	Cerium	0.0004
Argon	0.6	Antimony	0.00033
Nitrogen	0.5	Silver	0.0003
Lithium	0.18	Yttium	0.0003
Rubidium	0.12	Cobalt	0.00027
Phosphorus	0.07	Neon	0.00014
Iodine	0.06	Cadmium	0.00011
Barium	0.03	Tungsten	0.0001
Aluminum	0.01	Lead	0.00005
Iron	0.01	Mercury	0.00003
Indium	<0.02	Selenium	0.00002

Table II

Ionic Composition of Seawater (mg/1)

Constituent	**Normal Seawater**	**Eastern Mediterranean**	**Arabian Gulf At Kuwait**	**Red Sea At Jeddah**
Chloride ($C1^{-1}$)	18,980	21,200	23,000	22,219
Sodium (Na^{+1})	10,556	11,800	15,850	14,255
Sulfate (SO_4^{-2})	2,649	2,950	3,200	3,078
Magnesium (Mg^{+2})	1,262	1,403	1,765	742
Calcium (Ca^{+2})	400	423	500	225
Potassium (K^{+1})	380	463	460	210
Bicarbonate (HCO_3^{-1})	140	--	142	146
Strontium (Sr^{-2})	13	--	--	--
Bromide (Br^{-1})	65	155	80	72
Boric Acid (H_3BO_3)	26	72	--	--
Fluoride (F^{-1})	1	--	--	--
Silicate (SiO_3^{-2})	1	--	1.5	--
Iodide (I^{-1})	<1	2	--	--
Other	1	--	--	--
Total Dissolved Solids	34,483	38,600	45,000	41,000

-- = not reported

Desalination technologies

Following is a brief overview of several common desalination technologies.Desalination Processes remove dissolved salts and other materials from sea water and brackish water. Related processes are also used for water softening and waste water reclamation. The principal desalination technologies in use are reverse osmosis (RO), and distillation. Electrodialysis and vacuum freezing also have some applications.

Reverse osmosis (ro)

Reverse osmosis systems reverse the natural process driven by osmotic pressure of solvent transport across a semi-permeable membrane from a region of lower solute concentration into one of higher solute concentration to equalize the free energies. In RO external pressure is applied to the high solute (concentrated) water to cause solvent (water) to migrate through the membrane pores leaving the solute (salts and other non permeates) in a more concentrated brine. The membrane provides a form of "hyperfiltration" by restricting passage of substances. Some membranes will reject 99% of all ionic solids and commonly have molecular weight cut off as low as 50 to 100 Daltons. The mechanisms of salts removal by RO membranes are not fully understood, and some salts (e.g. borate, arsenite) are not removed with high efficiency. Some believe the pure water preferentially passes through the membrane, while others believe that surface charges on the membrane polymer affect the polarity of the water. Increased pressure increases the rate of permeation, however fouling would also increase. Figure 1 illustrates the basic RO process which includes Pretreatment, Membrane Transport, and Post Treatment prior to distribution. RO processes can produce water in the range of 10 to 500 ppm TDS.

Figure 1

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Saline Feed Water                Pressure   Membrane
-------------------→Pretreatment-------→    ---------→Freshwater

                                       ↓                  ↓

                                     Brine             Post Treatment
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Pretreatment

Feedwater is treated to protect the membranes and to facilitate membrane operation. Suspended solids are removed by filtration, pH adjustments (lowering) are made to protect the membrane and control precipitation of salts; antiscaling inhibitors are added to control calcium carbonates and sulfates. Iron, manganese and some organics are also fouling contaminants. A disinfectant is added to control biofouling of the membrane. Disinfection can involve chlorine species, ozone or UV light and other agents. Marine organisms, algae and bacteria must be eliminated, and if ozone or chlorine are used they should be neutralized prior to contact with the membrane.

Membranes

Common membranes are polymeric materials such as cellulose triacetate or polyamides and polysulfones. Selection factors for membranes include pH stability, working life mechanical strength, pressurization capacity and selectivity for solutes. Membranes are located in a module and they can be configured as hollow fiber, spiral, plate and tubular. Each has its own characteristics that affect selection in particular cases. Hollow fiber and spiral configurations generally have more favorable operating characteristics of performance relative to cost and they are most commonly used. Operating pressures are in the range of 250 – 1000 psi (17 to 68 atm).

Membranes are typically layered or thin film composites. The surface contact layer (rejection layer) is adhered to a porous support, which can be produced from the same material as the surface. Thin film membranes can be made by polymerization of the rejection layer to the surface of the porous support. Membrane thicknesses are on the order of 0.05 mm.

Post Treatment

Product water must be treated to stabilize it and make it compatible with the distribution system. Adjustment of pH to approximately 8 is required and addition of corrosion inhibitors like polyphosphates may be necessary. Carbonation or other chemicals may be applied, or blending with source water may be done to increase TDS and stabilize the water. Post disinfection is also necessary to control microorganisms during distribution, as well as to eliminate pathogens from the blending process. Degasification may also be necessary.

Distillation technologies

Principal distillation (Vaporization→ condensation) systems include Multistage Flash (MSF) distillation, Multi-effect Distillation (MED) and Vapor Compression Distillation (VCD). Distillation plants can produce water in the range of 1 to 50 ppm TDS.

In distillation processes source water is heated and vaporized and the condensed vapor has very low TDS, while a concentrated brine is produced as a residual. Low theoretical plate distillation processes can be applicable to desalination because significant amounts of volatile chemicals are usually not present in seawater and brackish waters. Inorganics, salts and high molecular weight natural organics are non volatile and thus easily separated, however there are circumstances where volatile petroleum chemicals are present due to spills and other contamination. Even though their vapor pressures can range from low to very high many of them of higher molecular weight will be steam distilled in a physical process where the vapor pressure of the steam and the vapor pressures of the organic chemicals together contribute to the total vapor pressure of the mixture. In addition, some physical entrainment may also allow low volatility substances to be carried over into the distillate.

$$\text{Solution + Energy} \rightarrow \text{Vapor} \rightarrow \text{Liquid + Energy}$$

For water, the boiling point (where the vapor pressure of the liquid is the same as the external pressure) is 100°C (212°F) at 1 atmosphere (760 mm Hg or 14.7 pounds per square inch). Boiling temperature is a colligative property of solutions; as the concentration of solute increases the boiling point increases. As the pressure is decreased, the boiling temperature decreases.

The amount of energy required to vaporize a liquid is called the heat of vaporization. For water, this amounts to 2,256 kilojoules per kilogram at 100°C

(970 Btu per pound at 212°F). The same amount of heat must be removed from the vapor to condense it back to liquid at the boiling point. In desalination processes, the heat generated from vapor condensation is transferred to feed water to cause its vaporization and thus improve the thermal efficiency of the process and reduce cost and fuel consumption.

Multistage Flash Distillation (MSF)

MSF plants are major contributors to desalting capacity. The principle of MSF distillation is that heated water will boil rapidly (flash) when the pressure of the vapor is rapidly reduced below the vapor pressure of the liquid at that temperature. The vapor that is generated is condensed on to surfaces that are in contact with feed water thus heating it prior to its introduction into the flash chamber. This will recover most of the heat of vaporization.

Approximately 25 to 50% of the flow is recovered as fresh water in multistage plants. Characteristics of MSF plants include high feed water volume and flow, corrosion and scaling in the plant, and high rates of use of treatment chemicals.

Multiple – Effect Distillation (MEF)

Several configurations of MEF plants exist including vertical and horizontal tubes. In all cases steam is condensed on one side of a tube causing evaporation of saline water on the other side. Pressure is reduced sequentially in each effect (stage) as the temperature declines, and additional heat is provided in each stage to improve performance. Scale formation and removal seem to be less problematic in vertical tube vs. horizontal tube units. (see Figure 3)

Vapor Compression Distillation (VCD)

VCD systems do not use steam heat and function by compressing water vapor causing condensation on a heat transfer surface (tube) which allows the heat of condensation to be transported to brine on the other side of the surface resulting in vaporization. The principal energy requirement is in the operation of the compressor. The compressor functions to increase the pressure on the vapor side and lower the pressure on the feed water brine side to lower its boiling temperature.

Maintenance

Periodic cleaning is required to remove scale and salts deposits from pipes, tubing and membranes. Alkaline cleaners remove organic fouling and acid cleaners are used to remove scale and salts.

Other Systems

Electrodialysis processes utilize selective membranes that contain cation and anion exchange groups. Under a direct current electric field, cations and anions migrate to the respective electrodes so that ion-rich and ion-depleted streams form in alternate spaces between membranes. Reversal of electric fields reduces scaling and flushes the membranes.   Pretreatment is required to control scale and extend membrane life and to prevent migration of non ionized substances such as bacteria and organics and silica.

Potential technical issues associated with desalination

Health Issues

In general, it is assumed that food is the principal source of nutrients and hazardous substances exposures for humans. Water can also be a source of beneficial dietary substances, as well as harmful contaminants such as chemicals and microorganisms that can mitigate dietary components. The presence or absence of beneficial ions can affect public health in the population over the long term, just as the presence or absence of toxicants. Water components can supplement dietary intake of trace micro nutrients and macro nutrients or contribute undesirable contaminants. As is usual in toxicology and nutrition, the line between health and illness in a population is not a single line but rather a matter of optimal intake, versus adequate intake, versus intake that is inadequate to maintain good health, versus a toxic intake that will lead to frank illness in some segment of the population. Some parts of the population such as young children, pregnant women, the aged and infirm and immune compromised can be more sensitive than the typical healthy adult to essential and hazardous dietary components. In many cases the specific requirements for optimal health states and minimal risk are not understood for these high risk segments of the population so often generalizations must be the basis for public health decisions.

Some of the chemicals of interest in drinking water include calcium, magnesium, sodium, chloride, lead, selenium, potassium, bromide, iodide, fluoride, chromium, manganese. Seawater is rich in ions such as calcium, magnesium, sodium, chloride and iodine, but low in essential ions like zinc, copper, chromium and manganese. Desalination processes significantly reduce virtually all of the ions in drinking water to the point that people who traditionally consume unreconstituted desalinated water may be consistently receiving smaller amounts of some nutrients relative to people who consume water from more traditional sources and thus are disadvantaged if their diets do not provide sufficient intake. Since desalinated water is stabilized by blending, some of these ions will be replenished in that process.

Calcium/Magnesium/Cardiovascular Disease

Over about 40 years, a body of epidemiology work e.g. in UK, USA, Canada and Scandanavia has fairly consistently suggested that cardiovascular disease mortality rates in many communities are inversely proportional to the hardness of the water supply. Calcium and magnesium are the principal contaminants of hard water so many researchers have concluded that calcium and magnesium may have a protective effect, and there are biochemical arguments that can be raised in support of the hypothesis, however the issue is not resolved with certainty. More recent studies seem to be finding greater positive effects from magnesium rather than calcium intake particularly in regard to reduced risk from stroke or ischemic heart disease.

Some researchers have argued that softening effects also reduce trace nutrients and increase sodium (ion exchange) in drinking water or that there is a negative health effect from decreased mineralization (total of dissolved salts and electrical conductivity changes). Others argue that demineralized water is more aggressive to piping and thus increased risks could be caused by exposure to extracted trace elements like lead and cadmium. Some have suggested that cooking foods in demineralized water increases the depletion of essential minerals from the foods, thus adversely affecting health.

The health significance of these hypothesized relationships with drinking water in any given population would be highly dependent upon many factors including diet, lifestyle, smoking, population genetics, occupation and other confounders.

Trace Nutrients

In general, drinking water is not be relied upon as a contributor of significant trace nutrients to daily intake, but rather as a serendipitous supplement whenever it occurs. The geographic distribution of the nutrients in drinking water will be varied and inconsistent so an appropriate diet should be the principal source.

Dietary supplementation is, however, widely practiced for general benefit e.g., Vitamin D in milk, Vitamin C in drinks, iron and B Vitamins and folic acid in bread. The only therapeutic substance added to drinking in some areas is fluoride with the intent of strengthening dental enamel and reducing the incidence of tooth decay (dental caries). Water fluoridation is controversial in some quarters but generally believed by the dental community and many public health officials to be beneficial without demonstrable risk. Fluoridation is a matter of national policy. Seawater is low in fluoride and the fluoride is depleted by desalination so desalinated water does not contribute significant fluoride to daily intake unless it is present in blending waters or other additives.

Sodium

Sodium can be present in desalinated water depending upon the efficiency of salts removal and the post treatment blending or stabilization. Typical daily dietary intake of sodium can be in the range of 2000 to 10,000 mg and more ,and is a function of personal taste and cultural factors. Most experts believe that some segment of the population is salt sensitive (hypertensinogenic) which means that blood pressure elevation and its commensurate adverse effects occur to a greater degree in those individuals associated with their total salt consumption. Estimates of salt sensitivity are in the range of 15% of some populations.

Water is usually not a significant contributor to total daily sodium intake except for persons under physician care who are required to be on highly restricted diets of less than 400 mg sodium per day. Thus, sodium concentrations of 20 mg/l (assuming 2 L per day consumption) would contribute 10% of the total permissible daily intake for those people. It is virtually impossible to limit salt intake from food to less than 360 mg/day.

Petroleum Contamination

Raw and refined petroleum contains a very large number of toxic substances and substances that impact undesirable taste to finished water. Crude oil contains aliphatic and aromatic hydrocarbons and heterocyclic and other components that contain nitrogen and sulfur. Aliphatic hydrocarbons can range from gaseous methane (C1) and other small molecules, to midrange liquids (C_5 to C_{16} approximately) like heptane (C_7) and cetane (C_{13}), to high molecular weight solids that are dissolved or suspended in the mixture. Many of these are neurotoxins at higher doses and some like hexane (C_6) are neurotoxins at relatively low doses. Usually these are slightly soluble in water.

Aromatic hydrocarbons range from benzene and toluene to polynuclear aromatic naphthalene (2 rings) to benzopyrene (6 rings) and above. Benzene is known to cause leukemia, and benzopyrene causes skin cancers and others.

Numerous sulfur compounds are present both as heterocycles and as thiols and other forms including sulfur, and hydrogen sulfide which is highly toxic and particularly malodorous at very low concentrations. Refined petrochemicals and gasoline products challenge the treatment processes with high concentrations of mobile, volatile and often more toxic lower and mid-range fractions.

The molecular weight cut off is typically in the range of 100-300 Daltons. Larger molecules can be removed by RO membranes, however significant fouling would impede operations. Small molecules pass through the membrane. It is at least theoretically possible that some molecules, although rejected by their size, may, depending on their solubility characteristics and the chemistry of the polymeric membrane, dissolve in the polymer and diffuse through.

Distillation processes can theoretically separate any substance by fractionation based upon boiling point differences, however desalination distillation is not designed to be a fractionating system, thus substances with boiling points lower than water’s would easily be carried over in the vapors, and even many higher boiling substances would “steam” distill and be carried into the distillate even though their vapor pressures are very low at the boiling temperature of water.

In general, to avoid contamination of finished water by certain organics, pretreatments should be applied and these can involve an adsorption process using granular activated carbon or more frequently powdered activated carbon for intermittent contamination. Of course, contaminants in blending waters will be transported to the finished water thus appropriate pretreatment of blending water may also be required.

Waste management

Wastes from desalination plants include concentrated brines, backwash liquids containing scale and corrosion salts and antifouling chemicals, and pretreatment chemicals in filter waste sludges. Depending upon the location and other circumstances including access to the ocean and sensitive aquifers, concentrations of toxic substances etc., wastes could be discharged directly to the sea, mixed with other waste streams before discharge, discharged to sewers or treated at a sewage treatment plant, lagooned and dried and disposed in landfills.

Energy consumption

Desalination plants require significant amounts of electricity and heat depending upon the process, temperature and source water quality. For example, it has been estimated that one plant producing about seven million gallons per day could require about 50 million kWh/yr., which would be similar to the energy demands of an oil refinery or a small steel mill. For this reason, co-generation facilities provide significant opportunities for efficiencies.

Environmental impacts

Installation and operation of a desalination facility will have the potential for adverse impacts on air, water/sea, and ground water and possibly other aspects. These should be considered and their acceptability and mitigation requirements would usually be matters of national and local regulation and policies, and studies to examine these effects would usually be conducted at each candidate site, and post installation monitoring programs should be instituted. A brief partial listing of issues follows:

Construction: Coastal zone and sea floor ecology, birds and mammals habitat; erosion, non point source pollution.

Energy: Fuel source and fuel transportation, cooling water discharges, air emissions from electrical power generation and fuel combustion.

Air Quality: Energy production related.

Marine Environment: Constituents in waste discharges, thermal effects, feed water intake process, effects of biocides in discharge water, and toxic metals, oxygen levels, turbidity, salinity, mixing zones, commercial fishing impacts, recreation, and many others.

Ground Water: Seepage from unlined drying lagoons causing increased salinity and possibly toxic metals deposition.

Disinfection and microbial control

Sea and brine waters can contain microorganisms that could be pathogens – bacteria, protozoa and possibly virus. Disinfection processes can occur at several points during the treatment process. The question is, what is adequate disinfection to protect public health from exposure to pathogenic microbes and are there any unique risks that may be associated with desalination practices. During pretreatment a disinfectant, often chlorine, will be added to reduce biofouling and protect the membrane from degradation. Membranes also have the capacity to separate microorganisms by preventing their passage through the membranes. So long as the membrane is intact complete removals of microorganisms can occur, however some bacteria can grow through the membrane.

Even ultrafiltration membranes which have pores (~0.001 to 0.1 microns) have been demonstrated to achieve significant reductions of virus and protozoa. Better performance could be expected from RO membranes. Several challenge tests employing giardia lamblia and cryptosporidia cysts and MS2 bacteriophage virus with an ultra- filtration membrane of nominal pore size of 0.035 micron and absolute, 0.1 micron have demonstrated very effective removals.

Guardia cysts can vary from 4 to 14 microns in length and 5 to 10 microns in width; cryptosporidia on cysts range from about 4 to 6 microns. These intact ultrafiltration membranes (0.1 micron nominal) should completely remove the cysts. The calculated log reductions in Table III below are limited by the dose level and detection limits of the analytical procedures.

MS2 bacteriophage size is approximately 0.027 micron which is smaller than the pore size of the membrane. However, substantial removal was achieved probably due to adsorption of the virus on suspended particles, adsorption on the membrane or from the secondary filtration due to fouling of the membrane surface. Indeed there was a tendency for the MS2 removal to improve as membrane fouling increased in the study as indicated by higher transmembrane pressures.

Table III- Summary Data (Ultrafiltration)

	Feed Concentration	**Permeate Concentration**	**Log Removal**
Giardia	2 E + 09	<1	>9
(cysts/L)	1.5 E + 04	<1	>4.8
	1 E + 03	<0.05	>4.3
Cryposporidia	1.5 E + 09	<1	>8
(oocysts/L)	7 E + 03	<1	>4.4
	1.3 E + 05	<0.05	>6.4
MS2 Bacteriophage	~5 E + 08	~5 E + 4	~3.5+
(PFU/L est)	~5 E + 08	~6 E + 3	>4.9

Distillation at high temperatures close to the normal boiling point of water would likely eliminate all pathogens. However, reduced pressures are used in some desalination systems to reduce the boiling point and reduce energy demands. Temperatures as low as 50° to 60°C may be reached. Several pathogenic organisms are denatured or killed in a few seconds to minutes at temperatures in the 60° to 80°C range, but spores require higher temperatures and longer times.

Disinfection Byproducts

Since desalinated waters are lower in Total Organic Carbon than most natural waters it would be expected that the disinfectant demand and also disinfectant byproduct formation would be relatively low, and this has been indicated in some studies of trihalomethane production that have been reported. However, this could be significantly affected by the type of blending water that is used post treatment to stabilize the water. One of the factors to consider would be the amounts of brominated organic byproducts that could be formed from predisinfection od salt waters containing promibe, and from disinfection of blending waters, if bromide is reintroduced to the finished waters. This is a concern since data is accumulating that some brominated disinfection byproducts have greater carcinogenic potential than many chlorinated byproducts such as chloroform. Indeed chloroform may not be carcinogenic at all at levels typically found in drinking water. Since the TOC found in seawater could be different than TOC in fresh waters, it is also possible that there could be some differences in the chemistry of the byproduct formation reactions that could lead to some different byproducts or different distribution of byproducts.

Conclusion

Desalination of seawater and brackish waters offers the opportunity to significantly increase the world's supply of fresh water for drinking and other purposes. Due to the saline source waters and treatment processes involved, certain issues in finished water composition and process arise that are not typically dealt with in usual drinking water supplies. This monograph will address several of those issues in respect to trace ion composition and contribution to daily diet and health in respect to long term consumption of water that has been drawn from a saline source.

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This assessment was prepared in part for use by WHO/EMRO to investigate the appropriateness of developing WHO guidance for the health and environmental impacts of desalination practices.