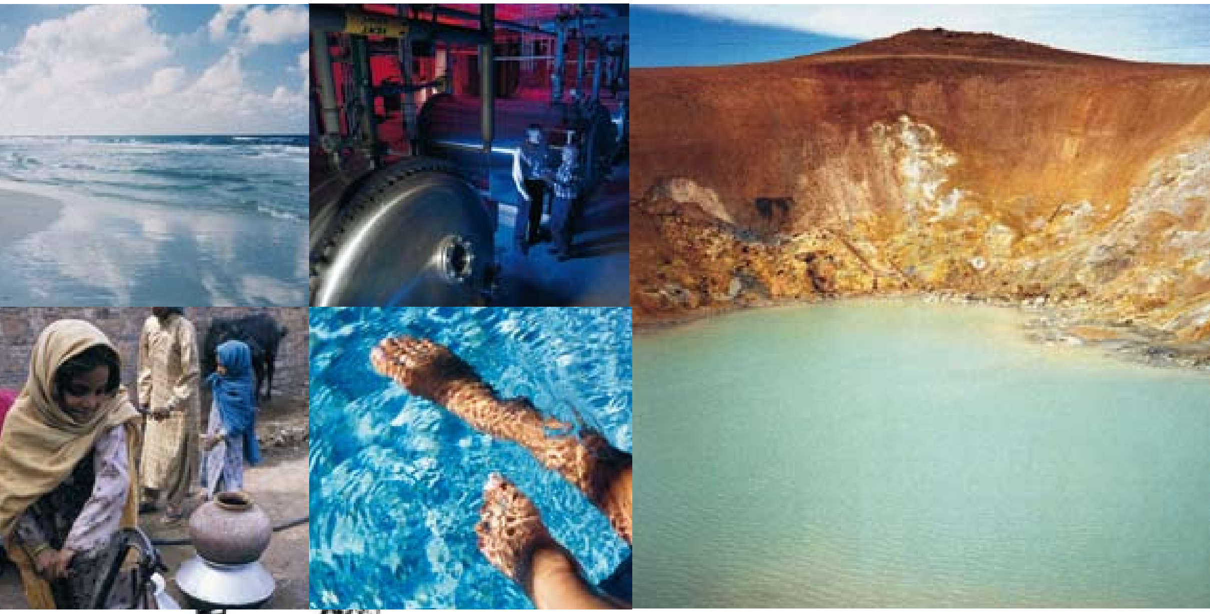
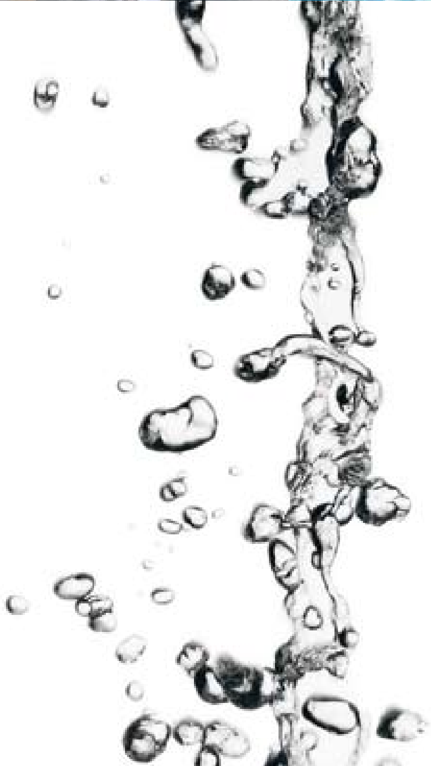
Drinking Water – Sources, Sanitation and Safeguarding





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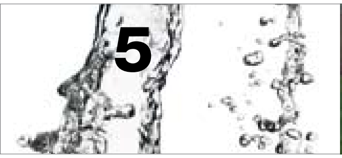

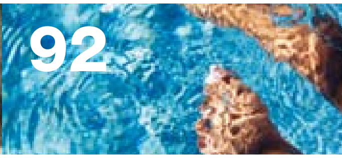

Drinking water – our most basic need

Drinking water is the only provision a human being needs daily. This basic fact makes access to safe drinking water a prerequisite for human survival and it is included among the Millennium goals set up by the UN to reduce poverty in the world.

Only a few per cent of the global water resources are accessible as fresh water, and only a fraction of it is available as flowing surface water. The vast majority of fresh water is stored in groundwater aquifers or locked in glaciers. Almost half of the fresh water resources are shared between two or more countries, but on the international arena cooperation dominates and conflicts are rare. The problems that occur seem to lie on a national level. In many countries, legislation or enforcement of laws is often weak, leading to pollution or overuse of local water resources.

Rolf Annerberg, Director General, Swedish Reaserch Council Formas.

Since the quality of surface water deteriorates quickly with population growth, the global dependence on groundwater sources has increased. This is true both for rural areas and the rapidly growing urban settlements. Using groundwater as a fresh water resource has many advantages over surface water: it's virtually free from infectious microbes

However, groundwater quality for human consumption varies with its origins, and often requires careful monitoring. Too high levels of some ions in ingested waters, like arsenic and nitrate, can cause severe health problems. Through wiser drilling practices, filtration and chemical treatments the problems can be overcome.

Acquiring and securing a safe drinking water necessitate source water treatment. It's mostly achieved through adding disinfecting chemicals, like chlorine compounds. This effectively reduces the levels of microbes, but also leads to less appetizing water and the formation of disinfection by-products such as harmful halogenated compounds. More research is now focused on identifying and reducing their occurrence. Alternative methods like ozonation of drinking water can be applied, both to improve water taste and odour and to reduce the levels of harmful agents. Used in combination with chemical treatment and biological filtration, the method can be highly effective for treatment of both drinking water and waste water, thus promoting water circulation and reuse.

Since the largest reservoirs of potential drinking or household water can be still found in the oceans, more research has been addressed towards increasing effectiveness and reducing costs for desalination. Recent developments in the desalination field have been highly successful and many methods that desalinate water alongside power production have been introduced. High-capacity plants that are powered by renewable sources, like windmills, have been constructed in many dry coastal areas.

In most developed countries, a safe and hygienic water supply is secured through a piped network. Provided that the choice of pipe material for the water quality is adequate, excessive release of chemical compounds and ions, or the after growth of microbes can be kept under control.

In many developing countries, available surface waters are polluted and municipal water services are unreliable. People living in these countries must often resort to alternative service providers, or store water temporarily accessed through their services in less sanitary tanks. There is also an increase in sales of bottled water, in these and in developed countries alike. Bottled water is however often subject to less strict regulations than those for tap water. Better communication between providers and end users are needed.

Managing water resources in a safe and sustainable way has thus become a key priority for the future. At a local level, results from research on water quality, disinfection and distribution need to be combined with practical considerations regarding management and training. Ongoing research projects have devised fruitful solutions for developing countries.

Rolf Annerberg
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Water supply in shared waters

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Access to clean water for consumption and basic sanitation is the single most important factor for human development. But fresh water constitutes only a small percentage of the global water resources and almost half of it is shared between two or more countries. The key to achieving a sustainable development and management of water resources lies in resolving long-term governance challenges; not least to enforce legislation and empower local communities and vulnerable groups. On the international arena, cooperation already is the norm. Successful water agreements outnumber conflicts over shared waters by almost ten to one.

Only 3 per cent of the world's water is fresh and only 0.3 per cent of this fresh water is available as flowing, surface waters.

A sufficient quantity of clean and wholesome water is essential for human health but only 3 per cent of the world's water is fresh and only 0.3 per cent of this fresh water is available as flowing, surface waters. To complicate matters further a significant proportion of these waters are shared. Globally, there are 263 river basins that cross the political boundaries of two or more countries. These basins represent about one half of the earth's land surface and forty per cent of global population. What is less known is that most of the world's fresh water is stored in groundwater (30.1 per cent) or glaciers (68.7 per cent). These are also often shared. There are an estimated 300 transboundary aquifer systems in the world which lie under 15 per cent of the earth's land surface.

Waters that cross national borders can carry pollution from upstream to downstream countries, impacting human health and livelihoods. But water also crosses political, administrative, ethnic and climatic boundaries within countries. Upstream users can extract too much water, or use it inefficiently, threatening the quality and quantity of water available for those living downstream as well as the environmental needs for water.

Increasing stress and competition for fresh water

The UN estimates that, by 2025, as many as 1.8 billion people will live in countries or regions facing water scarcity,

The world's water resources are finite and therefore under increasing pressure from demographic and environmental changes such as population growth, desertification and urbanisation and increasing consumption as a result of economic growth. Climate change, which is already altering the global water cycle at an unprecedented rate, adds further complexity to these challenges through its impacts on the timing, intensity and variability of rainfall, droughts and flooding. The projected sea level rise threatens the safety of coastal populations and imperils the supplies of freshwater upon which they depend. The United Nations estimates that, by 2025, as many as 1.8 billion people will live in countries or regions facing water scarcity, and as much as two-thirds of the world's population could be facing water stress.

Deteriorating water quality

In the near term, shrinking mountain glaciers (as a result of climate change) result in lower dry-season flows, and potentially more flooding during the wet season. In the long term, if glaciers completely disappear, overall flows may be substantially reduced. Both impacts can have a dramatic effect upon

Broken water pipe,
Democratic Republic of Congo.
Photo: Manfred Matz

the water supplies and livelihoods of downstream residents. Land use changes can also have a marked effect on water availability. Urbanisation and deforestation affect stream flows: flooding in Bangladesh for example is exacerbated by land use changes in upstream Himalayan countries. In Jakarta, rapid urbanisation of the upper catchment is blamed for frequent flooding in the city, polluting water supplies and causing serious sanitation problems.

Even the largest natural water bodies can be adversely affected by human activities. Kampala had to find an extra €9.5 M to extend the city's water intake into deeper water, when the level of Lake Victoria dropped. In Mongolia, numerous unregulated mining operations have allowed cyanide and mercury to enter watercourses, forcing the closure of small town water supplies and jeopardising Lake Baikal. UNDP-GEF is actively supporting the Russian and Mongolian governments' efforts to control these problems.

Similarly, poverty-driven gold mining operations in the upper reaches of the Pungwe River between Zimbabwe and Mozambique have led to extensive erosion and deteriorated water quality downstream. Miners use mercury in the gold panning process, which has elevated concentrations of mercury and other heavy metals such as lead and cadmium which are bound to the suspended sediments since they exist naturally in the soils. The suspended sediments make the water unsuitable for drinking, washing and irrigation, bury the aquatic fauna, prevent photosynthesis and have effects on the fish population.

Return flow from Mafambisse sugar estate just upstream of Beira water intake, Mozambique.
Photo: Björn Holgersson

Salinisation of freshwater resources is another problem jeopardising water supplies, and desalination remains prohibitively expensive for most people in the developing world. So much water was being abstracted from the Pungwe River that little freshwater reached the sea at Beira during the dry season. Sea water was intruding up the river and threatening the city water supplies. The Swedish International Development Cooperation Agency (Sida) is supporting transboundary cooperation and strengthening the capacities of local river basin organisations to address these issues through an integrated water resources management approach.

For many small island developing nations, relying on a thin lens of fresh groundwater balanced above denser salt water, the water supply situation is even more vulnerable. As sea levels rise many small islands will lose this resource, their only source of fresh water.

Poor groundwater management – such as the uncontrolled drilling of private water supply boreholes in Lima, Peru – allows sea water to penetrate aquifers, rendering them saline and useless. And natural disasters – such as tsunamis and storm surges associated with cyclones – can flood land with salt water and destroy drinking water supplies.

Chemical and biological pollution

Poor groundwater management and natural disasters can make aquifers or drinking water supplies saline and useless.

In many countries, regulation of industrial and mining discharges is weak, and agricultural practices allow pesticides and nitrates to contaminate water sources. Acid rain crosses international borders and pollutes water bodies. Pollution does not respect administrative boundaries. A complex system of land holdings in Papua New Guinea meant that only a small minority of residents were consulted in the development of the Ok Tedi mine near the Indonesian border. But up to 80 million tonnes of tailings entered the river system each year, with elevated levels of heavy metals. The complex land holding system also complicated claims for compensation. Distant residents, both in Papua New Guinea and in Indonesia, have struggled to receive any compensation.

Poor sanitation is another serious source of freshwater pollution. Globally, over 2.4 billion people lack adequate sanitation facilities. Much of their faecal waste pollutes groundwater and local streams causing diarrheal diseases and cholera outbreaks. But even where sewerage systems are available these are often poorly maintained, or built to too low a design standard to cope with urban growth and climate change. Untreated or poorly treated effluents upstream become the water source for those living downstream, jeopardising public health and the environment and adding significant cost to water treatment in downstream water works. At the border town of Malaba in Kenya inadequate sanitation facilities are available for the growing amount of truck drivers awaiting custom clearance. They use plastic bags, so called 'flying toilets', which are disposed into the river passing the problem downstream to the Ugandan population.

Globally, over 2.4 billion people lack adequate sanitation facilities.

Decision making capacity

Water specialists have long been aware that water is essential to sustainable development, but they are not the ones to make decisions on development and they do not control the necessary human and financial resources. Leaders in government are constrained by a range of social, political and financial factors that prevent them from safeguarding drinking water supplies. Another reason lies in the fact that environmental education is non-existent in many countries. Government officials may never have had the opportunity to learn about environmental management, and do not understand how to manage their water resources.

Environmental education is non-existent in many countries.

For example, on Nias Island (in Indonesia) the local government located a solid waste dump on a hillside above a spring that supplied a town with water. Within two years, oils and other chemicals seeping through the groundwater polluted the spring. Although acting in good faith, local officials had no understanding of groundwater flow and simply did not realise the problems the dump could cause.

And many communities do not understand the links between sanitation, pollution and health. Poor sanitation causes children to fall sick. But parents do not understand why their children are sick, and they are still reluctant to invest in better toilets.

Governance and enforcement constraints

Climatic changes take place over a long period of time. Unfortunately, most political systems and development programmes operate over much shorter time scales.

Many environmental problems are by nature chronic, long term issues – climate change in particular is one example, where significant changes take place over a long period of time.

Unfortunately most political systems and development programmes operate over much shorter time scales. Investing in climate change mitigation or adaptation measures might bring few immediate benefits. Project managers see little benefit in climate change resilience – river floods and sea level rise may eventually affect a community, but not within a typical project life cycle or political mandate of a few years.

Poor environmental practices harm people – especially poor people – as well as harming natural resources, plants and animals. But unfortunately many practitioners still see environmental management as a hindrance to development. Environmental safeguards are seen as obstructive and unhelpful, and staff are unfamiliar with their implementation.

In many cases, the means to enforce existing laws and permits simply do not exist.

In many countries, the enforcement of environmental regulations is weak. Some environmental regulators have never seen an Environmental Impact Assessment (even if one is required by law for all large developments). Sometimes the responsibility for enforcement of environmental rules is unclear; police forces, for example, may see environmental regulation as being outside their mandate. But more commonly the means to enforce existing laws and permits simply do not exist. Gauging and monitoring networks are inadequate or poorly maintained, and local authorities lack qualified staff, facilities, transport and equipment.

The quality and quantity of water resources determine the costs and availability of potable water but in many instances the institutional structures governing water supply and sanitation differ from those responsible for water resources management. The same applies for stakeholder participation and revenue collection.

Clearly, much work is needed to strengthen environmental governance, to define responsibilities for development control and to enforce existing laws. Otherwise water catchments will not get the protection they need, deforestation will continue, and more inappropriate developments will be built.

Financial challenges

Current aid levels for the water sector are lower than in 1997 in real terms.

Even when water management is recognised as a key issue, gaining a high level of political support, there is a failure to translate this into effective action and increased investment flows. Current aid levels for the water sector are lower than in 1997 in real terms, and since 1998 the ODA (official development assistance) for water has grown more slowly than ODA overall. The current global economic recession has depleted ODA even further.

Too often the returns on water management and investments are underestimated; as a result, the limited resources available are prioritised for other sectors perceived to be more productive. Yet the economic rate of return for each $1 invested in achieving the Millennium Development Goals water and sanitation target was estimated in 2006 at $8. Historically, management of water resources has been crucial in catalysing economic growth and development. Many of the earliest civilisations, and particularly those on the floodplains of the world's great rivers, succeeded by harnessing and managing water, thereby increasing production and reducing the risk of destruction.

Unfortunately, neglect of water and sanitation is nothing new. Despite numerous cholera outbreaks, little was done about London's sewerage until 1858, when the 'Great Stink' of the River Thames made the Houses of Parliament uninhabitable. The recent cholera outbreak in Harare is another example of how severe such problems need to become before politicians and donors are prepared to invest in water supply and sanitation

Given the importance of water to poverty alleviation, human and ecosystem health, the management of the water resources becomes of central importance. Key interventions are needed in a wide range of sectors to address these challenges and meet the Millennium Development Goals.

Local sea level rise flooding water sources and sanitation facilities, Sumatra Indonesia.
Photo: Alastair Morrison

Addressing decision making capacity

There are endemic skills shortages in the sector – both in developed countries, and more critically, in the developing world. And awareness of water issues must not be confined to a few specialists. Better environmental education is the key to helping decision makers to learn about the water problems we face, and to help find solutions.

Water and environmental issues should be mainstreamed into all development programmes, as a cross-cutting issue, and not considered in isolation. Water plays a pivotal role in sustainable development and poverty reduction and cannot be neglected in national adaptation programmes or poverty reduction strategies. Analyses of the 2006 UNDP Human Development Report indicate that no variable examined – access to energy, education, or health services – explains more of the variance in the Human Development Index than access to clean water and basic sanitation.

Information on water and sanitation coverage, water resources and water quality is still scarce in many countries. Better monitoring is needed so we can use our finite resources more efficiently.

Resolving governance and enforcement constraints

Resolving the governance challenges must be a key priority if we are to achieve sustainable water resources development and management.

Many costly mistakes can be avoided if polluters understand that they will bear the costs of the pollution they cause.

Most countries have environmental legislation, but few enforce their legislation thoroughly and effectively. Institutional responsibilities for enforcement need to be clarified, and the rules should be applied fairly and transparently. Budgets to local authorities and monitoring networks should be strengthened and staff need to be trained and furnished with adequate tools and equipment. To achieve better raw water quality, polluter pays/ pollution management systems should be improved and prioritized. Many costly mistakes can be avoided if polluters understand that they will bear the costs of the pollution they cause.

Local communities and vulnerable groups should be fully empowered to participate in development programmes. Social and environmental impact assessments should not be a purely bureaucratic exercise – they should be an integral part of all projects, and able to meaningfully influence project design.

To address long term and chronic problems (such as climate change), some governments have established special offices and committees with long-term mandates. These organizations can propose more sustainable solutions and realistic targets. Their independent mandate allows them to consider difficult issues that might otherwise be overlooked in the normal, short-term political cycle.

Solutions to financial challenges

Water professionals invariably promote their projects for their social and environmental benefits. These are important, but water projects are also some of the best financial investments a country can make. Professionals in the water sector need to reach out more to Financial Ministries (and donors) to make the case for more resources.

The current global economic recession may impede the necessary investment. On the other hand, many governments are looking to increase investment in public works to stimulate the economy and provide employment, and the water sector is an ideal vehicle for such investment. Water infrastructure has long-term development benefits and helps the poor, who are most at risk during the economic decline.

Water projects are some of the best financial investments a country can make.

The benefits of cooperation

History shows that cooperation, not conflict, has been mankind's prevalent response to the challenges presented by transboundary waters. Over the last 60 years more than 300 international water agreements have been reached while there have only been 37 cases of reported conflict between states over water. What is even more important, cooperation on shared waters has been shown to help build mutual respect, understanding and trust among countries and to promote peace, security and regional economic growth.

There are many examples of international co-operation to halt the destruction of water resources. In 2005 a chemical explosion at Jilin in Northern China caused 100 tonnes of benzene to enter the Songhua River, a tributary of the Amur on the Russian border. China notified the Russian authorities

Cooperation on shared waters has been shown to help build mutual respect, understanding and trust among countries.

in time for them to close down water supplies to border villages, and provided labour and materials to protect the water supply of the Siberian city of Khabarovsk.

And in Europe, concerted efforts, funded by UNDP-GEF, have seen demonstrable water quality and ecosystem improvements in the Danube basin. Across South-East Europe, numerous projects have been funded to install low cost wastewater treatment units, conserve wetlands, and reduce soil erosion. Nutrient loads entering the Black Sea have been substantially reduced, preventing harmful algal blooms and conserving fisheries.

Water supply for human consumption needs to be given the highest priority.

Water supply for human consumption might only constitute some 5 per cent of the water use in most developing countries, but it is this use which needs to be given the highest priority. As this paper has shown, real improvements are possible with an integrated approach, where different stakeholders, institutions and states co-operate.

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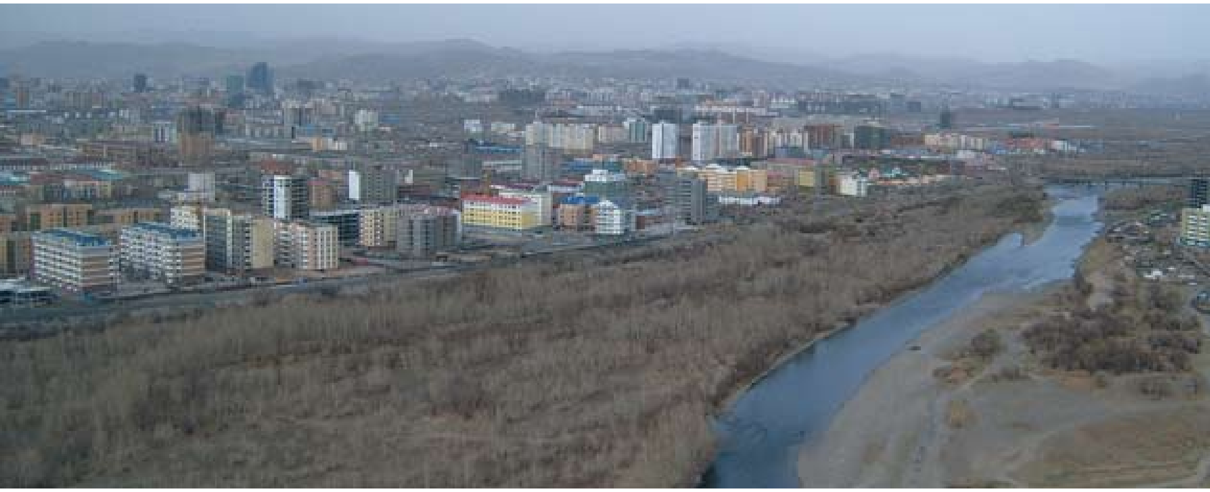

Ulaan Baatar on the Tuul River, Mongolia. Photo: Alastair Morrison

Drinking water from groundwater sources – a global perspective

Gunnar Jacks and Prosun Bhattacharya, KTH-International Groundwater Arsenic Research Group, Department of Land and Water Resources Engineering, Royal Institute of Technology (KTH), Sweden.

Groundwater has emerged as the most important source of drinking water supply in the world. In both the developed and developing world, there has been a manifold increase in the use of groundwater among the populations in rural areas, as well as in the rapidly expanding urban areas. Due to the inadequate availability of surface water and its continuous deterioration in quality, the dependence on groundwater will increase even further during the next decades. However, attention is required for its exploitation, and also for controlling a wide spectrum of problems related to groundwater.

Groundwater as a global freshwater resource

Groundwater is by far the largest freshwater resource of the globe. The use of groundwater started historically in arid regions where surface water availability was inadequate. During the later half of the last century, utilization of groundwater increased dramatically in most parts of the world due to the decreased availability and deteriorated quality of surface water. On a global scale, 97 per cent of the freshwater reserve is stored in aquifers which cater for the need for drinking water supply for a population of over 1.5 billion (Table 1).

Table 1. Global overview of the utilization of groundwater resources (Mukherjee & Bhattacharya, 2002).

Region	Groundwater utilization for drinking purposes (in %)	People served (millions)
Asia-Pacific	32	1,000–1,200
Europe	75	200–500
Latin America	29	150
United States	51	135
Australia	15	3
Africa	55	500*

Sources: UNEP, OECD, FAO, U.S. EPA, Australian EPA.

** British Geological Survey (pers. communication)*

Fresh groundwater constitutes about 30 per cent of the total freshwater resources. Quality-wise it has many advantages over surface water.

Fresh groundwater constitutes about 30 per cent of the total freshwater resources. Quality-wise groundwater has many advantages over surface water. In a natural state it is free from pathogenic bacteria and viruses. It has generally far lower concentrations of organic matter and has an even temperature. The most common quality problem in groundwater is excess iron. Removal of iron is normally an uncomplicated process. However, there are some inorganic species, both anthropogenic and geogenic, that are of health concern in groundwater.

Groundwater composition for use as drinking water

We drink and excrete about 2 litres of fluid per day. Water constitutes the major portion of this. A specific drinking water may have health effects, good or more or less deleterious. Among the good ones are the hard groundwater types that have for a long time been known to protect against heart and circulatory diseases. However, it was found only quite recently that it is not calcium but magnesium that is the effective element. Nitrate is an unwanted species in groundwater, mostly emanating from excess fertilizer application. Nitrate may cause methaemoglobinemia ('blue baby syndrome') in children below the age of six months. When it comes to minor elements, fluoride is found to protect against caries but a slightly higher concentration may cause dental fluorosis and considerably higher concentrations skeletal fluorosis. Among trace elements iodide is necessary for the formation of thyroid hormones. Iodide is cycling between the oceans via rain to groundwater. Far away from the sea, there may be too little iodide in the water, causing goitre. Other trace elements are arsenic and selenium which have similar water chemistry. Selenium is an essential element but also toxic in elevated amounts, while arsenic is not considered to be essential. Among heavy metals it is mostly chromium in the form of chromate that may be found in higher concentrations at neutral pH values. For other heavy metals like copper, lead, zinc and cadmium, either massive soil pollution or a very low pH is needed to cause elevated concentrations in groundwater.

It is thus observed that it is mostly anions that may cause problems with groundwater quality. This is due to the fact that anion adsorption in soils is less efficient than adsorption of cations. While cation adsorption increases with pH, anion adsorption decreases. However, it is not only the pH that matters in connection with the problematic inorganic species in groundwater but also redox conditions. Nitrate can be removed by denitrification under moderately reducing conditions and arsenic and selenium can be mobilized under more strongly reducing conditions.

It is mostly anions that may cause problems with groundwater quality.

Groundwater quality and potential contaminants

Several chemical contaminants which are potentially toxic to human and other animals have been identified in groundwater. Groundwater quality suffers significantly due to several anthropogenic fluxes such as discharge of industrial wastes, excessive use of fertilizers, pesticides, spillage of oil and gases, mine wastes, and landfills. On the other hand, natural geochemical reactions in the aquifers may release metals and other toxic chemicals in groundwater, and result in health risk when present at high levels. There are a number of naturally occurring contaminants in the ecosystem such as arsenic, lead, zinc, copper, cadmium, radium, radon, uranium, selenium, barium, thallium, iron, manganese, fluoride, sulphate, chloride, boron, microbial contaminants, and many others which are potentially toxic for humans (Table 2).

Table 2. Common inorganic contaminants in groundwater environment, sources, health effects and their principal geographical extents (adapted and modified from Sampat, 2000, USEPA, 2000a)

Origin	Contaminant type	Sources	Health and ecosystem effects	Regions affected
Natural Origin	Arsenic	Natural occurrence in sediments aggravated by overexploitation of ground water and inflow of reducing groundwater from the inundated paddy fields.	Arsenicosis primarily as skin disorders such as skin lesions, keratosis, melanosis and carcinoma, disorder in the nervous system and kidneys	Bangladesh, India, China, Taiwan, Japan, Thailand, Ghana, Argentina, Bolivia, Chile, Nicaragua, Mexico, United States, Hungary, Sweden, Finland, Romania and several others
	Fluoride	Natural occurrence	Dental and skeletal fluorosis, crippling and bone damage	Northern China, major parts of western, central and southern India, Sri Lanka, Thailand, parts of Africa.
	Salinity	Sea water intrusions due to overexploitation of groundwater from coastal aquifers, deicing salts on roads	Degradation of fresh water unsuitable for drinking or irrigation	Coastal China, India, Gulf coasts of Mexico and Florida, Australia and Philippines, middle east countries i.e. Oman
Anthropogenic Origin	Nitrate	Fertilizer runoff, manure from livestocks and septic systems, pit-latrines	Infant deaths due to 'blue-baby syndrome'	Midwestern and mid-Atlantic United States, Northern China, Western Europe, and north-western India.
	Heavy metals Arsenic, chromium, copper, zinc, thallium, lead, selenium, cadmium, mercury etc.	Mine waste and tailings, landfills, hazardous waste dumps, ammunition, electroplating, wood preservation, paper/pulp industries and others	Diverse metabolic disorders, damage to nervous and endocrine systems, retarded brain development, carcinogenic at high levels of exposure	United States, Central America and north-eastern parts of South America, Europe, India, Bangladesh, and other southeast Asian countries.

Arsenic

Arsenic is an age old poison, already used by the Romans to remove adversaries. It is no longer used in criminal novels as it is fairly easy to detect. Sweden has a long tradition of dealing with arsenic, not least due to a popular green dye made from copper and arsenic salts by the famous chemist C W Scheele. The dye was used, among other things, in wallpapers.

Health effects

Arsenic in groundwater has been identified as a major global threat to millions of people.

During the last two to three decades arsenic in groundwater has been identified as a major global threat to millions of people. The reasons are threefold: increased development of groundwater for water supply, the gradual discovery that arsenic is more toxic in chronic exposure than previously believed and better tools for analysis. The health effects related to the presence of arsenic in drinking water are manifested as arsenicosis and several other chronic toxicity symptoms manifested as skin lesions in the form of melanosis and keratosis which may lead to cancer. Another effect is bladder cancer.

Arsenic mobilization

The most affected area is the Bengal delta in Bangladesh and West Bengal in India. In Bangladesh alone 30–60 million people are exposed to excess arsenic in their drinking water depending on whether the national health limit of 50 µg/l or WHO:s limit of 10 µg/l is applied. Similar environments in the Ganges valley in India and in Nepal have also been discovered to have groundwater with elevated arsenic content, as well as sedimentary areas in Myanmar, Cambodia, Sumatra in Indonesia and Vietnam. The arsenic is released by reduction of iron-oxyhydroxides in anoxic strata. Another mobilizing mechanism is under high pH conditions when the adsorption capacity of sediments for anions is low. This is found in Argentine, and in areas with sandwiched volcanic ash in the aquifers. A third condition where arsenic may be elevated is in connection with sulphide ore bodies or mining waste at those sites. This is common in Mexico and in USA. In Sweden, there is elevated arsenic in rocks in association with gold deposits. In addition, countries in the close vicinity of active volcanic chains such as Bolivia, Chile, Costa Rica, El Salvador, Guatemala, Nicaragua, Peru, and Uruguay in Latin America also have elevated concentrations of arsenic in groundwater (Figure 1).

Figure 1. Global occurrence of arsenic in groundwater.

Arsenic in the Bengal delta

In Bangladesh, a drinking water with low arsenic levels can be detected through tasting the water for iron ions.

In the Bengal delta, the high arsenic groundwater is found in the recent, Holocene sediments up to depths of 60–80 metres. Deeper sections of the thick sediment pack have generally acceptable arsenic levels. Unfortunately most of the household wells, which are the common type of water supply in rural Bangladesh, are placed at shallow depths. Numerous filters of different types have been tested and found technically functioning. However, filters and rain water harvesting are not socially accepted. The women who are supposed to handle the systems have too many other tasks to be able to manage them. Well drillers, using only manual skill and force, have found that the sediment colour is of importance for water quality (Figure 2). In black and grey sediments reducing conditions prevail, mobilizing iron and arsenic, while yellowish and red sediments are more oxidizing and generally have groundwater with low iron and arsenic concentrations (Figure 3). The iron taste can be easily identified. Numerous wells are drilled today with this logic. While this gives an acceptable groundwater, with a cheap drilling technology and at shallow depths, there may be risks of cross contamination after long term use of the wells. This depends on the sedimentology and not least on the pumping rate which is very low for household wells. Numerous irrigation wells are sited at shallow depths and deliver groundwater high in arsenic which slowly accumulates in the cultivated soils. This could be avoided if the irrigation wells were deepened, which would however be a threat to shallow household wells.

Figure 2. Hand percussion drilling for installation of the domestic tube wells by local drillers in Bangladesh. The block arrows indicate the flow of water during the washing process of drilling.

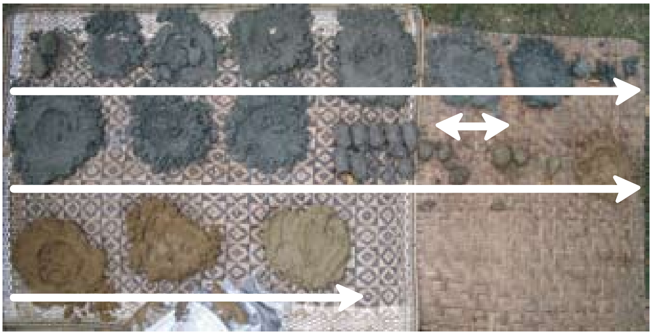

Figure 3. Sequence of aquifer sediments recovered from the boreholes characterised by distinct black, grey, yellowish and red colour characterising the redox characteristics of the sediments.

Selenium

Selenium is an element in the same group as arsenic and has a similar geochemistry. Selenium is an essential element and selenium deficiency in humans is far more common than selenium toxicity. In both conditions the drinking water is of minor importance compared with the diet. Selenium occurs in elevated amounts in groundwater in connection with sulphide ores and in areas with alkaline soils. In China both selenium toxicity and deficiency have been observed. In Punjab in India elevated selenium contents in crops are a problem, in part mediated via a selenium-rich groundwater used for irrigation.

Selenium deficiency in humans is far more common than selenium toxicity.

Fluoride

The average crustal abundance of fluorine is less than 0.1 per cent of mass. The mineral fluorite is abundant in volcanic rocks and thermal waters. In total 86 fluorine-bearing minerals are known among which the most important minerals are fluorite, cryolite and topaz. Fluorine also occurs in apatite, mostly carbonate fluorapatite that commonly constitutes the phosphorites etc. Fluorite is a very important biogenic element. The main sources that release fluorine to the biogeosphere are associated with volcanic eruptions and geothermal sources.

Health effects

Fluoride has been shown to decrease dental caries at a concentration of around 1 mg/L. However, the therapeutic interval is very narrow in hot climates with a high water consumption and dependence on the local water source with more or less the same concentration results in dental fluorosis (discoloured teeth). Protection of the teeth against caries is based on the lower solubility of fluorapatite compared with hydroxyapatite. At higher intakes this effect may result in skeletal fluorosis.

A too high intake of flourine can result in fluorosis of bone and teeth.

The skeleton is under continuous reconstruction throughout life for the skeleton to meet changing load conditions. If too much fluoride is incorporated in the bone matrix, the bone-degrading cells, the osteoclasts (Figure 4) will have a tougher task to dissolve the bone and excess accumulation of bone will occur especially at places where the skeleton has a fast turnover, like the knees and the vertebra, resulting in stiffness and difficulties in moving (Figure 5).

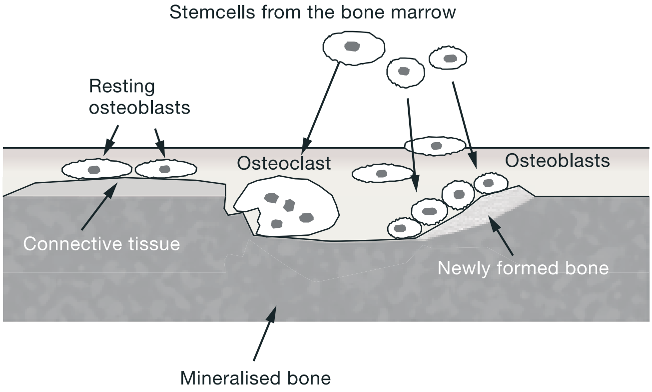

Figure 4. Bone remodelling under the influence of bone degrading cells (osteoclasts) and bone forming cells (osteoblasts).

Figure 5. A woman affected by skeletal fluorosis.

This effect depends not only on fluoride ingestion but also on calcium intake. It seems that skeletal fluorosis occurs at lower concentrations in India than elsewhere which may depend on a low calcium intake in the order of 300 mg/day compared with a recommended intake of 800 mg/day.

Occurrence of fluoride in groundwater

Fluorine is a common element in the earth's crust and the average content of fluorine in soil is 0.02 per cent. As for many other anions, soils have a low capacity to retain fluoride. Anions are retained by ferric and aluminium oxides and hydroxides which are positively charged at neutral and low pH. Thus a common characteristic of fluoride rich groundwater is that it has a high pH. Additionally, the solubility of fluoride seems to be limited by calcium fluoride or fluorspar which is a common mineral in especially granitic rocks. In alkaline soil, calcium tends to be precipitated as calcium carbonate, lowering the dissolved calcium concentrations and allowing fluoride to increase. In semi-arid climates with a precipitation below about 800 mm, calcium carbonate concretions (calcrete) are a common feature in soils.

Two regions in the world, India and East Africa, are characterized by especially high contents of fluoride in groundwater. In India the highest concentration recorded is 70 mg/L in Rajasthan. Also in Andhra Pradesh and Haryana concentrations up to 25 mg/L are recorded. In East Africa it is the Rift Valley region from Ethiopia via Kenya to Tanzania that is characterized by alkaline conditions that have groundwater with up to 36 mg/L.

In Tamil Nadu with a moderate topography it has been possible to observe the development of gradually more fluoride rich groundwater through the evapotranspiration of the groundwater and precipitation of different mineral phases along the flow path (Figure 6).

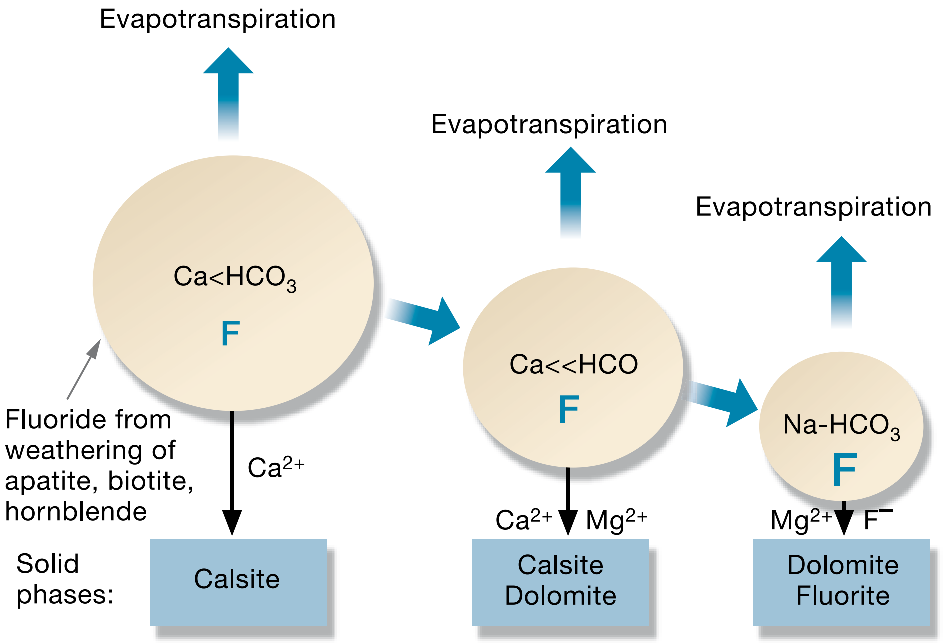

Figure 6. Evolution of groundwater chemistry along the flow path from uphill to valley bottom in Tamil Nadu, India.

Even in the temperate part of the world such as the Nordic countries high fluoride groundwaters occur. In Finland it is especially in bore wells in acidic granites, the so called rapakivi granite, that fluorspar is a common accessory mineral.

Fluoride removal

As in nature, fluoride can be removed by ferric and aluminium compounds. Activated alumina is the most commonly used filter medium. Ferric compounds are used in the form of crushed red bricks in Sri Lanka. This has a low capacity but is cheap. The use of filters in developing countries, in addition to technical aspects, also has a social dimension. In households it is mostly the women who are supposed to care for the family water supply. Women are heavily burdened by many tasks and caring for a water filter may be too much. Community filters also have their problems. In India the maintenance is poor and many plants are out of action. On the other hand, in Andhra Pradesh, one of the states with the most severe fluoride problems, water harvesting has been successfully employed. This needs little attention and improves not only quality but also adds to the abundance of groundwater.

Manganese

The occurrence of manganese is an aesthetic and technical problem but it is still not certified whether it is a health problem.

Next to excess iron, elevated manganese levels may pose the most common groundwater quality problem. Manganese is mobilized under moderately reducing conditions. In the Bengal delta in Bangladesh and West Bengal in India, Holocene sediments with different redox levels are sandwiched onto each other. Reducing sand with grayish to blackish colour is found to contain groundwater high in iron and arsenic which has been adsorbed onto the ferric hydroxides which are the source of the dissolved iron. More highly oxidized sediment, of yellowish to reddish colour, tends to contain groundwater high in manganese often in excess of the WHO limit while arsenic is below the permissible limits. Since the arsenic calamity was discovered, local drillers are now targeting the more oxidized sediments to avoid iron and especially arsenic in new wells. The occurrence of manganese is an aesthetic and technical problem but it is still not certified whether it is a health problem. In children who absorb higher amounts than adults and whose bioregulation is not yet fully developed, neurotoxicological effects have been observed even below the WHO limit of 0.4 mg/L. The development of drinking water quality in Bangladesh may be described by the sentence: 'From disastrous to toxic to safe?'.Bangladesh has experienced a drastic decrease in child mortality rate, from 150 per 1000 in 1990 to 60 in 2007. This is the result of a broad range of interventions among which the provision of germ free drinking water is certainly an important one.

Nitrate

Numerous articles are published every year on nitrate pollution of groundwater. The incidents have increased in conjunction with the use of commercial nitrogen fertilizers. The main health threat, methaemoglobinemia, is a rather uncommon condition mainly found in bottlefed children up to about six months of age. Methaemoglobin cannot carry oxygen to the peripheral tissues and the condition has also been called 'blue baby syndrome'. It is a rather uncommon condition, only a few tenths of thousands of cases have been recorded over several decades. Breast feeding provides good protection, in addition to all its other benefits. Other side effects of high nitrate drinking water have been suspected but so far there is no solid evidence for for example elevated cancer incidence.

Excess consumption of nitrate may lead to the 'blue baby syndrome'.

Groundwater overuse

Groundwater is usually bacteriologically safe and except for some of the components like arsenic and fluoride, covered above, good for consumption. However overuse of groundwater especially for irrigation is a serious problem. This is especially risky in coastal areas with the threat of sea water intrusion as a consequence. Coastal aquifers in South and South-East Asia are especially vulnerable due to a large water demand by the population in the densely inhabited coastal areas. The coastal aquifers differ considerably in groundwater turnover rate. The Tertiary aquifers on the Kerala coast in India have a very slow renewal rate, dating has shown the groundwater to be more than 20 000 years old. Overuse and sea water intrusion in such a case will probably be irreparable. In other cases the turnover rate is faster and measures to increase the recharge rate may have a good effect. One example is the Salalah aquifer in southern Oman. There, artificial recharge of treated sewage water has a pronounced effect in protecting the aquifer from further sea water intrusion. The re-establishment of a fog-collecting forest in the upstream region of the aquifer will also contribute.

Overuse of groundwater is a serious problem, especially in coastal areas with the threat of sea water intrusion as a consequence.

In some areas, groundwater is exclusively used for community water supply as in the Mekong delta. On the other hand, in the Bengal delta in Bangladesh up to 70 per cent of the irrigation water is supplied from groundwater. In the latter case this is a threat to crop production as many of the irrigation wells have excess arsenic and, in addition, cross-contamination by arseniferous groundwater or by sea water may occur.

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Health aspects of minerals in drinking water

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The composition and concentration of minerals and salts play an important role in the quality of drinking water. There has also been a growing interest in later years for the mineral composition of bottled waters and its presumed effects on health. The relative levels of various minerals do vary between soft and hard water, and careful monitoring becomes necessary when water is treated for consumption. A reduction or addition of chosen minerals can lead to undesirable or even hazardous changes in the concentration of elements that may have been overlooked.

Note: For readability, mineral elements in the text are presented without charges.
However, they all appear as charged ions in drinking water.

During the 18th and 19th centuries, the health effects of drinking water that was taken from certain wells were discussed and tested, for example among groups of wealthy people. They spent some time now and then at so-called health resorts, drinking their local special ‘healthy’ water. Well water with elevated concentrations of iron (Fe) was good for people with anaemia, bicarbonate (HCO_3) neutralized acids in the stomach and formed carbon dioxide which inflated the stomach and relieved pain. Water rich in magnesium sulphate ($MgSO_4$) was good against constipation, since the salt absorbed water, and it was also known to relieve pain caused by gall stones.

The importance of balanced mineral waters for health is of growing interest.

More recently, especially during the last decades of the 20th century, a similar renewed interest has appeared regarding bottled water. The health effects of water intake have been discussed as well as the importance of maintaining the water balance, for example in connection with sporting activities. The importance of balanced mineral waters for health is of growing interest.

Hard versus soft water

A large number of scientific studies clearly show that intake of hard water for decades, with elevated levels of elements like for example calcium (Ca) and magnesium (Mg), protects against heart diseases. There are also some studies indicating that hard water may be protective against diabetes, osteoporosis, senile dementia and some forms of cancer.

The hardness gives an indication of the amount of divalent metals in the water, especially Ca and Mg. Soft waters have hardness below 5 °dH (German degrees), while hard waters have hardness above 10 °dH. Hard waters originate from especially limestone bedrock, while waters from barren districts, where hard weathered gneiss and granite dominate, are soft. However, limestone also includes elements and ions like for example bicarbonate (HCO_3), sulphates (SO_4), iron (Fe), selenium (Se), molybdenum (Mo) and chromium (Cr). Calcium and magnesium are macronutrients, as mg-levels of daily intake are required. This may be the reason why they have been regarded as most important. Selenium, molybdenum, chromium (III) and some other elements in drinking waters are micro nutrients, and we need only some tens to hundreds of micrograms of these on a daily basis. Good calcium levels in drinking water seem to be 60–70 mg/L, magnesium 8–15 mg/L and bicarbonate (HCO_3) 60–150 mg/L.

Calcium is needed for teeth, bone tissue, heart function, nerve impulses, pH regulation and contraction of muscles. Magnesium is included in about 300 different enzyme reactions, and is important for the carbohydrate metabolism, heart, muscles and nerve impulses. Bicarbonate is the most important buffering agent in nature as well as in humans. Bicarbonate from water may decrease dissolution of bone tissue and raise the stomach and body pH. Sulphur, mainly present in drinking water as SO_4, is antagonistic against heavy metals, and is regarded as decreasing the health risks connected with intake of heavy metals. Sulphate (SO_4) is also active against constipation.

In an American study the death rates due to high blood pressure and arteriosclerosis were higher in cities where the drinking water had low conductivity, water hardness, concentration of magnesium, sodium, potassium, sulphate and barium, as well as low concentrations of bicarbonate, chlorine, silicon, lithium, strontium and vanadium, but high concentrations of copper. Most of these elements and ions are limestone related and appear at higher concentrations in hard water. Copper concentrations are generally higher in soft waters, as was the case in this study, and originate from pipes. If there are high levels of limestone related elements and ions, like for example Ca and Mg in the water, a protective layer of limestone will prevent from further dissolution of copper. Copper from drinking water may cause diarrhoea and other disturbances in the intestines at levels above 0.2 mg/L, especially in infants and small children. If consumption of two litres is assumed, 12.2 per cent of the daily magnesium intake came from water in the cities with the smallest death rates from blood pressure and arteriosclerosis, and 5.6 per cent of calcium.

However, there is probably an upper level for nutrient elements and ions in drinking water, since there is a study indicating that the cognitive function in elderly people does not increase further with calcium level when it exceeds 86 mg/L.

Changes resulting from acidification

Acidification, owing to emissions of especially sulphur dioxide, SO_2, from the European continent in the later part of the 20th century, negatively affected parts of southern Sweden dominated by primary bedrock. When well waters from these acid areas were compared to limestone waters, the difference in mineral element content was obvious (tab. 1).

Table 1: Metals and ions in acid compared to alkaline well waters.

	Median acid (st.dev.)	Median alkaline (st.dev.)	unit
pH	5.9 (0.49)	7.7 (0.39)	
Ca	9.9 (0.16)	54.6 (0.82)	mg/L
HCO_3	14.2 (11.8)	169 (61)	mg/L
Cr	0.1 (0.1)	3.6 (2.9)	mg/L
Mo	0.1 (0.08)	3.5 (3.8)	µg/L
Se	0.3 (0.2)	1 (2.3)	µg/L
Sr	49.8 (34.6)	165 (96.4)	µg/L
Ba	48.8 (29.5)	11.7 (14.7)	µg/L
Cu	0.34 (0.64)	0.085 (0.25)	mg/L
F	361 (298)	39.3 (60)	mg/L

Women from the areas suffering from acidification reported a larger number of negative health changes during the time they had been drinking their specific well water than women from the alkaline area. Boron, barium and copper concentrations were higher in the hair of women from the acid area, while calcium, strontium, molybdenum and iron, were significantly higher in hair samples from the alkaline area. Selenium was not detectable in hair samples from the acid area.

Drinking water is an important source of mineral elements.

Strong positive correlations were observed between element levels in hair and water for calcium, strontium, molybdenum and lead, which shows the importance of mineral elements from drinking water.

The concentrations of bicarbonate, calcium, chlorine, chromium, magnesium, sodium and sulphate were highest in the interval pH 7–8, indicating that pH should not be raised to levels above pH 8. If the pH is above 8, calcium and other divalent metal ('Me') ions precipitate as $MeSO_4$ and $MeCO_3$, and if it is below 7 mineral elements are dissolved in the acid environment. If a municipal water or well water is acid, limestone should be used as pH raising agent. If alkaline sodium salts, like caustic soda (NaOH) are used, only sodium and hydroxyl (OH) levels are increased, and the water becomes corrosive, which could harmfully affect both the intestines and the skin.

The bioavailability of calcium in the gastrointestinal tract depends on the concentration of calcium ions in the small intestine, and calcium, as well as all other mineral elements, is in ionic form in drinking water.

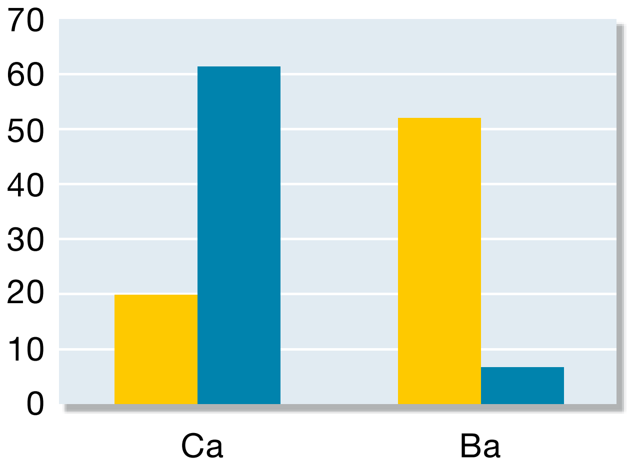


Figure 1. Median concentration of Ca (mg/L) and Ba (µg/L) in acid (yellow) and alkaline (blue) well waters.

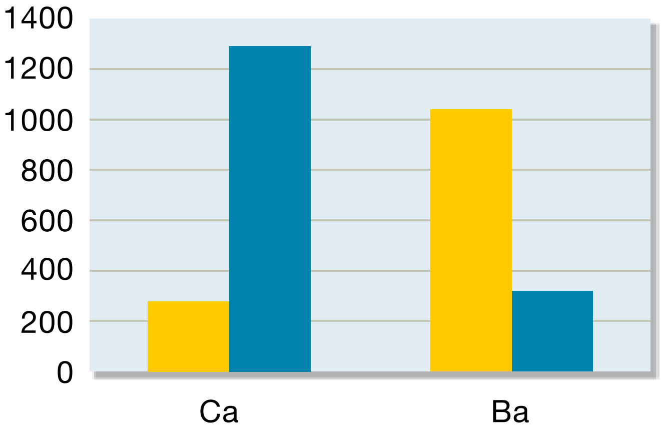


Figure 2. Median concentrations of Ca (µg/g) and Ba (ng/g) in the hair of women drinking acid (yellow) and alkaline (blue) well waters.

Minerals in bottled water

There is also a large variation of mineral element concentrations in bottled waters. Ten of the brands analyzed in Sweden in 2001 showed calcium levels below or equal to 10 mg/L and magnesium levels below 3 mg/L (Fig. 4), indicating very soft waters. In addition three of these bottled waters also had low concentrations of sodium < 7 mg/L, potassium < 3 mg/L and bicarbonate ≤ 31 mg/L, and conductivity, < 10 mS/m. None was carbonated.

There is a large variation of mineral element concentrations in bottled waters.

Some bottled waters, on the other hand, were very hard (Fig. 4), with increased concentrations of calcium (highest: 287 mg/L), magnesium (97 mg/L), chromium, sodium and bicarbonate, as well as aluminium, arsenic, beryllium, boron, lead, manganese, nickel, silicon, strontium and sulphate.

Some bottled waters have been supplemented with high levels of sodium salts.

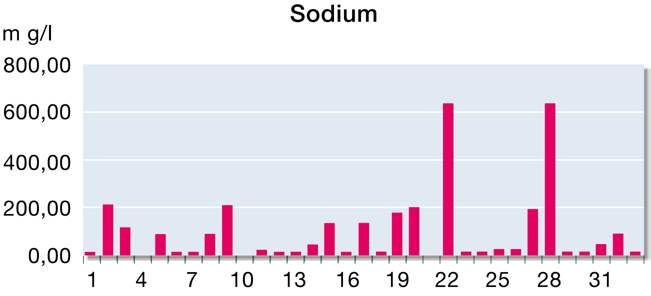
Two soft and carbonated waters had been supplemented with carbon dioxide CO_2, sodium carbonate Na_2CO_3 and common salt NaCl in order to improve the taste of the water. They showed increased concentrations of sodium (644 mg/L and 648 mg/), and chlorine (204 mg/L and 219 mg/L, Fig. 3). A daily consumption of 2 litres of these waters would contribute about two thirds of the recommended daily intake of salt. An increase in salt intake at that level may lead to hypertension.

One brand had elevated uranium (U) concentration, 72 µg/L, which indicates the necessity of analyzing not only for calcium and magnesium, before a certain brand is marketed. It also had among the highest levels of mercury (Hg), cadmium and cobalt in the total material. Exposure to uranium from drinking water is associated with kidney problems, and negatively influences for example bone tissues. Some bottled waters had fluorine levels above the health based guide line value 1.5 mg/L. Aluminium cans were regarded less suitable for storage of carbonated mineral water, since the Al level was raised in an Al can compared to a bottle of the same label.

Table 2. The median and concentration ranges of some mineral elements in tested bottled waters.

Element	Median	Range	Unit
pH	5.79	4.42–8.29	
HCO_3	188	12–1743	mg/L
Ca	23.8	2.47–289	mg/L
Mg	3.23	0.37–96.6	mg/L
Na	24.7	0.98–648	mg/L
K	3.23	0.54–268	mg/L
U	0.11	0–72.0	µg/L
Al	2.1	0.8–71.6	µg/L

Figure 3. Na levels in 33 bottled waters on the Swedish market.



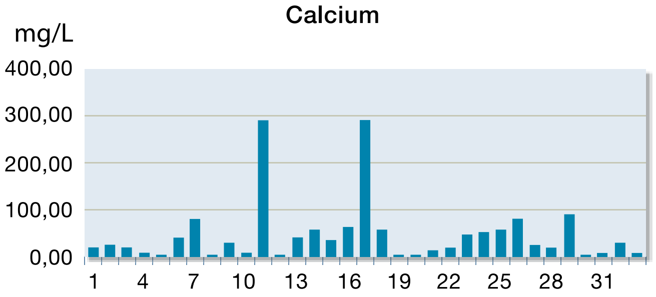


Figure 4. Ca levels in 33 bottled waters on the Swedish market.

As can be concluded from Tab.2 and Figs. 3 and 4, some bottled waters gave almost no contribution to the daily intake of elements and ions. Two gave a lot of Na, and two other brands substantially contributed to the daily intake of Ca.

Specific elements and their significance in drinking water

There are indications that humans and animals may suffer from iron (Fe) in water in concentrations of some mg/L. Reported symptoms on cows and calves were diarrhoea, loss of appetite and weight, apathy, paralysis and finally death. Horses and humans may also suffer. Hair levels mirror Fe concentration in drinking water.

Iron ions in drinking water have many negative effects on organs and cells.

The explanation may be that there is a direct corrosive effect of Fe on tissue, which may lead to severe haemorrhagic necrosis. In addition, excess Fe in the intestines leads to absorption of Fe directly into the circulation causing capillary endothelial cell damage in for example the liver. High Fe intake may cause haemochromatosis in humans, with symptoms as above. The disease is hereditary, and men are more often affected than women High Fe levels are visible as rusty precipitates on clothes and sanitary ware, and this is why filters are generally installed.

Acid rain affect drinking water copper levels, which may be harmful.

In the early 1970s, when acid rain negatively affected barren areas of southern Sweden, some infants given an infant formula prepared with acid well water with elevated copper (Cu) concentrations suffered from diarrhoea. Cu is bactericidal and may kill bacteria in the intestines. In addition its sulphate, $CuSO_4$, has been used as a vomiting agent. Another cause of high Cu levels in drinking water is softening filters. Cu levels above 0.2 mg/L may be harmful. Flushing decreases the Cu concentration.

Arsenic (As) has its origin in the bedrock. In drinking water, it may cause skin problems, after some years of exposure, and in the end cancer. The guide line value is 10 µg/L.

High levels of nickel (Ni) in drinking water may increase eczema on for example the hands. Ni in drinking water generally has its origin in pipes and installations.

Some municipal waters in Sweden, and a large number of waters from drilled wells, have high levels of uranium (U.) At present, one municipality softens the drinking water by adding calcium hydroxide $Ca(OH)_2$ to increase the pH and precipitate limestone. Thus, U is decreased to less than 15 µg/L. However, the calcium (Ca) content is also decreased, to a third of the original concentration, which is bad since Ca from drinking water is important.

Radon (Rn) from drinking water may cause lung cancer and is, after smoking cigarettes, the most common cause of the illness. In addition, stomach cancer may be an effect of Rn in drinking water.

Filtering affects the mineral content

Both addition and filtration may change the overall mineral composition in undesired ways.

Filtration may change the whole pattern of mineral contents in water, even if the aim was to alter the concentration of only one element or ion. There are filter cans and filters connected to the tap that release silver (Ag) in order to kill bacteria. However, the Ag levels may increase to more than 50 µg/L. There is no guideline value for Ag, but water with an Ag concentration that high cannot be regarded as safe.

Reverse osmosis filters have also become very popular. They produce “clean water” with no minerals, comparable to distilled or demineralised water. There are no scientific studies of health effects from reverse osmosis water, but a large number of studies clearly show the importance of dissolved minerals in drinking water.

Softening filters are commonly used when the raw water is hard, since precipitates of limestone are problematic in pipes and installations. However, softening often produces almost completely demineralised waters, which makes it important to adjust the filter to make sure some hardness remains in the water. Furthermore, copper (Cu) may be released from pipes if the hardness is completely or almost eliminated.

A future paradigm shift?

Drinking waters from acid areas or soft waters in general may not contribute at all to the daily intake of mineral elements, while alkaline water may give substantial contributions (Tab. 3). Thus, nutrient and as well as toxic elements and ions elements should be monitored in both soft and hard waters.

Nutrient and toxic elements and ions should be monitored in both soft and hard waters.

Table 3. Range for lowest to highest contribution of the daily intake of some elements and ions from drinking water, in the Swedish studies mentioned, based on a two litre daily consumption.

	Well waters	Municipal waters	Bottled waters
Ca (mg/L)	0.4–33	2.3–13.4	2.7–72
Mg (mg/L)	0.3–4.2	0.9–6.9	0.2–62
Na (mg/L)	0.1–10	0.5–7.6	0.1–65
K (mg/L)	0–2.2	0.05–0.4	0.03–13.4
Si (mg/L)	0.2–125	33–243	6–243
Cr (µg/L)	0–2.4	0.7–2.4	0–69
Cu (µg/L)	0–256	0–4.2	0–1.2
F (µg/L)	0–62	14–44	14–218
Mo (µg/L)	0–18	0–4	0–29

If a water source is rich in minerals, and also has elevated levels of uranium (U), lead (Pb) or other toxic metals, the water is not as poisonous as if the water was poor in minerals. Calcium (Ca), for example, is a very good antagonist against Pb. In addition, if the drinking water is rich in limestone, precipitates on the pipes will prevent further dissolution of for example Pb and Cu.

Most toxic elements in drinking waters are regulated by WHO and EU, and there are also upper guide line values for some nutrient elements. However, there are no lowest acceptable levels. When the toxic elements are completely regulated and we have found processes to eliminate unhealthy levels, the time will have come when we need to include nutrient elements and ions in the discussion. In the end there should be accepted lower levels in addition to the upper ones, which the regulations are dealing with at present. Some suggested ranges in mineral concentration levels are presented below Tab. 4.

In the end there should be accepted lower levels for nutrient elements and ions in addition to the upper.

Table 4. Suggested ranges in drinking water for some elements and ions.

Element or ion	Interval	EU guide line value
Alkalinity (Bicarbonate) HCO_3	100–250 mg/L	
F (fluorine)	0.8–1.5 mg/L	1.5 mg/L
PO_4 (phosphates)	0.06–0.6 mg/L	
Hardness	6–14 ° dH	
I (iodine)	10–20 µg/L	
Fe (iron)	0.02–0.2 mg/L	2 mg/L (not established)
Ca (calcium)	20–80 mg/L	
K (potassium)	2–20 mg/L	
Si (silicon)	4–10 mg/L	
Cl (chlorine)	10–100 mg/L	250 mg/L
Cu (copper)	0.02–0.2 mg/L	2 mg/L
Cr (chromium)	5–50 µg/L	50 µg/L
Mg (magnesium)	8–30 mg/L	
Mn (manganese)	0.005–0.05 mg/L	50 µg/L
Mo (molybdenum)	5–20 µg/L	
Na (sodium)	20–100 mg/L	200 mg/L
pH	7–8	>6.5 and <9.5
Se (selenium)	2–10 µg/L	10 µg/L
SO_4 (sulphates)	20–100 mg/L	250 mg/L

Table 5. Chemical formula and names of elements and ions.

Ag	Silver	**Co**	Cobalt	**Li**	Lithium	**PO_4**	Phosphate
As	Arsenic	**Cr**	Chromium	**Mg**	Magnesium	**Rn**	Radon
B	Boron	**Cu**	Copper	**Mn**	Manganese	**SO_4**	Sulphate
Ba	Barium	**HCO_3**	Bicarbonate	**Mo**	Molybdenum	**Ti**	Titanium
Be	Beryllium	**Hg**	Mercury	**Na**	Sodium	**U**	Uranium
Ca	Calcium	**I**	Iodine	**Ni**	Nickel	**V**	Vanadium
Cd	Cadmium	**K**	Potassium	**Pb**	Lead	**Zn**	Zink

Conclusions

Drinking water is the single most important human provision, consumed in quantities of around two litres every day throughout adult life. There is a large variation in the concentration of mineral elements in well waters, as well as municipal and bottled waters. It is of the greatest importance that the drinking water is free from toxic substances like heavy metals, but the content of nutrient elements is just as important. If the drinking water has a balanced mineral content, the chances o of remaining healthy throughout life are improved.

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Desalination – a critical element of water solutions for the 21st century

Lisa Henthorne, President, The International Desalination Association.

In the face of climate change and the water needs from a growing world population, the use of seawater or brackish water through desalination has increased in importance. The energy efficiency and production costs for desalination plants have been markedly improved. Recent techniques have made it possible to acquire reasonably cheap desalinated water from plants that are fully powered from wind energy, or to perform desalination alongside power production.

Desalination (also called “desalinization” and “desalting”) is the process of removing dissolved salts from water, thus producing fresh water from seawater or brackish water. While desalting technologies can be used for many applications, the most prevalent use today is to produce potable water from saline water for domestic or municipal purposes. Desalinated water, including wastewater treated with desalination technologies, may also be used for agricultural or industrial purposes.

Desalination is a natural, continual process and an essential part of the water cycle.

While the term is usually applied to man-made processes, desalination is actually a natural, continual process and an essential part of the water cycle. Rainwater falls to the ground and eventually flows to the sea, moving over and through the earth. On its route to the sea, it accumulates dissolved minerals and other materials and becomes increasingly salty. As water evaporates through the sun’s energy, it leaves the salts behind, and the resulting water vapor forms clouds that produce rain, thus continuing the cycle.

In addition to nature, people have been desalinating water for centuries. In fact, one of the first references to desalination was by Aristotle, who wrote of seawater distillation in 320 BC. Since then, adventurers and scientists have experimented with and employed many different techniques in the quest for new sources of fresh water.

Today, with advances in desalination technologies and construction of desalting facilities all around the world, desalination has become an increasingly important part of the solution to the world’s thirst for fresh water. Statistics point to its growing importance and use. For example, the 2008–2009 issue of the *IDA Desalination Yearbook*, published by Global Water Intelligence, reports that in 2007 alone, the total global contracted (planned) capacity rose by 43 per cent, as compared to the capacity contracted in 2006.

Growth in desalination is being spurred by a variety of factors. These reasons include the higher cost and availability of traditional surface water and groundwater supply, growing economies and populations in areas that rely on desalination for their water, the impact of climate change and drought, the desire of people to live coastally where water availability is limited, and the relative decrease in the cost of desalination.

Today, there are nearly 14,000 desalination plants in more than 150 countries around the world.

Today, there are nearly 14,000 desalination plants in more than 150 countries around the world, from Australia to China and

Japan, the United States, Spain and other European countries, the Middle East and North Africa. As of June 30, 2008, the cumulative contracted capacity of desalination plants around the world was 62.8 million m³/d (cubic meters per day), while the cumulative installed capacity (the amount currently being produced) was 52.3 million m³/d.

More than 80 per cent of the newly contracted capacity is composed of desalination of sea water or brackish water.

Sixty-two per cent (39 million m³/d) of the newly contracted capacity is composed of seawater desalination. Brackish water desalination represents another 19 per cent, or 12.2 million m³/d, followed by river water at 8 per cent, and 5 per cent for pure water. Wastewater applications of desalination technologies for water reuse are growing fast, currently representing 5 per cent of total capacity.

As of May 2009, the largest single desalination plant in operation was the 947,890 m³/d facility at Jubail-2 in Saudi Arabia. The largest operating hybrid MSF-RO (multi-stage flash distillation and reverse osmosis) plant is the 456,000 m³/d plant serving Fujairah 1 in the United Arab Emirates. Additionally, there are five other plants with capacities exceeding 500,000 m³/d under construction in the Middle East region. The largest of these is the 880,000 m³/d Shoaiba 3 unit in Saudi Arabia, which is expected to achieve full operational capacity by July 2009.

A thermal, multi-stage flash distillation (MSF) plant, in which successive condensation of evaporated brine generates energy for the next step.

While tightening across the world's credit markets has impacted the desalination industry, plans continue to advance. In fact, the desalination industry has found ways to minimize capital costs. Additionally, the industry has become more creative in using non-traditional procurement and financing, including privatization of some existing facilities. These topics are more fully explored in the following pages.

The quest for water continues, and desalination is an important part of the solution for a thirsty planet. It is also critical to acknowledge that desalination, including its application to recycling water, is only part of the water supply solution. Water conservation, demand management and leak minimalization also play very important roles toward creating sustainable water supply systems for the 21st century.

The quest for water continues, and desalination is an important part of the solution for a thirsty planet.

An Overview of Desalination Technologies

Desalination technologies have advanced steadily through the years. Through the mid-1900s, the most commonly used techniques involved evaporation and distillation. The development of desalination processes took a major step forward in the 1940s during World War II, when military establishments operating in arid areas needed a way to supply their troops with potable water. By the late 1960s, commercial desalting units producing up to 8,000 m³/d – approximately 2 million U.S. gallons per day – began to be installed in various parts of the world. Most of these installations used thermal (distillation) processes.

The Torrevieja 240,000 m³/day (63 MGD) Seawater Reverse Osmosis (SWRO) Desalination Plant located in Alicante, Spain. Designed and built by ACCIONA Agua, it consists of 16 trains of 15,000 m³/day capacity each with 20 PX-220 units per train.

In the post-war years, however, scientists also began studying osmotic processes to desalinate water. The first reported use of the term "reverse osmosis" – now a popular desalination technology – appeared in the1955 annual report of the US Department of Interior's Office of Saline Water Commission. Development continued, and in the 1970s, commercial membrane processes, such as reverse osmosis (RO) and electrodialysis (ED), began to be used more extensively. Since ED could desalt brackish water more economically than distillation, more interest was focused on using desalination as a way to provide water for municipalities with limited fresh water supplies and the availability of brackish water sources.

The use of membrane technologies for desalination became fully commercial in the 1980s. By that time, thermal desalination was well established, especially in the Middle East, where municipalities relied heavily on thermal desalination technologies.

Today, the major desalination processes employ membrane and/or thermal technologies.

Today, the major desalination processes employ membrane and/or thermal technologies. Reverse osmosis (RO), the predominant membrane process, accounts for 58 per cent of installed capacity, followed by thermal processes such as multi-stage flash, or MSF, at 27 per cent and multiple effect distillation (MED) at 9 per cent. Electrodialysis and electrodialysis reversal (ED/EDR) constitute approximately 4 per cent of installed capacity and hybrid technologies, 1 per cent.

Membrane desalination technologies include RO, ED/EDR and Nanofiltration (NF)

RO involves separating water from dissolved salts by passing feedwater through a semi-permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved salts. Steps in the RO process include:

- Pretreatment of the feedwater via mechanical and chemical means to remove suspended solids, adjust the pH and control scaling

- Use of high pressure pumps to increase the feed pressure before the raw water is delivered to the membranes

- Separation of the dissolved salts from the product stream through the membranes

- Degasification (if needed), pH adjustment and stability enhancement of the product water before it is transferred to the distribution system

Spiral wound elements, used in reverse osmosis (RO).

RO is the most prevalent technology used outside the Middle East region for purposes of desalinating water. Ongoing advances in this technology have produced membranes with improved performance characteristics and greater productivity and energy recovery devices that result in lower pumping energy requirements.

ED/EDR is the separation of a solution's ionic components through the use of semi-permeable, ion-selective membranes operating in a direct current (DC) electric field. ED was originally developed as a less expensive alternative to distillation as a method to desalinate brackish water.

Another desalting membrane process is nanofiltration (NF), which rejects solutes larger than approximately one nanometer (10 ångströms) in size. Nanofiltration is used primarily in water softening applications for removal of hardness ions. It has replaced lime softening in many municipal projects around the world and also removes color sometimes found in ground and surface water supplies. Nanofiltration has also found a niche application in the offshore oil and gas industry for purposes of treating injection water for water flooding of reservoirs in enhanced oil recovery processes.

Thermal desalination technologies

Multi-stage flash evaporation (MSF) is a desalination process where a stream of brine flows through the bottom of chambers, or stages, each operating at a successively lower pressure, and a proportion of it flashes into steam and is then condensed. MSF is also known as Flash Distillation.

Multiple effect distillation (MED) is a thin film evaporation process, in which the vapor formed in one chamber, or effect, condenses in the next one, providing a heat source for further evaporation.

Thermal processes are widely used for seawater desalination in the Middle East. Some "hybrid" plants in the region are now being built or retrofitted to employ both thermal (for example, MSF or MED) and membrane technologies (RO).

Many desalination plants produce both electrical power and desalinated water within the same facility.

It should also be noted that many desalination facilities, particularly in the Middle East and North Africa region, have been constructed as co-generation facilities, which simultaneously produce both electrical power and desalinated water within the same facility. Certain types of desalination processes, especially distillation, can be structured to take advantage of a co-generation situation.

Desalination and the Environment

The desalination industry has made major advances pertaining to environmental considerations, such as impact on marine life and energy requirements.

To mitigate impacts on marine life, the industry has created advanced seawater intake designs that greatly reduce the threat of entrainment or impingement of marine species, improved brine or concentrate outfall designs that efficiently discharge and diffuse the brine concentrate, and developed new methods for the handling and disposal of backwash solids.

In the last decade alone, the industry has been able to reduce power consumption and also significantly lower or eliminate greenhouse gas emissions. Technological advances include development of more efficient energy recovery devices (ERDs); improved efficiency, lower RO flux designs; straight-through pumping designs; and indirect coupling of renewable energy and desalination on a large scale.

In Australia, a high growth in desalination has been combined with strong environmental consideration.

There is no question that desalination can be implemented in an extremely environmentally conscious way. Australia is perhaps the most vivid example of high growth in desalination combined with dramatic environmental pressures. This continent has witnessed an annual growth in desalination of over 30 per cent, most of which is powered by renewable energy with high design standards for environmental requirements and monitoring.

The Perth Seawater Desalination Plant is an excellent example of a plant where environmental considerations were factored heavily into the design. At this plant, salinity issues associated with brine discharge and potential dissolved oxygen impacts have been closely monitored over several years, and studies indicate no evidence of negative effects due to dissolved oxygen levels or brine discharge. The plant, which produces 140,000 m^3/day of desalinated water using RO, is indirectly fully powered using wind energy.

The International Desalination Association encourages the use of desalination in an environmentally responsible way, and actively supports the ongoing development and application of technologies that address environmental aspects of the processes involved.

The Cost of Desalination

As with environmental concerns, the desalination industry has focused heavily on cost considerations. Today, with tremendous advances in technology, the cost of desalinating water has been reduced significantly.

The cost issue involves two major elements: the capital costs associated with construction and the operating costs.

Desalination plants are major pieces of infrastructure, and as such, they are not inexpensive to build. In addition to construction labor and the cost of financing, materials costs comprise the significant portion of this overall capital expense. Over the past few years, the financing component as well as some material costs (for example, metals) have experienced wide swings, and thus affected the funding needed for construction. Of course, desalination plants are not the only construction projects to feel these effects.

When people talk about the cost of desalination, however, many are referring to operating costs, which are driven largely by the cost of energy.

As stated above, technological advances have been successful in making desalination much more cost-effective to operate. For example, in the early 1970s, typical multi-stage flash distillation systems consumed more than 20 kilowatt hours per cubic meter (kWh/m^3) or 76 kWh per 1000 gallons.

In the late 1970s, coincident with the development of high performance reverse osmosis membranes, the first large scale municipal seawater reverse osmosis (SWRO) plant was installed. Energy requirements for this plant were approximately 8 kWh per cubic meter – just 40 per cent of the energy requirement of early large scale distillation plants.

Further advances in SWRO have continued to lower energy requirements. One of the major developments was the introduction of energy recovery devices in RO desalination plants. For example, in 2006, energy consumption in the core SWRO process of a demonstration plant in Southern California was measured at just 1.58 kWh/m^3 (6.0 kWh/kgal), and the overall energy consumed by this plant was 3.1 kWh/m^3 (12 kWh/kgal) – comparable to the power required to convey surface water to Los Angeles and treat it (approximately 2.4 kWh/m^3, or 9.2 kWh/kgal).

A thermal MED plant.
Photo: Courtesy Sidem/Water Desalination Report.

Today's thermal MED plants use less than 3 kWh of electrical energy per m^3 of desalinated water in addition to the steam input required, very significantly less than the thermal plants built in the 1970s.

One way of looking at the cost issue is to examine the estimated "water cost" for various plants around the world. (Water cost is defined as the amortized capital cost plus all operating costs divided by the total volume of water produced).

In September 2008, the *Water Desalination Report* explored this issue. According to the report, the lowest water cost, estimated between 2006–2008, among plants in operation was \$0.48/m^3 for the Tuas, Singpore SWRO plant, with a capacity of 136,360 m^3/d. The highest for a land-based facility was \$1.53/m^3 at the Taunton, Massachusetts, USA SWRO plant, which has a capacity of 18,925 m^3/d Most of the facilities reported water costs in the \$0.70–1.10/m^3 range.

The cost issue regarding desalination is complex, not only because of varying construction and energy costs, but also because of varying governmental policies, including subsidies, in different parts of the world. While cost is, of course, an important consideration, the International Desalination Association believes that the fundamental issue is the value – not simply cost – of water. Access to clean, fresh water is vital for human life and health, and is also critical to the economy.

According to the World Health Organization (WHO), "About 20 per cent of the world's population lives in countries where water is scarce, or where they have not been able to access the natural sources available. At present, 1.1 billion people lack access to safe water."

Moreover, the United Nations Committee on Economic, Cultural and Social Rights considers access to safe drinking water a human right, commenting that, "The human right to water is indispensable for leading a life in human dignity. It is a prerequisite for the realization of other human rights."

Desalination technologies are a key aspect to ensuring a reliable supply of potable water, whether augmenting the existing local supply or providing the primary source of water in regions where other sources are scarce or virtually non-existent. IDA is a strong proponent of making desalination as affordable as possible, while also taking the necessary steps to utilize desalination in an environmentally responsible manner.

Desalination technologies are a key aspect to ensuring a reliable supply of potable water.

Innovations in Financing

Technology is not the only arena for innovation within the desalination industry. The industry has been aggressive in responding to the effects of the global economic crisis, seeking new funding and creative alternatives to combat tightening of traditional sources of funding.

According to sources such as Global Water Intelligence, which has been tracking the situation closely, some of the emerging trends include:

- Use of bridge financing. With this arrangement, one pays a higher interest rate for a time to get through to a healthier place in the market. This option is being looked at by both very large and small projects around the world.

- A shift to regional sources of financing, rather than traditional Western sources. This is especially prevalent in the Middle East, where many regional banks have come together to provide funding for projects.

- Curtailment of some capital expenditures on the front end to reduce the overall financing package.

- More distinct phasing of projects, with shifting of more capital expenditures for expansions into out-years.

- Investment in projects by private equity sources and water funds, especially for projects such as vessel-based desalination.

Over the past few years, one of the most significant emerging trends in financing and operation of desalination plants has been the increased involvement of the private sector.

This represents a shift from the traditional model, where the financing, construction oversight, plant operation and facility maintenance are the province of governments. Today, the industry is witnessing a new model where the private sector is assuming responsibility for the financial and/or operational aspects of the plants, leaving governments free to focus on maintaining and policing regulatory frameworks regarding quality standard, service, protection of the health of their people, and sustainability.

Privately financed water projects are identified by such titles as:
- Private-Public-Partnerships (PPP)
- Concessions or Utility Outsourcing model of contracts
- Independent Water and Power Projects (IWPP), where water is produced usually through desalination alongside power generation
- Build Own Operate (BOO), or
- Build Own Operate with a Transfer component attached (BOOT)

To date, private sector involvement has proven to be successful using such measurement criteria as project completion dates, quality of services provided, and adherence to budgets. There is also evidence that transferring the responsibility to finance, design, build, operate and maintain the necessary infrastructure is also leading to innovation, particularly true when competitive procurement processes are utilized to select and award long duration water supply contracts.

There are several examples to prove the efficacy of this new paradigm. For instance, a plant with capacity to deliver 800,000 cubic meters per day (m^3/d) utilizing the multiple effect distillation (MED) process is currently being undertaken with private finance in one of the largest co-generation projects underway in the world, utilizing the IWPP framework.

Similarly, increasingly large desalination plants are now being undertaken which utilize the reverse osmosis technology.

These cases include a plant of 400,000 m3/d under development using the IWPP model.

These examples point to the efficacy of the PPP/IWPP model. At a time when global financial issues demand creative problem-solving, this is very good news for both the desalination industry and the end-users who need a reliable supply of quality water to meet their needs.

Summary

Desalination is a vital part of the solution to addressing global water issues in the 21st century. Its use is expected to continue to grow throughout the world, with the industry continually developing new or enhanced technologies aimed at environmental considerations and reducing cost, and utilizing new financing models to ensure that new projects continue to come online to meet increasing water demand.

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Ozonation for drinking water

Jeff Neemann, Black & Veatch and Secretary of the International Ozone Association.

Ozonation of water is a growing technique which has been applied to water for more than 100 years. Its main strength lies in the disinfection, but also the oxidation of harmful agents and substances. To drinking water it confers a taste and odour control, superior to that of other treatments. And in combination with chlorination or biological filtration, ozonation becomes highly effective both for drinking water preparation and for the cleaning of wastewater. With recent developments in ozone generation efficiency it is thus a technique which facilitates future water management with a desired reuse of water resources.

Although the first plant-scale use of ozone was in 1893 in Oudshoorn, Netherlands, most people consider Nice, France, which had its first plant installed in 1906, as the birthplace of ozone for drinking water treatment. Ozone has been used more extensively throughout Europe than in any other part of the world because of its benefit as a disinfectant and oxidant. Thousands of communities have installed ozone in Europe during its 100-year history. The first installation in North America was in 1908, but widespread use of ozone did not happen until the 1980s and 1990s when chlorination by-products were beginning to be regulated and people were looking for an alternative to chlorine.

There is a trend for high purity oxygen being used in the process.

For most of its history, ozone has been generated from clean, dry compressed air. Air, which contains about 21 per cent oxygen, was favored because it is readily available and only required energy on-site to make ozone. However, a significant trend in the past 15 years has been the transition to using high purity oxygen that is either delivered to the site as liquid oxygen or produced on-site with pressure swing adsorption or vacuum swing adsorption. The transition to high purity oxygen has allowed ozone generation efficiency to improve and its use to be more widespread.

Cleanness and taste

Ozonation continues to be used in drinking water treatment plants due to its many water quality benefits which include disinfection, oxidation, taste and odour control, and micro-flocculation (see below). Because it is a powerful oxidant, it can oxidize a variety of inorganics, such as iron and manganese; organics, such as atrazine; and even compounds of emerging concern, such as estrogen and caffeine.

Ozone is more effective in controlling bacteria and pathogens than most other common disinfectants.

Disinfection is probably the most prominent reason for the use of ozonation in drinking water treatment. Ozone is more effective in controlling bacteria and pathogens than most other common disinfectants, such as chlorine, chloramines, chlorine dioxide or ultraviolet (UV) irradiation. Using concentration multiplied by time (CT) values recommended by regulatory agencies such as the United States Environmental Protection Agency (USEPA), ozonation has been shown to be 80 times more effective for inactivating *Giardia lamblia* and seven times more effective for enteric viruses than free chlorination. Compared with chlorine dioxide, another strong oxidant and disinfectant, ozone is 20 times more effective for inactivating

Giardia lamblia and 30 times more effective for viruses. Some regulatory agencies require inactivation or removal of *Cryptosporidium parvum*, a pathogen that has high chlorine resistance and was the cause of outbreaks of cryptosporidiosis in Milwaukee, Wisconsin, USA. Research has shown that ozonation can more effectively inactivate *Cryptosporidium parvum* at elevated water temperatures than at low water temperatures, and that ozonation followed by chloramination is more effective for inactivating *Cryptosporidium parvum* than either disinfectant alone.

Ozonation is very effective for removal of taste and odour compounds.

It is the other water quality benefits of ozonation that often lead to its selection. It is very effective for removal of taste and odour compounds, such as the by-products of algae, Geosmin ('earth smell') and methylisoborneol (MIB). While taste and odour control is an aesthetic issue and is often not regulated, it can be an important aspect of drinking water treatment in maintaining public confidence. Utilities that practise ozonation rarely have to cope with customer complaints about taste and odour in their drinking water, and they may even receive compliments from customers about the pleasant taste of the water after implementing ozonation.

Ozonation has also been shown to enhance the coagulation, sedimentation and filtration processes, commonly referred to as microflocculation. Oxidation with ozone preceding coagulation can reduce the coagulant dose required to meet water quality goals or can improve the quality of the water at the same coagulant dose. Many facilities that use ozone also observe improved filter performance, as is evident by higher filter productivity and lower effluent turbidity.

Ozone is a very powerful oxidant that can react with a variety of compounds, both organic and inorganic. Ozonation of inorganic compounds, such as iron and manganese, makes them easier to remove by sedimentation or filtration. While ozone also oxidizes organic compounds, it usually does not take them to complete mineralization of carbon dioxide and water. For example, in some facilities, ozonation is used to remove atrazine; however, ozonation of atrazine forms daughter by-products, which may still need to be removed.

Ozonation has also been shown to be very effective in oxidizing endocrine disrupting compounds (EDCs) and pharmaceutical and personal care products (PPCP). Concern about the presence of these compounds in both wastewater and drinking water has led many utilities to consider or even implement ozonation as a barrier to protect public health.

Undesired side effects of ozonation

Although ozone is a powerful disinfectant and oxidant, there are several disadvantages to its widespread use, such as the absence of a sustained residual and the formation of disinfection by-products. Because ozone is very reactive, its residual lasts only minutes, whereas the residual of chlorine and chloramine can last for days. While the absence of a sustained residual is acceptable in some areas – for example, in Europe, many water systems do not maintain a disinfectant residual in the distribution system – in many parts of the world, ozonation must be followed by the application of chlorine or chloramines. Ozonation of water that contains bromide can also result in the formation of bromate, a potential carcinogen that is limited by both the World Health Organization (WHO) and the USEPA to a maximum concentration of 10 parts per billion. However, there are many bromate control methods, such as pH suppression and ammonia addition, that can limit its formation.

Because ozone is very reactive, its residual lasts only minutes, whereas the residual of chlorine and chloramine can last for days.

Ozone can also react with natural organic matter in the water to increase the concentration of readily biodegradable compounds, which can lead to biological regrowth in the distribution system. In essence, ozonation takes long-chain organic compounds that are not readily biodegradable and "chops" them into smaller-chain, more readily biodegradable organic compounds. This phenomenon is often quantified by measuring the concentration of biodegradable dissolved organic carbon (BDOC) or assimilable organic carbon (AOC).

In Europe and in many other parts of the world, this increase in biodegradable compounds is actually encouraged, and the compounds are removed downstream by biological filtration or a similar process. After passing through the biological filter, the water is very "biostable," meaning that most of the food sources for microbiological regrowth have been removed, and therefore a residual disinfectant is not required.

North America

There are estimated to be 500 ozonation facilities for drinking water in North America with a capacity greater than 3.7 million litres per day (MLD). About 450 of these installations are located in the United States. In addition, it is estimated that there are at least hundreds of other small-scale facilities. Ozonation is considered a strong disinfectant as USEPA lists it as part of the regulations governing the inactivation and removal of *Cryptosporidium.*

One example of the success of ozone is in Las Vegas, Nevada. Here, ozone was installed to provide inactivation of *Cryptosporidium* at two treatment facilities that have a combined capacity of 3,400 MLD. The Southern Nevada Water Authority, which operates both facilities, has become a leading researcher in the application and operation of ozone. It has developed a new method of bromate formation control, the chlorine-ammonia process, and has set the standard for optimizing operations and maintenance of the ozone system.

Another example of the use of ozone is the North Texas Municipal Water District, located in suburban Dallas, Texas. Here, ozone is being added to a facility that can treat 3,400 MLD because of its many water quality benefits. Ozone will be used to help lower chlorinated disinfection by-products, such as trihalomethanes and haloacetic acids, by reducing the need for free chlorine for disinfection and by oxidizing disinfection by-products precursors, which limits their formation later. Ozone will also provide taste and odour control, a problem that occurs because of algal growth in their source water reservoirs.

Europe

Europe has a long history of ozone use, with an estimate of thousands of installations that date back more than 100 years. The estimated use by some of the countries is 300 to 500 in France, about 100 in Germany, 50 to 100 in Italy, and 15 to 20 in Sweden. However, some of the cities that installed ozone many years ago, may no longer operate their ozonation system. Ozonation continues to be used because of its properties as a strong disinfectant and oxidant that does not form many disinfection by-products and does not leave a residual. The top reasons citied for its use include: preoxidation to improve flocculation, color removal, disinfection, and removal of taste and odour. In Europe, ozone is often used to oxidize organics to make them more readily removed by biological filtration, which is usually done with granular activated carbon (GAC) filters.

Asia

Asia is an emerging market for ozonation of drinking water. In China, disinfection is the primary drivers for its selection, but its benefits as a preoxidant are also important. In Hong Kong, the Tai Po Water Treatment Plant is currently expanding to 800 MLD and is adding ozonation for disinfection and its benefit of oxidation of iron and manganese.

Japan

Japan has extensive use of ozone for drinking water and wastewater treatment. It is estimated that there are more than 51 of a total of 2,200 treatment facilities that use ozonation. On a volume basis, ozonation treats about 7,250 MLD of drinking water, which is about 16 per cent of the total treated water. Based on a survey of ozone use, it is primarily used for drinking water treatment because of its removal of colour and taste and odour (48 per cent). Control of chlorinated disinfection by-products, such as trihalomethanes accounts for 29 per cent of its use. While it does provide disinfecting properties, ozonation is not approved for disinfection credit by the regulatory agency in Japan.

One of the largest uses of ozone in Japan is actually in wastewater treatment. There are estimated to be 239 plants with a combined treatment capacity of about 27,400 MLD.

Trends

Some of the trends in the use of ozone for drinking water treatment include improved generation efficiency, expanded applications, improved contacting systems and optimized disinfection calculations.

Ozone generation efficiency

Ozone generator manufacturers have been making substantial improvements in the efficiency of ozone generation. The use of high purity oxygen has allowed the gap between the dielectric and stainless steel ground electrode to get smaller and smaller, improving the energy efficiency. Since 80–85 per cent of the energy that is applied to make ozone is converted to heat, improvements in cooling water systems and gas flow dispersement have increased efficiency. A combination of these factors and others has also allowed ozone generators to be designed to increase the concentration of ozone after generation to greater than 15 per cent, which has improved oxygen efficiency.

Applications

The trend in ozone applications is that many communities are looking beyond drinking water treatment; they are looking to apply it for wastewater and reuse. For many of the reasons mentioned previously, ozone can be a very effective process for wastewater. In addition to being a strong disinfectant that can help meet effluent requirements, ozonation can improve the colour and odour of the effluent. It also oxidizes organics in the effluent and increases the UV transmittance, which could make downstream UV irradiation more cost effective. The same holds true for water reuse, where ozone is being considered at the end of the treatment for its disinfecting capabilities and its oxidation benefit. One of the drivers for both applications is its ability to remove many different types of microconstituents, such as EDCs and PPCPs.

Many communities are looking to apply ozonation for wastewater and reuse.

Contacting – sidestream

When many people think of ozonation for drinking water, they think of large concrete basins with ceramic diffusers to add the ozone. However, the trend in the ozone industry is towards using smaller basins or even pipelines and sidestream systems to add the ozone. Sidestream systems consist of taking 5–10 per cent of the main water flow, adding the ozone with an eductor and then mixing the sidestream with the main water flow. Sidestream systems can achieve transfer efficiency greater than 95 per cent and allow for most of the equipment that require maintenance to be outside the basin, unlike diffuser systems. The use of sidestream systems has also allowed for more flexibility in ozone contactor design, with some utilities even using a pipeline for ozone contact time.

Disinfection optimization

As regulations require increasing levels of disinfection while limiting the concentrations of disinfection by-products, many utilities are looking for methods to optimize their ozonation process. One way of optimizing is through increased monitoring and more advanced disinfection calculations. Ozone contactors are being designed with residual ozone analyzers at multiple locations. More analyzers mean more

residual data and a better characterization of the level of disinfection achieved. With more analyzers, more complex equations can be used to more accurately calculate the level of disinfection.

The trend of using sidestream injection is also helping optimize disinfection since more freedom in contactor design is available. The contactors can be designed with better hydraulics, which means less dead space and a more uniform ozone residual, and, in some cases, a pipeline contactor is even used because it approximates plug flow disinfection, which is very efficient. All of these methods mean that ozone use is optimized to achieve disinfection while minimizing disinfection by-products.

The future

The use of ozone for treating drinking water will become even more widespread.

So what does the future hold for ozone? The use of ozone for treating drinking water will become even more widespread for several reasons. One reason will be that advances in ozone generation technology will continue to improve the efficiency and make it more affordable for all sizes of communities around the world. Another reason is that as health research finds more chlorine-resistant pathogens, a stronger disinfectant like ozone may be required. As the demand for fresh water increases around the world and the supply of high quality sources is limited, communities will need to treat previously untapped lesser quality sources. These impaired sources will require advanced levels of treatment from technologies such as ozonation to meet drinking water treatment regulations. And as science continues to detect trace levels of microconstituents, such as EDCs and PPCPs, the effectiveness of ozone in their removal will become more important to protect public health.

Further reading

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Arsenic in drinking water

– state of the art and future innovations

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Arsenic is a highly toxic and widespread element on earth. Too high concentrations in aquifers and wells have been found in many parts of the world, which may lead to chronic toxicity, as well as various cancers. Modern techniques for lowering the arsenic concentrations in drinking water rely on the different properties of its species. The use of membrane processes like nanofiltration and reverse osmosis through small scale desalinators integrated with pre-oxidation agents has proved very effective in handling the different species. Ongoing research shows that this integrated concept allows for a lowering of arsenic contents far below the limits recommended by WHO and USEPA.

Introduction

Groundwater contamination by arsenic is a serious threat to mankind all over the world. It can also enter the food chain through either potable water or food.

Arsenic (As) is a natural tasteless and odourless element, which is widely distributed in the environment and highly toxic to humans. Arsenic exists in the earth's crust at average levels of between two and five thousands µg/kg (parts per million). Contributions from natural and anthropogenic sources result in a significant input of arsenic to the environment. Natural processes like erosion and weathering of crustal rocks lead to the breakdown and translocation of arsenic from the primary sulfide minerals, and the background concentrations of arsenic in soils are strongly related to the nature of parent rocks. There is an extensive range of anthropogenic sources that may enhance concentration of arsenic in the environment. Among the two modes of arsenic input, the environment is mostly threatened by anthropogenic activities. Arsenic and its compounds are mobile in the environment. Groundwater contamination by arsenic is a serious threat to mankind all over the world. It can also enter the food chain through either potable water or food. However, human arsenic exposure is also caused by the presence of this toxic element in foodstuffs such as meat, fish, poultry, grain and cereals.

Figure 1. Groundwater wells placed in the shallow alluvial aquifers in rural Bangladesh used for drinking purposes.

Arsenic-related health problems were first recognized in the early 1980s in West Bengal, India, where groundwater of the alluvial aquifers covering an area of 38,000 km² was found contaminated. A groundwater survey reveals that arsenic content of 40 per cent of the analyzed samples remained below WHO guideline values (10 µg/l), 55 per cent below and 45 per cent above the National Standard (50 µg/l). Arsenic contaminated water wells are reported from 60 districts of Bangladesh covering an area of nearly 118,000 km². The shallow alluvial aquifers in Bangladesh are significantly contaminated with arsenic with concentrations ranging between 10 to 1000 µg/l. The occurrence, origin and mobility of arsenic in groundwaters of sedimentary aquifers are primarily influenced by local geology, hydrogeology and the geochemistry of the sediments as well as several other anthropogenic factors such as the land use pattern. At present, arsenic is widely reported in groundwater in many countries including the US, Canada, Argentina, Mexico, Chile, Ghana, Hungary, the UK, Finland, Mexico, Taiwan, China, Japan, southern Thailand, Cambodia, Myamnar, Vietnam, Sumatra in Indonesia. More recently evidence of arsenic exposure via drinking water has also been reported from several countries in Latin America where a large proportion of groundwater is contaminated with arsenic at levels from >10 to 2000 µg/L (see the Chapter by Jacks and Bhattacharya, this volume).

Arsenic-related health problems were first recognized in the early 1980s in West Bengal, India, where groundwater of the alluvial aquifers was found contaminated.

Drinking water criteria for arsenic

Arsenic in drinking water affects human health and is considered one of the most significant environmental causes of cancer in the world. When the toxic effects are considered, it is thus necessary to understand the level of arsenic in drinking water, and its chemical speciation, when establishing regulatory standards. Because of the toxic effects of inorganic arsenic on humans and other living organisms, the FAO health limit for arsenic in groundwater was 50 µg/L, but in view of the widespread incidences of arsenic poisoning in South-Asian countries, a decrease in the groundwater arsenic concentration to 5–10 µg/L is being considered or being undertaken by several regulatory bodies throughout the world. The health-based drinking water guideline for arsenic was proposed to be fixed at 0.17 µg/L, but the WHO guideline value adopted for arsenic in drinking water is 10 µg/L, which is based on a 0.06 per cent excess skin cancer risk.

It is necessary to understand the level of arsenic in drinking water, and its chemical speciation, when establishing regulatory standards.

The EPA estimates that the adoption of its lower arsenic standard, in the US alone, will require 3,000 community systems, serving 11 million people, to lower the current level of arsenic in their drinking water.

The US Environmental Protection Agency drinking water standard for arsenic was 50 µg/L, set in 1975 and based on a Public Health Service standard originally established in 1942. On the basis of the investigations initiated by the National Academy of Sciences, it was concluded that the previous standard did not eliminate the risks of long-term exposure from low arsenic concentrations in drinking water causing cancer of the skin, bladder, lungs, nasal passages, liver and prostate. There are several non-cancer effects of low level arsenic ingestion, which include cardiovascular disease, diabetes and anemia as well as reproductive and developmental, immunological, neurological and endocrine (for example diabetes) disorders. Besides its tumorigenic potential, arsenic has been shown to be genotoxic. The EPA thus recommended, for achieving its goal of protecting public health, a lowering of the safe drinking water limit to 5 µg/L, higher than the technically feasible level of 3 µg/L. However, the USEPA later in January 2006 established a health based non-enforceable Maximum Contaminant Level Goal (MCLG) for zero arsenic and an enforceable Maximum Contaminant Level (MCL) of 10 µg arsenic/L in drinking water, which means a reduction of the arsenic levels by 80 per cent, applicable to both non-transient, non-community water systems and to community water systems. The EPA estimates that the adoption of this lower arsenic standard, in the US alone, will require 3,000 community systems, serving 11 million people, to take correction action to lower the current level of arsenic in the drinking water. Therefore, there has been a growing concern and need during the last few years to develop appropriate arsenic removal technologies for drinking water supplies.

Aqueous speciation of arsenic in drinking water

Arsenate, As(V), predominates in surface waters, whereas arsenite, As(III), is often found in groundwater.

The chemistry of arsenic is a very extensive subject. Arsenic occurs in both inorganic and organic forms in natural water. Inorganic arsenic is the result of dissolution from the respective mineral phase, such as arsenolite (As_2O_3), arsenic oxide (As_2O_5), orpiment (As_2S_3) or realgar (As_2S_4). In the natural environment; it may be present in two oxidation states, as arsenate As(V) or arsenite As(III) depending on the governing pH and redox potential (Eh). Arsenate is the thermodynamically stable form of inorganic species and it generally predominates in surface waters. Arsenite is favoured under reducing conditions and is often encountered in groundwaters of the reduced or partially reduced aquifers. In the predominant pH range in natural waters As(III) appears as neutral H_3AsO_3, the dominant species for As(V) at pH less than 7 is $H_3AsO_4^-$, whereas $H_3AsO_4^{2-}$ predominates at higher pH.

Due to its neutral charge the removal efficiency for As(III) is poor compared to that for As(V) by any of the conventional technologies for elimination of arsenic from water. It is widely believed that arsenate is the major water soluble species in groundwater, even if there is increasing evidence indicating that arsenite might be more prevalent than has been previously understood since groundwater is often reducing (negative Eh value). As(V), as already reported above, is the dominant arsenic species in surface water.

In addition to geochemical factors, microbial agents can influence the oxidation state of arsenic in water, and can mediate the methylation of inorganic arsenic to form organic arsenic compounds. Microorganisms can oxidize arsenite to arsenate, reduce arsenate to arsenite or even to arsenine (AsH_3). Organic arsenical compounds, such as dimethylarsinic acid and methylarsonic, were reported to have been detected in surface water more often than in groundwater.

Removal of arsenic from contaminated water

The removal of arsenic from water is an important issue worldwide. Millions of people are drinking water with higher levels of arsenic than recommended in drinking water standards. Incidences of elevated arsenic concentrations in groundwater within developing countries with poor infrastructure demand technologies that are effective and affordable for the provision of safe drinking water. Many people in the developed world are also drinking water with unsafe levels of arsenic. Large numbers of treatment technologies are available to remove arsenic from water, ranging from sophisticated technologies such as ion exchange and reverse osmosis to much simpler and often highly effective coagulation-flocculation techniques.

The majority of contaminated water remediation techniques are based on mechanisms that involve an initial oxidation of As(III) to As(V) and subsequent precipitation using chemicals. Successes in water treatment for arsenic in the past have generally relied on the relatively poor solubility of arsenate (AsV). If As(III) is present in the influent, then an oxidant such as chlorine (Cl_2), potassium permanganate ($KMnO_4$) or oxygen (O_2) is typically used to oxidize As(III) to As(V) prior to arsenic removal. Coagulation, adsorption onto activated alumina,

The majority of contaminated water remediation techniques are based on mechanisms that involve an initial oxidation of As(III) to As(V) and subsequent precipitation using chemicals.

ion exchange with strong-base anion exchange resins, reverse osmosis and membrane processes are technologies that have been used to treat arsenic-contaminated water. There are several other emerging technologies for the in situ removal of arsenic from groundwater such as the use of new adsorbents, passive-reactive barriers, bioremediation with chemical precipitation and aquifer oxygenation.

Reverse osmosis (RO) and nanofiltration (NF) are very promising techniques for arsenic removal from drinking water, because they have the advantage of also removing other compounds.

A wide variety of innovative technologies have been developed for arsenic removal from drinking water. Among these reverse osmosis (RO) and nanofiltration (NF) are very promising techniques because they have the advantage of removing dissolved arsenic along with other dissolved and particulate compounds. So far, however, this kind of membrane filtration has needed bulky and sophisticated units with high use of energy. In recent years a new generation of energy efficient techniques, so called low pressure RO, as well as NF membranes, for brackish and tap water application, have been emerged on the market. In this present chapter we focus on the membrane processes which have emerged as innovative approaches for cost effective and viable arsenic removal techniques for drinking water treatment in regions with elevated arsenic in drinking water.

Membrane technologies for treatment of arsenic contaminated water

The different membrane technologies which are employed in arsenic removal make use of different driving forces. Most commonly pressure driven processes such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF) have been studied. The solution to be treated is usually passed across the filter membrane (crossflow), where the pressure gradient forces the water (so called permeate) through the membrane, while basically being able to retain particulates down to solutes (see Fig. 2). Fig. 3 shows the different pressure driven membrane processes. Depending on particle size or molecular weight of separated substances, different techniques such as MF, UF, NF and RO (applied at different pressure difference) are distinguished. MF can be used to remove bacteria and fine particles, whereas UF can also retain colloids and viruses. Separation by MF and UF is usually described via mechanical sieving. NF and RO rely on rejection based on molecular size, in which the mass transport is commonly described by solution- diffusion models. NF, as far as ions are concerned, has high rejection efficiency only for multivalent ions. RO is also very efficient in rejecting all categories of ions including monovalent species. In membrane separation electric fields and thermal energy can also be used as driving forces in techniques such as electrodialysis and membrane distillation.

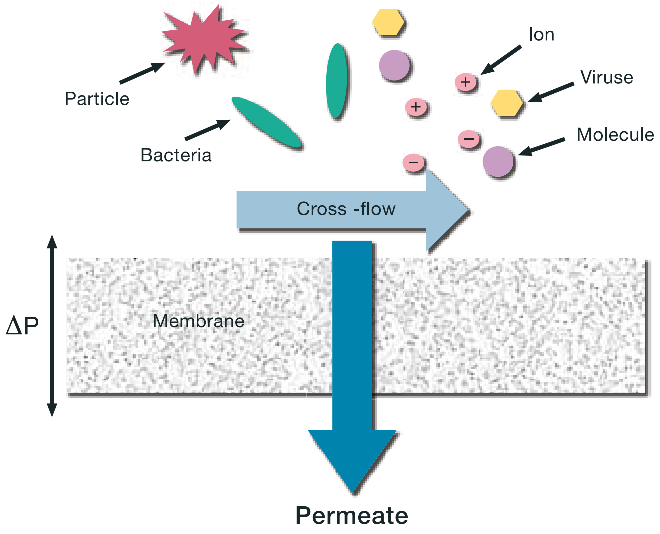

Figure 2. Basic principle of membrane technology.

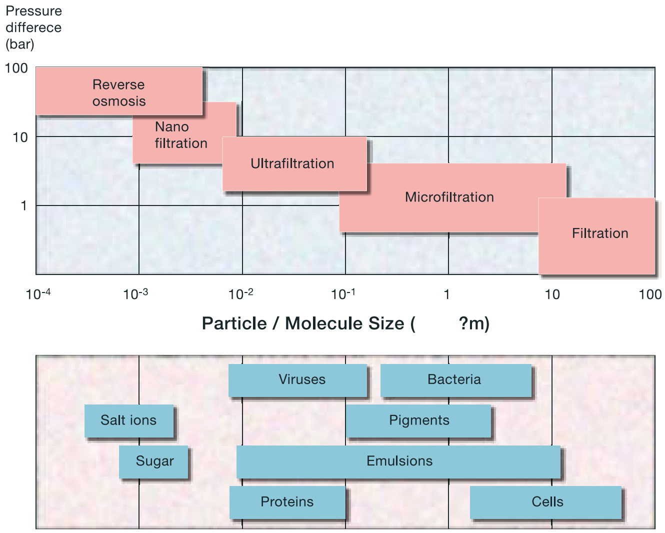

Figure 3. Overview of different pressure driven membrane processes.

In many cases, one membrane process can be integrated with another to produce water of even higher quality. In these processes, the membrane can be viewed as a barrier between contaminated and purified water streams. The separation of the two streams often allows for operation with no or minimal chemical water pre-treatment, which otherwise can form deleterious by-products.

However, in physical membrane processes, but also in more conventional techniques such as adsorption, the retained compounds (for example arsenic) are not destroyed but concentrated and the concentrate disposal can be costly and difficult to permit in many cases; therefore, post-treatment of the concentrate stream or hybrid membrane-assisted technologies capable of converting contaminants to harmless products are highly desirable.

The application of membrane techniques for water purification involves a number of advantages, which include principally the following:

- low energy consumption,
- no chemical substances needed,
- easy to scale up,
- separation carried out in a continuous mode,
- possibility to easily join membrane with other unit processes (hybrid processes),
- possibility to improve the separation properties of membranes during the operation of the system
- separation carried out under mild environment conditions

There are also some disadvantages, for example a decrease in capacity caused by concentration, polarization and membrane fouling, which particularly involves the processes of microfiltration and ultrafiltration. The limited lifetime of membranes and their low selectivity for a given separation problem may also be regarded as a disadvantage. Membranes, in particular polymeric ones, are in many cases characterised by limited chemical or thermal resistance.

One of the major advantages of these membrane processes over adsorption is that removal efficiencies are relatively less affected by the chemical composition of the feed.

Since arsenic compounds in drinking water are typically solutes, NF or RO is needed for effective removal. One of the major advantages of these membrane processes over adsorption is that removal efficiencies are relatively less affected by the chemical composition of the feed. This is especially true for RO systems. Table 1 shows performances of arsenic removal by various membrane processes and is based on the work reported by Kartinen and Martin in 1995. Shih and Uddin, and their respective co-workers have illustrated an overview of arsenic removal by pressure driven membranes. Basically RO and NF are advantageous over UF. This is particularly true for As(III) removal. Therefore these membrane techniques, which generally show the best arsenic removal efficiencies, will be described in more detail in the following section. However, the feasibility of a combination of flocculation and microfiltration has also been studied in several publications. Brandhuber and Amy investigated the efficiency of arsenic removal by MF coupled with ferric chloride pretreatment in bench-scale studies. Ghurye, Wickramasinghe, Han and their respective co-workers also studied coagulation with ferric chloride and ferric sulfate and MF for removal of arsenic. The studies demonstrated that a membrane pore size of around 0.2 µm is usually necessary in order to achieve a high degree of arsenic removal, whereas the removal effectivity depends on coagulant dose, pH and ferric counter-ions.

Table 1. Arsenic removal by membrane processes (Kartinen and Martin, 1995)

	Removal efficiencies (%)		
	Total As	**As (V)**	**As (III)**
RO	-	96– ~100	40–85
NF	95–99	60– ~100	10–75
UF	-	50–65	10–53

Reverse Osmosis (RO)

For many years RO has been a well-established technology for drinking water production in water desalination. RO membranes are asymmetric, i.e. consist of a thin polymer layer, usually made of polyamide, combined with a porous support to give the membrane mechanical stability. The RO membranes discriminate on the basis of molecular size and solubility, and due to dense properties of the separating layer very high sodium chloride rejection (>99 per cent) can be achieved. Moreover, the RO treatment process can be easily automated and controlled.

Contaminated water usually requires pre-treatment before entering reverse osmosis modules.

The treated water stream may lack the right balance of minerals, but this can be easily adjusted downstream through passing the water over natural minerals. Another disadvantage of RO is the energy on needed to maintain the required pressure difference. RO membranes are very sensitive to polarization phenomena (ion accumulation) at the membrane surface in contact with the concentrate (retentate) side. The presence of non-toxic components, such as hardness (Ca^{2+}, Mg^{2+}) and SO_4^{2-} anions, can interfere with the separation of toxic anionic species due to problems that these components may cause with water recovery and ionic strength (osmotic pressure). Therefore, the contaminated water usually requires pre-treatment (at least filter cartridges to remove particulates) before entering RO modules.

Since RO is not yet applied on a major scale for arsenic removal, several laboratory and pilot studies have been performed on arsenic removal by RO technology. Amy and co-workers performed bench-scale RO experiments using a membrane of type DK2540F manufactured by DESAL. The experiments comprised single element testing and flat sheet on lake water and on spiked deionized water. The results show very high removal efficiency for arsenate up to 96 per cent, but low removal efficiency from 60–85 per cent for arsenite. Waypa and co-workers observed that thin-film composite-type membranes exhibit better removal efficiency of arsenic than the cellulose-acetate type. Thin-film composite membranes also showed higher permeate flow rate, and they need a much lower applied pressure.

Brandhuber and co-workers showed that if the main arsenic species are present as As(III) only RO membranes would be effective. In a pilot-scale study, removal efficiencies between 96–99 per cent for As(V) and 46–84 per cent for As(III) have been reported. Pre-oxidation will guarantee better removal.

The solution pH strongly affects the removal efficiency of arsenic.

Kang and co-workers used two types of RO membranes, ES-10 (polyamide) and NTR729HF (polyvinyl alcohol), manufactured by the Nitto Electric Industrial Co., Japan. The removal efficiency of arsenite was lower than that of arsenate over the pH range of 3–10. The arsenate removal by using ES-10 membrane was over 95 per cent through all the investigated pH range. The removal of arsenate using NTR729HF was around 80 per cent at pH 3, jumping to 95 per cent with increasing pH from 5, 7 and 10. The removal efficiency of arsenite using ES-10 was around 75 per cent with increase of pH from 3, 5 and 10, and increased sharply to around 90 per cent at pH 10. The removal efficiency of arsenite by using NTR729HF was about 20 per cent at pH 3, 5, and 7. These results indicate that solution pH indeed affects the removal efficiency of arsenic.

Ning concluded in an overview in 2002, that in the commonly high oxidation state of As(V) it can be effectively removed by RO, whereas the weakly acidic As(III) removal needs special attention by the operation of RO at sufficiently high pH.

Designing RO processes

The Environmental Technology Verification Programme, operated by the USEPA, used the TFC-ULP RO membranes from Koch Membrane Systems to test the removal of arsenic from drinking water. The average arsenic concentration of the feed water was 60 µg/L and the membrane system reduced the total arsenic concentration to around 0.9 µgL/L in the permeate water. This result shows total arsenic removal efficiency around 99 per cent.

Gholami and co-workers in 2006 examined a model water with As(V) by using a commercial RO membrane (2521 TE, CSM, Co. Korea) in a pilot plant set-up. The effect of arsenic concentration, pressure, pH and temperature on the membrane performance were studied. The results showed that under optimal conditions (13–14.5 bar, 0.2–0.5 mg/L As(V), 25–30 °C and pH 6–8) the removal efficiency was around 99 per cent. Walker and co-workers examined the performance of different household RO systems and factors associated with arsenic removal efficiency in 59 households in Lahontan Valley (Western Nevada, USA). Lahontan Valley is an area where naturally-occuring arsenic concentrations commonly exceed 100 ppb in groundwater. In 2001 arsenic concentrations in 89 of 100 wells sampled in Lahontan Valley exceeded the MCL of 10 µg/L. The study came to the conclusion that household RO systems can be an effective method to treat arsenic contaminated water, with the majority of the RO systems removing more than 90 per cent of the arsenic. However, treatment with RO failed to lower arsenic concentrations to safe levels when arsenic in the well was very high. The study demonstrated that the proportion of As(III) present in groundwater was the most important factor associated with the efficiency of arsenic removal. Several RO systems removed less than 50 per cent of the arsenic when As(III) was the dominant arsenic species. However, the authors concluded that a limitation of the study was that inadequate data were available to determine the importance of other potential chemical factors, membrane types, and system age and maintenance history, on rejection efficiency.

Several experiments have shown that reverse osmosis removes arsenate, As(V), much more effectively than arsenite, As(III).

Deowan and co-workers used two types of low pressure polyamide RO membranes, XLE and LE (both manufactured by Dow), in a laboratory work to study the rejection of As(V) and As(III). They prepared a model water using arsenic spiked local tap water. It was shown that the arsenic rejection was significantly higher for As(V) (exceeding 95 per cent) than for As(III) (usually below 80 per cent). With regard to As(V) the LE membrane can comply with the WHO recommended MCL of 10 µg/L up to feed concentration of 2000 µg/L, whereas for the XLE the As values in permeate exceed the MCL at feed concentration around 800 mg/L. As for trivalent arsenic, the arsenic values in permeate can be kept below the MCL only up to a feed concentration of 50 µg/L. Both membranes showed only an insignificant pH and temperature dependency. Deowan and co-workers also reported parameters of a solution-diffusion model fitted to the experimental data which can be used for scaling up.

To date, RO membrane filtration has mostly used bulky and sophisticated units with high energy use. In view of the developing and newly industrializing countries' situation, such as low annual income and low electrical popularisation, application of traditional RO technology seems difficult. Therefore Oh and co-workers investigated the rejection of arsenic by using HR3155 membrane (Toyobo Co., Ltd) made of cellulose triacetate coupled with a bicyle pump operated at 4 MPa. It was shown that the pentavalent arsenic removal efficiency was over 95 per cent and the trivalent arsenic rejection was around 55 per cent.

Smaller, less energy consuming devices for an efficient arsenic removal are now being developed.

Geucke and co-workers tested a small-scale marine RO desalinator with three different technical spiral wound membranes (size 2.5 X 21 inch) for As(V) and As(III) removal using arsenic-spiked local tap water (see Fig. 4). All tested membranes were manufactured by Dow: tap water (TW), seawater (SW) and low energy (XLE) membranes. The RO pump of this system makes use of an energy recovery system which takes advantage of stored energy in the high pressure reject water that is typically wasted in conventional systems. Hence this energy is kept in the system resulting in less work to achieve fresh water. The energy consumption per litre of treated water is given between 8–9 Wh/L. Moreover the recovery rate is kept at only 10 per cent, which makes the membrane process robust with regard to scaling or fouling. With two of the tested membranes (TW, SW) As (V) rejection was so high, that the permeate water quality complied with the MCL up to feed concentration of 2400 µg/L. In the case of As(III) only feed concentrations below 350 µg/L resulted in permeate concentration below the MCL (for the SW membrane). The removal efficiencies for the low-energy XLE were in agreement with the the results of Deowan and co-workers. The work of Geucke and co-workers aims to eventually develop a simple and cost effective RO water filter for developing and newly industrializing countries.

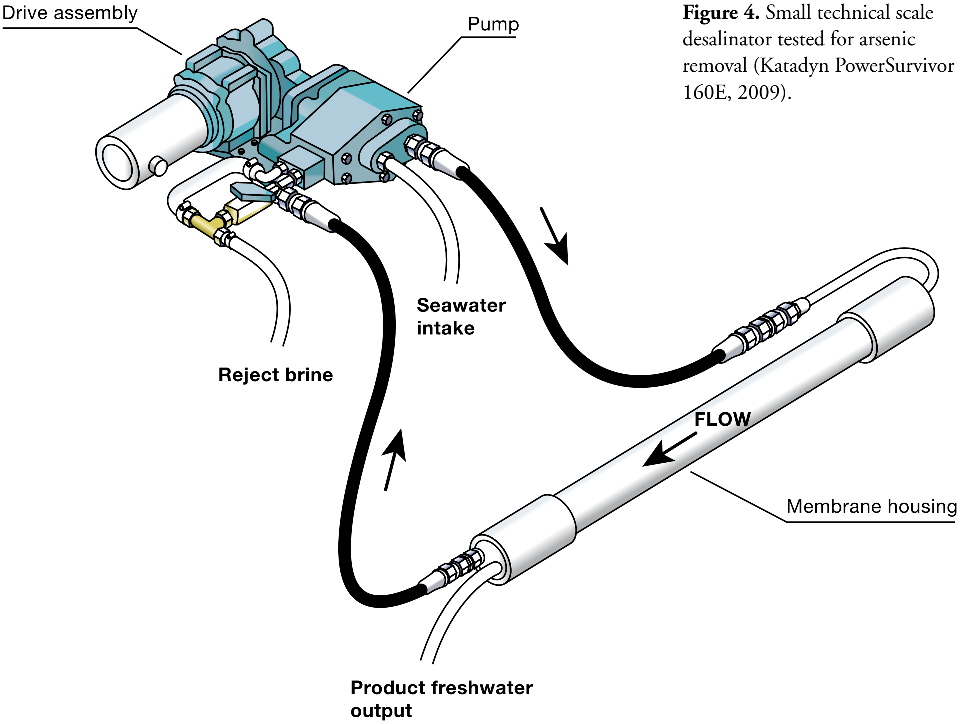

Figure 4. Small technical scale desalinator tested for arsenic removal (Katadyn PowerSurvivor 160E, 2009).

Nanofiltration (NF)

Nanofiltration (NF) uses membranes which can provide selective desalination, and is usually applied to separate multivalent ions from monovalent ones; it is also possible to achieve a certain separation of ions of the same valence by selecting the proper membrane and operating conditions. Sometimes, NF membranes are designed as "loose" RO membranes, since they provide higher water fluxes at lower membrane pressure. These membranes are usually asymmetric and negatively charged at neutral and alkaline drinking water pH. Therefore, separation of anions is based not only on different rates of their diffusion through the membrane (at low pressure), but also on repulsion (Donnan exclusion) between anions in solution and the surface groups, which is obviously higher for multivalent anions. The advantage of introducing this additional mechanism of ion exclusion (in addition to size-based exclusion) is that high ion separation degrees (ion rejections) similar to those in RO can be achieved but at higher water

Table 3. RO membranes rejection (%) for arsenic removal

Membrane and manufacturer	Water origin	Rejection (%) As(III)	As(V)	Reference
DK2540F, DESAL	Arsenic spiked DI water, natural water	60–85%	96%	Amy et al., 1998
TFC4921, Fluid System	Pilot studies at various groundwater sites (USA)	65%	96%	Brandhuber et al., 1998
TFC4820-ULPT, Fluid System	Idem	75%	99%	Brandhuber et al., 1998
AG 4040	Idem	70%	99%	Brandhuber et al., 1998
4040 LSA-CPA2	Idem	85%	99%	Brandhuber et al., 1998
Different membranes and manufactures	Pilot studies	46–84%	96–99%	Ning, 2002
ES-10 (polyamide), Nitto Electric Japan	-	75–90%	95%	Kang, 2000
NTR729HF (PVA), Nitto Electric Japan	-	20%	80–95%	Kang, 2000
HR3155 (TCA), Toyobo Co. (Japan)	Groundwater (Japan)	55%	95%	Oh et al., 2000
TFC-ULP RO, Koch	Groundwater, Utah (USA)	Total As reject. 99%		Koch Membrane Systems, 2001
2521 TE, CSM Co. Korea	Model water	~99%		Gholami et al.
Different membranes and manufactures	Groundwater	Total As reject. up to >99% Average 80.2%		Walker et al., 2008
LE, Dow Water Solutions XLE, Dow Water Solutions	Arsenic spiked local tap water	<80%	>95%	Deowan et al., 2008
XLEDow Water Solutions TW, Dow Water Solutions SW, Dow Water Solutions	Arsenic spiked local tap water	70–97%	96–(>99%)	Geucke et al., 2009
NF90 and NF200	Synthetic water	65%	98%	Uddin et al., 2007

fluxes through the membrane. On the other hand, the NF process is much more sensitive than RO to the ionic strength and pH of source water. Despite these challenges, several studies dealing with the removal of arsenic from groundwater have been performed, see Table 4.

Experiments with groundwater, to which arsenate As(V) and arsenite As(III) were added, were performed by Urase and co-workers in 1998, who showed that the As(V) rejection between 90 and 97 per cent from the negatively charged NF membrane used was almost uninfluenced by water pH; however the As(III) rejection increased with pH, being 50 per cent at pH 3 and 89 per cent at pH 10. At pH 10, most of arsenite

Table 4. NF membranes rejection (%) for arsenic removal

Membrane and manufacturer	Water origin	Rejection (%) As(III)	As(V)	Reference
NF70 4040B, Film Tec (Dow Chemical)	Pilot studies at various groundwater sites (USA)	50%	99%	Brandhuber et al., 1998
HL-4040F1550, Desal	Idem	20%	99%	Brandhuber et al., 1998
4040-UHA-ESNA Hydranautics	Idem	30%	97%	Brandhuber et al., 1998
ES-10, Aromatic polyamid (Nitto)	Groundwater spiked with 0,6 mg/l As (Japan)	50–89%	90–97%	Urase et al., 1998
NF45 Filmtec (Dow Chemical)	Synthetic water	-	90%	Vrijenhoek et al., 2000
ES-10, (Nitto Electric Industrial, Japan)	Synthetic water and groundwater	60–80% 60–80%	95% >95%	Sato et al., 2002
NTR-729HF, (PVA), (NittoElectric Industrial, Japan)	Synthetic water and groundwater	10–23% 10–23%	91–94% 95%	Sato et al., 2002
NTR-7250 (PVA), (NittoElectric Industrial, Japan)	Synthetic water and groundwater	10% 10%	86% >90%	Sato et al., 2002
192-NF 300, Osmonics	Model water and surface water	-	93–99% 95%	Saitua et al., 2005

is in a monovalent anion form, while at low pH the neutral form dominates because the pKa value of arsenite is 9.1. For the same reasons, As(III) was not effectively removed in two other studies while As(V) removal reached 90 and 95 per cent, respectively.

Nanofiltration produces similar results concerning arsenic removal as reverese osmosis, but allows for higher water fluxes through the membrane.

The removal of arsenic from synthetic water and surface water was investigated by Sato and co-workers in 2002. In synthetic solutions, arsenic rejection increased with arsenic retentate concentration. Arsenic was removed by 93–99 per cent from synthetic feed waters containing between 100 and 382 µg/L As(V), resulting in permeate arsenic concentrations of about 5µg/L. Under the studied conditions, arsenic rejection was independent of transmembrane pressures, cross-flow velocity and temperature. In surface water, the mean rejection of As(V) was 95 per cent and the co-occurrence of dissolved inorganic solutes did not significantly influence arsenic rejection. In this study, the difference of the arsenic removal efficiency between synthetic water and groundwater by nanofiltration membrane has been studied. In both cases, the removal efficiency of As(V) was almost the same in all the different studied membranes. In particular for synthetic water, the membrane NTR-7250 showed an As (III) rejection value of around 10 per cent, the NTR-729HF a value of 20 per cent and the ES-10 a rejection value of 80 per cent. This is in agreement with their NaCl removal efficiency, which is the highest for the ES-10 (99.6 per cent) and the lowest for the NTR-7250 (70 per cent). Removal of As(III) by all membranes showed also the same efficiency in both synthetic water and groundwater. Removal efficiencies of As(III) by NTR-729HF and NTR-7250 were less than 22 per cent due to the relatively larger pore size of these membranes. However, removal efficiency of As (III) by ES-10 was greater than 75 per cent in both water samples. Consequently, both As(V) and As(III) were not affected by source water compositions.

In 2007, Uddin and co-workers investigated the removal efficiency of two commercial polyamide NF membranes (NF-90 and NF-200) for As(III) and As(V), by analyzing the effect of the operating conditions on the rejections achievable. The feed stream consisted in tap water to which arsenate and arsenite were added. In all tests, As(V) was better rejected than As(III) and the highest removals obtained were above 98% for As(V) and around 65% for As(III). It was reported that by controlling the operating parameters, source water containing As(V) may be recovered as drinking water to EPA maximum contaminant level quality standards, but that water containing As(III) must undergo a pre-oxidation treatment before passing through the nanofiltration membrane in order to maintain drinking water quality.

Table 5. Evaluation of different membrane techniques for arsenic removal.

	MF	UF	NF	RO
As speciation				
Particulate	o	o	–	–
Dissolved				
As(III)	–*	–*	–**	+/o**
As(V)	–*	–*	+	++

++ very good, + good, o possibly effective, – not recommended

* viable option only with precipitation/coagulation as pre-step

** Pre-oxidation of As(III) to As(V) can achieve better performance

Conclusions

The research on the development of appropriate arsenic removal technologies for drinking water has increased over the last years mainly due to the lowering of the maximum contaminant level of arsenic (from 50 µg/L to 10µg/L) by the USEPA in the year 2006. Membrane systems, both as single units or in an integrated scheme, can be employed to reach the new standard. Table 5 summarizes the findings from the different publications and offers a guide for the selection of membrane treatment for arsenic removal.

In arsenic removal by membrane technology, the operating conditions such as membrane material, water source, and pH value of solution, affect the arsenic removal efficiency. In particular, in RO and NF processes, on the basis of literature results, the removal efficiency for As(V) is reported to be remarkably higher than for As(III) by using membrane processes. Therefore, the use of an oxidizing agent, such as chlorine, is necessary for the improvement of higher arsenic removal rate if arsenic in the source water is primarily present as As(III). On the other hand, the improvement of oxidation could result in damage to the membrane. The use of some microorganisms, able to transform arsenite to arsenate, could be a solution.

RO and NF membrane processes may both have a high removal efficiency of arsenic depending on the specific conditions. However, integrated membrane systems can become an increasingly attractive alternative to the traditional water treatment. In particular, with the pre-oxidation step, the integrated system allows to be far below the arsenic permeate concentration value of 10 µg/L, the recommended As limit value by EPA and WHO.

Integrated membrane systems can become an increasingly attractive alternative to the traditional water treatment.

As reported in this article, many studies have been carried out on arsenic removal using NF and RO, but more experience is needed, particularly with natural water. Therefore the authors of this article are contributing to the development of a simple and cost-effective membrane RO water filter for developing and newly industrializing countries like Bangladesh. Field tests are running at the moment near Sylhet /Bangladesh using a small scale desalinator (Figure 5).

Figure 5. Field tests on arsenic removal in Bangladesh using a small scale desalinator.

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Disinfection by-products and drinking water treatment

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Provision of clean and safe water for human consumption or sanitation requires disinfection, usually through chemical treatments. These treatments, however, have been shown to lead to the formation of undesirable by-products which can be harmful. Similar contamination can arise from environmental pollutants that have entered the water reservoirs. More water research is now addressed towards identifying and tracing the origin of by-products, and finding countermeasures against their occurrence.

Chemical disinfection has produced quality drinking water in developed nations, but also an unintended health hazard.

The disinfection of drinking water has been rightly hailed as a public health triumph of the 20th century. Before its widespread use, millions of people died from waterborne diseases. Now, people in developed nations receive quality drinking water every day from their public water systems. However, chemical disinfection has also produced an unintended health hazard: the potential for cancer and reproductive and developmental effects (including early-term miscarriages and birth defects) that are associated with chemical disinfection by-products (DBPs). Research is being conducted worldwide to solve these important human health issues.

Chemical disinfectants, like chlorine, ozone, chloramines, and chlorine dioxide, are used to kill harmful pathogens in drinking water, and produce safe, potable water. However, these disinfectants are also powerful oxidants, and can chemically react with the naturally occurring organic matter (mostly present from decaying leaves and other plant matter), and also bromide and iodide salts naturally present in some source waters (rivers, lakes, and groundwaters). Chlorine, ozone, chlorine dioxide, and chloramines are the most common disinfectants in use today, and each produces its own suite of DBPs in drinking water. Two non-chemical means of disinfecting drinking water—UV light and reverse osmosis (RO) membranes—are also gaining in popularity for disinfecting water, and these technologies may hold promise in reducing levels of DBPs formed in drinking water.

Table 1. Popular Drinking Water Disinfectants

Disinfectant	**Chemical structure**
Chlorine	Cl_2 (gas) or HOCl (liquid bleach)
Monochloramine	NH_2Cl (generated from adding chlorine to ammonia; dichloramine and trichloramine are also formed at lower levels)
Ozone	O_3
Chlorine dioxide	ClO_2

Chloroform and other trihalomethanes (THMs) were the first DBPs identified in chlorinated drinking water in 1974. Soon after their discovery, the THMs were found to cause cancer in laboratory animals. As a result, they became regulated in the United States in 1979, and are also currently regulated in several other countries. A few other DBPs are now regulated, including haloacetic acids (HAAs), chlorite, and bromate. Chlorite is a DBP from chlorine dioxide, and bromate is a DBP mostly from ozonation.

New issues and problems can result from changes in disinfection practices.

Of the four major disinfectants used today, chlorine generally produces the highest levels of THMs and HAAs. Because drinking water treatment plants can have difficulty in meeting the regulatory limits on them, many plants have changed their disinfection practices. Often, the primary disinfectant is changed from chlorine to “alternative” disinfectants, including ozone, chlorine dioxide, and chloramines. In some cases, chlorine is used as a secondary disinfectant following primary treatment with an alternative disinfectant, particularly for ozone and chlorine dioxide (to maintain a disinfectant residual in the water distribution system). However, new issues and problems can result from changes in disinfection practices. For example, the use of ozone can significantly reduce or eliminate the formation of THMs and HAAs, but it can result in the formation of bromate, especially when elevated levels of bromide salts are present in the source waters. Bromide (and iodide) salts can be present in source waters (for example, rivers) near coastal areas, due to salt water intrusion into the water supplies. Bromate is a concern because it causes cancer in laboratory animals. Nitrosodimethylamine (NDMA), another carcinogen, can form at higher levels with chloramination. In addition, a new class of DBPs – iodinated THMs and iodinated acids – which are highly mutagenic and toxic in cells, can be present at higher concentrations with chloramination. Similarly, another new class of DBPs – bromonitromethanes – are substantially increased with preozonation. Differences in source water conditions, including concentrations of bromide or iodide salts, concentrations of natural organic matter, and pH, can have a dramatic effect on the formation of various DBPs (chlorine-, bromine-, or iodine-containing) and the levels formed.

Over the last 30 years, significant research efforts have been directed towards increasing our understanding of DBP formation, occurrence, and health effects. More than 600 DBPs have now been reported in the scientific literature. Examples of some of these are shown in tab. 2. However, only a small number of these have been addressed either in quantitative occurrence or health effects studies. The DBPs that have been quantified in drinking water range from ng/L (ppt) to µg/L (ppb) levels. However, more than 50 per cent of the halogenated DBP material (containing chlorine, bromine, or iodine) formed during the chlorination of drinking water, and more than 50 per cent of the DBPs formed during ozonation of drinking water are still not accounted for, and nothing is known about the potential toxicity of many of the DBPs present in drinking water. Much of the previous health effects research has focused on cancer or mutagenicity. There are concerns that the types of cancer observed in animal studies (primarily liver cancer) for the regulated DBPs do not correlate with the types observed in human epidemiology studies (primarily bladder cancer). It is possible that emerging, unregulated DBPs may be responsible. It is also possible that ingestion (the primary route included in animal studies) is not the only important route of exposure.

DBPs from showering and swimming in pools

Disinfection by-products are not only ingested by drinking the water, but some can also be inhaled or can penetrate the skin.

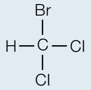
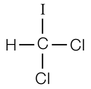
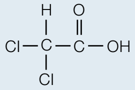
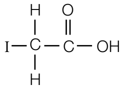
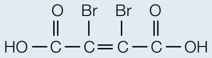
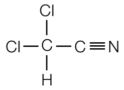
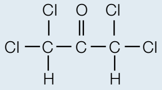
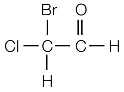
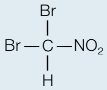
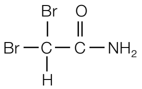
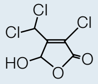
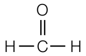
New research also indicates that exposures from other activities, including showering, bathing, and swimming in chlorinated swimming pools can increase exposures to certain DBPs. DBPs are not only ingested by drinking the water, but some can also be inhaled or can penetrate the skin. In particular, volatile DBPs that easily transfer from the water to the air (including THMs) can be inhaled during showering or visiting an indoor chlorinated swimming pool—either through active swimming or from sitting near the pool, breathing in the pool vapours. THMs have been measured in human blood and exhaled breath after showering or swimming. These exposure routes are now being recognized in human exposure and human epidemiologic studies. Recent results indicate that these other exposure routes increase the risk of bladder cancer, and chlorinated swimming pool exposures have also been linked to respiratory effects, including asthma.

Analytical methods to identify by-products

Experiments to identify disinfection by-products (DBPs) have been carried out using two different procedures. In the first, natural waters (for example, river, lake, etc.) are reacted with the disinfectant, either in a pilot treatment plant, an actual treatment plant, or in a controlled laboratory study. In the second type of procedure, aquatic humic material (the major constituent of natural organic matter) is isolated and reacted with the disinfectant in purified water in a controlled laboratory study. This latter type of study is relevant because humic material is an important precursor of THMs and other DBPs. Aquatic humic material is present in nearly all natural waters, and isolated humic material reacts with disinfectants to produce most of the same DBPs found from natural waters.

Because DBPs are typically formed at low levels (ng/L-µg/L), samples are usually concentrated to allow their detection.

Table 2. Examples of DBPs.

Class	Example	Chemical Structure
Trihalomethanes (THMs)	Bromodichloromethane	 $\mathrm{H-\overset{Br}{\overset{\mid}{\underset{\underset{Cl}{\mid}}{C}}}-Cl}$
Iodo-THMs	Dichloroiodomethane	 $\mathrm{H-\overset{I}{\overset{\mid}{\underset{\underset{Cl}{\mid}}{C}}}-Cl}$
Haloacetic acids	Dichloroacetic acid	 $\mathrm{Cl-\overset{H}{\overset{\mid}{\underset{\underset{Cl}{\mid}}{C}}}-\overset{O}{\overset{\parallel}{C}}-OH}$
Iodo-acids	Iodoacetic acid	 $\mathrm{I-\overset{H}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-\overset{O}{\overset{\parallel}{C}}-OH}$
Other Haloacids	Dibromobutenedioic acid	 $\mathrm{HO-\overset{O}{\overset{\parallel}{C}}-\overset{Br}{\overset{\mid}{C}}=\overset{Br}{\overset{\mid}{C}}-\overset{O}{\overset{\parallel}{C}}-OH}$
Haloacetonitriles	Dichloroacetonitrile	 $\mathrm{Cl-\overset{Cl}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-C\equiv N}$
Haloketones	1,1,3,3-Tetrachloropropanone	 $\mathrm{Cl-\overset{Cl}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-\overset{O}{\overset{\parallel}{C}}-\overset{Cl}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-Cl}$
Haloaldehydes	Bromochloroacetaldehyde	 $\mathrm{Cl-\overset{Br}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-\overset{O}{\overset{\parallel}{C}}-H}$
Halonitromethanes	Dibromonitromethane	 $\mathrm{Br-\overset{Br}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-NO_2}$
Haloamides	Dibromoacetamide	 $\mathrm{Br-\overset{Br}{\overset{\mid}{\underset{\underset{H}{\mid}}{C}}}-\overset{O}{\overset{\parallel}{C}}-NH_2}$
Halofuranones	MX	
Non-halogenated DBPs	Formaldehyde	 $\mathrm{H-\overset{O}{\overset{\parallel}{C}}-H}$

Concentration methods that are commonly used include solid phase extraction (SPE), solid phase microextraction (SPME), liquid-liquid-extraction, and XAD resin extraction (for larger quantities of water). Gas chromatography (GC)/ mass spectrometry (MS) continues to be an important tool for measuring and identifying new DBPs. Large mass spectral libraries (NIST and Wiley databases) enable rapid identifications. When DBPs are not present in these databases, more advanced MS techniques are used to obtain structural information. Liquid chromatography (LC)/MS is increasingly being used to identify highly polar DBPs and probe high molecular weight DBPs that are not possible to measure with GC/MS. For measuring known or targeted DBPs, new direct, online techniques are also being used.

DBPs can also form from contaminants

Both natural organic matter and environmental pollutants can contribute to the formation of disinfection by-products.

In the same way as natural organic matter, environmental contaminants (or pollutants) also can react with chemical disinfectants to form DBPs. These contaminants enter drinking water sources from treated municipal or industrial wastewater. Contaminant DBPs have been reported from pharmaceuticals, anti-bacterial agents, estrogens, pesticides, textile dyes, bisphenol A, alkylphenol surfactants, UV filters (used in sunscreens), and diesel fuel. Contaminant DBPs have also been found in swimming pools, from the reaction of chlorine with active ingredients in sunscreens. It is not surprising that DBPs can form from these contaminants, as many of them have activated aromatic rings in their chemical structures that can readily react with oxidants like chlorine and ozone. However, until recently, these types of DBPs had not been investigated.

Minimizing or removing DBPs

DBPs can be minimized using several different approaches. First, before the disinfectant is added, the precursor natural organic matter can be removed or reduced significantly with enhanced coagulation, granualar activated carbon filtration, or with membranes (including reverse osmosis membranes). Removing the precursor organic material reduces resulting DBP levels formed. DBPs can also be reduced by changing the type of disinfectant used, as many drinking water treatment plants have done to meet the tightened regulations on THMs and HAAs. Switching from chlorine to chloramines, ozone, or chlorine dioxide will drastically reduce the THMs and HAAs formed. However, as mentioned earlier, sometimes other DBP issues can arise with these alternative disinfectants. Other non-chemical disinfection methods can be used, including UV irradiation and reverse osmosis membranes, which are now becoming more common for treating seawater for drinking water purposes. Finally, DBPs can be removed after they are formed, through the use of granular activated carbon filtration (which is already widely applied at drinking water plants using ozone), or by home filters (typically carbon-based filters), which can remove DBPs and other contaminants at the point of use.

The way forward

Through more than 30 years of research, many DBPs have been identified, and we have a greater understanding of how they are formed, as well as ways to reduce or eliminate many of them. However, despite much research, more than 50 per cent of the halogenated DBPs in chlorinated drinking water remains unaccounted for, and much less is accounted for with ozone, chloramine, and chlorine dioxide. Beyond the three most popular alternative disinfectants (chloramines, ozone, and chlorine dioxide), there is also a trend towards non-chemical disinfection, such as UV irradiation and membrane technology. UV irradiation is sometimes presented as a DBP-free disinfectant, but it has the potential to form hydroxyl radicals in water (as ozone does), which can produce oxygen-containing DBPs. New research indicates that some DBPs may increase in formation when UV is used before chlorination or chloramination. The use of membranes in desalination plants can cause shifts to brominated DBPs when the disinfectant is added (due to the considerable amount of bromide that can traverse the membrane). It will be important to continue to investigate these new treatments to determine their relative safety compared to existing treatment technologies.

Finally, it is paramount to determine which DBPs are responsible for human health effects observed and eliminate or minimize them in drinking water. As mentioned earlier, it is still not known which DBPs are responsible for the bladder cancer observed in human epidemiologic studies or which DBPs are responsible for the reproductive/developmental effects observed. Investigating new, emerging DBPs that show a toxic response is an important element in solving this important human health issue, as is investigating human health effects from routes of exposure beyond ingestion.

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Drinking water distribution

– effects on water quality

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Drinking water has to be wholesome and clean when it becomes available for the consumers. However, from the time water leaves the water works, an array of processes may affect its quality during transport and storage. These processes have to be considered when the distribution network is constructed and when the materials to be used are selected.

It is not enough that the water works produces water of a high quality; this good quality has to be maintained through all the transport and storage of the water.

Drinking water has to be wholesome and clean at the consumer's tap, as clearly stated in the EU Drinking Water Directive from 1998. Thus it is not enough that the water works produces water of a high quality; this good quality has to be maintained through all the transport and storage of the water.

A number of processes may alter water quality during transport in the distribution network to the consumer – this may be due to inherent properties of the water which may lead to microbial after growth or corrosion, or to the choice of materials in contact with drinking water which may allow migration of organic materials that can sustain microbial growth or may release heavy metals such as copper, lead or nickel. Finally, leaks or fractures may permit the entry of pollutants such as organic micropollutants (for example gasoline compounds) or pathogens from surface or waste waters (Box 1).

Box 1. Processes affecting drinking water quality during transport and storage in the distribution network.

Inherent properties

- Microbial after growth - due to organic matter in the water (AOC)
- Corrosion – due to for example pH, high hardness, hydrogen carbonate, high electrical conductivity (for example neutral ions such as chloride and sulphate)

Contact with construction products

- Release of metals from pipes, household installataions and taps (copper, zinc, lead and nickel)
- Migration of organic compounds from plastic pipes (for example phenols, ketones and quinones)
- Microbial growth and biofilm formation

Contamination of the network through leaks and fractures

- Intrusion of pathogens (for example *Campylobacter*) – survival dependence on biofilm
- Presence of small animals (invertebrates for example) *Asellus aquaticus* (water louse) and *Cyclops* (water flee)

One way to get an overview of the these effects and to identify the most critical ones could be to make a risk assessment, but so far these have mainly been theoretically based, and the basic processes have to be understood.

Inherent properties of the water – microbial after growth

The risk for bacterial after growth is important to consider if the water lacks disinfection residuals.

Drinking water contains dissolved organic matter which is the primary substrate for bacteria and which may lead to growth of bacteria during transport and storage of the water. Such an increase in bacterial numbers during distribution is called after growth. This is especially important if the water lacks disinfection residuals such as chlorine as for example in Denmark and in an increasing number of European countries. The organic matter may vary substantially in composition and consequently as a substrate, depending on whether the water arises from surface water with algal growth or from old ground water, and the concentration of organic carbon as such does not express the substrate value. Therefore an assay where the bacterial growth is quantified under standardized conditions is usually made to estimate this after growth potential – the Assimilable Organic Carbon (AOC) which is typically in the range of 5–20 µg/L.

Microorganisms that grow on the surface of the pipes form biofilms.

The consequences of after growth are for example reduced oxygen concentration which may affect the fresh taste of the water – and in extreme cases the water may turn anaerobic with production of sulphides, which also affect the smell. The bacterial growth will not only occur in the water phase, but may also result in biofilm formation, where the microorganisms grow on the surface of the pipes. The growth rate of the bacteria in the biofilm is generally slower than that of bacteria in the bulk water phase, and represent a completely different microbial community which is growing in thickness and complexity over several years. Other substrates such as nitrite may also be a substrate for the biofilm.

Bacteria also grow in household hot water installations where biofilm formation may become even more evident and may form insulating coverings in the systems, reducing the heat transfer in heat exchangers.

Biofilms can be important for the survival of intruding microorganisms – indicator organisms and pathogens – and in hot water systems biofilms may lead to growth and outbreaks of *Legionella*, causing a pneumonia-like disease which may be fatal.

Microbial growth may also sustain a population of small animals. Recently it has been realized that populations of invertebrates for example *Asellus aquaticus* (water louse) and *Cyclops* (water flee) are occurring in clean water tanks and distribution systems. In temperate countries they are mainly seen as an aesthetic problem, but their function is unclear.

Inherent properties of the water – metal release

The release of metals from the installation into the water may certainly affect water quality.

The composition of ions in the water first of all depends on the raw water source, and the different ions may affect the corrosiveness of the water; especially high concentrations of hydrogen carbonate and high electrical conductivity, the pH value and oxygen content but also neutral salts (chloride, sulphate) are important. Corrosion is mainly considered in relation to damage to pipes in the networks and the installations leading to fractures with water loss and damage caused by flooding. This is of course troublesome and expensive, but another aspect – release of metals from the installation into the water – may certainly affect water quality.

A survey of metal release, screening water from consumers' kitchen taps in 51 domestic installations on Sjælland, Denmark where the water supply is groundwater based, revealed that copper was released from copper pipes reaching up to 2,369 µg/L in water when tapping 800 mL which has been stagnant in the pipes for four hours. Also significant amounts of zinc were released, with up to 3,891 µg/L in water which has been stagnant in the pipes for four hours. To prevent such release and corrosion it is recommended not to install such pipes in areas with water types characterized by a high electrical conductivity (high salt content), high hardness (especially important for corrosion of galvanized pipes) and high concentration of hydrogen carbonate.

Drinking water in contact with materials – metals

On its way to the consumer the water is in contact with various materials which may affect the water quality. The above mentioned survey of metal release in domestic installations on Sjælland, Denmark also revealed that the average lead concentration after four hours stagnation was 2.8 µg/l in the first tapped 200 mL and 7.3 µg/l in the following 800 mL and the release was substantially higher in water from taps which were less than one year old. At the same conditions the average nickel concentration after four hours' stagnation was 11.8 µg/L in the first tapped 200 mL with 11 samples higher than 20 µg/l and a maximum value of 68 µg/L. In the following 800 mL the average concentration was 4.9 µg/L. These values were significantly increased compared to the water in the main distribution system, as measured in a fully flushed sample. This pattern demonstrated that copper is released from the copper pipes in the household installations, and lead and nickel are released from the tap – especially when they are newly installed. To maintain a good water quality it is thus important to choose the proper materials for distribution and, not least, for household installations.

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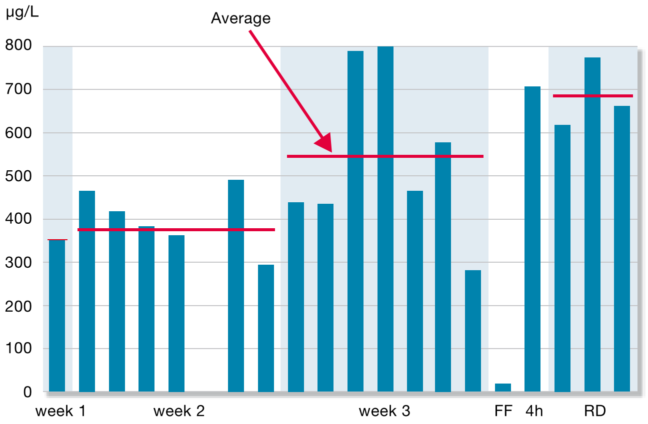

Figure 1. Monitoring of the copper concentration in drinking water used for consumption – daily and weekly average (red line), a fully flushed sample (FF), a sample after 4 hours' stagnation time (4h) and a random daytime sample (RD) (Corfitzen & Albrechtsen, 2008).

These patterns also stress the challenges in sampling and monitoring for metals in the drinking water, and the approaches are currently heavily debated. The EU guideline is based on a sample that is representative of a weekly average value ingested by the consumers, and to achieve such a sample a sampling equipment has been adapted and tested, enabling the consumer, by handling a split-valve device, to collect a subsample based on a side stream, every time water was taken to be used for intake – but not just to for example washing hands (Fig. 1). This investigation demonstrated a wide variation from day to day but also from week to week – and not least from household to household, and this guideline is therefore very hard to apply in practice.

Alternative sampling approaches are discussed such as sampling after four hours of stagnation time which is also difficult to handle in practice, or ‘Random daytime sampling’ where the sample is taken randomly during working hours and collected as the first litre without any previous flushing.

Drinking water in contact with materials – polymers

An increasing use of plastic pipes in the main distribution system as well as in the household installation has also focused research on migration of compounds from these polymers.

Some of the additives from polymer pipes may migrate into the water.

Polymer pipes made of for example polyethylene (PE) are during manufacturing added a number of additives such as antioxidants, stabilizers, and stains. Some of these compounds may migrate out of the pipe and into the water although the main additives for example the antioxidants Irganox® 1010 and 1075 only very slowly migrates through the pipe materials, and it is modeled that the maximum concentration is between 1.2 and 2.0x10–^{18} g/L. However, their degradation products such as phenols, ketones and quinones which are formed inside the polymer, will migrate into the drinking water.

One aspect of getting these organic compounds in the water is their effect on health, and although the observed concentrations are considered to be harmless, the health effect of many of these compounds is presently unknown.

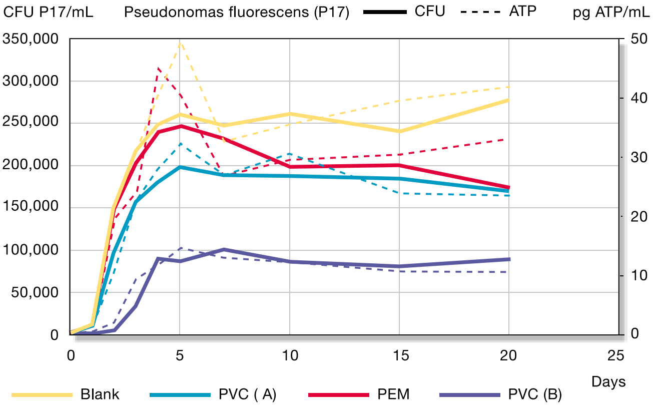

Figure 2. Growth of the bacteria strain P17 at 15ºC in drinking water extracts of polymers (two PVC materials and a PEM material) and in blank (water alone) measured by HPC and ATP (Corfitzen et al., 2002).

Since compounds migrate from them into water, plastic pipes have to be investigated for the growth potential they offer microbes.

However, these compounds are excellent substrates for microbial growth as shown by letting bacteria grow in water which has been in contact with different plastic pipes, for example PEM and different PVCs (Fig. 2); concentrations are much higher than in water which has not been in contact with the plastic pipes. Furthermore this may lead to a significant biofilm formation, and currently efforts are made to establish a method to test plastic pipes for microbial growth potential.

Contamination through leaks and fractures

Unfortunately, sometimes the distribution network gets contaminated, for example when pipes break . Under these conditions surface water or even waste water with pathogenic microorganisms may intrude into the distribution network. It is often the small water supplies which are hit by microbial contamination, as seen in a Danish investigation where 94 per cent of all the serious contamination was found in small water supplies, with distribution less than 350,000 m³/yr (equivalent to 4,500 consumers). Some of this contamination (22 per cent) is observed both at the water works and in the distribution system, indicating that such contamination is spread to the distribution network from the water works. 30 per cent of all the contamination was only observed in the distribution network, emphasizing that this part of the water supply is vulnerable.

It is often the small water supplies which are hit by microbial contamination.

When bacteria are introduced into the network they can be spread to the consumers, but the drinking water environment is harsh to many pathogens and they will only survive for a certain period in the network. Since it is impossible to measure for all pathogens, the water quality is usually monitored by indicator organisms (for example *E. coli*) since this organism is a significant inhabitant of the human intestine and its presence in a water sample thus indicates faecal contact and a high risk of the presence of pathogens.

The indicator organism *E. coli* can survive in drinking water for relatively long periods – more than 40 days. However,

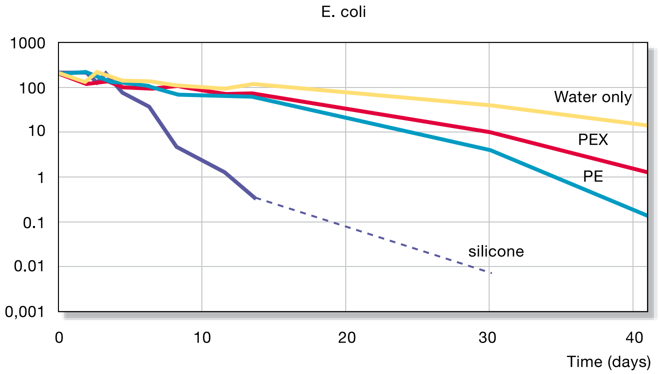

Figure 3. Survival of the indicator organism *E.coli* in drinking water, and in drinking water in contact with plastic pipes (from O.K. Vang, unpublished).

laboratory investigations conducted in glass bottles can be difficult to interpret in relation to real distribution systems since the survival is reduced in the presence of different pipe materials (for example PEX pipes and galvanized steel) (Fig.3). However, in investigations conducted in up to 12 year old PE pipes from real distributions systems, *E. coli* could still be detected after 3 weeks. Investigation of a range of pathogenic bacteria *Campylobacter jejuni* strains only showed that they could be detected for only a few days.

Furthermore, a small fraction of *E. coli* migrates into the biofilm, where it may be present for an even longer time, and thus biofilm formed from after growth or migration of organics from plastic pipes becomes important.

Conclusion

A number of processes affect water quality during its distribution to the consumers and consideration of these during construction of networks and in the choice of materials will improve water quality at the consumers' tap.

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Tap, tank or bottle?
– aspects of drinking water consumption

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Usable drinking water is the most basic requirement for human survival and wellbeing. The accessibility, safety and selection of sources for drinking water vary widely around the world. In urban settings of developing countries, unreliable service conditions may force inhabitants to employ alternative providers or arrange for less sanitary long-term storage of water in household tanks. Even in many developed countries, where services run well and regulations and control of tap water often are stricter than for bottled water, distrust of municipal water quality has increased sales of bottled water. Better communication between utilities and end users is needed.

Achieving water and sanitation millennium goals in developing countries is crucial for sustainable development and poverty reduction.

Water is essential for meeting basic human needs and for addressing poverty, economic development, health and hygiene. Water supply has a long history in this respect and the rationale for its promotion has always been driven by the need to protect public health, reduce mortality and morbidity among populations and promote economic development, not least in the developing world. Achieving water and sanitation millennium goals in developing countries is crucial for sustainable development and poverty reduction. Meeting this challenge necessitates the development of integrated management of water resources. Sustaining these activities protects and promotes public health, reduces disease burden and achieves socioeconomic growth and development.

The mean water consumption in society varies depending on how the consumption is defined. In an investigation among Swedish consumers, water consumption differed with demographic and socio-economic factors. On average, women consumed 0.95 litres of cold tap water per day while men drank 0.79 litres. People in urban areas consumed less than in rural areas. Tap water consumption decreased with increasing income but increased with age. The oldest age group in the study, 70 years and above, had the highest daily intake. The heated tap water consumption was somewhat lower than the cold tap water consumption and men appeared to consume more water in hot beverages than did women. A similar study of US consumption behaviour indicated slightly higher cold tap water consumption, with a mean value of one litre per day. In arid hot areas, the drinking water intake should be higher, but the water volume drunk seldom exceeds 3–4 litres per day. This is the water actually imbibed.

Water is the only food a human being needs daily.

Water is the only food a human being needs daily. During the period when Mahatma Gandhi fasted to show his stern belief in political matters during the emancipation of India, he only allowed himself some bottles of water, sodium hydro carbonate and salt as food. The daily need of drinking water is thus limited to some litres per day and capita, yet the total water need is much larger, since the indirect use of water is very high. WHO in 2003 recommended domestic water managers to design a water supply of more than 100 litres per day of tap water to consumers in order to allow the consumer a healthy, hygienic, clean and pleasant life with a very low level of health concerns. If the concept of 'virtual water' is adopted, which was introduced by the 2008 Stockholm Water Prize winner, John Anthony Allan, the figure for water requirement rises even higher. Virtual water calculations sum up all the water needed for producing all commodities that humans use, like clothing and food, besides the actual water intake.

Guidelines and regulations regarding water quality

Water quality demands vary with where the water is consumed and for which end use the water is directed. Hardness is always a problem when water is heated, since scaling occurs on heated surfaces. Microbial content is a concern if water is used for irrigation, food production or as drink. Organic content promotes biofilm formation in the distribution pipe network.

To address this, national guidelines and standards developed gradually during the first part of the 20th century. In 1958 the World Health Organization published International Standards for Drinking Water. In 1982, WHO changed the terminology from 'International Standards' to 'Guidelines', by publishing Guidelines for Drinking Water Quality.

WHO published 'Guidelines for Drinking Water Quality' in 1982, to promote a risk-benefit approach for the establishment of national standards all over the world.

The change was made to promote a risk-benefit approach (qualitative or quantitative) for the establishment of national standards all over the world. Countries should take into account sociocultural, environmental and economic conditions on a national level and execute risk assessment and risk management for the water supply of the country, and the national water quality standards may look slightly different in different countries. The Guidelines for Drinking Water Quality are recognized as the UN system's position on drinking water quality. Many countries use the Guidelines in setting national standards. The Australian Drinking Water Guidelines are based on the WHO Guidelines, the United States Environmental Protection Agency (USEPA) and Canada actively observe and participate in the process of development of the WHO Guidelines. The European Commission and Japan use the Guidelines as the 'scientific point of departure' for their drinking water directive and drinking water quality standards, respectively. These guidelines can also be used if guidelines or standards are unavailable.

In the EU, the concept of water quality is very well defined in the European Council Directive 98/83/EC of 3 November 1998. Its title is “on the quality of water intended for human

The WHO guidelines and, for EU, the drinking water directive, are powerful consensus documents for drinking water quality.

consumption" and its objective is to protect human health from the adverse effects of any contamination of water intended for human consumption. This is done by ensuring that the water is wholesome and clean. The quality criteria for what is wholesome and clean are further defined as a drinking water that is free from any micro-organisms and parasites and from any substances which, in numbers or concentrations, constitute a potential danger to human health, and meets specific minimum requirements for microbiological, physical and chemical parameters. The WHO guidelines and, for EU, the drinking water directive, are powerful consensus documents for drinking water quality. If the water fulfils the criteria, it is suitable as drinking water, but it might not necessarily be palatable.

A consumer confidence report (CCR), or drinking water quality report, is a short report from the consumer's local water supplier that sets out where the water comes from and what is in it. In the US, it should be published annually by 1 July. In the EU drinking water directive it is stated that member states are to ensure that the water consumers get information on any adverse effects resulting from any contamination of water intended for human consumption and be advised when a potential danger to human health arises out of the water. Drinking water quality is to be monitored regularly, in order to check that it meets the requirements of the drinking water directive. Representative samples must be taken for the quality of the water consumed throughout the year. Another obligation for the member states is to take the "measures necessary to ensure that adequate and up-to-date information on the quality of water intended for human consumption is available to consumers." Further, the member states are to publish a report every three years on the quality of water intended for human consumption with the objective of informing consumers, which includes, as a minimum, all individual supplies of water exceeding 1,000 m^3 per day on average or serving more than 5,000 persons.

The differing tastes of water

Personal preferences for drinking water are based on both psychological and physiological factors.

The public perception of water quality is clearly influenced by the quality of water received through the consumer's tap. The sensory properties of water are made up of a combination of its chemical content and the responses of a person's senses. Personal preferences for drinking water are based on both psychological and physiological factors. People expect water to be clear and pure tasting. If it does not taste or look right, some of the consumers react with mistrust. They may worry when there is a variation in taste during a short period; if water is cloudy or discoloured; if chlorine or other disinfection products and by-products affect health and if the level of substances thought to be harmful is high enough in drinking water to constitute a health risk (i.e. arsenic, lead, fluoride, pesticides, fertilizers etc).

Figure 1. A taste and odour wheel. Adapted from Mallevaille and Suffet, 1987.

People make intuitive judgments about risks based on their experience and environment. A good-tasting water has a very sublime taste, since consumers generally expect their water to have little or no flavour. It is possible to detect variations in pH, mineral, and organic content by tasting drinking water. Aesthetic evaluation is used as a critical tool for assessing the quality of drinking water. The taste and odour of drinking water are an important factor for consumers. A good-tasting water is positively associated with healthy and safe water. The opposite is also true. Water should have a quality and quantity that is similar to what it was when it was previously enjoyed, since consumers do not want major variations in the flavour of their drinking waters. Organic odorants present in concentrations of nanograms per litre can give it a bad taste and smell. Inorganic substances cause taste at parts- per-million concentrations. The threshold level for chloride for example lies in the range 300–500 parts- per- million depending on the person; the perceived tastes or odours can vary with concentration, temperature, and an individual's senses and genetic make-up.

Flavours and odours are more easily identified with the help of words. By expressing sensory experiences in words, the brain can remember and distinguish many thousands of tastes and odours. A way to enhance taste targeting is to use a taste and odour wheel. For drinking water the first was one proposed by Mallevialle and Suffet in 1987, to be later refined. It has been widely used to help in identifying unpleasant flavour problems in drinking water. A taste and odour wheel comprises three categories: taste, odour and mouth feel/nose feel. Moreover, the taste category is further classified into sour/acidic, sweet, salty, bitter and astringent; odours are classified in several segments – Suffet and his coworkers suggest a number of different subsegments (fig. 1). The mouth feel/nose feel category can also be further classified.

Deterioration of perceived water quality

A number of factors affect water taste. The natural chemical and microbial composition of the water gives its taste the basic characteristics. Any addition or removal of chemical products during treatment may alter the taste. Further changes which occur during distribution and storage of water add on the final taste experience, whether the water is from a public water system, treated on-site, or bottled and sold. The quality of water that finally reaches consumers is not always the same as that of the water leaving the treatment works. External factors such as post-contamination due for example to ingress of contaminated water, and water quality deterioration due to prolonged storage in pipes and storage reservoirs, are known to largely impact the final quality of water that reaches consumers. This means that, while compliance with drinking water quality standards at production level is important, the management of drinking water quality beyond the treatment works is equally important in the global effort of meeting drinking water quality targets in piped systems.

The mineral and organic matter contents of natural waters vary because of geology, season and temperature. Surface waters usually have higher dissolved oxygen, microbial, organic matter and particulate content over a range of temperatures from cold to warm. Microbial growth in surface waters can give fishy, musty, fruity, grassy, earthy or similar off-flavour to the water; organic content such as humic acids may give the water a rounded, rich taste. Groundwaters are generally cool and have typically a higher mineral content than surface waters. The minerals can add a salty, sweet, bitter, or sour flavour to water. If the mineral content is low in water, the taste is often described as astringent giving the slightly paradoxical experience that the water tastes 'dry'.

Disinfection treatments and by-products often change the water taste, especially when chlorination is used. It is generally regarded by consumers as unpleasant to experience when imbibed. Also the distribution or packaging and storage of water affect the taste. Publicly supplied water is pressurized in pipes and passes valves, gaskets, storage tanks, etc. in a distribution system and into the home, where it comes into contact with domestic plumbing and home water treatment devices. Complaints about water quality can often be explained by microbial, chemical or physical changes that take place in the distribution systems. Tastes and odours encountered in distribution and plumbing systems occur mostly as a result of chemicals from pipe or lining materials that corrode or leach into water, and subsequent reactions of the leached compounds in the water with the disinfectant residual within the distribution system.

Water tower for peri-urban area water supply, Lusaka, Zambia.

There are many examples of aesthetic problems from distribution-system materials leaching into drinking water. Chemicals leached from an acrylic coating used to line water storage reservoirs have resulted in phenolic odours. Medicine-smelling compounds have been produced from the reaction of leached chemicals from liners with chlorine in bromide-containing water. New polymeric pipes may result in plastic or chemical tastes and odours. Lining materials for pipes and water towers can produce chemical, plastic or gasoline type odours. Polyethylene materials can produce fruity odours, while metal pipes not surprisingly can lead to metallic tastes and odours.

The role of consumers

Surprisingly few studies have been performed in the area of consumer satisfaction regarding drinking water. This is in sharp contrast to the fact that many important decisions at all levels (international, national, regulatory and utility/water company) are more or less driven not by scientific but by subjective judgments. Knowledge of water quality standards amongst consumers appears to be sparse, but when asked, consumers do generally express a desire to be better informed. The public perception of water quality can be a powerful force in this context and a better understanding of the factors which can influence consumer opinion could assist utilities or water companies in their public relations exercises.

In a survey done for DWI (Drinking Water Inspectorate) in the UK, 70 per cent said they drank tap water on its own at home, whereas 30 per cent did not. Over a third bought bottled still water to use or drink at home (37 per cent). One in five said they boiled water to drink later on and another 22 per cent used a water filter or purifier. The use of filters or purifiers was more common among those with above average incomes. The group who did not drink tap water had often not done so for many years. The reasons for this could be due to habits from their childhood (doing like their parents did) or by a specific disturbance, such as disliking the taste of the water in the new home after moving, experiencing discolouration problems or scaring incidents. The group who did drink tap water was generally satisfied with it and had no or only minor concerns with it. Persons who avoided drinking tap water did so mainly because of unsatisfactory taste and colour, but seldom because of concerns about the safety of the water.

In a Swedish survey among 34 municipalities with water utilities, between 5 and 35 per cent of the consumers considered the water quality to be inferior in one or several ways. Another survey indicated that 10 per cent of the consumers were worried about the health effects when drinking tap water. An underdeveloped communication strategy from the municipal utilities was regarded as a part of the reason why people were worried. Another reason was inferior water quality due to insufficient treatment or distribution.

Two surveys of consumer satisfaction with drinking water by Taiwan Water Supply Corp were performed after significant changes in the water treatment processes. The studies showed that over 60 per cent of local residents of Kaohsiung City in Taiwan still avoided drinking tap water even after the changes, which included softening and reduction of mineral content through membrane treatment. Over half of the respondents thought that traditionally treated water was not a good drinking water, whether in the first or second survey, whereas almost 60 per cent of respondents felt that samples from advanced treatment processes were good to drink. The main reason that respondents did not drink tap water was that they considered the water sources as inappropriate and that the water gave an unpleasant mouth feel. Less than 20 per cent of respondents did not drink tap water because of health concerns. Some researchers stress that strong initial views on perceived quality are very resistant to change, in spite of new information, because prior perceptions influence how the information is interpreted. An important conclusion from the study was that the supplier should engage in further promotion of its new product.

Beirut – distrust and consumption of bottled water

Beirut City and its suburbs (Greater Beirut) is the residence of about 2.4 million citizens, or two thirds of Lebanon's total population. Although the city has an extensive drinking water network, many consumers rely on complementary water sources, especially vended water, to supplement municipal water. For general household water use, 32 per cent of the population depended on well water, 52 per cent on municipal water and 16 per cent on vended water. For drinking water, vended water represented 68 per cent of all drinking water consumed. Mainly due to distrust in municipal water quality, water is bought by households so that 25 per cent of the sampled population spends more than USD 100 on water, 35 per cent of the sampled population spends USD 100/month and 36 per cent of the sampled population spends USD 50. In Greater Beirut, as much as 10–16 per cent of low income basic salary was found to be spent on water, and 60 per cent of this cost concerned drinking water. Unfortunately, this did not guarantee the quality of drinking water.

Capitalizing on the lack of trust in the quality of municipal water supply, a large number of water vending companies extract water from agricultural and domestic zones all through Lebanon, bottle the water and sell it to the population of Beirut. A possible source of nitrate can be related to deficient sewage management and/or an excessive use of fertilizers. Faecal coliform bacteria were reported in 56 per cent of samples from vended water bottles investigated in Greater Beirut, while in 22 per cent of samples of municipal water from one distribution zone and 45 per cent in samples from another. The contamination in well water was due to the infiltration of waste water into aquifers or wells from leaking sewerage pipes or from cesspools. Cross-connection between domestic sewer pipes and domestic water pipes also occurred. If sewers do not exist and sanitation is mainly provided through septic tanks, cesspits and dry-pit latrines, seepage from on-site sanitation represents the most widespread and serious source of pollution (both point and diffuse) to the aquifer system. However, the extent and risk of groundwater contamination depend on many factors, though mainly on the degree of attenuation of contaminants during percolation through the unsaturated zone and, eventually, through the aquifer system.

Distribution problems in developing countries

In developing countries, water supply is provided to secure sufficient amounts of treated water of good quality at any time and location downstream from the treatment facilities. Piped water supplies are generally distributed according to three levels of services: house connections, yard connections and public standpipes. In industrialized countries, virtually all households are directly connected to the distribution network. In developing countries, the distribution of consumers by service level is different from town to town. Unfortunately, a pipe connection is no guarantee of high quality. A number of factors contribute, such as intermittency, flow and pressure fluctuations, and frequent discontinuities in service provision. Furthermore, upstream from the distribution pipes, lack or malfunction of treatment facilities, inappropriate or insufficient treatment, operational constraints at existing treatment works and lack of supplies cause severe reduction in experienced water service.

Ingress of contaminated water during periods of low or no supply and prolonged storage in pipes and storage reservoirs were the main factors behind a deterioration in water quality in a study from Maputo, Mozambique. Intermittent water supply is mainly driven by the need to reduce water losses during water distribution. It was found to largely contribute to the observed problems of drinking water quality in the network. The consequences of intermittent supplies are the risk of water contamination due to ingress of impure groundwater, storm water and surface water. If leakage occurs, the pipes will operate as drainage pipes when no internal pressure is applied.

Another consequence is the reliance on alternative water supplies, some of which may not be safe for human consumption. If no water is delivered in the municipal pipe, another source must be utilized. Because intermittent supplies are used not only in Maputo but in almost all urban water supplies of Mozambique, the situation in Maputo resembles that of other cities of the country where existing conditions in piped systems are similar or even worse. This means that, together with efforts to increase drinking water availability, the challenge facing water governance institutions in this respect is the need to implement actions to reduce inconveniences resulting from intermittent supplies and the public health risks associated with this (for example reviewing water re-chlorination strategies and implementing mandatory rules for the construction and location of household tanks).

Water storage tank for household use in Maputo, Mozambique.

Intermittent water supplies and lack of piped water supplies generally force consumers without a supply to provide their own solutions to cope with water shortages by constructing household tanks. These are however also an important source of drinking water quality deterioration due to prolonged storage and bad management. Household tanks are never or seldom cleaned. Some of them are subterranean and do not even have openings for cleaning. Many tanks provide living space for insects and birds. Several of them are comparatively large and introduce an extended storage time, up to one week or more from intake to consumption. These conditions severely deteriorate the quality.

A market for alternative water providers

For those consumers living in areas lacking piped water supplies, the solution to meet their water demands is to rely on alternative service providers, such as small scale independent providers (SSIPs) and household water resellers. Returning again to the city of Maputo, most (if not all) alternative providers operate within the informal water market and they are estimated to account for about 32 per cent of unconnected households in peri-urban Maputo as compared to roughly 62 per cent of households that rely on formal water supply services. The situation in other parts of Mozambique is probably worse than in Maputo, since in some of those areas alternatives service providers are the sole source of access to piped water supplies.

Service quality with alternative providers is generally assessed as good in matters related to coverage, service reliability and accessibility to consumers. Analysis of water quality aspects around these services indicates that, so far, the groundwater tapped by independent providers is virtually free from microbial and/or organic contamination and is thus safe for human consumption and domestic use. Factors contributing to that were identified as: limited hydraulic loads due to low population densities (less than 100 inhabitants per hectare) and the availability of a relatively thick stratum of the unsaturated zone (greater than 30 metres), where attenuation of contaminants still occurs at sufficient levels.

Service provision with the help of alternative providers is viewed by water governance authorities as a viable alternative to expanding service coverage to areas presently lacking formal water supplies. This however comes with a number of issues deserving urgent attention, one of which is the fact that they are currently not formally regulated. Also, the long term sustainability of service expansion with the help of alternative providers is faced with possible threats associated with their capacity for providing quality water of sufficient quantity in the long run. Main challenges facing the sector in this respect are the need to establish mechanisms to allow the formalization of alternative service providers and expand the existing regulatory framework to allow the enforcement of more stringent protective measures around water supply services offered through this segment of service providers.

The situation in the city of Maputo resembles that of other cities in the developing world, where alternative service providers in the form of SSIPs are reported to have a dominant role in service provision to unconnected residents. This includes examples from Asia and Latin America where SSIPs are estimated to reach as much as half the urban population in some countries in Asia and nearly a quarter of the urban population of Latin America. In African countries, nearly half of the urban dwellers are said to rely on alternative service providers for at least a portion of their drinking water supplies. The list of examples in Africa includes the cities of Bamako, Cotonou, Conakry and Dar es Salaam, where alternative service providers are the main source of potable water to more than 60 per cent of households, and cities like Abidjan, Nairobi and Ouagadougou, where they are reported to reach 22 to 28 per cent of unconnected households.

Water stand post for peri-urban area water supply, Lusaka, Zambia.

SSIPs are an important water supply service, especially in peri-urban areas. Most SSIPs generally tap their water at depths to the water table greater than 10 metres, thus sufficient depth is generally obtained through the unsaturated zone to prevent pathogens and nitrates from reaching the groundwater table. Construction and completion details of boreholes are also crucial factors in that they may increase the risk of groundwater contamination by creating localized pathways for ingression of pathogens or by shortening the distance and time required for pathogens to reach the groundwater table.

More action from regulators of SSIPs is required so that they may be regarded as safe suppliers. Regulated procedures for borehole design and location in order to minimize risks of groundwater contamination must be considered. Emphasis should be put on aspects such as wellhead protection, positioning of filter screens and the location of boreholes in relation to existing pit latrines. A minimum radius of influence 25 metres away from pit latrines is generally accepted in Mozambique, yet this is a modest distance during the rainy period. Mandatory rules for direct protection of boreholes used for drinking water supply (for example, a 5x5 metres surrounding fence) and mandatory rules for all types of alternative providers regarding chlorination of the water before distribution are necessary for a safe water supply. Added to this, legal and regulatory aspects based on matters concerning service quality and protection of consumers′ interests should be dealt with.

Is bottled water a safe alternative?

Around the world, bottled water is chosen as an alternative source when tap water is regarded as unreliable or less tasty as drinking water. Bottled water consumption increases rapidly in the world. In 2004, it reached 154 M (cubic metres), up 57 per cent in five years.

The per capita consumption of bottled water in the EU varies from one country to another with the average consumption at 105 litres per year. Finland has the lowest consumption level with 18 litres a year per inhabitant and Italy the highest. Italians drank the most bottled water per person, at nearly 184 litres in 2004 – more than two glasses a day. Mexico and the United Arab Emirates consume 169 and 164 litres per person. Other countries with high bottled water consumption per capita are Belgium, France, Spain, and Mexico.

Some environmental concerns are raised for the rapid increase in bottled water consumption. Tap water is distributed through an energy-efficient infrastructure, while bottled water may be transported long distances. The plastic most commonly used for making water bottles is polyethylene terephthalate (PET), which is derived from crude oil. Worldwide, some 2.7 million tons of plastic are used to bottle water each year. This produces significant amounts of waste. In some countries the plastic is recycled, but certainly not everywhere. According to the US Container Recycling Institute, 86 per cent of plastic water bottles used in the United States become garbage or litter.

In a number of places, including Europe and the United States, there are more regulations governing the quality of tap water than for bottled water. US water quality standards set by the US Environmental Protection Agency for tap water, for instance, are more stringent than the US Food and Drug Administration's standards for bottled water. The United Nations Millennium Development Goal for environmental sustainability calls for halving the proportion of people lacking sustainable access to safe drinking water by 2015. Meeting this goal would require some USD 30 billion a year to be invested in water supply and sanitation globally, or roughly a doubling of the investment budget. This can be compared to an estimated USD 100 billion spent each year on bottled water.

The technical committee of the Bureau of Indian Standards (BIS) in 2003 rejected the stringent EU norms for maximum permissible pesticide residue limit for bottled drinking water and mineral water for India. In the EU, the limit in drinking water is 0.1 microgram per litre. WHO in 2004 suggested health-based guidelines for individual pesticides, which BIS supported. BIS had decided to review quality standards for packaged drinking water and mineral water with a view to protecting the interests of both the consumers and the industry. The Indian analysis was that it was very difficult to ensure zero pesticide residue limits in drinking water in a situation where both pesticides and fertilisers were used extensively for agricultural production. A reasonable level of pesticide residue can, however, be ensured through integrated pest management and more organic farming.

The future – awareness and clearer communicaton

The importance of consumer awareness is crucial in all countries. The lack of trust in supplied domestic water leads consumers to use compensatory water sources that are neither safe nor cheap. As such, the concept of water quality and its link to water-borne diseases should be made clear to the end user by:

- Preparing short educational messages.
- Ensuring transparency in the management system to enable consumers to have access to quality control activities conducted by official bodies.
- Building trust in domestic water supply based on documented profiles.
- Motivating NGOs in consumer awareness programmes.
- Instructing consumers on how to handle water quality problems in case of emergency.
- Instructing consumers on simple methodologies to ensure safe microbiological water quality.

Virtually all utilities have a very technical view on water supply and water quality. For the future, it should be complemented with information to and communication with the end user on water quality. The excessive growth in sales of bottled water is neither necessary nor economically feasible for the consumer, if a corresponding water quality can be delivered by tap.

The use of tap water has been actively promoted by many utilities. National competitions on the best-tasting tap water have been performed for instance in Sweden, Denmark and Norway, the UK and the US. This is fun, a nice happening which attracts media coverage. The competitions are normally useful in raising the awareness among consumers of how tasty a good tap water is as drinking water. Yet the producers, or utilities, must be more active in communication. If investments are made for improving water quality to the consumers, these will of course be noticed in due time. If the water quality is inferior, the utilities should not pretend anything else, but accept complaints and take necessary measures to remedy the errors. And it is very clear from the foregoing that just because water leaving the waterworks is of good quality, this is never a guarantee that the water leaving the tap will be of good quality. A number of quality changes occur in the water during the transport, and the utility must control the entire system. But if properly done, any utility can distribute water that will cause the consumers' children to be proud of their own water and take it for granted that the water served in their home is the best – as it should be.

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Water supply risk assessment in a rural village of a developing country

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Safe management and supply of drinking water is of crucial importance to people in developed and developing countries alike. In the large drinking water project TECHNEAU, risk management methods and tools have been compared between different countries. The studies have covered a range of scenarios, system sizes and water sources. Combining consequences and likelihoods into risk estimation matrices proves to be a useful tool, which is also easy to communicate to managers and end users.

View of the Upper Mnyameni Village.

Drinking water is our most important provision and to ensure that water producers distribute a safe and healthy drinking water to the consumers is therefore of the highest priority in both developed and in developing countries. Effective risk management procedures are the key for the water suppliers to accomplish this goal. The World Health Organisation (WHO) stresses the importance of using a risk-based approach when managing drinking water supplies and in particular through comprehensive Water Safety Plans (WSPs), where all steps in the water supply chain, from catchment to consumer, must be integrated. Different risk assessment methods are available which may be either qualitative, suggested in WSP and where the different risks are simply ranked, or quantitative, where the size of the risk is given a certain value. In a large drinking water research project, TECHNEAU (2006–2010), development and testing of new risk management methods and tools are undertaken to be provided to all kinds of drinking water utilities in all stages of development and size. A generic framework for integrated risk management has been developed and is based on the basic risk management process and the WSP procedure (fig. 1). Among the tools that have been developed in the project are a hazard database, a risk reduction option database and guidance reports on risk analysis, To demonstrate and improve the tools, six risk assessment case studies have been conducted in different countries and for different system types, such as surface water/groundwater sources and large/small systems but also qualitative/quantitative risk assessment methods have been tested. In this article we present a risk assessment study of a small, surface water source, system in South Africa where a qualitative risk assessment method is tested.

WHO stresses the importance of using a risk-based approach when managing drinking water supplies and in particular through comprehensive Water Safety Plans.

Case Study Site: Location

Upper and Lower Mnyameni are two rural villages in the Amatola Mountains in the Eastern Cape province in South Africa, about 80 kilometers from the south east coast (fig. 2). Amatola Water Board is the local drinking water supplier which is one of totally 20 water boards and utilities in South Africa. In the two villages approximately 2 500 people are supplied with drinking water by one water treatment plant that takes its raw water from a dam. The villages are low income communities with a very high unemployment rate (approximately 80 per cent). There are no major industries except for some forestry activities and some non-formalized low scale farming activities such as roaming cattle within the villages.

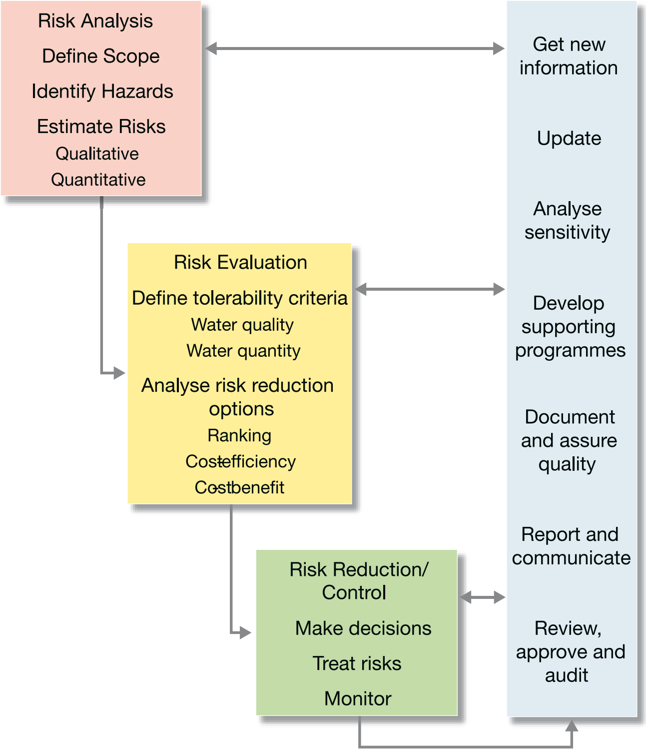


Figure 1. TECHNEAU Generic framework for integrated risk management in drinking water systems.

Figure 2. Location of Upper Mnyameni.

Raw Water Source

The raw water source is the Mnyameni Dam situated approximately one kilometer from Upper Mnyameni village. The dam was originally used for water supply for large scale farming, but is today only used to supply raw water for the

The Mnyameni Dam is fed with water from rain, melting snow and groundwater and also protected from pollutants from farming or industry.

treatment plants in Upper Mnyameni and a neighbouring city Masincedane. The dam is surrounded by precipitous mountains and the flow of water into the dam is mainly from rain and snow melting, but also from groundwater flow into the dam which makes the supply of raw water stable for long periods with dry weather. The inflow is much higher than the demand from two water treatment plants.

The raw water is characterized by moderate turbidity levels, usually around 10 NTU (Nephelometric Turbidity Units), but this level can increase drastically as a result of heavy rains. High turbidity negatively affects the aesthetic quality of the water and, more importantly, decreases the effectiveness of the disinfection process. Since there are neither roads nor any formal industrial activity in the area around the dam, oil or other chemical substances cannot contaminate the water source. The dam is also protected from farming activities because it is located in a nature reserve where such activities are forbidden.

Left photo: Typical household with livestock around the garden.

Right photo: Water abstraction point in the Mnyameni Dam.

Treatment Processes

The water gravitates from the dam to a balancing chamber located just outside the treatment plant (fig 3). In the balancing tank pre-chlorination takes place, but the main purpose of the tank is to have a static head flow into the treatment plant. Chlorination is not effective at this stage because the turbidity is too high for successful disinfection to be achieved. From the balancing tank the water gravitates down to the filter house. Before the water reaches the filter house, a coagulant is pumped into the pipe. Inside the filter house there are two parallel flocculation tanks and six parallel pressure sand filters. The function of the flocculation tanks is to increase the residence time of the flocculation process to prevent flocs forming after the water has passed through the filters.

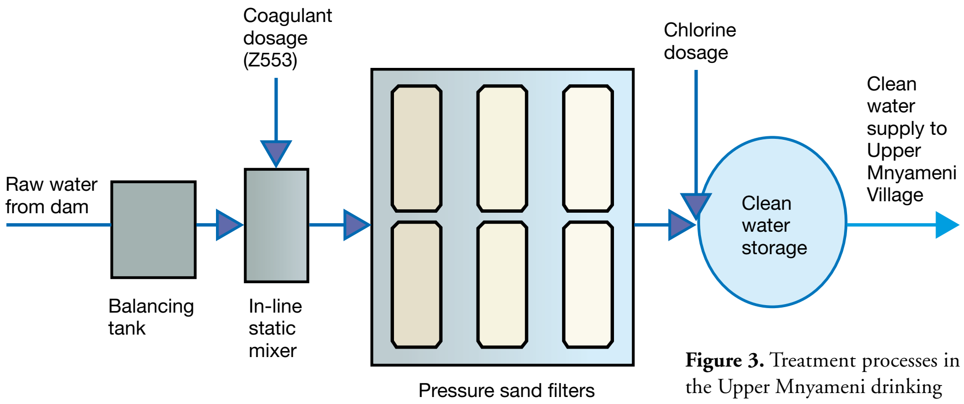


Figure 3. Treatment processes in the Upper Mnyameni drinking water treatment plant

The flocs are then filtered out in the lower sand layer of the filter. A booster pump then carries the water to the clean water reservoir at the plant. Inside the reservoir chlorination takes place through chlorine tablets.

Distribution

Disinfected water is pumped from the water treatment plant to a high altitude reservoir in the upper part of Upper Mnyameni. From this reservoir some of the water gravitates to a smaller reservoir in the middle of the village and some of the water is directly distributed to consumers. Most taps are standing taps outside and there are approximately 20 houses per tap. In-house storage is usually some kind of container that the villagers fill up with water.

Operation

The plant works 24 hours a day all year around, but it is only manned during office hours. During this time samples of water are taken and analyzed every hour. The analysis includes turbidity and pH-value in the raw water and for the treated water analysis includes turbidity, pH-value and amount of residual chlorine. The levels in two of the reservoirs on the distribution system, one in Upper Mnyameni and one in Lower Mnyameni, are monitored in the operator's office at the plant. The water level in the clean water reservoir at the plant is also measured. This information is also registered at a larger water treatment plant in Sandile, which is located [X] km from Upper Mnyameni and manned 24 hours a day. If, for example, there is a pump failure at the Upper Mnyameni treatment plant this is also noticed in Sandile and action can be taken.

During office hours, samples of water quality are taken and analyzed every hour.

Risk Assessment Methods

Risks were ranked using risk matrices.

Risk assessment in a drinking water system consists of several steps (fig. 1) where one has to identify the hazards, estimate and evaluate the risks of water supply failures and insufficient water quality, but also investigate the consequences for humans and the development of society. The objective of the qualitative risk assessment method is to present the risks and to provide a simple tool that can be used in small water treatment plants. The most common qualitative risk assessment method is a risk ranking method using risk matrices, which WHO also suggests in the WSP. This method has been used in the Upper Mnyameni case study that assesses the probability and consequence of each identified hazard and puts them into different classes in the risk matrix. This method is often referred to as a semi-quantitative risk assessment method since the classification has a somewhat quantitative approach. To cover the whole water supply system a "source-to-tap" approach has been used. Hazards were identified by both using the hazard database developed in TECHNEAU and brainstorming sessions by researches and experts from Amatola Water. In the risk ranking the likelihood and consequence were assessed for each identified hazard and the risks were presented in a risk matrix with three different tolerability zones, i.e. which risks can or cannot be accepted. Rating of likelihood and consequences for the risk matrix were made in collaboration with Amatola Water experts.

Hazard Identification

The following eleven hazardous events in the water supply system were identified from the brainstorming session and the TECHNEAU hazard database:

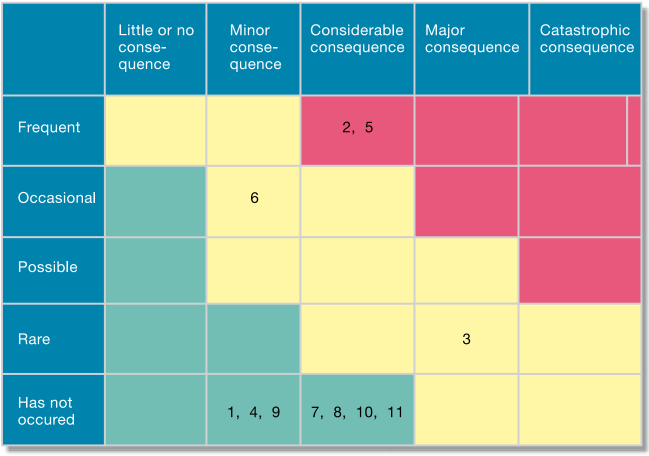
1. High turbidity causing ineffective chlorination
2. Contaminated standing taps due to animals leaning/scratching against them
3. Inadequate personal hygiene due to low water availability in homes
4. Contaminated groundwater leaking into pipes
5. Poor storage of water
6. Lack of treated water leading to use of untreated water
7. High turbidity when the WTP is unmanned causing high bacterial count
8. Ineffective mixing of chlorine leading to high bacterial count

9. Sabotage at any part of the system
10. Incorrect actions due to lack of sufficient operational skills
11. Pump failure when the plant is unmanned

Risk estimation and presentation of risks with risk matrices

Both the probability (likelihood) of the different hazards and the consequences of the events were ranked on a scale from one to five. The consequences of the events were ranked with respect to *health consequences* and to *number of people* affected. These two risk matrices were weighted and merged into a *Total risk matrix*. The risk matrices are divided into three tolerability zones (fig. 4). The green field shows risks that are considered to be acceptable and the red field indicates that the risks are unacceptable and could not be tolerated, i.e. must be reduced immediately. The yellow field indicates the ALARP (As Low As Reasonably Practicable) zone. That means that the risk can be accepted if it is not economically and technically reasonable to reduce it. The risk matrix on health effects showed that the most serious problem for water quality was at the taps and the handling of the water. The risks that concern the water treatment processes are considered fairly low. The reason for this is that the raw water is fairly clean and could be used mostly untreated. While both pumps are electrical and no back-up power supply is available, longer power failures always lead to lack of water for the consumers. For the risk matrix number of people affected, the hazardous events affect the whole population of the villages.

The most serious problem for water quality was at the taps and the handling of the water.



	Little or no consequence	Minor consequence	Considerable consequence	Major consequence	Catastrophic consequence
Frequent	🟨	🟨	🟥 2, 5	🟥	🟥
Occasional	🟩	🟨 6	🟨	🟥	🟥
Possible	🟩	🟨	🟨	🟨	🟥
Rare	🟩	🟩	🟨	🟨 3	🟨
Has not occured	🟩	🟩 1, 4, 9	🟩 7, 8, 10, 11	🟨	🟨

Figure 4. Risk matrix of the total risk (health effects and number of people affected) estimates for the 11 identified risks for the water supply in Upper Mnyameni.

The health consequences were weighted as three times as important as the number of people affected by an incident.

In order to combine the two factors *health consequences* and *number of people affected* the two factors have been weighted in order to create a third *total risk* matrix (fig. 4). A decision was taken to make the health aspect more important than the number of people affected. The health consequences were weighted as three times as important as the number of people affected by an incident. It is reasonable to think that severe health consequences for a few people result in greater consequences than a minor discomfort for many people.

Sensitivity analysis

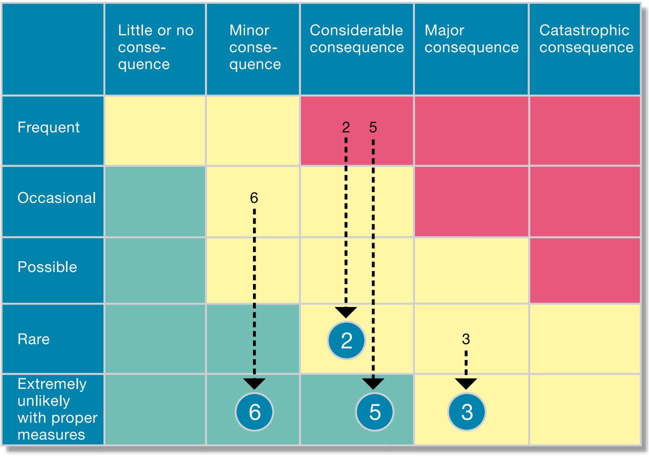
There are several uncertainties in the input data. Upper Mnyameni is a small village in an underdeveloped country and the information about the system is limited. The lack of information, for example pipe information, number of taps, and number of people in the villages leads to greater reliance on the experts. A system that is not very well documented requires a more thorough field study, even though a lot of information will still be missing. Likelihood, health effects and the number of people affected by a certain hazardous event are always difficult to estimate. The experts at Amatola Water have long experience in the field of water engineering and thorough knowledge of small drinking water systems in rural areas, which increases the reliability of the experts' estimations. Communication with local people can also lead to uncertainties due to lack of language skills or misunderstanding in other ways.

Risk reduction options

A number of different risk reduction measures can be taken to decrease the risk of the 11 identified hazards. The risk matrix in fig. 5 shows how the risks decrease when different measures are taken.

Hazardous event 2: Contaminated taps caused by animals leaning against the taps

Contamination may spread when people, especially children, drink from taps and this hazardous event is in the red field in the risk matrix. That means the risk is not acceptable and should be reduced as soon as possible. The best action would be to make household connections for all the households in the villages. This is a long term ambition and will be an extensive project that will require large investments. It must also



	Little or no consequence	Minor consequence	Considerable consequence	Major consequence	Catastrophic consequence
Frequent	🟨	🟨	🟥 2 5	🟥	🟥
Occasional	🟩	🟨 6	🟨	🟥	🟥
Possible	🟩	🟨	🟨	🟨	🟥
Rare	🟩	🟩	🟨 ②	🟨 3	🟨
Extremely unlikely with proper measures	🟩	🟩 ⑥	🟩 ⑤	🟨 ③	🟨

Figure 5. Risk matrix that shows how the hazardous events decrease when different risk reduction measures are suggested

be taken into consideration that household connections probably will increase the water demand. A more simple measure would be to add some protection for the taps, for example fences, etc to prevent animals coming in contact with the taps.

Hazardous event 3: Inadequate personal hygiene due to low water availability in homes

Owing to the presence of only a few taps in the village, water accessibility is low (one tap per 20 houses and distances up to 200 meters to the nearest tap), which might lead to inadequate hygiene. For example, improper washing after using latrines might cause spread of bacterial infection. This risk falls into the yellow zone in the risk matrix and should therefore be prevented if it is reasonable. This risk can also be minimized if all the villagers get household connections, which is the long term ambition for the water supply in South Africa.

Hazardous event 5: Poor storage of water

This risk, for example storage of water in open buckets or dirty bottles, falls into the red zone in the risk matrix and needs to be prevented. This risk will be also be minimized if all the villagers get household connections. It can also be reduced if people get information on how to handle and store their water in a hygienic way.

Hazardous event 6: Lack of treated water leading to use of untreated water

Long-time power failure or other incidents may lead to lack of treated water and people might use the untreated water at

Mnyameni River instead (a quality related problem). This risk falls into the yellow zone and should therefore be prevented if measures are reasonable. As it would need major upgrades in the power supply system to prevent the occurrence of long term power failures it would take major large scale actions and it would fall outside feasible measures for this study. It is also difficult to reduce the time it takes to restore power as these failures are often a result of storms, which also reduces the access to the villages. A power generator at the WTP is the only reasonable short-term option to ensure a sufficient quantity of drinking water.

Ranking consequences might be difficult since a consequence is hard to define. It can for example include the number of people affected and the severity of a certain event for one individual. Despite these difficulties, the risk matrices were found to be a useful tool for presentation of risks.

Conclusions

Risk estimation with risk matrices is a useful and efficient tool.

Risk estimation with risk matrices is a useful and efficient tool. It is easy to understand and present data. When choosing what consequences are of importance it is vital to think it through thoroughly. For this case study it was decided to use *health* and *number of people affected* by a certain hazardous event as consequence factors. The major risks were found at the water taps (most households do not have taps), and from insufficient storage of water, inadequate hygiene due to lack of easily accessible taps and from the lack of power supply. Suggested risk reduction options were found to reduce the risks significantly.

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