Use of saline water in sanitation: change of paradigm in water resources management in urban environments

Carlos M. Lopez-Vazquez[1], Christine M. Hooijmans[2], Guang-Hao Chen[3],
Mark C.M. van Loosdrecht[4] and Damir Brdjanovic[1,4,‡]

[1.] Department of Urban Water and Sanitation, UNESCO-IHE Institute for Water Education.
Westvest 7, 2611 AX Delft, The Netherlands.
[2.] Department of Environmental Resources, UNESCO-IHE Institute for Water Education.
Westvest 7, 2611 AX Delft, The Netherlands.
[3.] Department of Civil Engineering, The Hong Kong University of Science and Technology,
Clear Water Bay, Kowloon, Hong Kong
[4.] Department of Biotechnology, Delft University of Technology.
Julianalaan 67, 2628BC Delft, The Netherlands.

Abstract

Water shortage is becoming an increasingly dominant problem in many coastal cities in both low- and high-income countries (supporting about 60% of world population). Due to rapid urbanization and climate change, traditional (like water saving, fresh water transport from far away or rainwater harvesting) and advanced solutions (sea water desalination by reverse osmosis) become insufficient, non cost-effective and/or environmentally unsustainable to matching the ever growing water demand. Direct use of seawater for toilet flushing, and other non-potable uses, is often forgotten, easily rejected and traditionally perceived as problematic due to corrosion issues and requirements for dual system. However, the benefits are often overlooked and, in general, not well-studied and documented despite its potential and as a means towards sustainable water cycle management, opening a new paradigm towards the use of saline water as secondary quality water in urban environments.

Keywords: saline water, water resources management, paradigm, urban environments, sustainability.

Introduction

Water shortage is becoming an increasingly dominant problem in many coastal cities in both low- and high-income countries. Even countries that at present do not face water shortages may have to address the problem of fresh water scarcity in the near future (Karagiannis and Soldatos, 2008). Due to high population growth, rapid urbanization and climate change, traditional solutions, like water saving, fresh water transport from far away or rainwater harvesting, become insufficient to matching the ever growing water demand. The coastal zone occupies 18% of Earth's surface, supports 60% of world population and contains two-thirds of cities with at least 2.5 million people each (Figure 1). Moreover, urbanization in developing countries doubled from less than 25% in 1979 to more than 50% in 2006, with most of the largest urban centers located in coastal zones.

From total world water reserves, estimated in around 1.338 million km^3, 96% is saline and only 4% is fresh water. However, from the fresh water reserves, 30% underlies the Earth's surface, being too deep to access in a cost-effective manner, and 68% is locked up in ice and glaciers. This only leaves about 0.08% of total fresh water resources in surface water bodies (such as rivers and lakes). In other words, fresh water reserves are unevenly distributed on Earth and, even more importantly, limited and being depleted in an alarming rate, whereas oceans potentially represent an infinite reserve of water.

[‡] **Corresponding author:** E-mail address: d.brdjanovic@unesco-ihe.org; phone number: + 31 (0) 15 215 1776 (Prof. Damir Brdjanovic).

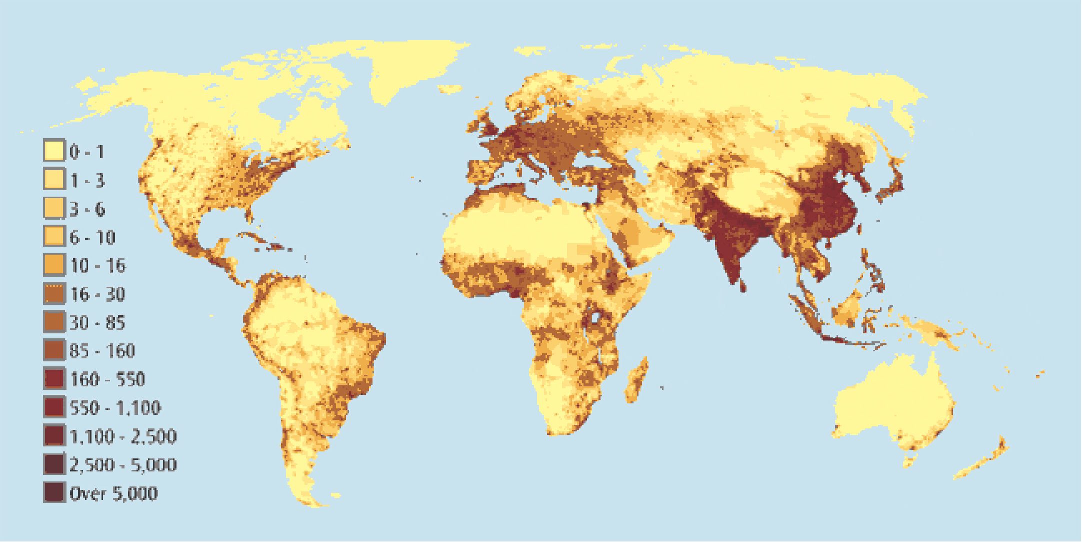

Figure 1. World population distribution (source: www.context.org/socimages)

Overview of desalination technologies

Despite that seawater is unsuitable for human consumption due to high salt content, thanks to different technological advances on desalination technologies; saline water (seawater or brackish water) is assumed to be an important and virtually unlimited supply of fresh water. A desalination process separates saline water into (i) a fresh water stream containing a low dissolved salt concentration and (ii) a concentrated water stream. In general, any desalination process requires energy and makes use of different separation steps. Furthermore, regardless the desalination technology applied, potabilization is strictly needed since the desalinated fresh water stream is not suitable for direct human consumption.

Over the years, a wide variety of desalination technologies has been developed (van der Bruggen and Vandecasteele, 2002; Khawaji *et al.*, 2008). From an operating cost perspective, the most promising desalination technologies are (a) thermal processes, such as multi-stage flash distillation (MSF) and multiple-effect-distillation (MED), and (b) membrane processes where reverse osmosis (RO) has emerged as the most cost-effective technology (Khawaji *et al.*, 2008). The total installed capacity by process has been estimated in around 44% for MSF, 42 % for RO and 4 % for MED (Tsiourtis, 2001). Despite its relative low installed capacity, in the last years MED has re-emerged as an efficient technology as a consequence of different process improvements (Khawaji *et al.*, 2008). Other technologies, like vapour compression (VC) distillation, freezing and solar evaporation have been seen as promising desalination processes. However, they have not achieved the level of commercialization success that MSF, MED and RO due to higher operating costs (Mathioulakis *et al.*, 2007) or, like in the case of solar desalination, because of particular requirements such as considerable large footprint (Khawaji *et al.*, 2008). According to an international report, the global market for desalination currently stands at about US $35 billion annually and could double over the next 15 years (SEMIDE/EMWIS, 2009).

Multi-stage flash (MSF) distillation

This process is based on the principle of flash evaporation where seawater is evaporated by reducing the pressure as opposed to raising the temperature. Average operating temperature ranges between 90 and 120^{o}C depending upon the scale control method selected. To operate the plant close to the upper temperature limit of 120^{o}C increases the plant efficiency, but also increases the energy consumption and the potential for scale formation. Despite that part of the heat provided can be recovered by applying regenerative heating, where seawater flashing gives up some of its heat to the incoming seawater, the MSF process has high energy requirements (Khawaji *et al.*, 2008). Moreover, in addition to the energy costs involved in this process, operating costs increase due to the use of high temperature additives, inhibitors and acids for scale control.

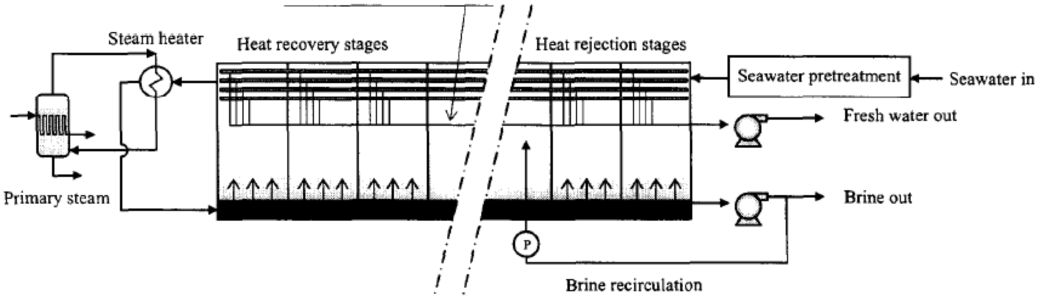

Figure 2. Principle of multi-stage flash (MSF) distillation (van der Bruggen and Vandecasteele, 2002).

Multiple-effect distillation (MED)

The oldest desalination method is multiple-effect distillation (MED) process, which is considered very efficient thermodinamically. The MED takes place in a series of evaporators, known as effects, and uses the principle of reducing the ambient pressure in the consecutive effects (Figure 3). Thus, seawater can undergo multiple boiling without supplying additional heat after the first effect. In the first effect, seawater temperature is raised to the boiling point after being preheated in tubes. Thereafter, it is sprayed onto the surface of evaporator tubes to promote rapid evaporation. Evaporator tubes are usually heated with steam produced by a dual purpose power plant. The steam is condensed on the opposite side of the tubes, and the steam condensate is recycled to the power plant for its boiler feed-water. The economy of an MED plant is proportional to the number of effects. However, the total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next one. Due to the high thermodynamic efficiency, the performance ratio and power consumption of a MED plant is higher than those of a MSF plant, boosting the development of MED plants, particularly in the Middle East (Khawaji *et al.*, 2008), although the number of MED plants is still small when compared to the number of MSF plants installed.

Reverse Osmosis (RO)

In the reverse osmosis (RO) process, the osmotic pressure is overcome by applying external pressure higher than the osmotic pressure of the seawater. Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration. The reject water or concentrate is discharged into the sea (Figure 4). No heating or phase separation change is necessary. The major energy required for desalting is for pressurizing the seawater feed. A typical RO plant consists of: feed water pre-treatment, high pressure pumping, membrane separation, and permeate post-treatment.

In general, pretreatment is an essential stage for the proper operation of RO and MSF processes and to a lesser extent to MED systems. Pretreatment is needed to eliminate undesirable constituents in the seawater, which would otherwise cause scaling and biofouling. Moreover, various chemicals, such as sodium hypochlorite, ferric chloride, sulfuric acid and sodium bisulfite, are added to the seawater to prevent biofouling, reduce scaling, and for pH adjustment and dechlorination purposes, respectively (Latteman and Hoepner, 2008). These chemicals end up ultimately in the concentrate or reject water which is usually returned to the sea (Laspidou *et al.*, 2009).

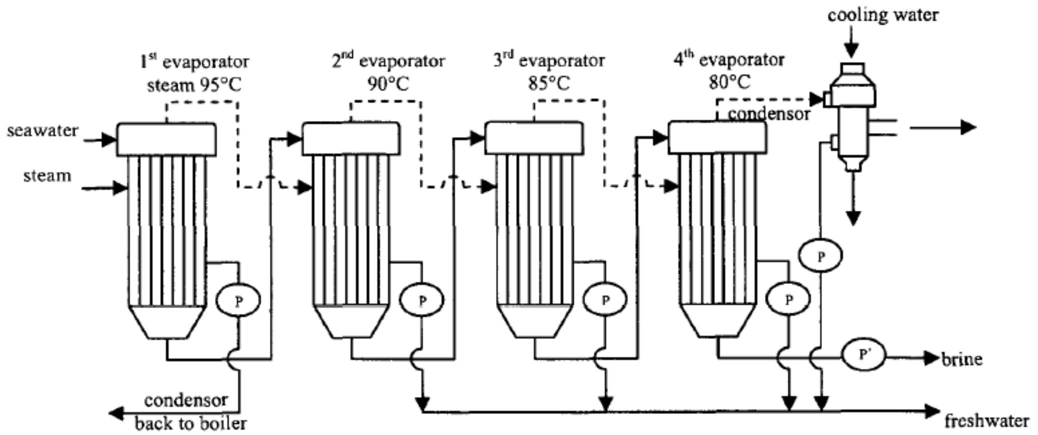

Figure 3. Principle of multi-effect distillation (MED) desalination (van der Bruggen and Vandecasteele, 2002).

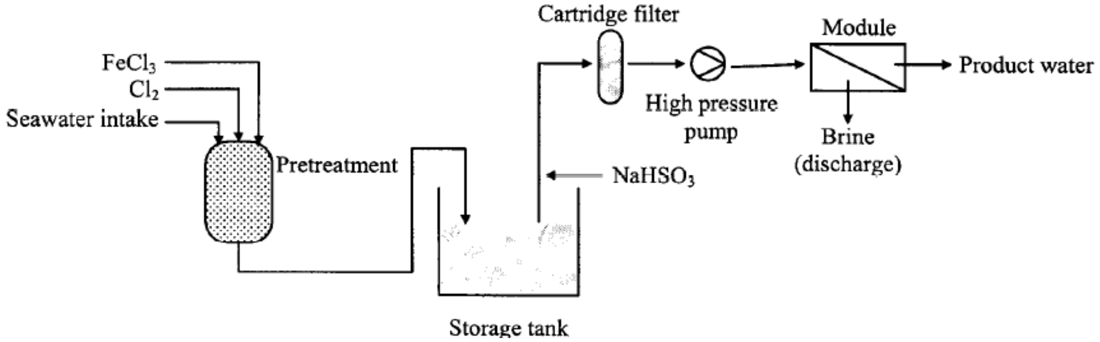

Figure 4. Principle of multi-effect distillation (MED) desalination (van der Bruggen and Vandecasteele, 2002).

Drawbacks of conventional desalination technologies

Despite the potential production of high quality water for human consumption, issues like (a) high energy and operating costs, (b) low production efficiency, and (c) environmental emissions are severe drawbacks of the most popular desalination technologies.

High energy and operating costs. Desalination is an energy intensive process. The high energy demand can be assumed to be the highest operating cost, which can only go as low as 1.8-2.0, 2.0-3.5 and 3.5-4 kWh/m^3 for MED, MSF, and RO systems, correspondingly (IWACO, 2000; Khawaji et al., 2008; Muñoz and Rodriguez, 2008).

By reducing the high energy requirements, recent developments have contributed to decrease the cost of water produced to costs as low as €0.76-1.56/m^3 and €0.42-0.81/m^3 for middle-to-high size MED (12,000-55,000 m^3/day) and MSF systems (23,000-528,000 m^3/day), respectively (Karagiannis and Soldatos, 2008). Meanwhile, middle size RO systems (15,000 to 60,000 m^3/day) have reached costs as low as €0.38-1.30/m^3 when treating seawater and from €0.21 to 0.43/m^3 for brackish water desalination (Karagiannis and Soldatos, 2008). Nevertheless, it should be underlined that certain capital costs (e.g. development, design and permitting costs) are somewhat independent on plant production capacity which, combined with the inherent modularity of desalination systems, tends to decrease the desalination costs as the desalination plant capacity increases (Figure 5).

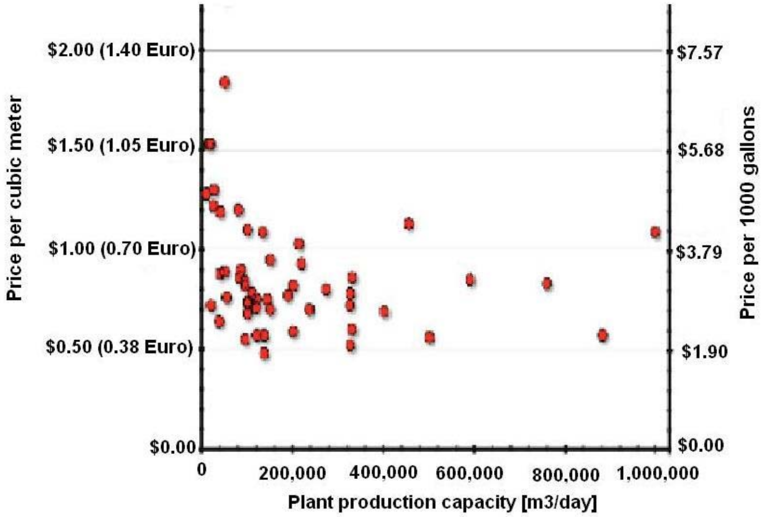

Figure 5. Water production costs as a function of plant capacity size (source: Water Desalination Report, 2008, based on data collected from 1991 and 2008).

Despite their considerably decrease in costs in the last years, the desalination systems are still considerably expensive compared to conventional fresh water treatment, whose operating costs are estimated in about €0.18/m^3 (Rita Costa and de Pinho, 2006). Therefore, desalination systems can only be seen as a cost competitive option when, due to severe water scarcity in nearby locations, fresh water must be brought (usually pumping) from far away using long-distance piping systems (Lamei *et al.*, 2008). The latter requires and involves considerably high capital investments and operating costs that justify the implementation and operation of desalination systems over bringing fresh water from far away locations. However, the costs are so high that different studies have estimated that, without access to low interest loans or donor funding, many countries are unable to afford desalination technologies as a fresh water resource (Tsiourtis, 2001; GWI, 2004; Karagiannis and Soldatos, 2008; Khawaji *et al.*, 2008). This aspect may significantly hinder the availability of the technology, particularly in low- and middle-income countries.

Low efficiency. Due to significant advances on the development of membranes, RO systems are able to achieve water production efficiencies as high as 50 % with regards to intake seawater (although an average efficiency of around 30-35 % is usually observed) and MED and MSF systems of about 10 % (IWACO, 2000; Hoepner and Latteman, 2003). These efficiencies reveal a relatively low water production associated with a relatively high concentrate generation. As a comparison, conventional water treatment systems achieve production efficiencies higher than 95 %.

Environmental emissions. The most concerning environmental emissions of the desalination processes are the generation of concentrate or reject water and CO_2 (associated to the high energy requirements with an estimated potential CO_2 production of almost 2 kgCO_2eq/m^3 of produced water) (Muñoz and Rodriguez, 2008).

Likely, the concentrate is the most concerning emission from desalination processes. Besides the expected high temperature and salt concentration (Einav *et al.*, 2002), it also contains a wide range of chemicals which are used throughout the desalination process: pre-treatment and cleaning chemicals, by-products, heavy metals, anti-foams, corrosion inhibitors, anti-scale solutions and biocides (Einav *et al.*, 2002; Hoepner and Latteman, 2003; Latteman and Hoepner, 2008; Muñoz and Rodriguez, 2008). These compounds have a major impact on marine ecosystems impairing the coastal water and sediment quality, affecting seriously the marine life (Einav *et al.*, 2002; Hoepner and Latteman, 2003; Latteman and Hoepner, 2008). Moreover, considering the low desalination efficiencies, the volumes of concentrate are considerably high since per 1L of drinking water produced usually between 3 to 10L of concentrate are produced (IWACO, 2000; Hoepner and Latteman, 2003).

Regarding the air emissions, in 2000 a conservative calculation of CO_2 emissions estimated that the desalination industry generates about 36 million ton CO_2 per year, which corresponds to about 0.5% of the total man-made world emission (IWACO, 2000). If according to predictions the desalination industry doubles by 2025 then the CO_2 generation may also double reaching a preoccupying 1% of the total CO_2 emissions in the world (IWACO, 2000). Moreover, the production and disposal of different operating materials and equipment, dismantling and transport of waste materials are important factors that must be taken into account when assessing the environmental impact of a desalination process (Muñoz and Rodriguez, 2008).

Change of paradigm

As observed, most of the technological advanced desalination technologies appear to be (i) non cost-effective and therefore hardly accessible particularly to low-and middle-income countries, (ii) environmentally unsustainable at mid- and long-term and (iii) inefficient due to the fact that only a minor fraction of saline water turns into drinking water (in average between 10 and 30% depending upon the desalination process).

According to different estimations, a human being drinks between 2 and 3 litres of water per day in average, whereas their total water consumption ranges from 140 and up to 300 L/day, depending upon region and location (GWI, 2004). This implies that in fact only a minor fraction (few percent) of produced high quality ‘drinking water’ is used for human consumption and lavish part is used as an ‘efficient way’ to transport waste out of the city (e.g. 30-40L for toilet flushing). If seawater can be used for non-potable water activities (like toilet flushing) this may lead to a reduction in drinking water supply of up to 30 % and similar reductions in energy requirements and CO_2 generation. Furthermore, since the salt content is less relevant in toilet flushing, the replacement by seawater requires less investments and energy than the wastewater reuse does (Tsang *et al.*, 2009). With growing concerns regarding not only water scarcity but also global warming and the energy crisis (the latter manly affected by the high prices of fossil fuel) these potential reductions can not be neglected.

However, despite that (i) seawater is easily accessible and an infinite water resource for coastal cities, (ii) often large amounts of brackish water are available for inland urban agglomerations, and (iii) the standard practice to use drinking water for toilet flushing is considered non sustainable, the direct use of saline water is often forgotten and perceived as problematic (mainly due to corrosion issues and requirements for dual system). As a consequence, it is easily rejected as a solution for water shortage by conventional thinkers believing in traditional paradigms who overlook its benefits (which are in general not well studied and documented).

Although dual systems cannot be avoided for the direct use of saline water, corrosion issues can be limited through the implementation of urine separation toilets (Wilsenach and van Loosdrecht, 2003). Thus, yellow water collected in the dry toilets (rich in ammonia) could be, first, exposed to aerobic conditions in order to oxidize ammonia to nitrate and, thereafter, discharged into the sewer where it would catch up with the black water. The presence of nitrate in the sewerage network would reduce corrosion issues by creating anoxic conditions avoiding the reduction of sulphates to hydrogen sulphide by sulphate reducing organisms (and its potential conversion to sulphuric acid). Instead, denitrifying organisms would utilize nitrate as final electron acceptor for organic matter removal along the sewer, contributing to reduce the treatment costs of wastewater treatment plants.

The use of seawater is not new to the industrial sector; however, it is commercially driven and has its applicability limited to cooling purposes. The pioneer in innovative demonstration of large-scale use of seawater in urban sanitation is Hong Kong, revealing the enormous potential of seawater as a source for toilet flushing and other non-potable uses in water-poor urban coastal areas as a means towards sustainable water cycle management (Lau *et al.,* 2006; Wang *et al.*, 2009). The success of this innovative management approach has been mainly driven by the development of the SANI process (Tsang *et al.*, 2009).

SANI (which stands for sulphate reduction, autotrophic denitrification and nitrification) is a novel integrated process which has shown remarkable results for saline wastewater treatment (Figure 5) (Tsang *et al.*, 2009). In the first stage of the SANI process, organic matter is removed anaerobically by sulphate reducing bacteria (SRB) which grow on the high sulphate concentrations (up to 600mg/L) outcompeting the methanogenic bacteria and producing sulphide (Wang *et al.*, 2009). In the second stage, autotrophic denitrifying organisms use the sulphide present in the water phase as electron donor and the nitrate recirculated from the aerobic phase (third stage) as final electron acceptor for denitrification purposes. Thus, sulphide is oxidized to sulphate during denitrification ensuring full sulphur recovery and negligible hydrogen sulphide losses to the environment (Wang *et al.*, 2009). Furthermore, CO_2 production has been observed to be also negligible as most of the influent COD is converted to alkalinity (Lu *et al.*, 2009). Finally, in the third stage, ammonia is aerobically oxidized to nitrate by nitrifying bacteria and recirculated to the anoxic phase to drive the autotrophic denitrification and accomplish nitrogen removal (Tsang *et al.*, 2009). Since all microorganisms involved in the SANI process are slow-growing bacteria, zero sludge discharge has been observed (Lu *et al.*, 2009), which makes it also very attractive in view of the major environmental concerns and high costs associated to sludge handling and disposal (Odegaard, 2004).

Overall, by applying the SANI process, different and remarkable benefits have been achieved which make it a feasible solution towards sustainable water cycle management: (i) high organic matter and total nitrogen removal efficiencies (97 and 74 %, respectively), (ii) low energy requirements, (iii) minimized air emissions and (iv) negligible sludge production. Furthermore, the high sulphide concentrations observed in the SANI process contribute to achieve a relatively high fecal coliform removal (2.2 log) when compared to conventional wastewater treatment systems (Adbeen *et al*., 2009).

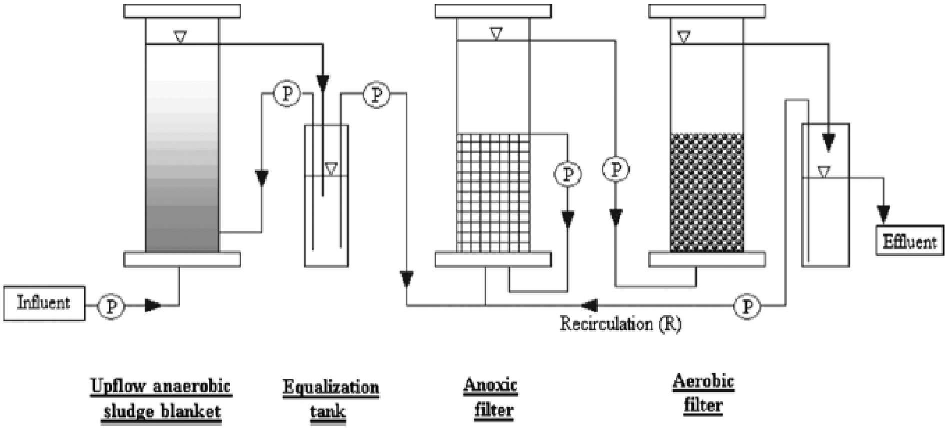

Figure 5. The SANI process concept (Tsang *et al.*, 2009).

The SALINE project

Looking after achieving sustainability in the urban water cycle (UWC) and finding solutions and applications to reduce fresh water scarcity in coastal regions (where a big fraction of the world's population lives) and in the areas rich with brackish water, a consortium consisting of different universities and institutions worldwide named the SALINE project has been established. This consortium involves partners from Cape Town, Delft, Habana, Birzeit and Hong Kong, where already for many years experience has been build-up in the application of innovative water supply and sanitation options which can be reflected on the development and success of the SANI process (Lau *et al.*, 2006; Tsang *et al.*, 2009; Wang *et al.*, 2009).

The SALINE project will develop a novel integrated process model focusing on the effect of saline water on sulfate, nitrogen and phosphorus reduction in both sewerage systems and sewage treatment plants. It will focus on the development of novel technologies which will allow for the use of saline water in UWC. From a process perspective, the research will be also of importance and relevance to industry as salinity is often an issue in industrial effluent treatment. It is expected that the project spin-off will also include pilot applications in The Netherlands (new utility buildings, Schiphol development project, etc). Thus, SALINE is expected to provide a significant contribution towards knowledge and application of the use of seawater as well as of brackish water as secondary quality water for urban environments. Its research outputs are expected to be relevant for both municipalities and industries. Furthermore, this innovative research is expected to open a new paradigm in integrated urban water cycle management towards the use of saline water as secondary quality water in urban environments.

Conclusions

In view that the technological advanced desalination technologies involve serious economical constraints and environmental concerns, the use of saline water in the urban water cycle as secondary quality water appears to be promising towards (i) reducing the water stress, (ii) alleviating the global warming and (iii) reducing the environmental impact of urban areas.. Overall, the present innovative concepts open new insights into sanitation and wastewater management in urban systems, opening and bringing up new management options into the urban water cycle.

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