Increasing urban water self-sufficiency: New era, new challenges

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ARTICLE INFO
Article history:
Received 3 November 2009
Received in revised form
28 July 2010
Accepted 5 September 2010

Keywords:
Cost
Desalination
Drivers
Energy
Rainwater collection
Wastewater reclamation

ABSTRACT

Urban water supplies are traditionally based on limited freshwater resources located outside the cities. However, a range of concepts and techniques to exploit alternative water resources has gained ground as water demands begin to exceed the freshwater available to cities. Based on 113 cases and 15 in-depth case studies, solutions used to increase water self-sufficiency in urban areas are analyzed. The main drivers for increased self-sufficiency were identified to be direct and indirect lack of water, constrained infrastructure, high quality water demands and commercial and institutional pressures. Case studies demonstrate increases in self-sufficiency ratios to as much as 80% with contributions from recycled water, seawater desalination and rainwater collection. The introduction of alternative water resources raises several challenges: energy requirements vary by more than a factor of ten amongst the alternative techniques, wastewater reclamation can lead to the appearance of trace contaminants in drinking water, and changes to the drinking water system can meet tough resistance from the public. Public water-supply managers aim to achieve a high level of reliability and stability. We conclude that despite the challenges, self-sufficiency concepts in combination with conventional water resources are already helping to reach this goal.

1. Introduction

Water-supply systems have undergone several revolutions in the era of human civilization. Advanced irrigation systems existed in the ancient Middle East and India thousands of years before the Romans refined the art of conveying water with impressive aqueducts and sewage systems (Mays et al., 2007). Later, in 19th century Europe, the hygienic movement triggered massive investment in water infrastructure. Systems were constructed to deliver clean drinking water and remove sewage from urban areas in separate systems (Hallström, 2003). Today distant water transport and separate water-supply and sewage systems are the most common water systems. They have enabled people to grow crops and live where freshwater is not readily available and have been a huge success as they have practically eliminated waterborne diseases in most of the developed world.

We are now entering an era of a new water revolution, again driven by population growth and increasing urbanization, which is challenging the limits of our conventional water resources. In recent decades, as populations have grown, cities in the developed world have expanded abstraction rates, imported water from further away, and struggled to reduce consumption rates to cope with increasing water demand.

Water suppliers are now turning to new technologies and strategies that increase self-sufficiency by enabling the use of water sourced from within cities. Localization of water cycles through neighborhood reclamation and distribution of water has several benefits including minimization of piping systems and reduced water extraction and discharge of sewage to the environment (van Roon, 2007). However, localization of water treatment is only one example of increased water self-sufficiency; water is sourced closer to the city rather than being transported from distant resources. On the city scale, several options for increasing self-sufficiency exist, including unconventional water resources like centralized wastewater reclamation, desalination and local and central rainwater collection.

The aim of this study was to investigate the implications of a worldwide increase in urban water self-sufficiency, to identify the drivers behind the change, and to investigate the main consequences and scientific challenges that follow. We analyze and discuss the techniques and concepts used to increase water self-sufficiency on the city scale.

2. Method and data collection

Examples of current projects that attempt to increase the self-sufficiency of an urban area were identified in the scientific literature as well as the internet. Numerous examples exist and a screening list of 113 cases was compiled with examples from
Cases analyzed in depth as background for this article. In-depth descriptions of the 15 cases are presented elsewhere (Rygaard et al., 2009).

The screening list was presented at a seminar with participants from DTU Environment and Copenhagen Energy (Copenhagen’s water utility). Based on a discussion among the seminar participants, 15 cases (Table 1) were selected for in-depth analysis and represent all the major techniques and concepts for self-sufficient water supplies. The analysis had 3 main focuses: 1) to identify the driving forces (drivers) and policies leading to the change to a more self-sufficient water supply, 2) to describe and analyze techniques

Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Technology &amp; concepts in use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Stenløse Syd, Egedal municipality Denmark</td>
<td>Water planning, Rainwater</td>
<td>Mandatory rainwater collection for toilet and clothes washing from the roofs with local infiltration. Good experiences with obligatory rainwater collection, reducing drinking water consumption by 25% in a new residential area.</td>
</tr>
<tr>
<td>2 Hammarby Sjöstad, Stockholm Sweden</td>
<td>Water planning</td>
<td>Green district, water-saving installations and local management of all wastewater. Despite the focus on water savings, the consumption is still higher (150l/(cap/d)) than most efficient cities, e.g. Berlin (110 l/(cap/d)).</td>
</tr>
<tr>
<td>3 Millennium Dome, London Great Britain</td>
<td>Recycled water, Recycling</td>
<td>Rainwater, grey wastewater and polluted groundwater were used in toilets and urinals in the arena. Expensive full-scale demonstration project, where alternative water resources covered 55% of the building’s water consumption.</td>
</tr>
<tr>
<td>4 Torreele, Wulpen Belgium</td>
<td>Recycling</td>
<td>Recycling of wastewater via the groundwater zone. Used for drinking water supply. European example of recycling of wastewater for drinking water via groundwater with membrane filtration.</td>
</tr>
<tr>
<td>6 Berlin, Germany</td>
<td>Recycling</td>
<td>Partly closed water circulation around the town. Unplanned wastewater recycling for drinking water supplies via bank infiltration and artificial groundwater development. Experiences around transport of problematic substances in cases of household wastewater recycling for drinking water supply.</td>
</tr>
<tr>
<td>7 Potsdamer Platz, Berlin Germany</td>
<td>Rainwater</td>
<td>Collection of rainwater in town centre, cleaned via green roofs and beds, and used in artificial outdoor water settings and toilets. Integrated water management limiting wastewater and water consumption, and creating a better urban environment.</td>
</tr>
<tr>
<td>8 Orange County, California USA</td>
<td>Recycling</td>
<td>Artificial groundwater infiltration based on wastewater used as a salt water barrier. Groundwater is a part of the drinking water supply. One of the pioneer places within reuse of wastewater to which many people refer.</td>
</tr>
<tr>
<td>9 Rio Rancho, New Mexico USA</td>
<td>Recycling</td>
<td>Membrane bioreactor can be used for recycling of wastewater for irrigation and eventually to be injection in the drinking water aquifers. The MBR system is different from the other recycling systems, where conventional wastewater purification techniques are used.</td>
</tr>
<tr>
<td>10 Windhoek, Namibia</td>
<td>Recycling</td>
<td>Direct recycling of wastewater for drinking water use has been practiced since 1968. A unique example of direct utilization of household wastewater for drinking water supply.</td>
</tr>
<tr>
<td>11 Singapore</td>
<td>Desalination, Water planning</td>
<td>Comprehensive, long term plan to make Singapore self-sufficient with drinking water. Desalination of seawater, recycling of wastewater for industry and drinking water consumption and rainwater are a part of the plan.</td>
</tr>
<tr>
<td>12 Seoul, Korea</td>
<td>Water planning</td>
<td>Obligatory collection of rainwater as a secondary water supply, where the rainwater collecting is centrally coordinated with a view to levelling the wastewater discharge after heavy precipitations.</td>
</tr>
<tr>
<td>13 Tokyo, Japan</td>
<td>Recycling</td>
<td>Comprehensive use of recycled wastewater as a secondary water supply. Recycling is obligatory in all new buildings over 30,000 m². The example shows that wastewater can be treated and recycled locally in one single home or on a block of flats.</td>
</tr>
<tr>
<td>14 Perth, Australia</td>
<td>Desalination</td>
<td>A large scale membrane desalination of seawater for drinking water consumption, based on purchase of electricity from a wind farm. Interesting with CO₂ mitigated water supply, based on energy-demanding desalination.</td>
</tr>
<tr>
<td>15 Gold Coast, Australia</td>
<td>Desalination, Water planning</td>
<td>Comprehensive general plan for water management, including desalination of seawater, recycling for non-drinking water use, rainwater collection and water economising. In the town district Pimpama-Coomea, they aim for a reduction of up to 84% of the drinking water consumption.</td>
</tr>
</tbody>
</table>

Integrating water management, gathering many experiences of practical realization of water planning, planning and involvement of citizens.
and concepts put in place to realize aims of increased self-sufficiency, and finally 3) to analyze challenges met or occurring due to the change, including public perception, costs, and environmental impacts. The screening list and detailed description of the cases are reported elsewhere (Rygaard et al., 2009).

2.1. Self-sufficiency in water supply

A concept of urban water self-sufficiency has been proposed as a measure of urban dependency on water imports (Han and Kim, 2007). To evaluate self-sufficiency we define the self-sufficiency ratio as \( Q_d/Q_r \), where \( Q_r \) is the amount of water sourced from within a given area, and \( Q_d \) is the total water demand in the same area. The definition employed shows that the self-sufficiency ratio depends on the definition of the area or system boundaries and so it is important to use consistent boundary definitions in every case. Here the system boundaries for each case are defined to be its geographic boundaries. Although water demand management can be used to decrease dependence on imported water it is deliberately not considered in this work.

A majority of urban areas consume far more water than is available within their own city limits and often depend entirely on water imported from neighboring areas. As an example, the suburb Stenløse Syd, Denmark, consists of 750 dwellings with an annual water demand of 90 000 m\(^3\). 23 000 m\(^3\) is provided by rooftop collection of rainwater while the remainder will be imported from the public water supply (Nielsen, 2007). As defined above, the self-sufficiency ratio is found to be 23 000 m\(^3\)/90 000 m\(^3\) or 26% (Table 4).

Current water-supply systems commonly use no local resources, and the self-sufficiency ratio is 0%. However, some cities have reduced their dependency on imported water by more than 15% e.g. by rainwater collection (Fig. 1). Self-sufficiency ratios can be quite high, e.g. isolated islands with no freshwater import have a self-sufficiency ratio of 100%. Water reclamation, desalination and rainwater collection can contribute significantly to urban water self-sufficiency (Fig. 1). Thus the ratio varies in the selected cases, from 15% in Orange County, California, to more than 80% in Pimpama-Coomera, Australia. It is also noted that the technologies work on different scales ranging from, for example, Stenløse Syd (1500 inhabitants, Nielsen, 2007), to Wulpen (60 000, IWVA 2006) and Perth (1.5 mill., Water Corporation, 2007) (see also Table 4).

3. Solutions

3.1. Spatial distribution

The reviewed cases reveal that a variety of solutions to increased water self-sufficiency in urban areas are widely used around the world (Table 2). Examples are found on every continent, however our collection is biased towards larger European and other westernized countries, probably due to availability of information in English on the subject, rather than any geographic trends. A bias towards the industrialized parts of the world is intentional since the main focus is on solutions in industrialized urban areas.

3.2. Drivers

Five main drivers for increasing the self-sufficiency are discussed in the following (Table 3): 1) direct and 2) indirect lack of water, 3) constrained infrastructure, 4) high quality water demands and 5) the sectoral system.

3.2.1. Direct lack of water

We define direct lack of water as occurring when the supply cannot meet the anthropogenic demand needed for households and irrigation. The deficit may occur as a result of decreased supply (drought), for example caused by climate change, or as a result of increased demand (population growth). Drought and population growth are common arguments for implementing alternative water strategies, for example in North America. The Rio Grande runs through a desert region (Colorado, New Mexico, Texas, and the Mexican state of Chihuahua), an area recently hit by extreme drought. More than three million people are dependent on the Rio Grande, among them the inhabitants of the Albuquerque Metropolitan Area (Rio Rancho, El Paso, and Ciudad Juárez), where a rapidly increasing population has complicated the task of managing water allocation for the population, agriculture and wildlife (Ward et al., 2006). Such examples are instances of direct water deficit with an insufficient amount of water available for anthropogenic demand. In Rio Rancho (Table 1, case 9) the situation has lead to reclamation of wastewater.

3.2.2. Indirect lack of water

Indirect lack of water can be defined as the case where water-resources are sufficient to meet anthropogenic demands, but available water resources may be allocated for other uses or the resources can be undesirable for political reasons. Such indirect

<table>
<thead>
<tr>
<th>Geographical distribution</th>
<th>Number of cases</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>46</td>
<td>41</td>
</tr>
<tr>
<td>North America</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Asia</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Australia</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>South America</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Middle East</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Total number of cases screened</td>
<td>113</td>
<td>100</td>
</tr>
</tbody>
</table>

Fig. 1. Reported water self-sufficiencies in selected urban areas and buildings (reported or planned year) (Table 4).
deficit occurs because water is needed to sustain ecosystems or because the water supply is based on politically undesirable water imports. For example, water resource pressures have increased in Europe due to the consideration of ecosystems in the European Water Framework Directive. Member states of the European Union are now obliged to meet legislative requirements that “... prevent further deterioration and protect and enhance the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems” (Article 1a). Member states must implement management plans that consider both water quality and quantity (The European Parliament and the Council of the European Union, 2000). Restoration of natural ecosystems is now a highly ranked political issue and has become an important driver for increasing the self-sufficiency. Reclamation of water in Costa Brava in Spain is one example (cf. Section 3.3.2).

Singapore is another example of indirect water deficit. The country currently depends on water imports from neighboring Malaysia. However, the two countries cannot agree on the price-setting mechanisms for water imports in the future (Tortajada, 2006) and Singapore sees a security risk in being dependent on water piped into the island (Luan, 2010). As a result, Singapore is now determined to become less dependent on water imports from Malaysia and has developed a plan for increased use of desalinated water, wastewater reclamation and rainwater collection. An indirect water deficit can therefore originate in a wish to allocate water to the environment or through a wish to avoid political conflict.

3.2.3. Constrained infrastructure

The driver constrained infrastructure is defined as the situation where bottlenecks in the water supply occur due to limited capacity of the infrastructure. Pipe systems designed decades earlier may be expensive to upgrade and restrain amounts of water to supply or remove from an area after use. Constrained infrastructure may drive a self-sufficiency trend (van Roon, 2007) e.g. as a direct driver for the development of local wastewater treatment in some of Japan’s megacities where it prevents expensive investments in up-scaling of the central sewer systems (Ogoshi et al., 2001).

3.2.4. Demand for high quality water

A fourth driver is defined as a demand for high quality water. Membrane processes employed in water reclamation schemes can produce water that is even purer than required for potable supply and industrial applications can create an additional demand for intensively treated wastewater. The electronics industry requires ultra pure water and is a driver for the expansion of water reclamation in Singapore (Qin et al., 2006, 2009) (cf. Section 3.3.2).

3.2.5. The sectoral system

Innovation and development occur within a sectoral or innovation system as a result of the knowledge base and interactions that exist among the system agents, i.e. firms, universities, authorities etc. (Malerba, 2002). Although not being a direct driver for specific self-sufficiency trends, the sectoral system defines the framework for the development. Commercial and institutional pressures are locally influenced by the technological paradigms employed by the commercial and non-commercial bodies and institutions in the area (Mulder, 2006). Paradigms are reflected in regulations, standards, labor markets etc. It is possible, when firms, authorities, universities and related organizations build up knowledge and experience within e.g. desalination, that they develop biases, intentionally or otherwise, towards their own commercial or institutional interests. It is difficult to measure how much such paradigms drive the development, but examples suggest an impact.

An example of a framework promoting advanced water treatment technologies is found in Singapore with a widespread consensus on a need for changes that favor both public systems and industry. Amongst industry, educational institutions and the government it is a common aim to develop state-of-the-art solutions to make the country a world leader in water technology. This aim has resulted in several high profile treatment plants, like the Sing Spring Desalination plant, Changi water reclamation plant (Landers, 2008), and the combined networking and educational facility WaterHub. Sing Spring Desalination Plant is one of the World’s largest desalination plants based on reverse osmosis technology and is operated by a local membrane manufacturer (Foo et al., 2007). The WaterHub (2008) operates as a centre for exchanging research on water management between academia and industry, domestically as well as internationally (WaterHub 2008).

3.3. Techniques and concepts for self-sufficiency

Increased self-sufficiency is linked to rapid developments of three main solutions to water supply, namely wastewater reclamation, desalination and rainwater collection. These major solutions are represented in the cases chosen for detailed analysis (Table 1). Other solutions, for example local groundwater abstraction, are not included since contribution to self-sufficiency is believed to be very limited or highly dependent on water fluxes from neighboring areas.

3.3.1. Wastewater reclamation

Wastewater reclamation as a source for irrigation and groundwater recharge for both urban and non-urban uses is increasing in all parts of the world. Thousands of water reclamation projects are running throughout USA, Japan and Australia and their number is increasing rapidly (European Commission, 2006). The EU has relatively few wastewater reclamation projects, but has a great potential for development of water reclamation facilities (Hochstrat et al., 2006).

For urban wastewater reclamation applications we distinguish between non-potable reclamation, indirect potable reclamation and direct potable reclamation.

3.3.2. Non-potable reclamation

Non-potable urban reclamation covers use of water for irrigation, nature restoration (environmental flows), household toilet flushing, and industrial process water. In Japan’s megacities there are now thousands of on-site reclamation plants connected to public and commercial buildings. These plants typically replace 30% of the water used in such buildings, mainly for toilet flushing (Yamagata et al., 2003).

Table 3

<table>
<thead>
<tr>
<th>Driving forces behind water reuse, desalination and rainwater collection</th>
<th>Case examples (Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Direct lack of water caused by:</td>
<td>3, 4, 5, 8, 9, 10,</td>
</tr>
<tr>
<td>a. Drought (reduced resource availability)</td>
<td>12, 13, 14, 15</td>
</tr>
<tr>
<td>b. Population growth (increased demand)</td>
<td>5, 11</td>
</tr>
<tr>
<td>2. Indirect lack of water caused by policy changes:</td>
<td>1, 7, 12, 13</td>
</tr>
<tr>
<td>a. Increased emphasis on environmental flows (nature restoration)</td>
<td></td>
</tr>
<tr>
<td>b. Wish to be independent of water imports (from surrounding areas/other countries)</td>
<td></td>
</tr>
<tr>
<td>3. Constrained infrastructure limiting capacity for water supply and drainage</td>
<td></td>
</tr>
<tr>
<td>4. Demand for high quality water from industry</td>
<td>11</td>
</tr>
<tr>
<td>5. The sectoral system governed by commercial, organizational and institutional interactions</td>
<td>All</td>
</tr>
</tbody>
</table>
On a larger scale, water is reclaimed for irrigation and to reestablish environmental flows where water is withdrawn for water supply. For example, in Costa Brava, Spain, wastewater reclamation includes a plant based on constructed wetlands (>600,000 m^3/yr) and an advanced treatment plant including coagulation, flocculation, clarification, filtration and disinfection (>3,000,000 m^3/yr) (Sala and Romero de Tejeda, 2007). In Israel, 73% of the treated wastewater is reused, mainly to irrigate agriculture close to the cities. Reclaimed wastewater supplies approximately 20% of the total water demand in Israel (Tal, 2006).

Reclaimed wastewater intended for industrial use has been heavily marketed under the name NEWater in Singapore, where it is supplied directly to the industry in a separate distribution system. It has been a target to supply 20% of Singapore's water needs from recycled water (Public Utilities Board of Singapore, 2007). The high quality water, essentially free of minerals, has proven to be so well accepted by Singapore's industry that newer projections estimate that NEWater will provide 30% of Singapore's water needs by 2010 (Seah, pers.comm. 2008).

3.3.3. Indirect planned potable reclamation

Indirect reclamation recirculates wastewater to drinking water after blending with natural sources. For example, in Orange County, California, reclaimed municipal wastewater is pumped back to replace 30% of the water withdrawn from the aquifer. In Wulpen, Belgium, 70% of the water withdrawn from the aquifers is replaced with reclaimed wastewater. In these cases the artificial recharge of groundwater leads to substitution of 15 (Orange County) and 40% (Wulpen) of the total water demand (Fig. 1). These reclamation systems use several barriers to prevent pollutants from entering the drinking water supply. For example, in Orange County, conventional wastewater treatment is improved by microfiltration combined with reverse osmosis and UV and hydrogen peroxide disinfection before filtration through the groundwater zone (Deshmukh and Steinbergs, 2006).

3.3.4. Indirect unplanned potable reclamation

Indirect potable reclamation occurs in an unplanned manner, where supply is based on water discharged by upstream users. For example, Berlin, Germany, has a water-supply system entirely based on local groundwater abstraction. However 70% of groundwater withdrawal is recharged to the aquifer via recharge of river water through the river banks and the volume of treated wastewater returned to local surface water is more than the volume recharging aquifers via bank infiltration (Massmann et al., 2004). The influent to one local water works has been estimated to contain up to 28% wastewater (Ziegler, 2001). Thus, although Berlin is not declared a reclamation system, it is so in practice and Berlin's water supply has a self-sufficiency ratio of 70%. The ratio is high because groundwater abstraction is replaced by river water, which in turn is sourced from treated wastewater.

3.3.5. Direct planned reclamation

Currently, Windhoek, Namibia, remains the only large scale example of direct potable wastewater reclamation. In Windhoek, the wastewater from households is kept separate from the industrial wastewater, treated by a series of processes, including flocculation, sand filtration, ozonation, activated carbon filter, and ultrafiltration, before re-entering the city's water supply (du Pisani, 2006). The system has the capacity to replace 35% of the water supply (Rygaard et al., 2009). Current self-sufficiency ratio is around 30% (Fig. 1).

3.3.6. Desalination

Membrane technologies are currently developing very rapidly with the number of membrane-based treatment plants increasing and treatment costs decreasing. In addition, to facilitate advanced treatment of wastewater for reclamation, the technology is also increasingly used for desalination of saline waters (Service, 2006). Desalination has been used for decades and the global installed desalination capacity now exceeds 60 million m^3/d (Pankratz, 2010). The currently largest desalination plants in the world are based on thermal desalination of seawater and are found in the Middle East, where single plant capacities exceed 800,000 m^3/d (Pankratz, 2010). The world's largest reverse osmosis desalination plant is situated in Israel (>270,000 m^3/d) (Tal, 2006). In the countries of the Gulf Cooperation Council, 2/3 of domestic water is supplied by desalination (Dawoud, 2005).

The booming growth in desalination capacity strongly correlates with a continuing drop in the unit production price. In the 1980s around 8 million m^3 desalinated water was produced globally per day, at costs of 1–3 dollars per m^3. In 2005 54 million m^3/d desalinated seawater was produced at a cost of as little as 0.5 US$/m^3 (Reddy and Ghaffour, 2007). The lowest costs are currently attained by state-of-the-art reverse osmosis plants (Reddy and Ghaffour, 2007). However, not all recent desalination projects achieve such low costs. For example, the Perth Desalination Plant has a production price of 1 US$/m^3 (2009) (Bath, pers.comm. 2010). Researchers are working to improve desalination performance and a vast range of technologies are being investigated on lab and pilot scale. These include improved membrane materials that prevent fouling, while enhancing water flux and salt rejection, with the goal of lowering pressure needs and hence energy requirements. For cities with excess and waste heat sources, alternative technologies like forward osmosis and membrane distillation may become commercially attractive (Service, 2006). The Perth Desalination Plant supplies 17% of the city's water demand. In Singapore, 140,000 m^3/d or 10% of the total water demand will be provided by desalination by 2011 (Foo et al., 2007) (Fig. 1).

3.3.7. Rainwater collection

Rainwater collection is another important contributor to urban water self-sufficiency. For example, Singapore plans by the end of 2007 to collect stormwater from 2/3 of the island's area, store it in reservoirs like the new Marina Barrage, and membrane filter it before sending it to drinking water supply (Public Utilities Board of Singapore, 2007).

Our analysis revealed that many cities are now legislating collection of rainwater from roof tops with requirements depending on construction date, type and size of buildings, e.g. Stenlose Kommune (2005), Denmark. In the Southeast Queensland, Australia, the state development code directly refers to rainwater tanks and recycled water as recommended means to comply with strict water-saving targets for new home owners (Queensland Government, 2008). In these places, rooftop collected rainwater is used for toilet flushing, washing of clothes and garden irrigation and typically supplies 25% of the domestic drinking water use. These cases confirm earlier studies which also show that rainwater collection has a limited capacity to supply domestic water. Domestic rainwater collection typically substitutes less than 1/3 of the household water consumption with the major limitation being

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1 H. Seah, Personal communication 2008, Director, Technology & Water Quality Office, Public Utilities Board, Singapore.

2 A. Bath, Personal communication 2010, Water Corporation, Perth, Western Australia.
the tank size (Mikkelsen et al., 1999; Zhang et al., 2009a,b). Rooftop rainwater collection is an acknowledged and in several cases proven and effective way to replace drinking water consumption in households.

4. Challenges of self-sufficiency

The main challenges of increased water self-sufficiency for water managers are: controlling energy demands (Section 4.1); controlling environmental impacts (Section 4.2); ensuring high quality water and avoiding negative impacts on human health (Section 4.3); ensuring public trust in the water supply (Section 4.4); and ensuring cost effectiveness (Section 4.5).

4.1. High energy demands

Energy consumption has become increasingly relevant because it is linked to climate change (Meehl et al., 2007). Environmental life-cycle studies show that electricity consumption in the operation phase is generally the most important factor affecting environmental performance indicators in water treatment systems (Vince et al., 2008). Therefore, energy consumption is a good indicator of the environmental burden of the use of different water treatment techniques. In the following sections we discuss the energy demands revealed by our analysis and options for making those demands greenhouse-gas-neutral so that they have no impact on the climate.

Energy consumption can contribute substantially to the total production costs (Dreizin, 2006) and global warming (Stokes and Horvath, 2006), and energy use is therefore a significant parameter to consider in decision making processes on urban water systems. Alternatives involving advanced treatment processes are more energy intensive when compared to conventional treatment (Fig. 2), both in decentralized on-site applications and in centralized large scale systems. Small scale on-site reclamation systems based on membrane bioreactors are quite energy demanding (2–8 kWh/m³), depending on efficiency of scale. High energy requirements are also of concern for larger centralized systems. Potable wastewater reclamation and desalination plants typically involve membrane technologies, which require high pressures (typically 5–80 bar) to force water through the membranes (Dreizin, 2006; European Commission, 2006).

State-of-the-art seawater reverse osmosis treatment requires as little as 1.6 kWh per m³ product water (excluding pre-treatment) if operational conditions are optimal (Dundorf et al., 2007). In addition, the energy consumption by pre-treatment, aeration and disinfection steps must be considered. Newer seawater reverse osmosis plants typically require around 4 kWh/m³ including pre-treatment (Fig. 2). Reducing seawater desalination energy requirement by more than 15% will require a breakthrough in alternative technologies (National Research Council, 2008). Despite the high energy demand of seawater desalination, a recent review concluded that the energy requirements for desalination are less than commonly thought. In Israel, the energy used for drinking water treatment constitutes 3.2% of the total household energy consumption, if all water was produced as desalinated seawater (Semiat, 2008). Although the marginal change in society’s energy consumption is relatively small when desalination is employed, Fig. 2 shows that there is a significant difference in the energy requirements of the water resource alternatives.

Cities in the vicinity of brackish water resources, such as the Baltic Sea, coastal groundwater or estuaries can benefit from significantly lower desalination energy consumptions. Treating feed water with salinity of 15 000 mg/l instead of ocean water (36 000 mg/l) requires less energy, and the overall environmental life-cycle impact is reduced by almost 50% (Munoz and Fernandez-Alba, 2008). Other environmental life-cycle assessments show that reclamation of wastewater is preferable to seawater desalination, because of the lower salinity of wastewater compared to seawater (Lundie et al., 2004; Raluy et al., 2005; Stokes and Horvath, 2006).

Household rainwater collection is energy efficient. In local rainwater collection systems where simple gravity driven screen filtering is used and a pump distributes the water to the household, the energy cost is 0.3–0.5 kWh/m³ (Mikkelsen et al., 1999). Although its contribution to water self-sufficiency is limited, decentralized rainwater collection can provide a low energy alternative to both reclamation and desalination because the electricity consumption is well below 1 kWh/m³ and is similar to conventional treatment of local groundwater and surface water resources. In this paper energy evaluations have only included energy in the treatment and local distribution of the water. In case of water imports over long transport distances, low treatment energy demands may be offset by large transport demands. Examples are found in both Spain and California, and show that planned desalination or wastewater reclamation schemes are expected to be more energy efficient than long transports of surface water (Raluy et al., 2005; Stokes and Horvath, 2006).

Intensive water treatment and high energy demands can be decoupled from potential climate change impacts by use of emerging greenhouse-gas-neutral energy generation. In Perth, a desalination plant is powered by electricity bought from a wind farm. The wind farm has been constructed to offset the increased energy requirements of the water production (Water Corporation, 2007).

![Fig. 2. Electricity demand per unit water produced before distribution with minimum and maximum values indicated. *: E.V. Houtte, Personal communication 2007, Inter-communale Waterleidingsmaatschappij van Veurne-Ambacht, Belgium.](image)
4.2. Environmental impact of feed water intakes and concentrate disposal

Life-cycle-assessment studies of water-supply technologies do not currently include environmental impacts of water abstraction and disposal of concentrate from membrane processes. For example, seawater desalination draws water from a huge resource with environmental impacts very different from inland freshwater abstraction. Feed water intakes may include impacts on fish populations and invertebrates, and loss of biological productivity in general.

Depending on the recovery rate of the membrane processes, a concentrate stream containing 2–15 times the feed water concentrations is discharged to the recipients. The concentrate may also contain chemicals used in the pre-treatment, such as biocides, detergents and anti-scalants (Cooley et al., 2006). Chemicals are typically discharged in levels that are considered non-toxic to aquatic ecosystems at the individual level, but possible nutritional effects and combined effects remain to be investigated (National Research Council, 2008).

Concentrate at the outlet can also alter flow and salinity levels in the local marine environment, as shown in the field investigations of the Perth Desalination Plant, where a dense plume formed in the vicinity of the diffuser system is persistent in calm wind conditions (Okely et al., 2007). One option is to blend the concentrate with existing wastewater discharges, and thereby obtain a combined dilution effect.

4.3. Multiple barriers against micropollutants

Today’s wastewater streams contain a wide range of chemical pollutants that pose risks to ecosystems and drinking water systems (Schwarzenbach et al., 2006). Controlling the release of pollutants to the waste streams is much more efficient than performing a difficult removal at treatment plants (Levine and Asano, 2004; Schwarzenbach et al., 2006).

However, trace levels of compounds like pharmaceuticals are already widely present in available wastewater streams and freshwater resources (Hall-Jon-Rosenfeld et al., 1998; Kolpin et al., 2002). It is important to acknowledge that even reverse osmosis treatment does not provide a complete barrier against pharmaceutical active and endocrine disrupting compounds. Rejection of these compounds by RO-membranes is effective but range from 40 to 100% for selected compounds and membranes (Kimura et al., 2002; Schwarzenbach et al., 2006).

Concentrate at the outlet can also alter flow and salinity levels in the local marine environment, as shown in the field investigations of the Perth Desalination Plant, where a dense plume formed in the vicinity of the diffuser system is persistent in calm wind conditions (Okely et al., 2007). One option is to blend the concentrate with existing wastewater discharges, and thereby obtain a combined dilution effect.

4.4. Public acceptance and trust

Interpreting the risk posed by mixtures of low level contamination is challenging for the scientific community, as possible combinations of compounds are numerous and the impact on public health complex (Sexton and Hattis, 2007). The actual risk is no less difficult to conceive for the general public. Even if scientifically sound assessments conclude that a water-supply technology is the best available option, actual planning and public communication can be the decisive factors for implementation.

4.4.1. Will people drink reclaimed water?

Recent improvements in analytical methods, increased focus on micropollutants, and widespread pollution of our waterways, have made it necessary to accept drinking water that is known to be contaminated by unwanted pollutants, although at very low concentrations. This conflict between the ability to analyze very low contaminant concentrations and a wish to drink clean water can be difficult to accept for the public and decision makers. Potable reclamation schemes are especially challenging since the short circulating of the water loop is particularly evident for the public. Analyses of public perception have confirmed that people are more positive towards reclamation when they are not in direct contact with the water. Thus, reclaimed water is preferably used for toilet flushing rather than cooking at home (Po et al., 2005).

Studies show that public perception of water quality is mainly related to trust in relevant agencies and personal perceptions of control rather than technical parameters of water quality (Fawell and Miller, 1992; Po et al., 2005; Syme and Williams, 1993). It has further been suggested that the history of the reclaimed water is of less importance than the process by which a decision to recycle the water is made (Russell and Lux, 2009). To avoid misunderstandings and to build trust, it seems crucial that new initiatives are preceded by public engagement and interaction between decision makers and the public.

One good example is the 2006 ballot on wastewater reclamation in Toowoomba, Australia. There the public turned down a government-proposed to add reclaimed wastewater to the city’s drinking water reservoirs. Even though wastewater reclamation was considered to be a technical and economic optimal solution, 62% of the voters were against the project and the government was forced to consider other solutions (Toowoomba City Council, 2006).

The sensitivity of the public to new technologies may have undesirable implications. There is a possibility that people will turn away from tap water to bottled water, and this may have undesirable implications, like increased costs and environmental burdens due to plastic consumption. Producing disposable plastic bottles is very energy intensive, typically using 50–70 kWh electricity per 1000 l product volume depending on the size of the bottle (Ekvall et al., 1998). Plastic bottle consumption and the relatively high sales price of bottled water also add to the negative impact of a shift from tap water to bottled water.

4.4.2. Convincing people

Public acceptance during the implementation of self-sufficient water is critical for success. In Singapore a combination of expert...
opinion published as an “Expert Panel Review”, and an extensive PR-strategy including a NEWater exhibition centre aimed at the general public, was used to maintain and ensure trust in the public water supply (Nam et al., 2002; Public Utilities Board of Singapore, 2007).

4.5. Costs

Comparing the costs of different techniques is challenging as they will depend on a range of factors which may vary significantly with location and be implementation specific. Furthermore, the costs vary greatly within and between solutions (Table 5). Keeping in mind this caveat, some patterns are revealed from the reported costs of water treatment and important factors include size and energy costs. For example, the cost of on-site wastewater reclamation is directly related to the size of the plant. A small membrane bioreactor plant installed to serve a single household (producing 400 m$^3$/y) is predicted to have a total cost in the range of 3.8–4.2 US$/m^3$. Membrane bioreactor plants, up-scaled to serve a block of houses and producing ~13 000 m$^3$/y are expected to cost 1.5–2.3 US$/m^3$ (based on Fletcher et al., 2007). The variance is due to the choice of membrane bioreactor design.

It is not surprising that costs are related to treatment intensity. It is seen that the lower bounds of estimated cost are significantly higher for indirect potable reclamation, on-site treatment and desalination than for more conventional sources and simple concepts such as surface water abstraction and rainwater collection (Table 5). The influence of local conditions becomes evident when comparing the lowest costs of desalinating seawater in Australia (US$ 0.9/m$^3$) with a plant like Ashkelon in Israel that has costs as low as US$ 0.5/m$^3$ (Reddy and Ghaffour, 2007).

A simple comparison of costs can often be misleading, and more holistic economic assessments are needed, including costs and benefits of externalities. Supplying reclaimed water or rainwater in separate distribution systems as a secondary water supply for toilet flushing, irrigation and clothes washing may be expensive in the construction phase. However, other benefits emerge since a compromise is not needed between low capacity/high quality demand for drinking water and the high capacity/low quality demand for e.g. fire hydrants and lawn watering. In the same way, large scale rainwater collection and local wastewater reclamation has to be evaluated in an integrated manner where lower demand for sewage capacity is included in the assessment. Holistic feasibility studies might prove local wastewater reclamation and rainwater collection to be feasible in more cases.

4.6. No single concept is a panacea to urban water stress

There is unfortunately no simple panacea to urban water stress. Each type of resource has its own strengths and weaknesses (Fig. 3). Wastewater reclamation and desalination are effective ways of increasing water self-sufficiency, while reducing the impact of climate variations, because such climate independent water-resources can provide a steady freshwater yield in dry periods. However, wastewater reclamation and desalination becomes less optimal when considering public acceptance and treatment intensity, which reflects energy consumption and costs.

Due to losses or intermittency, wastewater reclamation and rainwater collection cannot separately ensure complete urban self-sufficiency, and desalination is often the more expensive option. However, a diversified water system is more flexible and secure against policy changes and natural variability, and the panacea may actually be diversification.

There are only few reports of such truly diversified and integrated urban water management projects, with Singapore as the best example where technical solutions and public relations are extensively coordinated and integrated (Section 4.4.2). Full integration of water demand management, wastewater reclamation, desalination and rainwater collection can provide self-sufficiencies as high as 80%, as seen in Pimpama-Coomera, Australia (Fig. 1).

### Table 4
Water-supply alternatives and their volumes for selected cases.

<table>
<thead>
<tr>
<th>Location (reported or planned year)</th>
<th>Water source (1000 m$^3$/y)</th>
<th>Total consumption (1000 m$^3$/y)</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local desalination</td>
<td>Wastewater reuse</td>
<td>Collected rainwater</td>
</tr>
<tr>
<td>Stenlase, DK (2009)$^a$</td>
<td>23</td>
<td>90</td>
<td>750 Dwellings</td>
</tr>
<tr>
<td>Millennium Dome, UK (2000)$^b$</td>
<td>58</td>
<td>14</td>
<td>Public building</td>
</tr>
<tr>
<td>Com. build., Tokyo, JP (1997)$^c$</td>
<td>(30%)</td>
<td>N/A</td>
<td>Office building</td>
</tr>
<tr>
<td>Pimpama-Coomera, AU (2006)$^d$</td>
<td>168</td>
<td>94</td>
<td>Tenement</td>
</tr>
<tr>
<td>Wulpfen, BE (2006)$^e$</td>
<td>2199</td>
<td>5412</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Berlin, DE (2001)$^f$</td>
<td>139 300</td>
<td>199 000</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Orange County CA, US (2008)$^g$</td>
<td>888 111</td>
<td>594 538</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Windhoek, NA (2007)$^h$</td>
<td>4852</td>
<td>22 118</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Singapore SC (2011)$^i$</td>
<td>41 500</td>
<td>131 400</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Perth, AU (2006)$^j$</td>
<td>45 000</td>
<td>264 706</td>
<td>Supply zone</td>
</tr>
<tr>
<td>Gold Coast, AU (2030)$^k$</td>
<td>40 515</td>
<td>140 890</td>
<td>Supply zone</td>
</tr>
</tbody>
</table>

*a Neilsen (2007).
*b Hills et al. (2002).
*c Absolute consumption values unavailable, percentages from Yamagata et al. (2003). N/A – Not available.
*d Gold Coast City Council (2004).
*e IWVA (2006).
*f Ziegler (2001).
*g Deshmukh and Steinbergs (2006).
*h P.d. Pisani, Personal communication 2008, Infrastructure, Water and Technical Services, City of Windhoek, Namibia.
*i Reported by PUB Singapore 2008
+k Gold Coast City Council (2008).

### Table 5
Expected costs of technologies reported for Australia (Pickering et al., 2007) except *generic estimates for an MBR system (Fletcher et al., 2007).*

<table>
<thead>
<tr>
<th>Production price (US$/m$^3$)</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional surface water treatment</td>
<td>0.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Conventional groundwater treatment</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Indirect potable reuse</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>On-site non-potable reuse*</td>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>RO seawater desalination*</td>
<td>0.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Local rainwater collection</td>
<td>0.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>
5. Conclusion

Based on a review of 113 cases of increased water self-sufficiency, and an in-depth analysis of 15 cases, it is concluded that:

- Water self-sufficiency is a predictable response to urbanization and increasing water stress, and several cities are already taking advantage of low grade water resources within the city boundaries. Many cities reclaim wastewater and collect rainwater, and desalination is becoming increasingly common worldwide.

- Self-sufficient water supplies are driven by direct (physical) and indirect (political) water deficits, concerns of water quality, and constrained water infrastructure. The inter disciplinary nature of the drivers emphasizes that water management is not just an engineering challenge.

- Calculating the degree of water self-sufficiency allows direct comparison of cases. Self-sufficiency ratios between 15 and 80% are observed: from small scale implementations like local rainwater collection providing 25% of the household consumption in Stenløse, Denmark, to citywide water management strategies with desalination and wastewater reclamation plants producing more than 100,000 m³ of water per day, as seen in Singapore.

The move to self-sufficiency concepts has some major implications:

- Energy consumption varies by an order of magnitude for different technologies and is directly linked to production volume and is therefore a critical parameter in water systems design.

- A challenge when reclamation of wastewater is used as drinking water is the lack of scientific understanding of human exposure to micropollutants and the possible risk such a water technology can add to that exposure.

- Two-way communication is the crucial issue when convincing the public that new technologies are safe. In some places, people have been convinced to adopt wastewater reclamation schemes for water supply, while in other proposals for reclamation schemes have been rejected by the public.

The desire for self-sufficiency is a major trend and driver for new technologies and concepts in modern water supplies. Technologies like wastewater reclamation and desalination are attractive because of their reliability and stability, and rainwater collection can decrease pressures on other water resources. They will become increasingly common as water utilities seek more secure solutions by diversifying their approaches to water supply.

Acknowledgement

The work was partly sponsored by Copenhagen Energy.

References


DANVA, 2008. DANVA Benchmarking og statistik. (Danish Water and Wastewater Association — benchmarking and statistics). www.bessy.dk (accessed 07.08.08.).


