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# Characterisations and Interventions of the Water-Energy Nexus in Urban Water Systems

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# Abstract

This study explores the water-energy nexus of urban water services and the water-related energy demands that stem from them. The initial objective provides insight into the development of nexus analyses through a review of international literature. Based on data from recent urban water system metabolism studies, and process factors identified in literature, an in-depth analysis was also performed to explain the variations in energy consumption and emission intensities per unit of water demand. There is in fact a wide variation that is explained by local economic, natural, social, cultural and historical developments. Exploratory impact assessments on intervention options in Oslo demonstrated a range of material and energy efficiency gains, and that taken as a whole can result in a sum scenario of greenhouse gas emission reductions.

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# CHAPTER 01
# Introduction and Background

## Motivation

*Cities and climate change*

At a point in time referred to as the anthropocene (Steffen 2010), a notable milestone has been reached in which more than half of humanity now lives in cities. With the metropolitan migration making its impact in industrialised nations for quite some time, the increasing importance of *urban* to the sustainability agenda is without surprise. Ideas such as urban forestry and urban agriculture – agriculture long being the domain of rural regions and a symbolic notion of man living in harmony with nature – have emerged as sensible solutions to buffer against the adverse impacts of population growth. The need for "urban" tools is equally important in the global South, where unprecedented urbanisation is unfolding most notably in South and East Asia and Sub-Saharan Africa. Yet as humans tide into cities and conurbations all over the globe in search of profound social and economic opportunities, it is difficult to ignore the fact that rapid rises in urban population and the increase in commercial activity are exerting considerable pressures on the foundational ecosystem services that make much of what we depend on possible.

Cities serve as gateways, hubs and headquarters where natural resources are harnessed with infrastructure and transformed by industry and innovation into technological marvels that are consumed for both necessity and pleasure. The sustained growth in urban populations worldwide is expected to correspond with a rise in global demand for resources and services that serve as indispensible input for the intricate system of the city – namely electricity, transportation and, most important, water. As it currently is, each has already respectively brought on environmental concerns – air pollution stemming from energy production (Zand 2013), loss of wildlife habitats as they are paved over for roads and parking lots (Mitchell 1970), and the depletion of water sources such as the Colorado River (MIT 2012). Yet with the collective complexity of these systems and the vast scale of the planet, the elemental interactions are creating synergistic effects that are becoming more apparent and taken more seriously. Notable issues include air pollution and smog caused by transportation modes dependent on fossil fuels, while the impervious surfaces of dwelling and transport infrastructure have transformed stormwater into contaminated urban runoff with adverse impacts on aquatic environments. In many respects, there is a case to be made for the progress gained in terms of human and economic development with thanks to the new living standards and arrangements in urban environments. However, the current and looming circumstances of projected population growth in the range of nearly 10 billion, more affluent and consumptive lifestyles, and a severely limited natural resource base lie at the core of a potential progress trap (Wright 2004) that may be unfolding.

It is already evident that the recent history of economic and industrial activities have manifested into climate change. Hurricane Katrina and Superstorm Sandy in North America, as merely two examples, both demonstrate the severe consequences that this presents for urban settlements. A critical factor in these and other events is the notion that cities are likely responsible for more than 80 percent of global greenhouse gas emissions (Hoornweg, Sugar et al. 2011). While consumer consumption is certainly a culprit, the unavoidable production demands (eg deforestation, mining, etc.) that take place beyond city boundaries are additional complicating factors that serve to reinforce the climate change cycle – as middle-income classes rise in emerging and transitional economies striving to attain the idealised Western lifestyle of spacious homes and meat-based diets, swaths of forests are cleared to make way for cattle ranching and furniture products. Projecting towards 2025, it is expected that the urban population will rise to roughly 4.3 billion (Evans 2013), and barring any major paradigm shifts, it is a reasonable assumption to foresee likewise production and consumption demands.

Cities thus find themselves at the core of an unenviable cycle as both driver and impact bearer of climate change. The attractiveness of urban environments is fuelling population growth and service demand. Yet as more people move to work and live in cities, the collective vulnerability to climate change increases as population density and the importance of physical infrastructure makes urban areas particularly exposed to sea level rises, heat waves, floods and resource damages. At the same time, however, the source of these challenges presents opportunities to develop innovations and solutions. Indeed, local-level action will be the key to solving regional and global challenges, essentially making cities ground zero for climate change and environmental sustainability.

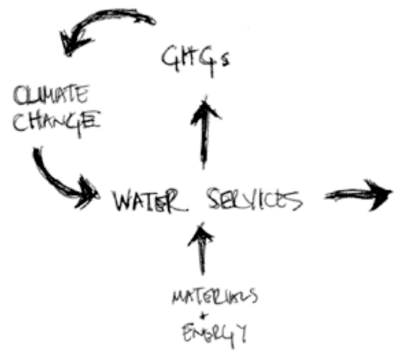
### *The water-energy nexus*

Considering modern cities and society, one is likely to ponder how all the diverse elements manage to merge and function. A quote by John F. Kennedy underlines the importance of water to both stability and sustainability: “Anyone who can solve the problems of water will be worthy of two Nobel Prizes – one for peace and one for science.” Yet in light of contemporary global problems, any one who pays attention to current events should understand the equally critical roles of energy and agriculture, be it oil embargos in the Middle East, nuclear disasters in Japan or renewable energy booms in Germany concerning the former, and issues of production, distribution, and wastage surrounding the latter. It is apparent that the problems of water are not just problems merely associated with water.

The inherent interconnectedness and interdependencies of resource systems brings forth the notion of nexus thinking that recognises the deep relationships between traditionally disparate sectors. The water, energy, food nexus, for example, cohesively frames each sector to help bring about resource efficiency and sustainability – water is required to produce energy, energy is required to produce and provide water, and the quality and quantity of both affects the extent and productivity of food production. This thesis concerns the water-energy nexus, and while the full water-energy nexus encompasses embodied energy in water production and consumption, and the water of the energy sector, only the portion of the nexus concerned with water provision (ie extraction, distribution and collection, and treatment of potable water) is analysed here.

An additional factor of consideration is the relationship between the water-energy nexus with carbon and climate. Within the water sector, quality is an obvious indicator of system performance. The initial sewer systems (and even some currently in operation) discharged wastewater into receiving water bodies without treatment, and in rectification of this, cities added wastewater treatment facilities to their infrastructure. Yet in light of this, additional energy use has been incurred and has shifted the problem from water pollution to air pollution through greenhouse gas emissions.

A greater cause for concern is climate change, and the overall energy demands of urban water systems to treat and provide water is contributing to and accelerating this development. Thus the urban water cycle is caught in a self-reinforcing challenge where its greenhouse gas emissions contribute to climate change, accelerate hydrological impacts, and intensify operational energy requirements only to create additional greenhouse gas emissions (Figure 1). At a time of rapid urbanisation, rising incomes, increasing demands for resources and unpredictable climate, the water-energy-carbon dynamics are critical considerations for tapping into sustainable development strategies.



Potential climate change affects [2] on urban water utilities:
Lower water levels reducing overall supply
Lower water levels reducing ability of intakes to draw water [3]
Lower water levels increasing cost and difficulty of hydroelectricity production[3]
Higher water temps. reducing water quality through greater microbes/algal blooms[3]
Stronger storms increase flooding, raw sewage spills and other public health hazards [4]

**Figure 1** The water-energy nexus and potential climate change effects on water utilities (Chan, own work).

# Theoretical framework

## *Industrial ecology*

The Conference Board of Canada (2007) notes that industrial ecology can help cities meet the sustainability and climate change challenge by providing the necessary framework for understanding, tracking and managing the energy, resources and wastes linked to human activities. Industrial ecology draws inspiration from the dynamics of both the human and natural worlds. The interdisciplinary and system-level field seeks to mimic and apply natural phenomena to anthropogenic artefacts and systems to develop more environmentally sustainable and symbiotic relationships. While whale fin-inspired wind turbines exemplify nature-based design and are welcome innovations, the core strength of industrial ecology thinking lies in teasing out the possibilities of broader ideas such as *closed loops* and *urban mining* – concepts that require fundamentally new ways of thinking about preconceived models and worldviews.

Recognizing the importance of ecosystems in supporting basic human needs and activities, the goal of industrial ecology is to avoid the generation of or to harness the hidden benefits of emissions, effluents and wastes. For systems, such as those involving water, fundamental principles include cyclical flows, renewable resources, low emissions, high recovery rates, and resilience through diversity (Brattebø 2012). Attainment of these objectives requires accounting for material and energy flows resulting from the various construction, operation and demolition activities. Whether to minimise the environmental impacts of a car or to improve the efficiency of industrial parks, a suite of tools is available to analyse system interdependencies at all levels from materials and products to the regional and spatial. The main methodological tools with respect to urban systems and relevant to this thesis are life cycle assessment and material flow analysis.

### *Life cycle assessment*

Life cycle assessment (LCA) is an increasingly adopted analytical tool by mainstream organisations. This approach typically focuses on consumer goods and products, where the environmental impacts across all phases of its life (from raw material extraction, manufacturing, use and end-of-life disposal) are brought forth and assessed. The general procedure for undertaking an LCA includes i) identifying the scope and system boundaries, ii) developing a lifecycle inventory to model the life cycle environmental inflows and outflows, iii) assessing the impacts to understand the environmental relevance of inflows and outflows, and iv) interpretation of the results.

LCA is a useful sustainability tool, yet is not without limitations. The quantification of impacts, such as health effects and toxicity, is not always clear-cut. Moreover, a cutoff point is always a necessary consideration for an LCA, and the point(s) in the production/consumption chain that is truncated will result in omissions of upstream/downstream processes. Nevertheless, the decision-making insights provided by LCA are helpful, and use of the tool continues to drive data reliability and overall development. More recent applications of LCA methodology focus on systems and services, such as waste management and oil extraction. This paper adopts a "stream-to-stream" LCA approach to assess the energy and greenhouse gas emission impacts of the urban water system.

### *Material flow analysis*

Material flow analysis (MFA) is a data analysis tool applied to a defined system. It uses mass balance principles to model the stocks and flows of a given resource or resources (material and/or energetic through the bounded system (Figure 2). As such, it can be applied at a variety of spatial scales, ranging from industrial processes to cities to entire national economies.

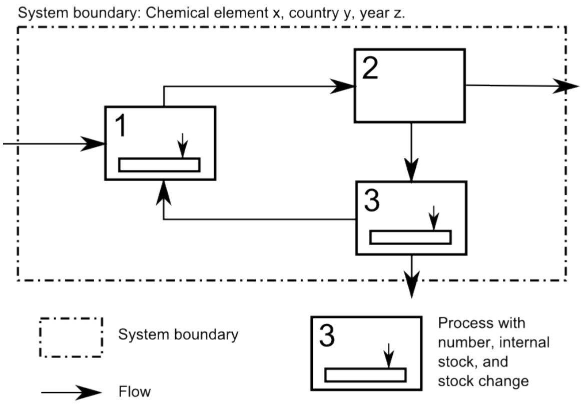


**Figure 2** Elementary MFA system, no quantification (Pauliuk 2011)

The fundamental principle of MFA methodology concerns itself with the mass balance theory, whereby mass conservation – mass cannot be created or destroyed – facilitates the calculation of unknown or highly variable flows. Thus, MFA lends itself well to early warning assessments, priority setting, and process and system designing particularly with respect to resource conservation (where scarcity is a concern) and waste management options such as recycling

(Müller 2012). Robust MFA analyses are dependent on extensive input and output data, which in practice are of variable quality. Some resources are well tracked nationally, some industrially and very few are well-monitored at the urban/regional scales. However, vast improvements to information technologies and economic transaction records compared to historical practices bode well for the increasing utility of this methodology.

### *Urban metabolism*

This paper also adopts the idea of urban metabolism, a concept derived from MFA and which frames the city or its sub-system as a "black box". In essence, the city is a complex system that calibrates, manages and configures various stocks and flows of resources essential to its aggregate functionality. Energy, water, capital, people, space and information are all aspects that can be analysed through their dynamic flux. The principle of sustainability – making do with less – can be met by reconfiguring the urban system into circular flows resources, rather than reinforcing the conventional linear logic of inputs and outputs in which raw materials are processed, packaged, distributed, consumed, and disposed. Abel Wolman undertook the seminal study in 1965 (United Nations University, 2003). Ensuing years have seen the metabolism concept applied to Hong Kong (Boyden & Celecia, 1981), Vienna (Brunner & Rechberger, 2004) and Sydney (Newman, 1999).

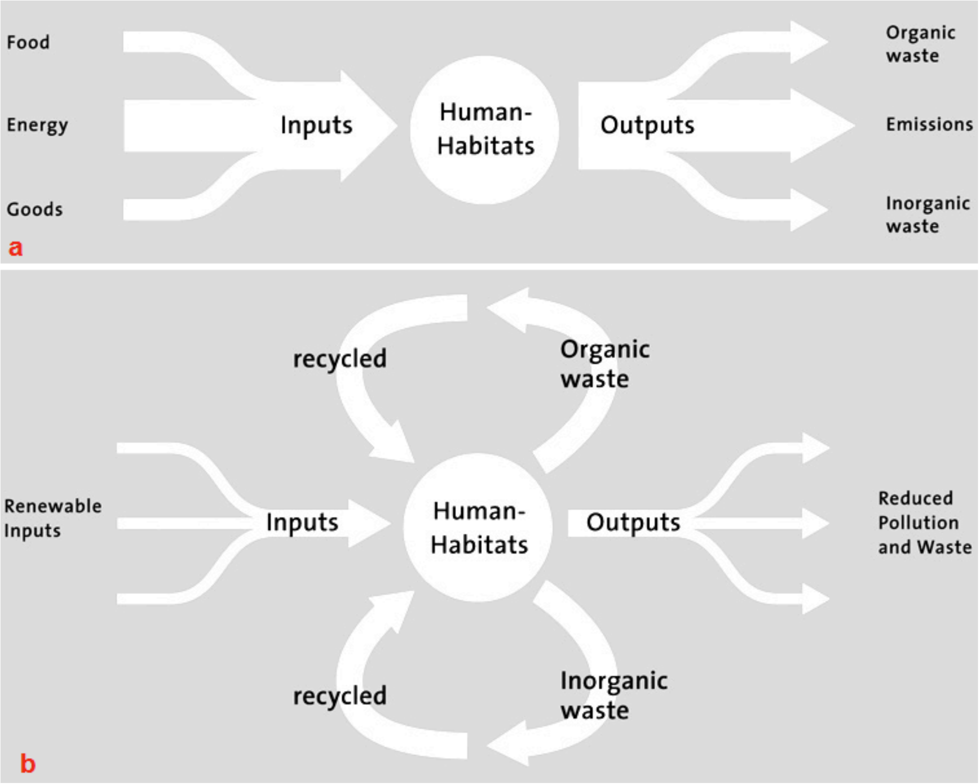


**Figure 3** Linear urban metabolism (a) with high consumption and pollution, and circular metabolism (b) with low input and high recycling rates (Rogers 1996).

## Objectives

Based on the above, this thesis seeks to provide insight into the characteristics of water-related energy consumption in cities. By developing an understanding of how cities and their urban water systems influence energy demands and the associated greenhouse gas emissions, the relationship will be applied to recommend approaches to water systems planning and climate change adaptation to meet the challenges of rapid urbanisation, increased service demands and unpredictable operating environments.

The structure of this paper is presented accordingly in three differentiated chapters. Chapter 2 provides a literature review on the *what* of the water-energy nexus and its current state of affairs. Chapter 3 analyses four case study studies to understand *why* the respective water and energy relationships are as they are, and provides intervention recommendations. Finally, Chapter 4 focuses more in-depth on Oslo to demonstrate *how* water-energy nexus considerations can inform the planning of urban water systems.

# CHAPTER 02 \\ What

# Perspectives on the Water-Energy Nexus

## Introduction

For the average individual, water is associated with a refreshing glass, a hot cuppa or a toilet flush. The material and energy investments required to produce this amenity are of a marginal concern given the relatively invisible nature of these inputs. Though hidden from plain sight as it is, energy is a considerable input throughout the production process. It is every bit an operational requirement, for example, for water pumping and distribution as it is a utilitarian one for heating it in our households to cook, shower and launder with. Deeper into the water system, the material and energy requirements are also noticeable and perhaps even more fundamental given the need for treatment chemicals and construction materials. Indeed, the standard water cycle that most urban authorities operate is a net energy consumer thus underscoring the importance of the background requirements for producing what is so crucial to comfort and cleanliness.

In the broader scheme of things, urban water systems may command a small fraction of total energy demand. However, this does not diminish the need for material and energy efficiency in the water sector given the circumstances and potential consequences laid out by environmental policies and commitments at the local, national and international levels (Hofman, Hofman-Caris et al. 2010). In light of climate change, every reduction in energy consumption and greenhouse gas emission is needed to avert physical and economic damage (Stern 2006). For urban water service providers, realising operational efficiencies and perhaps net energy provision is both a service and ethical imperative. In countries of all income levels, energy use (electricity in most cases) for water service provision is a rather significant budget item. In many cases energy can account for as much as 80 percent of the cost to treat and deliver water (Sandia National Laboratories 2005). In India, water supply was reported to be the largest expenditure item among all municipal services (ESMAP 2012). This along with rising population densities and increased climate change vulnerabilities combine to make efficiency gains at all stages of the urban water system fundamental considerations for municipalities around the world.

## The urban water system

For water utilities, the motive is fairly straightforward: distribute drinking water and collect and treat wastewater for residential, institutional and industrial consumers within the particular jurisdiction. A vast infrastructure is required for this throughout the service life cycle, and typical of most man-made constructs, the dominant urban water system in place is conceptually linear. Although these systems have performed relatively well in the strictest operational sense, it has made excessive water extraction and effluent release all too common while undermining the value of wet weather flows and wastewater. This has resulted in the modification of natural hydrologies and ecologies, and many adverse environmental impacts (Novotny 2010). Originally constructed as protection from disease and illness, it is ironically apparent that water infrastructure is putting life systems under extreme duress. Further understanding of the urban water system can be gained by examining each of the respective stages (Figure 4).

### *Raw water supply (Intake)*

In most municipalities, raw water is sourced from either ground wells or aquifers or surface water such as rivers and lakes. Intake and conveyance from the supply source requires construction materials to lay piping and establish conveyance pumps. The most important factor here is the energy required for operation of the latter, which is dependent of factors such as volume, distance and topography. However, demand for energy consumption may be near negligible if travel is fed by gravity.

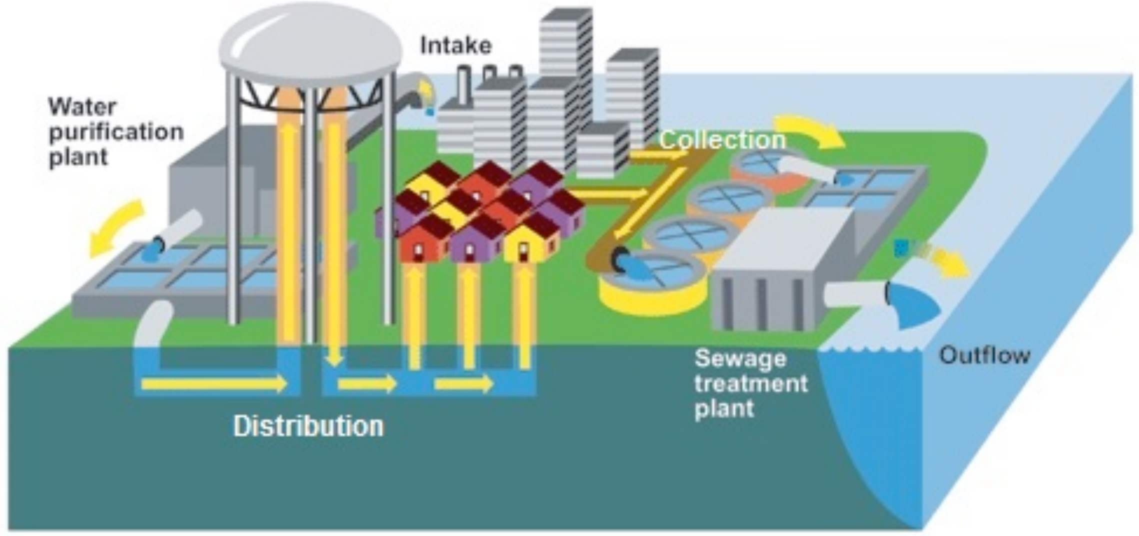


**Figure 4** The urban water system. Adapted from (Environment Canada 2011)

### *Water treatment*

Depending on the quality of the source, varying levels of treatment are required to bring the water up to acceptable public health standards. For large-scale municipal provision, this is achieved through chemical treatment in conjunction with mechanical multi-stage processes. Different treatment technologies are available, but between 2 and 3 percent of the world's energy consumption is used to pump and treat water for urban residents and industry (TRCA 2010). As with machinery, chemicals are a critical component of water treatment, which indirectly increases the overall energy budget through manufacturing processes and transport.

### *Water distribution*

A network of pipes conveys and distributes water from the treatment facilities into homes and businesses. Settlements are typically established above the water source, which necessitates electrical energy to pump water up ascending topography and throughout the network. Many of the networks in industrialised countries are centuries old. In London, England, for instance, the original cast iron pipes dating back to the 19th century are still in use. As is the case, water loss caused by pipe breakages is a common and critical concern. Leakages in well-run water utilities in OECD countries are in the range of 10-30 percent of water production, while they frequently exceed 40 percent and sometimes reach 70 percent in developing countries (OECD 2009). Given the process demands of the water treatment process, the production of water that never really fulfils its intended purpose is a drain on utilities, particularly as this ultimately incurs wasted chemical and energy investments. Even more, the repair and replacement of damaged water distribution pipes requires rehabilitation materials (ie lining, coatings, pipes, etc.), which indirectly increase the overall energy budget through manufacturing and transportation processes.

### *Wastewater collection*

From toilets, appliances and other household/industrial consumption demands, sewage passes along an array of sewer pipes ranging in different materials and sizes. These variances are reflective of the temporal and spatial characteristics of the system – the different pipe materials generally indicate particular eras and technologies, and larger pipes are laid to accommodate a convergence of flows from various parts of the service area. Two issues of concern for system operators are sanitary pipe corrosion caused by adverse wastewater composition, and combined sewer overflows caused by external wet weather flows such as rain and snow. The latter, if not directly discharged into the natural environment with little to no treatment (during extreme weather events), often cause a burden on the collection network and treatment facility, and incur unnecessary chemical and energy process demands. The repair and replacement of damaged sewer pipes requires material investments (ie linings, coatings, pipes, diesel, etc.), which also increase the overall energy budget through manufacturing and transportation processes.

*Wastewater treatment*

In the United States, wastewater treatment plants together with water treatment plants are typically the largest energy consumers of municipal government. By accounting for 30-40 percent of total energy consumption, this corresponds to over 45 M tons of greenhouse gas emissions annually (US EPA 2012). The reasons for this are generally the same as those in the water treatment process, where mechanical and chemical components make up the overall energy budget through manufacturing, transportation and operational processes. Moreover, the trend of increasing stringency required for effluent quality such as the recently enforced Wastewater System Effluent Regulations in Canada, and other similar legislation around the world, suggests a risk of problem-shifting whereby stricter treatment standards increases energy demands and climate change potential (Wang, Liu et al. 2012).

## Literature review

With population influxes and rising resource demands, operation of the urban water system will likely become a more pressing and daunting activity for local governments given the dynamics and implications at each stage of the service. Practically speaking, the provision of potable water and the assurance of clean water bodies is an energy intensive endeavour. With this, new developments in urban water management are emerging. Some municipalities have begun to implement a shift towards ecological sanitation models with even greater environmental benefits (Ministry of Sustainable Development 2004). For the majority of the case though, an argument can be made that the most sustainable choice is to work with the systems that are in place rather than build anew from scratch. Robbins (2012) notes that green infrastructure is becoming an important tool for capturing wet weather flows in a variety of cities. As for wastewater treatment, biogas and biosolids technologies continue to reach new frontiers in light of the fact that there is 2–4 times the amount of energy embedded in wastewater than it takes to treat (Lofrano 2012). More informed and nuanced planning and decision-making, however, is demanding a closer inspection and understanding of the water-energy relationship in various jurisdictions as this section demonstrates.

To understand the energy demands of water services, two viewpoints are helpful. On the one hand, a micro-scale analysis of a particular component or technology can yield benefits within a defined scope. A macro-scale analysis, on the other, takes into account multiple stages of the system to help guide more holistic solutions. Studies that deal with the former involve water source (Blanco, Newell et al. 2012; Sima et al. 2013), water treatment plants (Racoviceanu, Karney et al. 2007, Bonton, Bouchard et al. 2012), distribution (Venkatesh 2012), stormwater management (De Sousa, Montalto et al. 2012) and wastewater treatment (Pitas, Fazekas et al. 2010, Stillwell, Hoppock et al. 2010). While both perspectives are complementary, the main focus here will be on macro-scale studies, which indicate an increased adoption of systems thinking and analysis to yield more robust solutions for urban (water) sustainability.

### *North America*

Some of the earliest thinking on the water-energy nexus has been undertaken in the United States. The US Department of Energy (2006) reported to Congress on the interdependency of energy and water. While the request for the study focused on threats to national energy production resulting from limited water supplies, a chapter of the report is devoted to the energy requirements at various stages of the process for supplying water. The context of the report is so that it acknowledges the importance of municipal water systems and its role in overall sustainability.

In the preceding year, the California Energy Commission (2005) examined how energy is used and how it can be saved in the state's water use cycle (ie conveyance, storage, treatment, distribution, wastewater collection, treatment, and discharge). Aiming to address one of its highest priority infrastructure challenges, the study found that water-related energy use in California consumes 19 percent of the state's electricity, 30 percent of its natural gas, and 88 bn gallons of diesel fuel every year. With growing demand, the water-energy dynamic in the state is exacerbated by the fact that Northern California has two-thirds of the state's precipitation while two-thirds of the population resides in Southern California. On the basis of this study, the Los Angeles Department of Water and Power (2010) took the initiative to study the water-energy nexus and to evaluate the associated carbon footprint of its water system as part of its Urban Water Management Plan. The California Public Utilities Commission's Planning and Policy Division (2013) has more recently suggested that improving the overall efficiency of the water-energy nexus requires a portfolio management approach that balances technical constraints with the economic value of water and energy services.

Elsewhere in the United States, Minne et al. (2013) provide a brief comparison of the electricity consumption for water supply and treatment in Phoenix, Arizona and Atlanta, Georgia. They show that while the water-energy interdependence is five times greater in Phoenix, Atlanta also experiences turmoil with its water resources – cities are not the same and potential solutions vary a great deal. Ferrell et al. (2012) also report on the situation in Phoenix and surrounding cities, finding large variances in the energy required for water and wastewater treatment plants. Moreover, home water appliances are now the main drivers of electricity consumption associated with water. Perrone et al. (2011) developed a tool to quantify the water-energy nexus and the influence of geography on resource use in Tucson, Arizona. In terms of energy needed to deliver water, water from the Colorado River was the most energy intensive and averages 23 MJ per cubic m. This is nearly double the energy intensities of groundwater and recycled water sources. The large differences arise from energy use in the acquisition stage rather than local distribution and treatment. In terms of nexus energy (ie the energy for acquisition, municipal treatment, local distribution and end use), it accounts for 14 percent of Tucson's total electricity consumption.

Energy requirements for water-related services are also not well understood in Utah thus prompting a study by the state's water planning and development agency (2012). For a first glimpse at Utah's water-energy nexus, the Division of Water Resources examined the Jordan Valley Water Conservancy District, which delivers water to about half of the population living in Salt Lake County. It was found that due to natural geographic advantages (ie gravity-fed, high-quality snowmelt, and springs and groundwater requiring very little treatment) along with technology (ie trickling filter and sewage lagoon treatment) provide energy efficiency at each stage of water system. By extrapolating the results, it was estimated that Utah uses approximately 7 percent of its total energy budget to provide water, which is significantly less than that in California.

Looking at the water-energy nexus in Texas, Stillwell et al. (2009) found that the state uses an estimated 2.1 to 2.7 TWh of electricity for water systems and 1.1 to 2.2 TWh for wastewater systems each year. In preparing their study, the authors note that the trends and trade-offs between choices about water source and treatment technology need to be better understood, and that increased effort is needed on the part of authorities to collect electricity consumption data for public water supply and wastewater treatment plants and distribution systems. Furthermore, potential water, energy, transportation and carbon reduction policies implemented in isolation may likely have overall undermining effects if the interrelationships are not understood.

In Canada, Sahely and Kennedy (2007) modeled Toronto's urban water system to quantify economic and environmental sustainability. Among the findings is that energy recovery at the wastewater treatment process can provide approximately 9 percent energy savings and an associated 7.3 percent reduction in upstream greenhouse gas emissions. At the management level, Conrad et al. (2011) are developing a decision support system to help water utilities form a coherent strategy to understand their energy use situation and to address energy management and greenhouse gas emission issues.

### *Australia*

Significant insights into the water-energy nexus have also been formed in Australia. Lundie et al. (2004) carried out a life cycle assessment of Sydney Water's total operations as a basis for comparison to future scenarios, perhaps the first such study of an integrated water and wastewater system. Flower et al. (2007) applied a similar life cycle assessment approach to investigate the greenhouse gas emissions of Melbourne's urban water system to reveal that residential end water uses (ie showers, taps, appliances) are responsible for significantly more greenhouse gas emissions than all upstream and downstream operations – 2,320 kg $CO_2$ e per year and 7,146 kg $CO_2$ e based on gas and electric heating systems, respectively. This underscores the responsibility of water utilities to provide leadership in minimising water consumption among households.

Recent research has been operated under Australia's national science agency, the Commonwealth Scientific and Industrial Research Organisation. Kenway (2008) compiled operational energy data for water utilities operating supply and wastewater systems in Australia and New Zealand. In 2006/07, the total energy used for residential water heating amounted to 46 PJ, while the energy used by Australian water utilities was 7.1 PJ and approximately 0.2 percent of total urban energy use. The differences from city to city are reflected in local conditions including water use, topography, water sources, pumping distances and treatment levels.

### *Europe*

Amores et al. (2013) applied life cycle assessment methodology to carry out an environmental analysis of every stage of the urban water cycle in Tarragona, Spain. Because of high energy consumption, the main global warming potential impacts were caused by 35.2 percent of distribution network, 20.5 percent of collection pumping and 13.8 percent of wastewater treatment plant. In proposing possible scenarios to improve environmental performance, no improvements were observed under reclaimed water supplies, and performance worsened with desalination plants.

Also showing the adverse impacts of desalination plants (ie 74 percent of global warming potential) are Borghi et al. (2013), who performed a life cycle assessment of water supply in Sicily, Italy. By considering the collection, treatment and distribution stages of potable water through the regional network, and by excluding the use stage, water pumping and purification was calculated to demand 70 GWh per year. Water losses showed the next highest impact with 15-17 percent of the total global warming potential.

Rozos and Makropoulos (2013) adopt a metabolism modelling approach to simulate the complete urban water cycle from source to tap and back again in Athens, Greece. System modelling is also performed by Venkatesh and Brattebo (2011) in Oslo, Norway revealing that system sustainability is not merely a factor of water quality and quantity but also of the state of infrastructure. Of particular significance is the upstream network, which despite consuming half of the downstream energy per cubic m of water causes 22 percent greater greenhouse gas emissions.

In a detailed evaluation of the energy use in the water cycle of Amstelveen and Wijlre in The Netherlands, the operational energy for water treatment and transport, indirect energy from water treatment chemicals as well as energy for water heating were analysed (Hofman, de Graaff et al. 2012). Among the conclusions is that resource selection (eg deep groundwater wells or long transport distances) are considerable factors of operational energy, and that indirect energy related to chemicals is in the same order of magnitude as the operational energy. Another critical factor in the water cycle was found to be water heating, on average a factor 10 higher than the operational energy. Thus concluding that reducing warm water use and application of wastewater heat recovery can make large contributions to energy optimisation of the water cycle.

### *Low- and middle-income countries*

For the majority of urban water systems in the global South, integrated systems analyses are generally difficult as information is more difficult to find since several parameters are not measured (Lundin and Morrison 2002). As a result, energy efficiency improvements, which are still priorities for stakeholders such as international financial institutions and non-profits organisations, have been implemented on a stage by stage basis (Ijjaz-Vasquez 2005, ASE 2012).

Even so, there is a growing body of integrated analysis. Siddiqi and Anadon (2011) undertake assessments of the water-energy nexus in the Middle East and North Africa showing that energy dependence for water abstraction, purification and treatment is perhaps higher there than in other regions in the world. The Arabian Peninsula exhibits essentially an existential dependence on energy use for water obtained from the sea and underground aquifers. With growing evidence of ecological stress on the coast of some Gulf countries, water systems planning needs to account for a wider set of impacts before capital is locked into long-lived energy and water infrastructure.

Mehta et al. (2012) developed a metabolic framework for Bangalore, which has grown by 3 million habitants in a decade thus driving concomitant growth in water and energy demands. Like many Indian cities it relies on a mix of ground and surface water. The latter requires a network of 60 pumps, 52 reservoirs and 6,000 km of pipeline, resulting in a total energy consumption of 50 GWh per month and approximately 450 kt of $CO_2$ emissions. In terms of domestic water use, public supply causes 220 GWh per year and 165 kt $CO_2$ per year. By comparison, private supply (groundwater tables less than 100 m deep) results in at worst 164 GWh per year and 118 t $CO_2$ per year because the public supply is 100 km away and 500 m uphill.

Romero (2010) also illustrates the further complexities in developing regions such as Mexico City, where socio-environmental history and narrow interests contributed to a system with "absurd" energy expenditures and emissions. Pumping water from the Cutzamala system to the treatment plant west of the city of Toluca uses the same amount of energy consumed by the 1.5 million people in Puebla.

The global South also represents another dimension of the water-energy nexus, where there is inadequate energy to clean and distribute water – water without energy. Thus the challenge of addressing energy efficiency alongside universal service coverage in regions where billions are without energy access and with high urbanisation can be aided by integrated frameworks and urban metabolism models (Vairavamoorthy 2011).

### *Concluding remarks*

As the studies above show, systems and water-energy nexus planning can benefit from a multi-faceted approach involving ecological, social and cultural, economic complexities as well as historical perspectives. An increasing adoption of a systems-level approach to urban water sustainability is evident with on-going research related to the water-energy nexus. While most of the activity suggests more serious consideration in arid and water-stressed regions of the world, water-abundant cities would be wise to also pay heed to the issue as they are equally susceptible to the implications of rapid urbanisation and climate change. Appropriately, water-energy issues and perspectives are an increasing focus at the institutional level. Multi-lateral organisations such as the United Nations recently hosted a thematic debate on "practical solutions in the water-energy nexus" during the 67th session of the General Assembly (IISD 2013). The issue is a matter of national security for many countries, including the United States, whose military is applying its expertise to "help the nation make quantum leaps in energy and water use efficiencies" (Cardwell, Voinov et al. 2009). Academic collaborations, such as ReNUWIt, also aim to reinvent urban water infrastructure by developing breakthrough modular technologies and novel system-level approaches to substantially reduce energy use and related greenhouse gas emissions in water conveyance, treatment, distribution and reuse. In sum, these developments suggest that all aspects of society, not just city authorities, are coming to an understanding of how critical the dynamics of water and energy are and how industrial ecology thinking can help drive sustainable social and economic development.

# CHAPTER 03 \\ Why

# A Comparative Analysis of Oslo, Nantes, Toronto & Torino

## Introduction

### *Water and the city*

Water has been a fundamental factor of social development, and the advantages that it has afforded to human settlements are clear. China and India have long revolved around the Yangtze and the Ganges rivers. River floodings of the Nile in Egypt and the Tigris-Euphrates in Western Asia provided nutrient-rich sediment, which supported food production thousands of years ago and the world's earliest civilizations in the Fertile Crescent, including the first cities such as the Sumerian city-state of Ur. In North America, the transportation allowed by rivers is largely what made possible the development of Canada and its founding industry, the fur trade, further illustrating the effect of human adaptation to the natural conditions. More recently, the advent of water *management* has facilitated the modern city characterised by high population densities and a shift away from agrarian society. Particularly significant are the advancements in centralised water supply and sanitation in 19th century Europe that helped realise unprecedented health and safety standards with which (mega)cities would be hardly possible (Encyclopædia Britannica 2013).

The ability to extract, transform, distribute and dispose water at will, however, has altered our relationship with nature. With the flick of a wrist, water rushes into our homes and practically every building. But this convenience, thanks piping and drainage, has rendered us generally unaware of the fact that every interaction affects the quantity and quality of water that can be used. Despite its ubiquity, water is still very much a hidden element of the natural environment.

Whether in Bogotá, Berlin or Beijing, it is a common human tendency to take for granted what is not explicitly apparent. But it is also interesting to note the unique physical, cultural, social and economic characteristics of the world's cities. In a sense, water has facilitated the vast diversity encompassed in urban environments, but how does the urban environment influence the water-energy nexus? Building on four case studies of Nantes, Oslo, Torino and Toronto (Figure 5), this

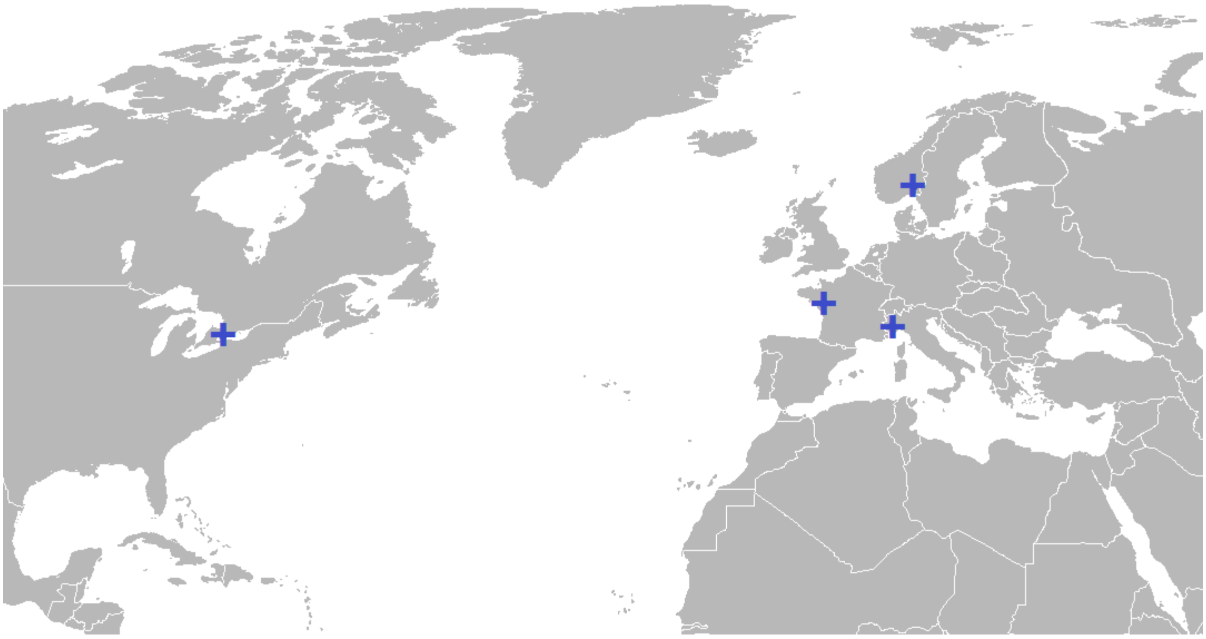


**Figure 5** Locations of case study cities – Toronto (Canada), Nantes (France), Torino (Italy) and Oslo (Norway)

section will analyse their local peculiarities (eg climate, socioeconomics, technology, geography, etc.) to develop an understanding of the extent of their effects on water-related energy consumption and greenhouse gas emissions to bring forth directions for process, program and policy interventions.

### *Accounting and characterising energy and emissions*

As action on climate change continues to focus on keeping global temperatures within two degrees of the pre-industrial revolution average, carbon emission policies and analyses driven by international summits and protocols in Kyoto, Copenhagen and Rio have been mainly framed at the national scale. City-level studies have been few, but cities are organising amongst themselves as it becomes commonly recognized that they are major contributors to global greenhouse gas emissions. Indeed, cities represent significant portions of national emissions, and comprise between 70 to 80 percent of emissions worldwide (Table 1). They are thus arguably the main catalysts for change, and numerous initiatives have been developed in light of this to better understand the variety of sources, contexts and patterns.

Various individual cities have taken the initial steps of conducting greenhouse gas inventories in recent years, but proper international standards and frameworks to effectively guide greenhouse gas accounting practices are lacking. A potential solution is the Global Protocol for Community-Scale Greenhouse Gas Emissions jointly developed by Local Governments for Sustainability (ICLEI), Cities Climate Leadership Group (C40), the World Bank, United Nations Environment Programme, and UN-Habitat. The initiative aims to harmonize emissions measurement and reporting processes for cities of all sizes and geographies in response to the increasing priority of accounting for greenhouse gas emissions in cities worldwide.

Emissions accounting in the water sector equally lacks harmonisation. The practice is very regionally driven and the main reason for this is because regulatory frameworks for emissions vary from country to country. In the United Kingdom, for instance, the regulatory needs are very clearly mandated, but greater uncertainty in the United States creates a mix of standards and procedures. In jurisdictions with no regulation, such as South Africa and Singapore, accounting is even more varied. Due to these differences, the methodologies and supporting tools adopted are tailored to the respective regulatory needs: clear reporting standards for all utilities in the UK, a mix of standards and mostly home-grown tools in the US, and global voluntary protocols or nothing at all for utilities where regulation is lacking (WRF 2013).

The main difficulties associated with city-scale greenhouse gas reporting consist of acquiring data at the urban level and interpreting the appropriate attributions. However, there are benefits to advancing efforts to standardise reporting processes: insightful temporal evaluations of subsequent emission inventories, improved support for urban policies, and stronger access to finances for city projects, as well as knowledge exchange opportunities between cities.

**Table 1** Comparisons of city and national greenhouse gas emissions, selected cities (Dodman 2009)

| City | GHG emissions per capita in tonnes of CO2 equivalent (year of study) | National emissions per capita in tonnes of CO2 equivalent (year of study) |
|---|---:|---:|
| **Europe** | | |
| Barcelona | 3.4 (1996) | 10.0 (2004) |
| Glasgow | 8.4 (2004) | 11.2 (2004) |
| London | 6.2 (2006) | 11.2 (2004) |
| **North America** | | |
| Washington DC | 19.7 (2005) | 23.9 (2004) |
| New York City | 7.1 (2005) | 23.9 (2004) |
| Toronto | 8.2 (2001) | 23.7 (2004) |
| **South America** | | |
| Rio de Janeiro | 2.3 (1998) | 8.2 (1994) |
| São Paulo | 1.5 (2003) | 8.2 (1994) |
| **Asia** | | |
| Beijing | 6.9 (1998) | 3.4 (1994) |
| Seoul | 3.8 (1998) | 6.8 (1990) |
| Shanghai | 8.1 (1998) | 3.4 (1994) |
| Tokyo | 4.8 (1998) | 10.6 (2004) |

Of course, greenhouse gas emissions in terms of human activity stems largely from energy consumption derived directly from fossil fuel combustion for electricity, heat and related processes. As such, exploring how and why urban environments contribute to greenhouse gas emissions demands understandings of the various respective elements. The complexity of urban systems makes it evident that a consistent albeit wide range of factors lends explanation to energy use patterns and greenhouse gas emissions. Not only are cities founded on inherent natural conditions, but they are situated at the confluence of technological and socioeconomic systems with their own identities, so to speak.

Kennedy et al. (2009) undertook a study of ten global cities to examine how and why greenhouse gas emissions vary between cities from an industrial ecology perspective. Of particular focus in the study were the transportation, building and waste management sectors. It showed that a balance of geophysical factors (climate, access to resources and gateway status) and technical factors (power generation, urban design, and waste processing) determine the greenhouse gas emissions that are attributable to respective cities.

Croci (2010) notes that energy use is strongly influenced in its extent and nature by specific urban features, namely the spatial structure of the city, its infrastructures and the characteristics of urban population and activities. Some of the key factors identified include socioeconomic features (eg elder/young ratio and labour force percentage), territorial characteristics (eg population density, dwelling density, availability of green spaces, and heating and cooling degree days) as well as transportation and waste management indicators (eg car ownership rates and amounts of solid waste collected).

Population is another key determinant of emissions to consider in addition to climate and natural conditions, economic base and affluence. Alber (2011) points to gender dynamics in particular, noting the differences in terms of wealth, behaviour and attitudes and how these may influence consumer behaviour.

Kenway (2008) compared water utility performance in Australia and New Zealand, and found that local circumstances and regulations have significant impact on the respective profiles. In some systems, conditions such as the location of treatment plants (eg elevation) and wastewater treatment processes (eg tertiary treatment) command higher energy use.

In California, the dramatically wide range of energy intensities in each part of the urban water chain depends on a number of highly variable factors (topology, hydrology and climate). But the two main drivers are the amount of water pumped and the quality of water subject to treatment (CPUC 2013). The United States Government Accountability Office (2011) identified several other factors that could explain how and why certain water-energy relationships are as they are. These include the type of water use customer, regulatory standards and system complexity.

Emissions accounting and analyses of cities is still relatively nascent, and efforts to assess how cities and their urban water systems influence water-related energy and associated emissions are less extensive. Moreover, the influence of non-physical factors (eg behaviour/culture, economics, existing infrastructure, local conditions, and decision-making processes such as regional planning) on water-energy linkages has not been determined (Kenway 2013). At this critical point in time, when infrastructure is in a state of disrepair in industrialised countries and in a state of emergence in lower income nations, these would be useful characteristics to help identify leverage points in the design of future systems that can support more sustainable cities.

## Background details and context

The results of the four previous assessments which quantified the energy and emission intensities of respective urban water systems will be assessed against each other to derive insight into some important considerations for water systems planning from a nexus perspective. Supplementary details to accompany the urban characteristics below can be found in Vachon (2012), Zappone (2012) and Chan (2012).

### *Case study I: Oslo, Norway*

Oslo was founded in 1048 by King Harald III and later established as a municipality on 1 January 1838. It was designated the capital of Norway during the 1300s and remains so to this day. With 560,000 inhabitants, Oslo is the most populous Norwegian city and has a corresponding population density of 1,230 per sq km. Given the city's northern latitude, winter months are cold and snowy with temperatures between –7 degrees C and –1 degrees C. The annual average temperature is 5.7 degrees C (Oslo Kommune 2008). There is moderate rainfall throughout the year with annual precipitation at approximately 763 mm. However, the city received 937 mm during the study year 2007. Snowfall occurs from November to April.

Oslo is among the world's wealthiest cities with a GDP per capita of 75,323 USD (OECD 2011). The local economy is varied, but is predominantly service-oriented and features significant financial, insurance and public administration organizations as well as research and development activities with particular emphasis on the maritime sector. With sustainable development as a major strategic focal point guided by the master plan, *Oslo Towards* 2025, and the Urban Ecology Program 2011-2026, the city often ranks high in various urban surveys.

Oslo Vann- og avløpsetaten (VAV) is the municipally-owned and self-financing company that manages the city's water supply (Figure 6) and wastewater systems. VAV is responsible for the operation, maintenance and renewal of the entire drinking water supply system, including the wastewater collection and transport system. The company provides oversight to the privately run Bekkelaget wastewater treatment plant, and financial support to the Veas wastewater facility.

### *Case study II: Nantes, France*

Maritime and river-based trade during the 15th century gave way to significant development in the town of Nantes up until its industrialisation in the 19th century. Nantes (Figure 6) is located in western France on the banks of the Loire River, and is one of the country's largest cities. The population during the study year 2010 was 590,000 corresponding to a population density of 1,140 per sq km (Vachon 2012). Nantes Métropole comprises of 24 towns and was established on 1 January 2001. Annual rainfall in Nantes has varied considerably during the past years ranging from 656 mm in 1990 to 889 mm in 2008 (EGC 2012), and totaled 690 mm during 2010 (Vachon 2012). Nantes is a temperate city with generally cool winters and mild summers.

The service sector has expanded considerably and now dominates the local economy. However, electric and electronic activities combined with the metallurgical industry (shipbuilding and aerospace) still represent the industrial core of Nantes. Agro-processing and biotechnology industries have also developed in connection with research laboratories (Urban Audit 2008). Per capita GDP measured in the Loire-Atlantique region is 27,395 USD (OECD 2011). Nantes was selected as the 2013 European Green Capital in recognition for environmental protection.

The city's Water Skill and Water Department manages the water supply, which in turn is operated by three entities: a public operator, the Community Authority, and two private operators. Wastewater treatment is under a similar management scheme of public and private operators. Overall, the public operator services 62 percent of the water utility subscribers and 68 percent of the wastewater service connections.

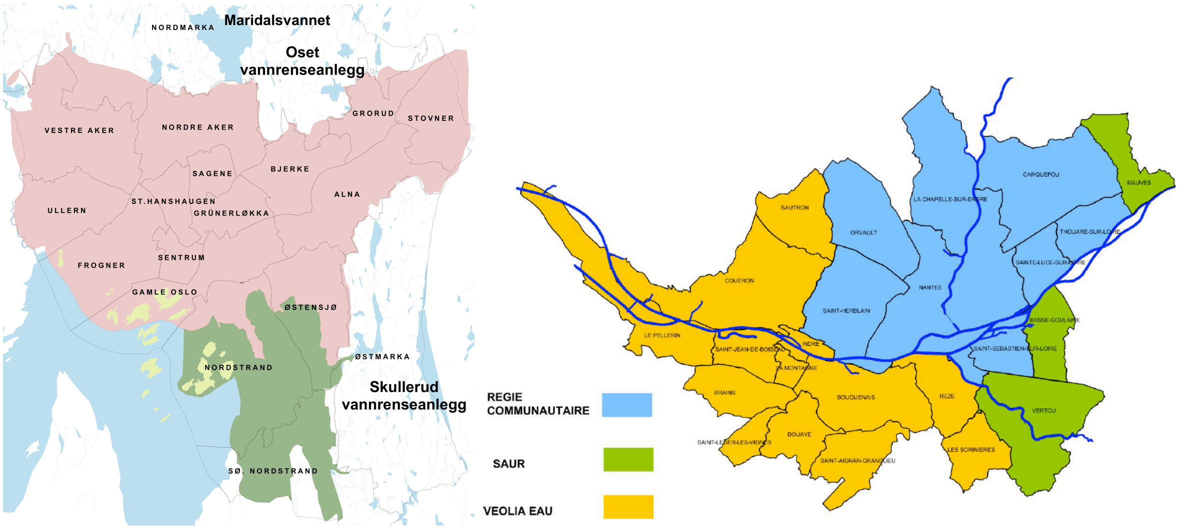


**Figure 6** *The urban boundaries of Oslo, Norway (Oslo VAV 2007) and Nantes, France (EGC 2012)*

### *Case study III: Toronto, Canada*

Toronto (Figure 7), an aboriginal word for "place where trees stand in the water", is found on the north shore of Lake Ontario. It began as a village at the mouth of the Don River, and was officially created in 1867 becoming the capital of Ontario province. An amalgamation of York, East York, North York, Etobicoke and Scarborough municipalities created in 1998 the City of Toronto, which now covers 630 sq km with a population of 2,615,060 making it the largest city in Canada. With 4,150 inhabitants per sq km, Toronto is considered a low-density urban area (Kennedy, Steinberger et al. 2009). Climatic conditions occupy both extremes with warm, humid summers and cold winters with temperatures frequently below –10 degrees C. Snowstorms are a common occurrence during winter from November to April with annual snowfall averaging 133 cm. Average precipitation is evenly distributed throughout the year and 936.8 mm of precipitation was received during the study year (Environment Canada 2011).

Generally known as the financial capital of Canada, Toronto is an international destination for business and financial firms while also serving as an important centre for life sciences research, business services and the creative industries. The local economy is primarily service-oriented with significant tourism, however, light industrial activity remains and contributes roughly 15 percent of the city's GDP (Invest Toronto 2013), particularly with food and textiles manufacturing. The cost of living is among the highest in Canada, and per capita GDP is measured at 34,228 USD (Toronto Board of Trade 2012). Toronto ranks consistently well in terms of livability and quality of life. It is among the most active North American cities in terms of environmental development implementing, for example, mandatory green roofs for large buildings and a lake water cooling system that reduces air-conditioning energy consumption in buildings by up to 90 percent.

Toronto Water delivers safe drinking water, treats wastewater and manages stormwater in the city. To this end, the entity manages more than $28 bn worth of assets for water production, transmission and distribution, wastewater collection and treatment, as well as storm water collection, transmission and treatment. It comprises six sections and together they serve under the guidance of the Safe Drinking Water Act, which regulates municipal drinking water systems, and the Ontario Water Resources Act, which focuses on sewage disposal and 'sewage works'.

### *Case study IV: Torino, Italy*

Among the cultural capitals of Italy, Torino is located in the Piemonte region of the northern part of the country. The metropolitan region spans approximately 6,713 sq km with a population of 2,200,000 (Zappone 2012). Population density stands at 328 per sq km. Contrasting the Mediterranean climatic conditions that characterise much of Italy, winters are relatively cold yet rarely below zero. Similarly, high but not excessive temperatures are experienced during the summer months. The proximity to the Alps makes for typically dry weather. Precipitation can be heavy, but is mostly restricted to late spring and autumn, averaging 752 mm.

GDP per capita in Torino is roughly 29,374 USD (OECD 2011). Historically considered as Italy's industrial powerhouse, Torino is no longer the "one company" manufacturing city that it once was. However, the province of Torino is still a major industrial centre, with car component and metal-mechanic industries forming the basis of the provincial economy (EUCO2 2011). Industrial production rose by 3.8 percent during 2006, and exports were up (for the first time since 2000) by 7.4 percent (Winkler 2007). There is also a concentration of engineering and aerospace industries being particularly important. The food and drink industry is also a large employer together with textiles, banking and insurance and the publishing sector. Innovation and knowledge-based sectors are providing a greater share of employment as Torino hosts a large number of research and development activities with the highest proportion of private research spending in Italy (Urban Audit 2008, Huxley 2010). Tourism is on the rise due largely to the 2006 Olympic Winter Games.

The Societa Metropolitana Acque Torino SpA provides integrated water services to the study area, Autorità d'ambito n.3 "Torinese" or ATO3 (Figure 7). This includes nearly 284 municipalities representing 93 percent of Torino province and 99.15 percent of its population (Zappone 2012).

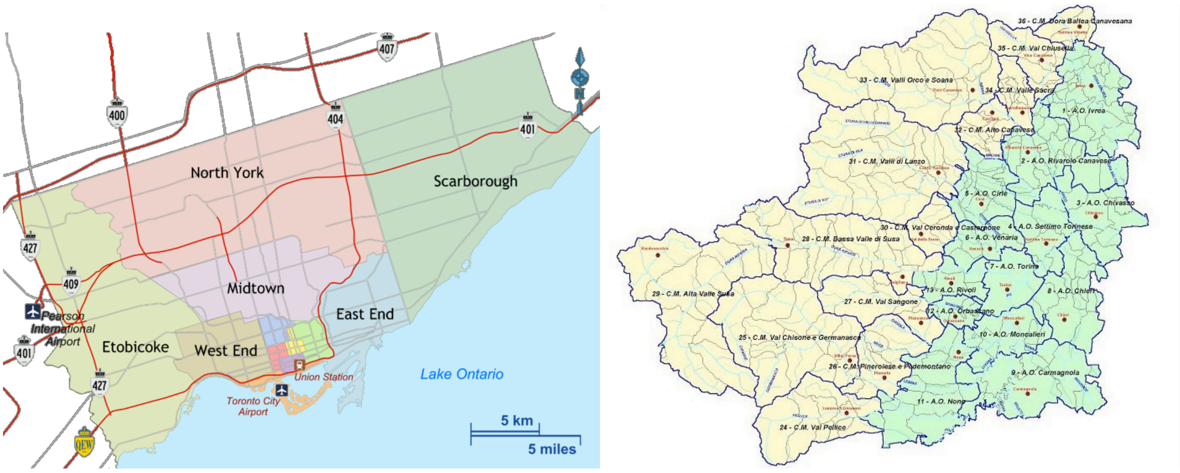


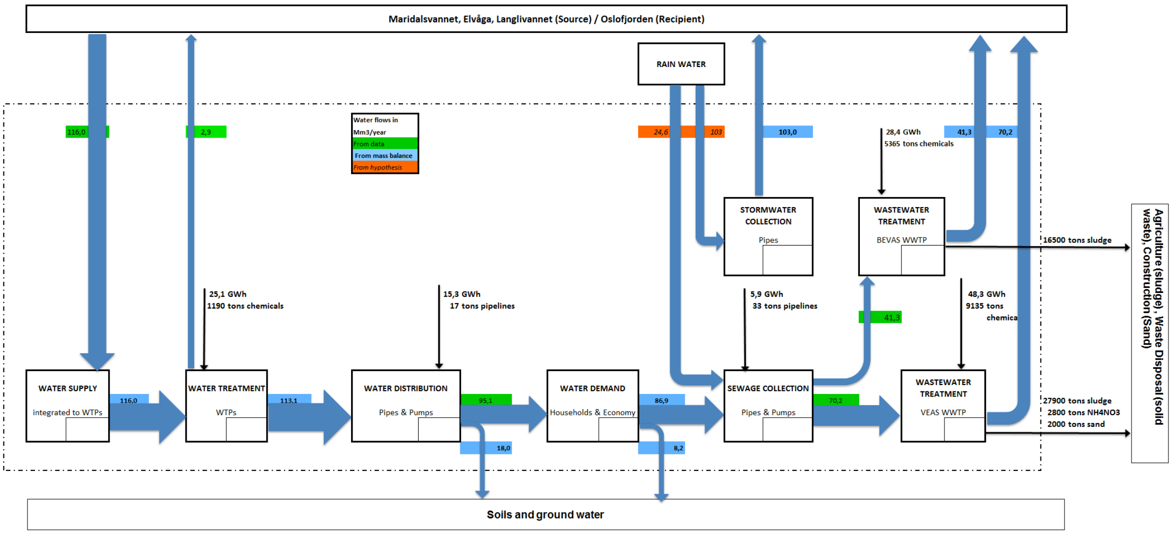
**Figure 7** The urban boundaries of Toronto, Canada (Shaundd 2013) and Torino, Italy

# Methodology

As it is with complex systems, additional insights can be gleamed from a greater analytical resolution. To understand the mechanisms and functionality of a watch, we can take it apart and examine the component pieces. Similarly, when trying to understand how much energy is consumed to acquire and use water, it is helpful to define different stages or segments (UDWRe 2012). Much like how climate policy breaks down the urban system into sectors and industries, we can similarly open up the black box of the urban water system and look at each stage to analyse internal dynamics and configurations to assess what contributes to what extent and why.

This in mind, the urban water systems and their respective metabolisms have been configured in the four previous studies (Figures 8 and 9). From these, the energy and greenhouse gas emission totals have been characterised at each stage of the system by taking into consideration the direct and indirect requirements (Appendix A). The manner in which they will be analysed is discussed below.

**Oslo**



**Nantes**

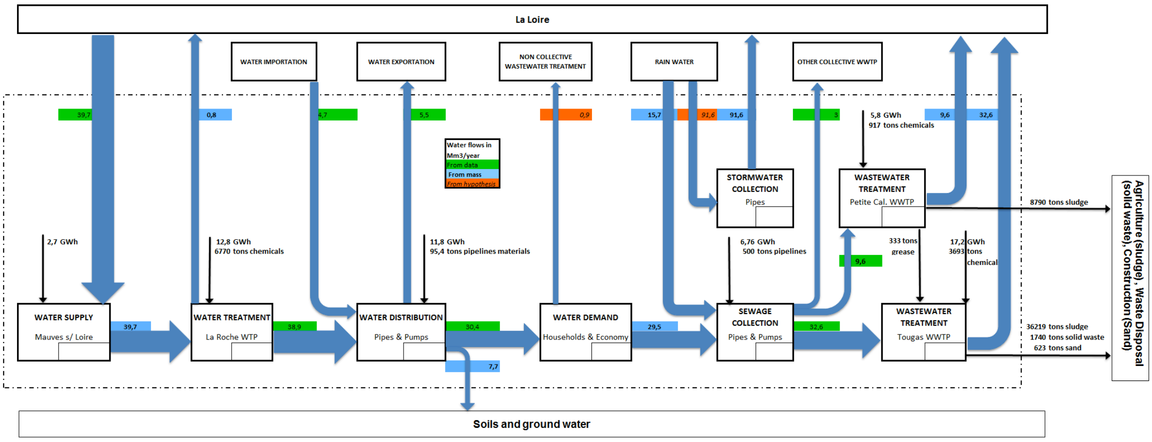


**Figure 8** Metabolic flows of the urban water systems in Oslo and Nantes (Vachon 2012).

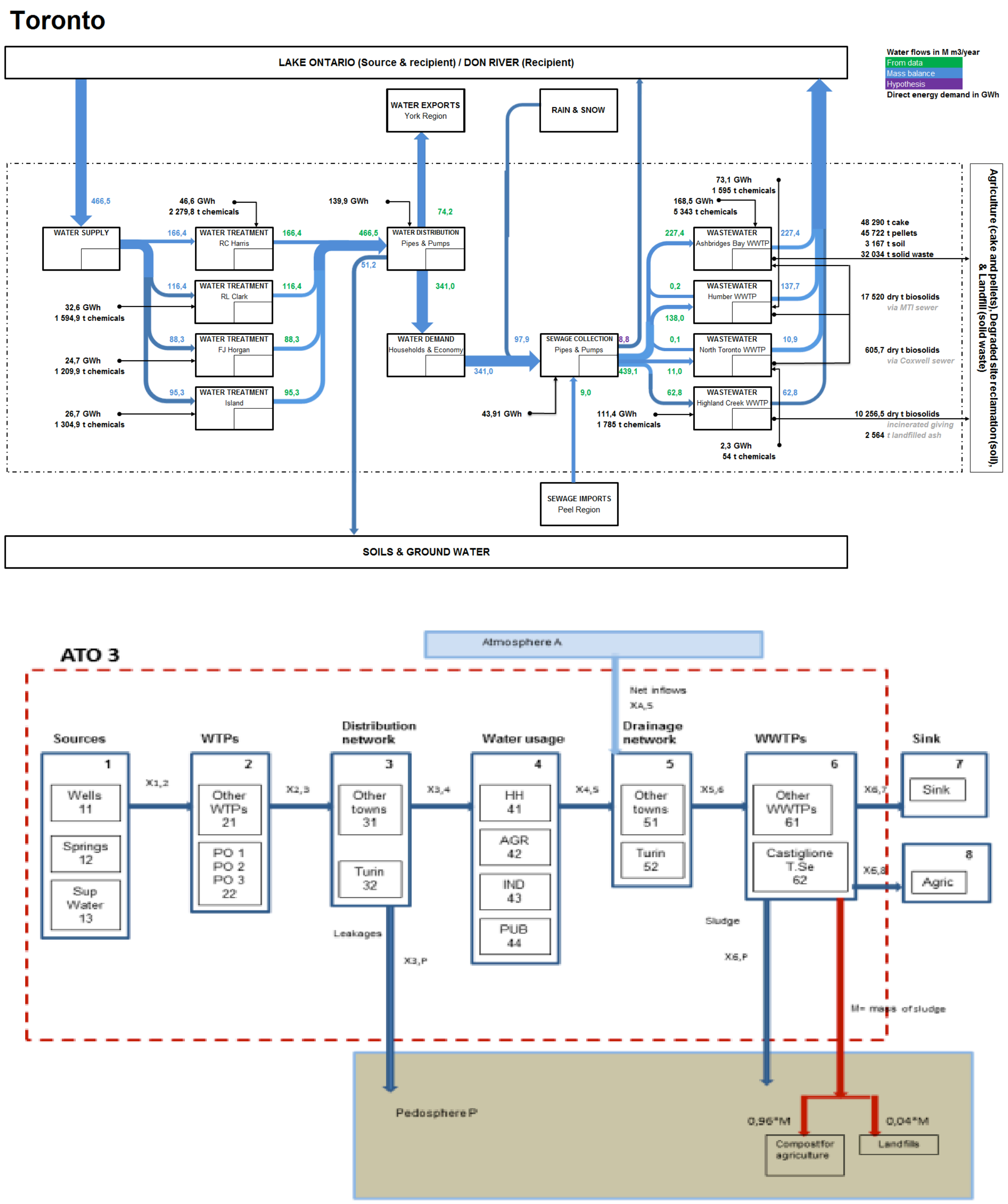


**Figure 9** Metabolic flows of the urban water systems in Toronto (Chan 2012) and Torino (Zappone 2012).

## *Scope of energy and emissions*

The inventory of system processes and elements are provided below (Table 2), however, it should be noted that the energy requirements for pipeline manufacturing, transportation and installation are omitted in the analysis due to a lack of system data in Turino and Toronto. Consequently, the carbon emissions for these aspects of the distribution and collection stages are not accounted for.

It is also worth mentioning that the nature of the water system in Torino makes precise material and energy accounting a difficult endeavour (Zappone 2012). The material and energy data relates to the area managed by Società Metropolitana Acque Torino, which oversees 90 percent of the system within the boundary, however, it is rather aggregated and is not wholly comprehensive with regards to each specific system element.

**Table 2** The scope of energy demands and greenhouse gas emissions considered in the metabolism studies

| Energy (GWh) | | I: Water Supply | II: Water Treatment | III: Distribution | IV: Consumption | V: Sewage Collection | VI: Wastewater Treatment |
|---|---|---|---|---|---|---|---|
| A - Direct Requirements | Fossil Fuels<br>Electricity<br>Heat | pumps | heat, processes, comfort, pumps | pipelines installation, pumps | beyond scope | pipelines installation, pumps | heat, processes, comfort, pumps |
| B - Indirect Requirements | Fossil Fuels<br>Electricity<br>Heat | | chemical manufacturing & transportation | pipelines manufacturing & transportation | beyond scope | pipelines manufacturing & transportation | chemical manufacturing & transportation |
| C - Energy Generation | Electricity<br>Heat | energy generated and used by utility | energy generated and used by utility | energy generated and used by utility | beyond scope | energy generated and used by utility | energy generated and used by utility |
| D - Avoided Energy | Fossil Fuels<br>Electricity<br>Heat | energy avoided outside utility | energy avoided outside utility | energy avoided outside utility | beyond scope | energy avoided outside utility | energy avoided outside utility |

| Greenhouse gas emissions (tons CO $_2$ eq) | | I: Water Supply | II: Water Treatment | III: Distribution | IV: Consumption | V: Sewage Collection | VI: Wastewater Treatment |
|---|---|---|---|---|---|---|---|
| A - Direct Emissions | Processes<br>NON-BIO<br>Combustion | | processes emissions, at plant heat | pipeline installation | beyond scope | pipelines installation | processes emissions, at plant heat |
| B - Indirect Emissions from Direct Consumption | Fossil Fuels<br>Electricity<br>Heat | pumps | processes energy, heat | pumps | beyond scope | pumps | processes energy, heat |
| C - Indirect Emissions from Indirect Consumption | Total GWP | | chemicals manufacturing and transport | pipelines manufacturing and transport | beyond scope | pipelines manufacturing and transport | chemicals manufacturing and transport |
| D - Avoided Emissions outside utility | Total GWP | emissions avoided outside utility | emissions avoided outside utility | emissions avoided outside utility | beyond scope | emissions avoided outside utility | emissions avoided outside utility |

### *Choice of indicator*

To compare the impacts of urban water systems, focus may tend towards either consumer behaviour and consumption patterns (per capita) or utility practices and adopted technologies (per cubic metre of water). Since the basis of this comparative analysis is primarily the service boundaries of the respective water utilities rather than a common geographic boundary (ie city, urban, metropolitan, etc.), one cubic m of water demand is applied as the functional unit. Furthermore, energy (kWh) per cubic m of water is among the suggested key performance indicators for water operations (Olsson 2012).

It is also helpful to determine what factors and variables affect the various stages of the urban water system. These are briefly discussed below and summarized by Table 3.

### *Factors: Raw water supply*

The extraction and conveyance of raw water can be an energy intensive process particularly in arid or stressed regions. In regions with limited freshwater supplies, desalination is a high energy technology that is typically used to source water. In places where water has been fully exploited, more audacious schemes are needed for water provision from salty, brackish water sources much in the same way that diminishing oil supplies are causing oil firms to explore deeper, more remote and risky environments. Spicewood, Texas relies on 7,000 gallon trucks to supply water four times a day, and a 300-mile pipeline is planned to distribute water to Las Vegas, where Lake Mead is drying up (Doig 2012).

In comparison, conventional water supplies (ie surface and groundwater) require less energy. Groundwater, however, typically requires more energy to pump than from a surface source since gravity has a higher likelihood of facilitating horizontal distribution than bottom-up pumping from underground aquifers. Nevertheless, distance may also increase energy intensity particularly if pipelines are exceedingly long and traverse variable topography (eg hilly terrain or mountain ranges).

### *Factors: Water treatment*

Water treatment facilities use energy to pump and process water, and this energy demand can fluctuate according to the quality standards that are adopted to provide acceptable colour and taste of drinking water. Preceding this, however, is the quality of the water to be treated – treatment of groundwater generally uses less energy than surface water because the initial quality is typically higher. This will obviously change from case to case though depending on the type and level of contamination. As a result, socioeconomic drivers such as the behaviour of upstream users and the activities undertaken by authorities to curtail adverse impacts on water supplies are large considerations.

Within the treatment facilities, energy demand is mostly a factor of electricity consumption for equipment and machinery. This can be affected by age with modern technologies providing more energy efficiency than those from previous generations (centuries, in some cases). At the same time, traditional treatment methods (eg chlorine dosage) can be more energy efficient than newer technologies, such as UV disinfection. The latter can account for 10-15 percent of a facility's total energy consumption (US GAO 2011).

### *Factors: Water distribution*

Topographical features that facilitate gravity pressurisation and distribution (eg when reservoirs are on higher ground than water users) can greatly reduce the energy demand for pumping and pressurising water. Conversely, if water users are located at higher elevations above sea level, mechanical pumping and energy consumption is required to deliver supplies.

With respect to the distribution system itself, energy demand generally increases with size, which to some extent is driven by the ideologies of planning authorities. Urban sprawl, for instance, commands greater infrastructural assets and investments (in terms of km of pipelines, at the very least). In any case, size is subject to a number of interpretations such as land coverage, the number of pumping stations and facilities or the structure of management entities, all of which shape the complexity of a system and the ability to manage data and operations. Additionally, technical aspects of the network (ie pipe materials, monitoring methods, and frequency and type of rehabilitation) play a role as well. Distribution networks are more susceptible to leakage and poor pressure management as they age, and if maintenance drops perhaps due to financial constraints, low priority and neglect, or lack of knowledge.

### *Factors: Wastewater collection*

Energy can be equally used to pump wastewater from homes to the treatment plant. As with the distribution system, topography can either help or hinder gravity. And in every bit the same way as in the preceding stage, the size of the network and its condition contribute to its relative performance. If pipes and equipment are nearing the end of their useful lives and are not properly upgraded, certain service levels become more difficult to meet. With the collection system, wet weather ingress, rather than leakage, is the main concern – a poorly maintained collection network can more easily allow water into the pipelines thus increasing overall energy consumption. Blockages are also important issues as tree roots, debris and deposits of fats, oils and grease can all cause friction and increase energy demands to properly convey water.

### *Factors: Wastewater treatment*

Residential sewage requires relatively less energy to process as compared to industrial wastewater, which is likely to contain higher levels of organic contaminants (some industries more than others). As a result, the type of water user dictates wastewater treatment facility investments. Aeration and filtration of wastewater at treatment facilities is a significant energy consumer within the overall urban water system. The composition of wastewaters received affects the type of treatment technology. Trickling filters or lagoon systems are low-energy processes, while the activated sludge process may require up to 70 percent of a facility's energy demands due to blower equipment that provides oxygen to sustain microorganisms (US GAO 2011). The estimated energy intensities for typical large wastewater treatment facilities in the United States are 0.177 kWh per cubic m treated for trickling filter; 0.272 kWh for activated sludge; 0.314 kWh for advanced treatment; and 0.412 kWh for advanced treatment with nitrification (ESMAP 2012). In Australia, advanced treatment commands on average 0.90 kWh per cubic m (Olsson 2012). Looking ahead, the regulatory trend involves increasingly more stringent treatment standards arising from concerns over nutrients and pollutants in water bodies. By increasing the required levels of treatment, utilities are likely to use more energy-intensive technologies (Wang, Liu et al. 2012).

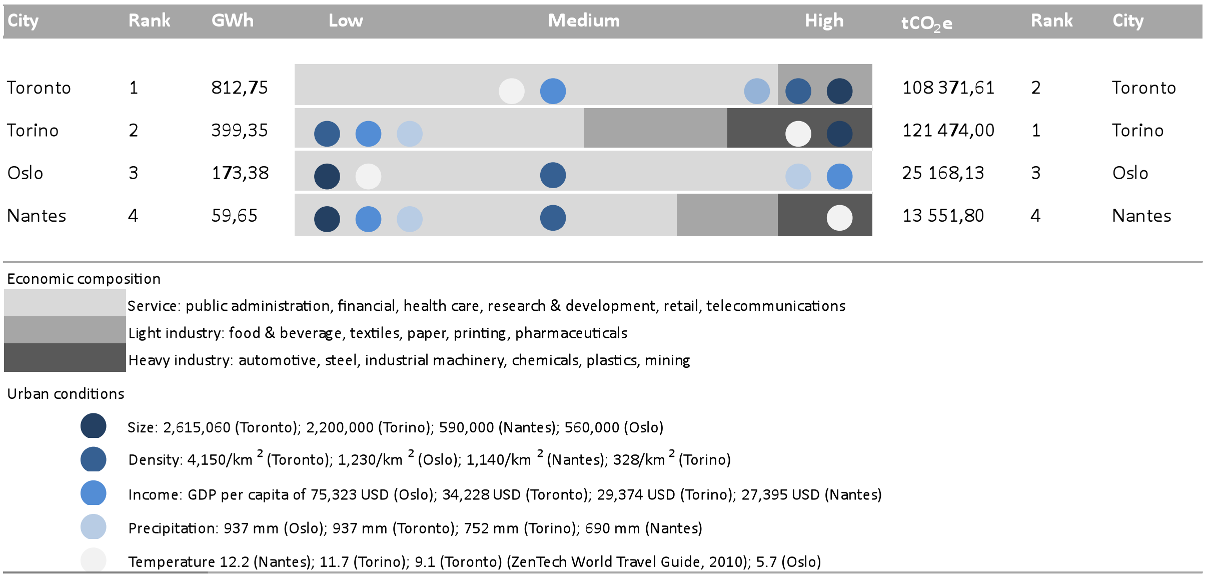
**Table 3** Prominent factors affecting energy demand in the urban water system

| Stage | Factor | Variable | General effect on energy intensity | |
|---|---|---|---|---|
| | | | − | + |
| Raw water | Climate | Water availability | Strong | Weak |
| | Geography | Water source | Surface | Ground |
| | Geography | Distance | Near | Far |
| Water treatment | Socioeconomics | Water quality | High | Poor |
| | Technology | Treatment equipment | Old | Modern |
| | Technology | Treatment process | Chlorination | Ozonation |
| Distribution | Geography | Topography | Gravity-fed | High elevations |
| | Socioeconomics | Network size | Small | Large |
| | Technology | System condition | Old | New |
| Collection | Geography | Topography | Gravity-fed | High elevations |
| | Socioeconomics | Network size | Small | Large |
| | Technology | System condition | Old | New |
| Wastewater treatment | Socioeconomics | Use and consumer type | Domestic | Industry |
| | Technology | Treatment equipment | Old | Modern |
| | Technology | Treatment processes | Trickling filter | Anaerobic digestion |

# Results

Table 4 represents preliminary perspectives on system performance based on the local urban conditions and the overall results of the studies. It is apparent, for example, that city size shows a clear affect on overall utility performance – Toronto and Torino being significantly larger than Oslo and Nantes in terms of population thus requiring greater service needs and resources. Moreover, industrial activity appears to have marginal impact on the water-energy nexus as economic activity in Torino is more reliant on industry than Toronto, but shows only slightly more environmental impact. Similarly, industrial activity in Oslo is practically non-existent as many large water consuming companies have moved out of the city (Oslo Kommune 2008), however, there is still greater energy consumption and emissions comparative to Nantes. This is an indication that factors do not operate in isolation from each other and are, of course, influenced by others (of equal

**Table 4** City typologies and the associated energy and emission impacts



| City | Rank | GWh | Low | Medium | High | $tCO_2e$ | Rank | City |
|---|---|---|---|---|---|---|---|---|
| Toronto | 1 | 812,75 | | | | 108 371,61 | 2 | Toronto |
| Torino | 2 | 399,35 | | | | 121 474,00 | 1 | Torino |
| Oslo | 3 | 173,38 | | | | 25 168,13 | 3 | Oslo |
| Nantes | 4 | 59,65 | | | | 13 551,80 | 4 | Nantes |

Economic composition

Service: public administration, financial, health care, research & development, retail, telecommunications

Light industry: food & beverage, textiles, paper, printing, pharmaceuticals

Heavy industry: automotive, steel, industrial machinery, chemicals, plastics, mining

Urban conditions

- ● Size: 2,615,060 (Toronto); 2,200,000 (Torino); 590,000 (Nantes); 560,000 (Oslo)
- ● Density: 4,150/km$^2$ (Toronto); 1,230/km$^2$ (Oslo); 1,140/km$^2$ (Nantes); 328/km$^2$ (Torino)
- ● Income: GDP per capita of 75,323 USD (Oslo); 34,228 USD (Toronto); 29,374 USD (Torino); 27,395 USD (Nantes)
- ● Precipitation: 937 mm (Oslo); 937 mm (Toronto); 752 mm (Torino); 690 mm (Nantes)
- ● Temperature 12.2 (Nantes); 11.7 (Torino); 9.1 (Toronto) (ZenTech World Travel Guide, 2010); 5.7 (Oslo)

or greater importance). Oslo and Nantes are fairly equal in terms of population density, yet there is a high variance in energy demands. Population density also illustrates the potential differences of water-energy policy from other aspects of urban sustainability policies. In Toronto, higher density and the corresponding energy requirements to pump water up taller buildings could be a factor in why there is only slightly less emissions than a less dense area such as Torino. This would run counter to transportation policy where increased density is known to decrease emissions, thus highlighting the dynamism of urban systems which can be further highlighted at each system stage.

### *Raw water supply*

For the most part, the four cities are located in countries with low levels of water stress. Canada and Norway especially are and will continue to be abundant in water supplies for the foreseeable future (Smith 2010). Water stress forecasts in European river basins by 2030 indicate that France will continue to have adequate water supplies in 2030, but Italy may deal with a moderate amount of water stress (EEA 2008).

Oslo draws water from surface sources in the 330 sq km forests surrounding the city. The city's two water treatment facilities are located in relatively close proximity to their sources. The Oset water treatment plant relies on Lake Maridalen, which receives a yearly average inflow of 184 M cubic m, and is pumped directly into the facility (Figure 10). Water into the Skullerud water treatment plant is normally gravity-fed through a 4 km long tunnel from the Elvåga lakes located in Østmarka (Oslo VAV 2008).

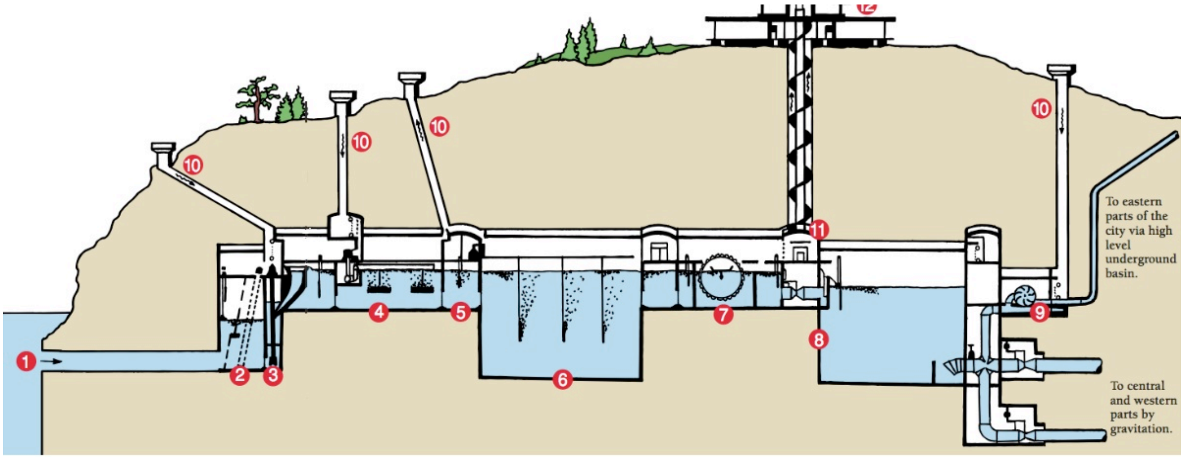


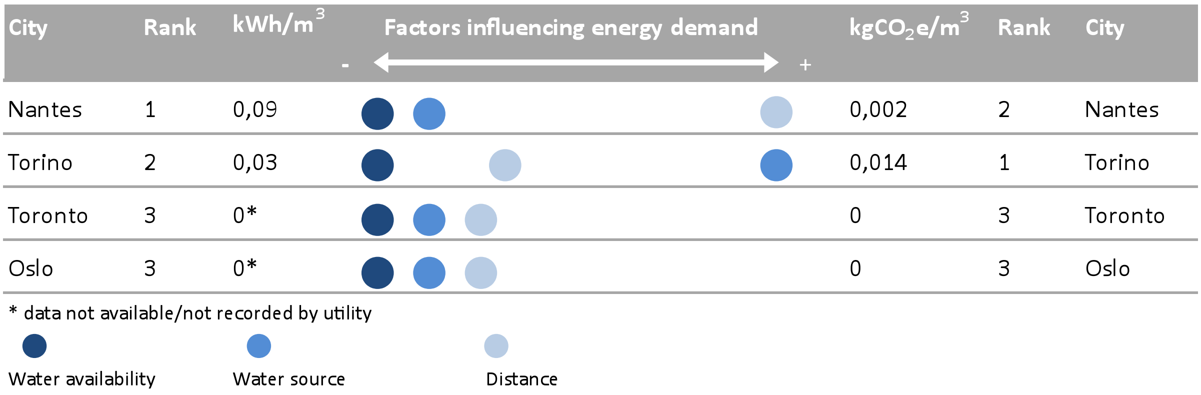
**Figure 10** Treatment process at the Oset water treatment facility (Oslo VAV 2008)

The Loire River is the longest river in France and stretches 1,010 km. The average flow of the river is 500 cubic m per second, and Nantes withdraws from it a flow of approximately 1.53 cubic m per second, thus only 0.3 percent of the average flow of the Loire (EGC 2012). Water that is extracted must first pass through the supply station in the commune of Mauves-sur-Loire before proceeding 15 km upstream to La Roche, the main treatment plant in Nantes Métropole. As such, it can be assumed with a good deal of certainty that a fair amount of energy is needed to transport water (Vachon 2012). Indeed, 0.09 kWh per cubic m is required in Nantes – more than any of the other cities (Table 5).

Toronto's reliance on well water discontinued in 1953 upon the creation of Metropolitan Toronto, which assumed responsibility for water services in Toronto and the surrounding towns. Lake Ontario, one of North America's five Great Lakes, became and is still the city's only water source. Its management is generally not a problem given that Toronto's annual consumption is less than one tenth of one percent of the Lake's volume (Metropolis 2002). As a whole, Lake Ontario represents roughly one percent of the world's total freshwater supply with approximately 1,640 cubic km. Three of the city's four water treatment plants are spread out directly along the lakeshore and one is located on Centre Island. The longest of the intake pipes extends 5 km offshore into the source. The RL Clark facility, for example, depends on a 1.6 km intake pipe, and because the plant is at the same level as the lake, water can flow without being pumped (Stahlman 2010). Thus, no energy is required to extract water in Toronto, as in Oslo, and this can explain why neither utility can avail of energy data for this particular stage of the water system.

Torino and the region's water supplies depend on a harmony between the Alp Mountains, the glaciers and its rivers. The Po River is a major Italian river with a basin that covers almost the whole northern part of Italy. This, however, is merely one water source for Torino from which almost 37 M

**Table 5** Energy demand and emission intensities for raw water extraction



| City | Rank | kWh/$m^3$ | Factors influencing energy demand<br>- ⟵⟶ + | kg$CO_2$e/$m^3$ | Rank | City |
|---|---|---|---|---|---|---|
| Nantes | 1 | 0,09 | ● ● ● | 0,002 | 2 | Nantes |
| Torino | 2 | 0,03 | ● ● ● | 0,014 | 1 | Torino |
| Toronto | 3 | 0* | ● ● ● | 0 | 3 | Toronto |
| Oslo | 3 | 0* | ● ● ● | 0 | 3 | Oslo |

* data not available/not recorded by utility

● Water availability
● Water source
● Distance

cubic m of water is derived annually. On the whole, surface water makes up 16 percent of the drinking water supply. The overall annual flow is approximately 300 M cubic m with 1,550 uptake points (Zappone 2012). Over 75 percent of the supplied water comes from groundwater wells, which are fed by water tables 40 to over 100 m deep (SMAT 2012). This is reflected in the relatively high amount of emissions caused by the energy demands for pumping.

### *Water treatment*

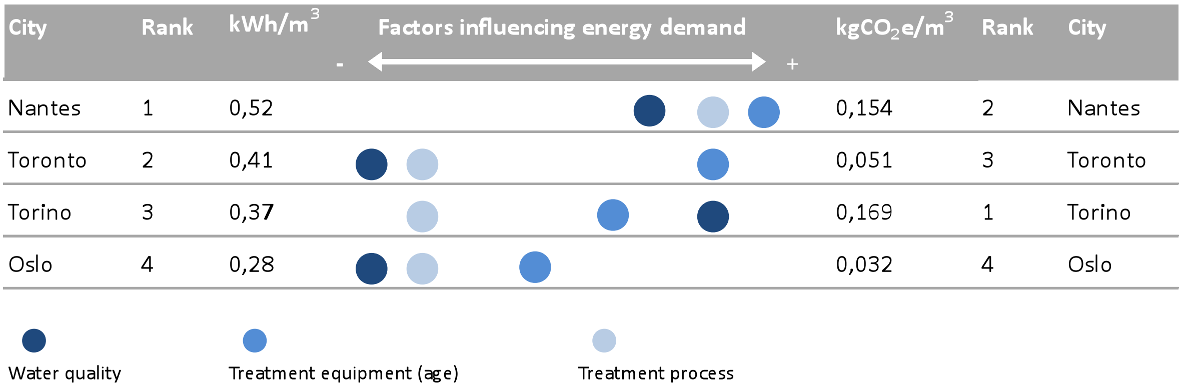
While the history of Oset can be traced to 1866, the new and current facility was opened in 1971. Skullerud covers around 10 percent of Oslo's water requirements and Oset supplies 90 percent, which comes from snow and rain precipitation fields in the forests and hills surrounding the city. Severe restrictions have been enforced for over one hundred years in these areas around intake points and the neighbouring upstream lakes and rivers, and include limitations on swimming, fishing, boating, picnicking and over-night camping (Oslo VAV 2008). All of this ensures high-quality raw water even prior to arrival at the treatment plants thus requiring merely 10.5 g of treatment chemicals per cubic m of water (Vachon 2012). The general treatment process at both facilities involves screening, alkalisation (with lime and carbon dioxide), coagulation, filtration with sand and plastic granules, UV disinfection, and acidity adjustments. The UV system has made previous chlorination treatment unnecessary (Oslo VAV 2008) and while this can be energy intensive, the relatively high water quality in Oslo would only require low temperature lamps (ie low energy) to generate the UV wavelengths for destroying micro-organisms.

The La Roche treatment plant produces nearly 40 M cubic m of water annually. Constructed in the 1970s, the actual facility is in effect much older dating back to the 1900s, and is currently undergoing renovations to meet regulatory requirements (Gambert 2013, SAGE Estuaire Loire 2013). The Loire River's water is of questionable quality and generally high turbidity is a reason why water must be first sourced 15 km away (Vachon 2012). Likely culprits of pollutants are the pesticides and herbicides containing glyphosate, which are widely used by homeowners (Lamprea and Ruban 2011). As a result, there is a significantly higher consumption of treatment chemicals in Nantes (174 g per cubic m of water) compared to Oslo (Vachon 2012). Owing to cultural reasons and the dislike of customers for the smell of chlorine, ozonation is the primary disinfection procedure – only an infinitesimal dose of chlorine (a few drops per thousand litres) is applied (Gambert 2013). The high energy requirements of ozone treatment systems (WRF 2013) together with very old treatment equipment and low water quality brings about a very high energy and emissions intensity at this stage of the urban water system in Nantes (Table 6).

Toronto's first treatment facility is the Island facility, but RC Harris remains the largest and produces nearly 50% of the city's water demand. The other two facilities began operations in 1968 and 1979, respectively. Lake Ontario's water is quite clean and, with the exception of sand and grit removal, is difficult to purify any further (Kupferman 2011). Nevertheless, all water passes through a multi-barrier treatment process that includes screening, coagulation, flocculation, sedimentation (in two out of the four facilities), filtration, disinfection, fluoridation and ammoniation. Naturally occurring compounds in the lake affect taste and odour during late summer, but these are easily counterbalanced. Toronto became one of the first cities in North America to use chlorine for water treatment and continues to be a leader in the field today, with super-chlorination, de-chlorination and pre-chlorination (City of Toronto 2012). This strong dependence on chlorination indicates that the relatively high energy demand during the treatment is because of electricity to operate equipment. This corresponds with the background data, where direct energy is the largest demand (Appendix A). Indeed, the pumps at the RC Harris facility, installed during constructed in the 1930s, were built to last and still remain in use (Kupferman 2011).

There are more than 150 water treatment plants in Torino, which is generally one for every municipality in the region (Zappone 2012). They together treat 42 percent of the total drinking water. The main treatment facilities based on surface water – Po 1, 2 and 3 – were constructed between 1959 and 1964, and most recently in 1981. The primary treatment method is chemical-based with chlorine, whereas UV disinfection is less common. A lagoon has been able to cap chemical expenses since 1994. As a result, 30 g of chemicals per cubic m are consumed, and a further important point of distinction is that a portion of these chemicals are delivered from Indonesia (Zappone 2012) – a likely factor in the high carbon emissions. While the chemical quantities consumed are significantly less than those in Nantes, it is still roughly three times more than Oslo. This is perhaps not surprising given the historical abuse of Torino's water supply. The Po

**Table 6** Energy demand and emission intensities for water treatment



| City | Rank | kWh/m$^3$ | Factors influencing energy demand (- ⟷ +) | kgCO$_2$e/m$^3$ | Rank | City |
|---|---|---|---|---|---|---|
| Nantes | 1 | 0,52 | ● ○ ◉ | 0,154 | 2 | Nantes |
| Toronto | 2 | 0,41 | ● ○ ◉ | 0,051 | 3 | Toronto |
| Torino | 3 | 0,37 | ○ ◉ ● | 0,169 | 1 | Torino |
| Oslo | 4 | 0,28 | ● ○ ◉ | 0,032 | 4 | Oslo |

● Water quality ◉ Treatment equipment (age) ○ Treatment process

River has been adversely affected by untreated sewage discharges from Milan, excessive amounts of benzoylecgonine, and a 600,000 litre oil spill in 2010 (Wikipedia 2013). Another concern for local water authorities with respect to groundwater supplies is the high levels of industrial halogenated compounds and nitrate pollution from agricultural, civil and industrial activities (Roveri, Genon et al. 2000).

### *Water distribution*

From the Skullerud treatment facility, some of the water supplying Lambertseter and Søndre Nordstrand is pumped up to reservoirs 236 m above sea-level, while other areas such as Homlia/Prinsdal and Østensjø are gravity-fed (Oslo VAV 2008). The majority of Oslo's water is produced at the Oset treatment facility, and from here there are eight pumping stations that carry the water 110 m up to the Årvoll reservoir. However, the rest is gravity-fed via the Grefsen tunnel and Nydals pipeline (Oslo VAV 2008). The distribution network with 1,500 km of pipelines (Vachon 2012) consumes the least amount of energy and is by far the smallest in size of the four cities. This is a product of local planning history and philosophy. Two-thirds of the city's area is actually intact blocks of forests, which have high social and cultural value among residents. This has combined with government policies to make the expansion of urban development into these areas legally and politically difficult despite persistent pressures (Beatley 2012, Perez 2013).

Nantes is relatively equal with Oslo in terms of population, however, the distribution network is more than double in size with 3,100 km of pipelines (Vachon 2012). In addition to the length of the network, the water intake point from the Loire River is merely 6 m above sea level, and as a result requires greater energy on a per unit basis to bring water up to many parts of the service area that are 50-60 m above sea level (Vachon 2012).

Significantly larger in size is Toronto's distribution network with 528 km of trunks and 5,427 km of water mains. The network is aided by ten reservoirs and four holding tanks, which manage supply during peak and off-peak intervals to lower energy costs. Nevertheless, the distribution system commands the most energy of all (Table 7), and this can be largely attributed to the 18 pumping stations that convey water up to the city's highest elevation points at 270 m above sea level.

As a distribution network ages, investments are necessary to ensure an upkeep of the required service levels, to decrease leakage rates and pipe failures, and to optimise energy and pressure management. A common estimation of leakage in Oslo's network, which has an average age of 51 years at the end of 2006 (Venkatesh 2011), is 20 percent as is the case with Nantes (Vachon 2012). The network in Toronto, with an average age of 54 years (City of Toronto 2012), has been estimated to experience a loss of 9 to 10 percent (Spears 2007), but 15 percent, at least during the study year 2011, is a more likely figure (Chan 2012). The situation in Italy is somewhat different with national statistics indicating 31.7 percent water loss in the Piemonte region (GWI 2010) and reportedly up to 70 percent leakage rates in Italian cities (EurActiv 2012). From this, it is a reasonable assumption that Torino's network lacks adequate maintenance and operates at low energy efficiency.

Nevertheless, it compares favourably to Toronto with a similar service population of +2 million inhabitants. A likely reason would be the hundreds of water treatment facilities within the system. So despite covering more surface area including many mountainous zones and high elevation points also 200 m above sea level, treatment plants are likely within close proximity to customers and require less pipelines and energy to convey and pump. Based on the total land area, each treatment plant in Torino covers 43.59 (157.5 sq km in Toronto).[1] This would suggest a benefit of "decentralised" urban water systems that is worth looking into.

### *Wastewater collection*

A simple assessment of the effect of topography on the collection system would be to assume the reverse of the distribution system (ie if drinking water travels upwards, sewage must be gravity-fed). Gravity certainly does have a role in wastewater collection, however, another angle to characterise energy demand at this stage would be based on the number of pumping stations. Oslo operates the least number of pumping stations in its network (2,200 km) with 65, which yields very low energy and environmental impacts. At the other end of the spectrum is Nantes, where there are 378 pumping stations despite a relatively small network of 3,530 km of pipelines.

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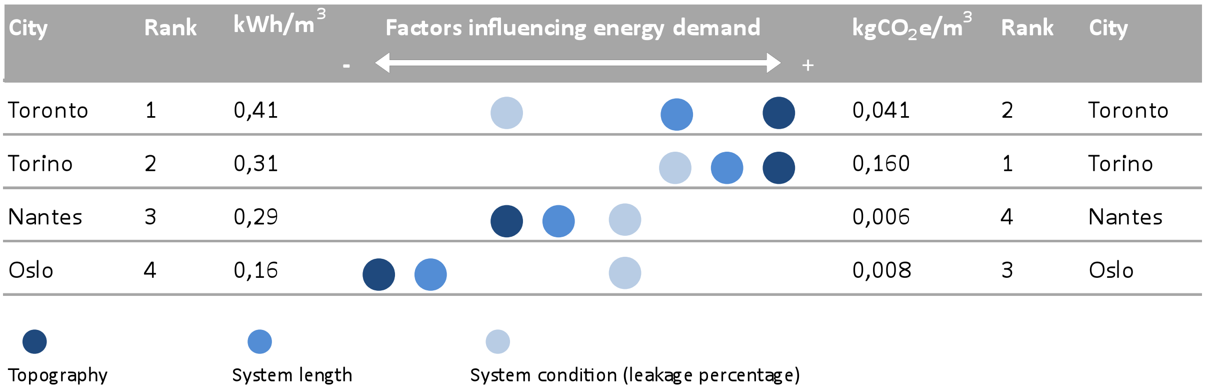
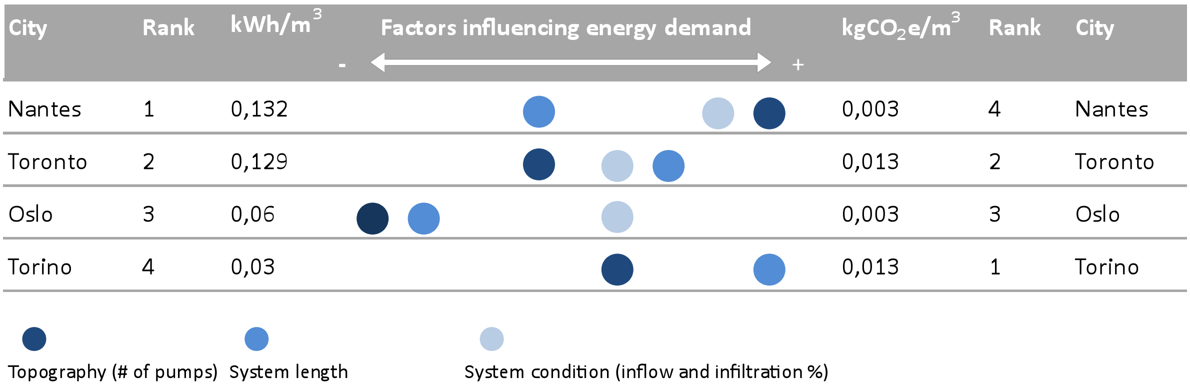
[1] Total land area divided by the number of water treatment plants (eg 6,713 sq km / 154 facilities).

**Table 7** Energy demand and emission intensities for water distribution



| City | Rank | $kWh/m^3$ | Factors influencing energy demand<br>- ⟷ + | $kgCO_2e/m^3$ | Rank | City |
|---|---|---|---|---|---|---|
| Toronto | 1 | 0,41 | | 0,041 | 2 | Toronto |
| Torino | 2 | 0,31 | | 0,160 | 1 | Torino |
| Nantes | 3 | 0,29 | | 0,006 | 4 | Nantes |
| Oslo | 4 | 0,16 | | 0,008 | 3 | Oslo |

**Table 8** Energy demand and emission intensities for wastewater collection



| City | Rank | $kWh/m^3$ | Factors influencing energy demand<br>- ⟷ + | $kgCO_2e/m^3$ | Rank | City |
|---|---|---|---|---|---|---|
| Nantes | 1 | 0,132 | | 0,003 | 4 | Nantes |
| Toronto | 2 | 0,129 | | 0,013 | 2 | Toronto |
| Oslo | 3 | 0,06 | | 0,003 | 3 | Oslo |
| Torino | 4 | 0,03 | | 0,013 | 1 | Torino |

An additional factor that contributes to high energy demand for wastewater collection in Nantes is the condition of the network. Rain volumes largely determine the extent of pumping energy used (Olsson 2012) – the relative amount of rain indicates the degree of soundness and integrity of pipelines (rain and snowmelt enter sewers either through structural defects or age-related deteriorations) and also how hard stations must pump. Thus, calculating the percentage of wet weather flows that seep into the collection system, there is a high proportion of such flows (35 percent) in Nantes compared to the other systems (approximately 22 percent).[2]

The sewage collection system in Torino uses the least amount of energy (Table 8), which is interesting given its size (7,000 km) and the number of pumping stations (125 compared to 82 in Toronto). As with the distribution system, the sheer number of treatment facilities in Torino is a likely benefit. In this case, there are 550 wastewater treatment plants of varying sizes in the study area (Zappone 2012), so despite a larger overall system size, less pumping energy would be required based on the shorter travelling distances into treatment facilities.

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[2] Total stormwater collected divided by total wastewater treated (eg 15.7 cubic m / 45.2 cubic m); Torino undetermined.

### *Wastewater treatment*

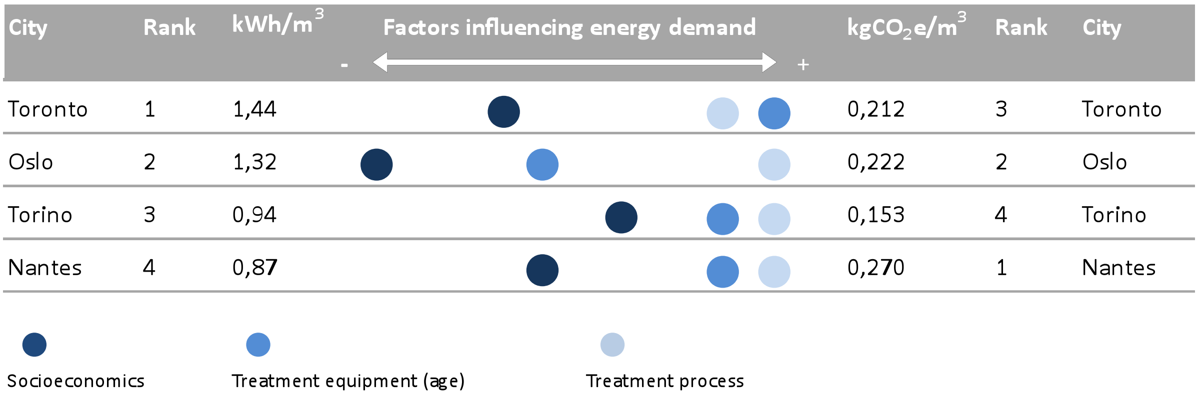
Veas and Bekkelaget are the two major wastewater treatment facilities in Oslo, treating 37 and 63 percent of the city's wastewater flows, respectively. Completed in 2001, Bekkelaget is a very modern facility that provides nitrogen removal. And although owned by the city, it is managed by a private operator. Both treatment facilities employ anaerobic digestion as a treatment process, thus producing organic fertilizer and biogas. During the study year, 2007, both treatment plants handled 111.4 cubic m of sewage (Vachon 2012). The approximate breakdown of water users is domestic consumption at 45.6 percent of the total supply, and 34.4 percent consumed by industrial units, commercial establishments and public services in the city (Venkatesh 2011). Given that there generally is very little industrial activity remaining in Oslo, the wastewater can be considered relatively less difficult to treat.

The predominant wastewater facilities in Nantes manage significantly less sewage flows, which amounted to 42.3 cubic m in 2010. The Tougas (Nord Loire) facility has a capacity of 600,000 inhabitant equivalents and handled 72 percent of the discharges, while Petite Californie (Sud Loire) at 180,000 inhabitant equivalents treated 21 percent. The latter has recently undergone renovations to its biological treatment process to become one of the most efficient and modern facilities in Europe, however, these developments are not reflected in the analysis so activated sludge, which requires a steady energy supply for the continuous operation of oxygen blowers and sludge pumps, is considered the primary treatment technology (Vachon 2012). The relatively robust capacity of Nantes' wastewater network means that industrial wastewater discharges containing biodegradable effluent can be properly handled (102 agreements were signed in 2009, with 477 authorisations and 2,094 files opened) (EGC 2012)

Toronto maintains four wastewater treatment facilities, which handled 439,116 ML of wastewater flows in 2011. The oldest and largest is Ashbridges Bay, constructed in 1910, and uses conventional treatment technology: a combination of physical, chemical and biological processes and operations to remove solids and organic matter from wastewater. Disinfection is provided using chlorine gas delivered to the plant in a rail car (City of Toronto 2009). The other treatment facilities include Highland Creek, which began operation in 1956, Humber (1960), and North Toronto (1929) later becoming one of the first plants in North America to employ a biological activated sludge process.

Institutional, commercial and industrial customers use more than one-third of the water produced by the city, and among the biggest users is a sugar company (Tokyo Bureau of Sewerage), so industrial discharges are relatively easy to treat. All sewage flowing into the treatment plants

**Table 9** Energy demand and emission intensities for wastewater treatment



| City | Rank | $kWh/m^3$ | Factors influencing energy demand<br>- ⟷ + | $kgCO_2e/m^3$ | Rank | City |
|---|---|---|---|---|---|---|
| Toronto | 1 | 1,44 | ● ● ● | 0,212 | 3 | Toronto |
| Oslo | 2 | 1,32 | ● ● ● | 0,222 | 2 | Oslo |
| Torino | 3 | 0,94 | ● ● ● | 0,153 | 4 | Torino |
| Nantes | 4 | 0,87 | ● ● ● | 0,270 | 1 | Nantes |

● Socioeconomics
● Treatment equipment (age)
● Treatment process

undergoes a common basic treatment process consisting of various stages as follows. Preliminary treatment involves degritting and bar screens to remove large matter. The separation of finer particles and materials occurs in primary settling tanks. Secondary wastewater treatment involves biological processes where aeration and the addition of oxygen facilitates the growth of microorganisms and the removal of organic matter before transferal to clarifiers for final sedimentation. Final treatment of wastewater involves chlorine disinfection for pathogen removal.

A number of key technologies differentiate the plants in terms of solids management. Highland Creek incinerates all biosolids in two multiple-hearth incinerators, which results in landfilled ash deposits and flue gas emissions. North Toronto and Humber both employ a two-step anaerobic digestion process with the sludge and treated biosolids diverted into the Ashridges Bay facility, where there is a pelletizer facility to produce biosolids for agricultural purposes, such as direct land application and fertilizer. Biosolids are also sent to landfills across Ontario and New York.

Anaerobic digestion is also used at the main wastewater treatment plant in Torino, which is the largest chemical-physical-biological treatment system in Italy and "a technical landmark for the high quality standards that are implemented" (SMAT 2012). In addition to this facility, there are nearly 550 other wastewater treatment plants in the study area, and they adopt a range of different methods although the majority (79 percent) reach tertiary treatment.

The respective energy mix of the studied areas explains the relationship of energy consumption and greenhouse gas emissions. The emissions factors for the electricity grid in Italy is corresponds to 0.53 kg CO2 e per kWh, 0.05 kg CO2 e per kWh in Norway and 0.02 kg CO2 e per kWh in France. In Ontario, Canada the factor that was applied is 0.1 kg CO2 e per kWh (nuclear and natural gas is 2/3 of mix). The Norwegian grid is predominantly hydroelectric, while France is heavily dependent on nuclear energy. In Ontario, there is a mix of nuclear and natural gas that comprises two-thirds of the overall mix. Italian electricity is derived from 51.5 percent natural gas, which is why Torino emits high levels of greenhouse gas emissions at nearly all stages of the urban water system.

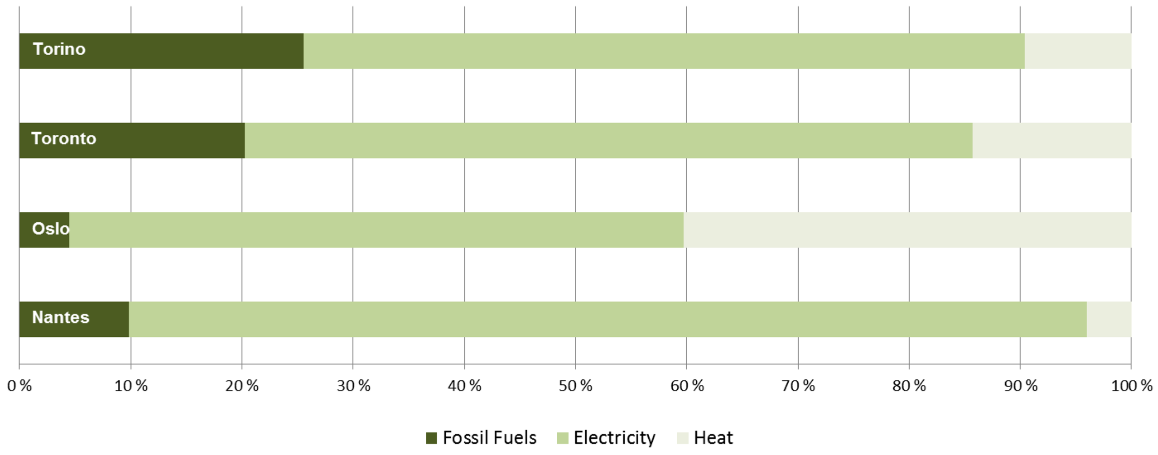


**Figure 11** Energy sources for the respective urban water systems

## Discussion

The results, also aggregated below in Figures 12-14, represent the specific characteristics of the urban water systems – the service needs, operational realities, energy demands and greenhouse gas emissions. The analysis demonstrates that urban metabolisms are location-specific and highly unique, representing the confluence of multiple economic, social and environmental drivers and their different interactions. Unlike humans (and animals), which are largely similar to each other, no two cities are alike. Even with two cities built on the same plan and ideals, they will be morphologically divergent due, at the very least, to differences in location (Penn 2012). As a result, the optimisation of service delivery and performance in a future where water and energy is expected to rise in scarcity and cost needs deep consideration of all life cycle aspects within the local contexts.

In a general sense, some interesting remarks can be made. Firstly, culture is an interesting aspect. There is certainly a wider discourse on *consumer culture* and "sustainability as a cultural phenomenon" (Ehrenfeld 2008), but with respect to water infrastructure and the water-energy nexus, it may be overlooked. At the Use stage (beyond the scope of this analysis) of the urban water cycle, every household is different (Kenway 2011) so behaviour plays a notable role in contributing to the overall environmental impact. But as is seen in Nantes, there are wider implications at other stages of water systems – customer dislike for the odours associated with chlorine, as opposed to the preference of Americans who find it reassuring, is a main driver for ozonation disinfection systems (Gambert 2013).

Secondly, discussions regarding new water service paradigms put an emphasis on proposals based on the decentralisation and de-regionalisation of infrastructure, and systems that switch from strictly engineered systems to more ecologically aligned systems (Novotny, Nelson et al. 2010). Future urban water management and treatment should be more varied and could involve, among other options, integrated semi-centralised systems at a district level with a focus on smaller, more compact units (Ødegaard 2012). While not quite representing the best version of such a vision, Torino does provide some indication on the merits of decentralising system elements. Based on the data, performance is poor regarding emissions (which reflects the energy mix), but it appears to be relatively energy-efficient compared to others. The fact that there are hundreds of water treatment (and even more wastewater treatment) facilities spread throughout the area – one per municipality, on average – appears to be a positive aspect. In California, the main reason for the high energy intensity of water in southern California is because it must be conveyed hundreds of miles and lifted 2,000 feet over the Tehahapi Mountains. In Torino, treatment and distribution infrastructure is likely located directly in or at least in close proximity to mountainous areas, thus significantly reducing the energy required to deliver water to customers in high-elevation points.

This issue of system configuration also relates to culture at the macro-level. Planning culture was also seen to influence material and energy metabolisms. In contrast to the sprawled development that has unfolded in Toronto, Oslo has severe limitations on the extent to which urban expansion can proceed. The city, in effect, only occupies one-third of its boundary as vast protected forested areas hem it in and have proved legally and politically difficult to remove over time. A natural limitation also exists with the fjord flanking the opposite side of the city. In any case, Oslo is a comfortably small and intimate city whose scale simply does not compare to those of North American cities (Architectural League of New York 2004). With population increases forecasted, if not restrictions on domestic and international migration into the city, then creative solutions will be necessary for Oslo to retain its positive attributes while managing its water-energy nexus and the carbon emissions.

As the planning mechanisms and paths of other cities have demonstrated, the greenhouse gas emissions that arise from water services are not merely associated with the direct and indirect requirements of the urban water system. Another major source is the car-dependent low-density development that centralised water infrastructure has enabled (Burns and Kenney 2005). This type of dynamic provides the rationale for applying a systems approach to complex challenges such as the water-energy nexus that climate change and rapid urbanisation are making more urgent in both industrialised and developing cities. Summed by Newell et al (2011), system optimisation cannot be achieved by isolating subsystems but must rather take into account the effect of interactions between them. On the one hand, this can be applied within the urban water system. In this case, taking into account the trend of stricter wastewater treatment regulations and the material and energy ramifications, an additional perspective for authorities should be to encourage solutions that minimise upstream contributions to water pollution (eg combined sewage overflows) and provide funding for green infrastructure and water-sensitive urban design policies in addition to its focus on wastewater treatment facilities.

On the other hand, it equally applies beyond the water sector. As arguably the main pillar on which cities depend on, water systems can be the ideal catalyst to convene different sectors (eg transportation, buildings, public health, energy, etc.) to manage not just the impacts of the water-energy nexus but also to develop a cohesive citywide climate change and sustainability plan. Car-based sprawl encouraged by water infrastructure is a major source of carbon emissions; groundwater nitrate pollution from both nitrogen dioxide in car exhausts and excessive agricultural fertilser use; high density buildings potentially contribute to higher energy costs for water pumping; and pharmaceuticals are increasing concerns for water quality – these are some of the issues that require proper planning among public agencies, and can yield effective solutions in tandem, rather than in isolation from each other.

Referring back to each case study city, some of the findings can be applied to inform the management of the water-energy nexus for the purpose of climate change mitigation and adaptation. The most efficient and effective use of resources simultaneously addresses level of service for urban water systems, energy and emission intensities, and citywide climate change vulnerabilities. Interventions are suggested on this basis for Nantes, Toronto and Torino. Oslo will be considered in the following chapter. In terms of energy demand and carbon emissions, wastewater treatment is the biggest concern. The prime solution is to maximise biogas productivity to offset this demand and to possibly transform the utility into a net energy producer. Further gains can be yielded in the preceding stages (eg by reducing influent), thus the focus below examines these upstream stages.

### *Nantes, France*

The major effects of climate change on France involve air temperature, which have risen more in France than elsewhere – 0.95 degrees C, compared to 0.74 degrees C globally (Centre for Climate Adaptation 2013). Resultantly, the number of heat-wave warnings is projected to increase from less than 1 day per year to 14 in urban areas (Lemonsu, Kounkou-Arnaud et al. 2013). The impacts of

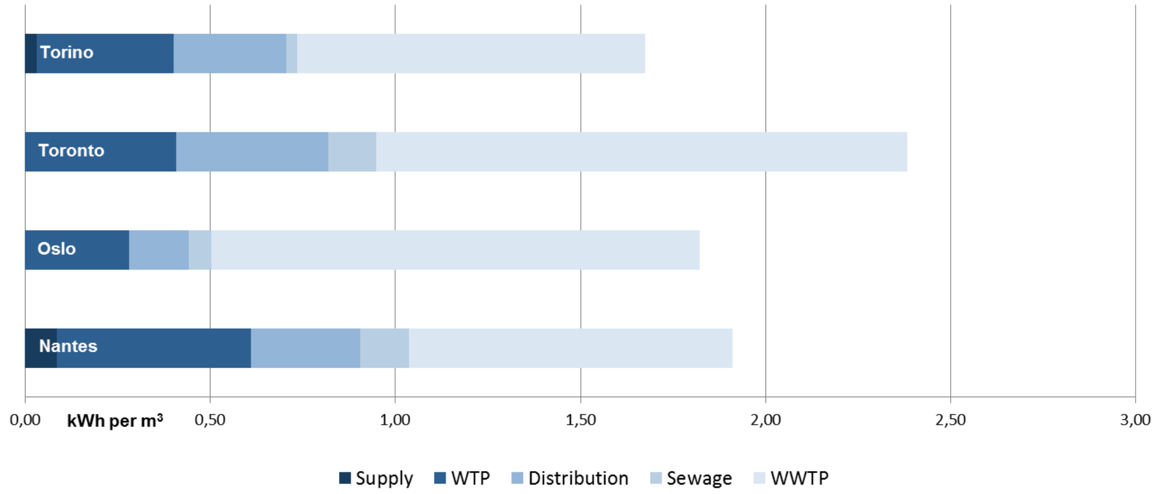


**Figure 12** Energy requirements per unit of water demand

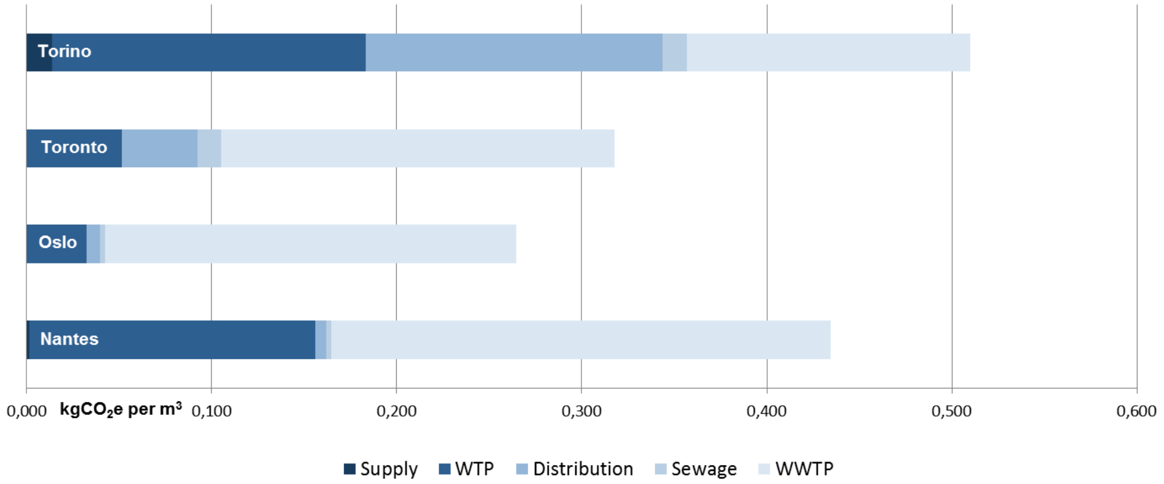


**Figure 13** Greenhouse gas emissions per unit of water demand

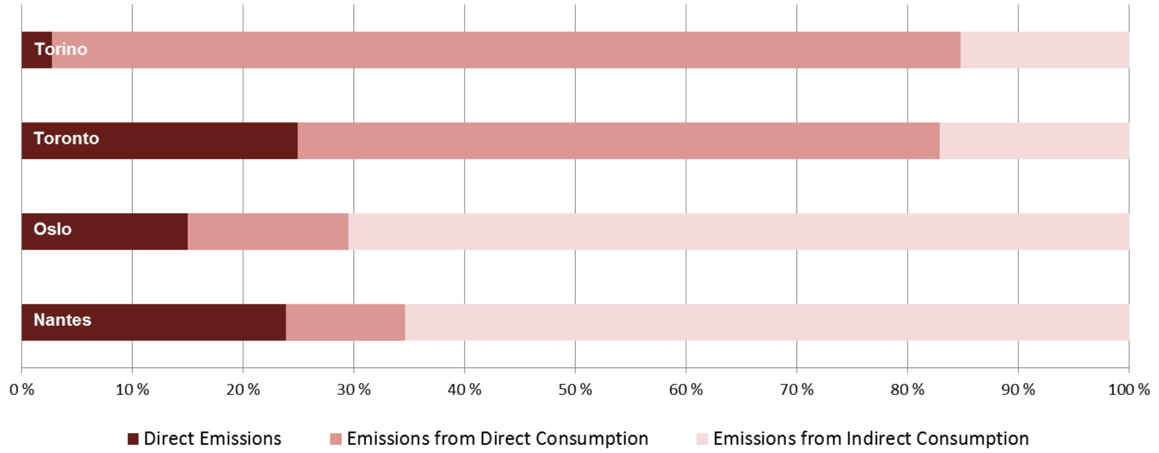


**Figure 14** Respective sources of carbon emissions

major heat waves in 2003, 2006 and 2011 have already been felt with temperatures at times beyond 42 degrees C causing vast damage to crops and in some events claiming as many as 15,000 deaths. Owing to this, annual heatwave-watch plans have started automatically on 1 June since 2004.

The largest contributor to greenhouse gas emissions in the Nantes water system (upstream) is the water treatment stage, which is the most energy intensive among the cities. As noted previously, reasons include high water turbidity and pollution largely from herbicides, ozonation treatment systems and the old age of the treatment facility and equipment. Low water quality and the subsequent treatment needs is the most likely reason based on the high chemical consumption in Nantes. Thus a top priority for authorities in Nantes would be to increase efforts to curb the use of pesticides and herbicides.

Another critical component is the wastewater collection network, which uses more energy than Toronto despite being half the size. Topography is a main cause as the system uses four times as many pumping stations. One method to address this would be to assess where pumps can be decommissioned and replaced with gravity pipes. The Midgardsormen project in Oslo is one such project that will shut down and replace pumping stations with gravity pipes (Oslo Kommune 2013). The high percentage of wet weather flows conveyed by the network also suggests that network conditions can be vastly improved. It would be wise for Nantes to increase the stringency of monitoring and rehabilitation programs because climate change and urban dynamics are expected to accentuate overflows into the environment (Mahaut, Andrieu et al. 2011). Increasing leaf coverage with green infrastructure such as green roofs, swales and constructed wetlands is also an important complementary method to capture stormwater where it falls thus reducing stress and general wear and tear of pipelines, not to mention reducing pollutant loads from combined sewer overflows. Moreover, green infrastructure effectively counteracts rising temperatures with cooling services by moderating the urban micro-climate and reducing air-conditioning needs (Farrugia, Hudson et al. 2013).

### *Toronto, Canada*

Toronto's greatest vulnerability to climate change is its infrastructure, which has been affected by violent weather with three 100-year storms in the past decade resulting in widespread damage, particularly overwhelming the aging electricity grid with blackouts, and the storm and sanitary sewers causing home floodings and washouts that have rendered streets impassable (Thistlethwaite 2012). While these have been relatively manageable, Superstorm Sandy in New

York reinforces what is possible for northeastern part of North America if adaptation is not strategically pursued in a timely manner.

The largest contributor to greenhouse gas emissions in Toronto is water treatment. However, high raw water quality helps to minimize the use of treatment chemicals unlike in Nantes. Rather, electricity consumption is the main cause as the city's largest facility RC Harris still uses the same pumps that were installed during construction more than 80 years ago. This energy demand can be offset by increasingly implementing renewable sources. A promising technology is small hydrokinetic turbine systems that generate power from the water conveyed through pipes, which is gaining attention from water utilities (Alberstat 2013). Additionally, biogas is not used to its full extent in Toronto and there is much room for improvement to offset in-house demand. An inadequate energy grid infrastructure in particular is why biogas is not fully tapped in Toronto (Winsa 2012) as it is in Oslo. Thus Toronto's priority should be to upgrade and modernise the city's energy grid so that sufficient capacity can accommodate renewable energy sources made possible by the water system. Through this, greenhouse gas emissions can be reduced, in addition to improving system reliability and resilience and its ability to cope with increasingly wild weather.

### *Torino, Italy*

Northern Italy's water supply is an important resource for the local economy, and is quite vulnerable to climate change. While domestic, agricultural and industrial activities have impacted on water quality, an increasingly warming climate is reducing the Alpine glaciers and is likely to induce water shortage in the Po Valley, a region not historically prone to a lack of water availability (Cassardo and Jones 2011).

Torino's wastewater treatment data is likely underreported as treatment is actually absent or hardly working in many important towns (Raggi, Ronchi et al. 2007). Quite obviously, increasing enforcement is the top priority for various reasons. With respect to the water-energy nexus, the reason is to reap the benefits of system dynamics and interactions – untreated effluent into the natural environment adversely impacts water quality thus increasing treatment efforts. Indeed, Torino's largest contributor to greenhouse gas emissions is water treatment at 0.169 kg $CO_2$ e per cubic m, and this incurs significant indirect energy resources (28 GWh) through chemicals consumption. By contrast, the impact of water treatment in Oslo is merely 0.28 kWh per cubic m with 0.032 kg $CO_2$ e per cubic m. This is due partly to investments in wastewater treatment, but also to upstream restrictions that protect source water quality thus showing the dividends that can be gained from stringent protection. New York City also illustrates this with its purchase of upstream land at a cost of $300 M over 10 years to restrict pollution and runoff from development that affects source water quality. By doing so, it has earned exemption for federal filtration requirements due to high purity levels and has avoided spending $8 bn to build a new filtration facility (DePalma 2007). Thus for Torino, putting forth the resources to implement and enforce wastewater treatment can play an important role in restoring the poor state of water quality and shifting energy demand from upstream to downstream, where the ability to generate electricity is possible.

Another important target for Torino is the raw water stage, where 0.014 kg of emissions comes from water pumping. This is rather high compared to Nantes, where water is conveyed approximately 15 km. Unlike Oslo and Toronto, Torino relies heavily on water from groundwater sources, which are therefore more difficult to extract. The low energy use and high emissions per unit, compared to Nantes indicates a fossil fuel dependent electricity supply. As such, offsetting the impacts of raw water pumping must be a priority. If the projected threats to water availability come to be, deeper groundwater pumping will be required thus increasing energy intensity and doing nothing to mitigate climate impacts. It is therefore a recommended strategy to increase photovoltaic electricity production particularly for water supply requirements. Solar power is used extensively for water pumping in Anantapur, India (Nagabhushanam 2013), but solar power is equally feasible in the "less sunny" Alpine regions with sufficient energy output potential year-round (Real 1982, Durisch and Bulgheroni 1999). Solar irradiance can provide in some places an intensity of up to 2,000 kWh per sq m similar to what is available in southern Spain (Schaan 2007).

### *Concluding remarks*

An assessment of material and energy demands and emissions intensity from urban metabolisms finding that a water agency's ability to treat, transport and deliver water is impacted by multiple geographic, climatic, technological and social factors. By studying and determining hotspots, water-energy nexus and urban metabolism studies can help water agencies take into account the energy intensity and greenhouse gas emissions of their planning and decision-making options. More importantly, it can illuminate cross-cutting issues and serve as a catalyst for bringing together different sectors to work together in making water services and overall urban development more sustainable in an increasingly uncertain future.

# CHAPTER 04 \\ How
# Intervention Planning for Oslo, Norway

## Introduction

### *Urban resiliency*

The city itself is a "complex order" (Jacobs 1961) and the external environment within which it operates is becoming equally, if not more complex. In light of the city as a metabolic ecosystem, resilience theory (Holling 1973) is appropriate to help cities navigate both sudden and slow developing disturbances. Resiliency is the most important adaptive approach for cities to climate change, and can help ensure that infrastructure and settlements are able to adequately maintain functionality and identity in the face of extreme unpredictable events. There are four fundamental factors of resiliency (Minne, Pandit et al. 2013):

- Robustness – the ability to withstand and recover from stress shocks and demand fluctuations
- Redundancy – the ease with which a system (or sub-system) can be replaced in cases of failure
- Resourcefulness – the capacity to deploy and make use of resources where there is disruption
- Rapidity – the capacity to quickly contain losses and prevent degradation

Resilient urban planning is characterised by targeting vulnerable infrastructure and resources, developing systems that are elastic and can cope with change, and diversifying dependencies to create backup systems to replace lost or failed ones. There is a wide array of strategies for the urban sector to pursue and will depend on the local context. Minimising the material and energy inputs for infrastructure is one general manner, however, the extent of this must be properly measured so as to maintain, rather than jeopardise, system functionality.

### *Oslo and climate change*

As previously mentioned, Oslo, and Norway in general, is blessed with an abundance of water, and given the northern latitude is likely to remain so into the distant future. As such, climate change is expected to have little effect on water quantity. However, adverse effects on water quality are highly likely. There is great certainty that Norway will be warmer and wetter with precipitation forecasted to increase up to 30 percent (Research Council of Norway 2013). Thus, winter conditions will be increasingly unstable with less snow and heavier rainfall causing subsequent combined sewer overflows and considerably reducing water quality and recreational enjoyment. Oslo has begun to prepare Akers River, the inner harbour basin and the Oslo fjord by carrying out renovations to wastewater system with Midgarden project.

Higher temperatures in Norway are expected to bring its fair share of impacts to the urban water system. In conjunction with more rain and less ice coverage, natural hygienic barriers over raw water will be compromised during winter, which will likely increase natural organic matter (Hem and Hult undated). An excess of natural organic matter is particularly problematic for water treatment and distribution systems (Ødegaard, Østerhus et al. 2010).

Climate change effects are expected to be exacerbated with forecasts in population growth and increased demand for resources and services, which will require significant planning. This chapter focuses on the water supply side of the urban water system in Oslo, which faces a water scarcity deficit from the perspective of supply security. In other words, in the event of a disturbance to current water sources (eg climate change developments or a man-made event such as cargo derailment into the lake), a significant portion of the population would be rendered without water services. As so, a main concern for Oslo VAV is to improve the resilience and robustness of the supply system while keeping energy use and emissions in check.

## Intervention strategies

In April 2013, a session with representatives from Oslo VAV and SINTEF prioritised eight intervention strategies that span the upstream urban water system from raw water to consumption (Table 10). The specific actions that these strategies could consist of are discussed below within the context of a Scenario 0. Such a scenario involves a stable population and water demand, and because of this, can help show what type of gains can be obtained compared to current service levels. This can in turn inform subsequent scenario planning considering population increases, fluctuations in water demand and other variables. Prospective gains will be further analysed from a material and energy perspective.

**Table 10** Upstream intervention options for the Oslo urban water system

| Intervention | Source | Treatment | Distribution | Use |
|---|---|---|---|---|
| 1 Increase raw water sources capacity and security | 🟦 | | | |
| 2 Increase WTP hydraulic capacity | | 🟦 | | |
| 3 Improve WTP processes regarding water quality | | 🟦 | | |
| 4 Improve distribution system performance | | | 🟦 | |
| 5 Water reuse | | | 🟦 | 🟦 |
| 6 Increase consumer awareness | | | | 🟦 |
| 7 Change in water pricing system | | | | 🟦 |
| 8 Energy management | | 🟦 | 🟦 | 🟦 |

### *Increase raw water source capacity and security*

The main freshwater supplies that Oslo draws upon are Lake Maridalen to the north of the city, and the Elvåga lakes located in the east. While both are well managed, a particular concern is the fact that 90 percent of the city's supply comes from Lake Maridalen. As a result, water services in Oslo would be significantly compromised in the event of a disturbance. Such an event could consist of deteriorating water quality from climate change developments, the effects of population growth or an immediate industrial accident. Potential new water sources for Oslo have been analysed and the most likely addition to the urban water system is Holsfjorden Lake to the west of the city. A Scenario 0 could entail the construction of a new water treatment facility; however, given the assumptions of current parametres it will not incur any additional operational activities but instead will serve as backup capacity (ie supply redundancy).

Additional steps that would serve the purpose of increasing source security include green infrastructure to handle wet weather ingress and to minimise the impact of combined sewage overflows on the current system networks. Thus by reducing the frequency and severity of pollutants discharged into the natural environment, deteriorations in quality can be averted. An alternative aspect of security breaches to water supply could involve the distribution network. In this case, the construction of backup trunks would help to alleviate the dependence on existing pipes and be put in operation should these be somehow compromised.

For non-potable water consumption, alternative water sources such as snow melt could be a consideration. In some areas of Japan with heavy snow conditions, many roads are embedded with sprinkler systems that melt snow with warm groundwater (Lund 2000). A more feasible option for collecting and treating snow melt, however, would likely involve the city's current method of collecting snow from streets by means of dumper trucks. Since 2012, the collected snow has been melted and filtered prior to dischargement back into the sea (AMIAD Ltd. 2013). However, considering the embedded energy costs of this system (ie collection and treatment) it would be worthwhile to explore alternative uses for this water to bring down freshwater consumption rather than simply letting it flow back into the natural environment. Capturing rainwater is another method of diversifying water sources, and has the benefit of falling directly onto customers rather than being conveyed through lengthy piping networks.

### *Increase hydraulic capacity of water treatment facilities*

The current capacities at the water treatment facilities are 370,000 and 43,200 cubic m per day for Oset and Skullerud, respectively. Any increases to the capacities of the facilities would entail retrofitting and upgrading the current set of equipment (ie pumps, treatment mechanics, filters, etc.). Another means would be to expand the overall system through the above mentioned Holsfjorden water source. Several options would be possible to exploit this source, and could involve constructing a new treatment facility in the west of Oslo or at the source. Similarly, the Oset facility itself could be expanded through brownfield development thus allowing for greater water intake. Within the context of a Scenario 0, however, where the Holsfjorden source would be available but not in daily operation, it would be more cost effective to work within the confines of existing infrastructure by undertaking technical modernisation and management efficiencies to optimise Oset and Skullerud. Installing more efficient motors, for example, can reduce energy use by 5-30 percent (US GAO 2011).

### *Improve processes at water treatment facilities regarding water quality*

As mentioned previously, Oslo VAV has taken steps to reduce the material and energy requirements for water treatment, specifically by replacing chlorination with UV disinfection. Additional measures worth pursuing would involve biological treatment such as bank filtration. A river bank filtration approach has been shown to perform as well or better than bench-scale conventional treatment, and also can play a role in potentially reducing treatment costs in addition to buffering against spills and terrorist events (Bouwer, Weiss et al. 2003). Bank filtration is likely to also assist with improving hydraulic capacities by providing a back-up supply of pre-treated water (thereby reducing in-plant treatment requirements). The high-quality raw water with very little pollutants in and around Oslo makes this a worthwhile consideration (de Vet, van Genuchten et al. 2010). Overall, bank filtration and other biological treatment methods, which are becoming more feasible and gaining wider public acceptance, offer several advantages including low operating costs, minimal or no added chemicals, and robustness over a wide range of operating conditions (Brown 2007).

### *Improve the performance of the water distribution system*

Maintaining optimal performance in the distribution network ensures that water is efficiently conveyed to customers. One way in which water is lost is through leakages in the distribution system (eg cracks and bursts in pipes). As such, strong leak detection efforts on the part of a municipality is an effective means of reducing unnecessarily wasted water. The water savings reduce strain on the supply source. Several methods of monitoring pipelines commonly include camera inspections, acoustic detection systems which monitor for sounds that indicate leaks, and fibre optic lines that can monitor pipelines at all times of the day.

Once having characterised the extent of network problems, rehabilitation efforts can commence to repair and replace faulty pipes. Oslo has currently invested at least 200 M Euro into network improvements (Hathi and Ugarelli 2011). Pressure management is a less capital and labour intensive approach than pipe rehabilitation. Leakages increase with water pressure and when it becomes too excessive it will result in excessive energy demands for water pumping and eventually pipe bursts. While a cost effective alternative, pressure management is also more technically complex since pressure is in constant flux throughout the day in accordance with demand. Furthermore, pressure management is a short-term solution so its extent is limited. In any case, variable pressure control methodology is gaining ground. Contrasting conventional pressure management via reduction valves in the distribution network, variable control maintains pressures as low as possible while still maintaining service quality. Through this, mechanical stress, electrical power and severity of leakages are all reduced but will require a flexible pumping and sensor system at various points in the network (Olsson 2012).

### *Water reuse*

Water reclamation is common in water scarce regions such as Singapore and California. However, this practice can increase energy demands for pumping because of the possibility of working against gravity. Such an option must then be assessed against the alternatives.

Greywater treatment and recycling is growing and already plays a prominent role in Japan, where it is mandated for buildings in Tokyo with an area of over 30,000 sq m or with potential to reuse 100 cubic m per day (Pacific Institute 2010). Systems are also successful in Australia, Germany, Norway and Sweden. The European Commission’s Urban Waste Water Treatment Directive indicates that between 25,000 – 100,000 liters of greywater per person annually is produced depending on the status of water saving devices in households (WECF 2011), so there is a large potential for improving water efficiency.

Greywater is the wastewater discharged from households. It includes water from showers, baths, sinks, laundry machines, kitchen, dishwashers and laundry machines. Greywater is simpler to treat than yellow or blackwater (Olsson 2012) since these sources are relatively less polluted (ie containing soaps, shampoos, hairs, toothpaste, etc.). As such, greywater is suitable for cascading purposes to maximise the productivity of water. Toilet water is considered as black water and is therefore not inclusive of greywater volumes. Greywater derived from kitchen sources such as the sink or dishwashing machine is also not recommended for cascading because of the fats and cooking oils and other materials in its composition.

A Norwegian example of a greywater system has been implemented in the Klosterenga apartment complex, where an on-site biological filter/constructed wetland system purifies greywater for the residents. The water is of high quality and while some is reused in landscaping (irrigation), most is discharged to the stormwater system and eventually to a local stream (CMHC 2009). Unlike rainwater, greywater recycling is not dependent on season or precipitation variability, and so can be considered a reliable water source that can be effectively reused to reduce operational demands on both water treatment and wastewater treatment facilities.

### *Increase consumer awareness*

Domestic resource consumption is a product of habitual behaviour that is developed to save time and decision-making efforts. Breaking unsustainable habits requires that the customer realises that his/her behaviour is relevant and that adjustments can lead to positive impacts (van Engelen and Collins 2010). Petersen, Shunturov et al. (2007) have shown that real-time feedback, education and incentives lead to conservation and reduced resource use. Educational campaigns through various media outlets are relatively low-cost investments that can lay the groundwork for more sustainable consumption. These could include standard information items to more creative initiatives such as fat-free cooking recipes in Japan to reduce household disposal of fats, oils and grease into the wastewater network. Financial incentives on water and energy efficient appliances can also help nudge individuals towards the right direction.

### *Change water pricing system*

A critical driver of consumer behaviour is economic, thus proper pricing plays an important role in optimising urban water services. In Oslo, water is priced exceedingly low. In relation to GDP per capita, the annual expenditure for water is 0.2 percent of household income (Bartoszczuk and Nakamori 2002). If conservation and efficiency are real objectives for water utilities and city governments, then low pricing sends the wrong signals to consumers: with water practically free, there are not incentives to turn off the taps. As is evident, however, water production and provision comes at significant material and energetic costs, and this requires proper economic mechanisms to appreciate. Increasing the base price of the resource and establishing a conservation tax can spark shifts in user behaviour (households and industrial) and encourage more thoughtful consumption. At the same time, low-income households can benefit from assistance schemes so as not to be excluded from drinking water access. Pricing is politically sensitive, however, from a systems level, offsetting increases in water prices with a decrease in some other sector (eg sales tax, income tax, etc.) can help make the transition more manageable.

Water metering works hand in hand with pricing mechanisms in that accurate accounting of water consumption makes people aware of the extent of their behavior. And by accurately gauging water use, pricing can be more precise and equitable. Water metres in Oslo are an action item in the city's Urban Ecology Programme, and installations are expected to follow the lead of other Norwegian cities. Advanced Metering Infrastructure allows for remote and real-time updates leading to increased efficiencies for water utilities and increased consumer convenience. The general rationale for water metre installation is to help utility companies reduce their operating costs and support energy savings, while providing quality services to their customers. These new services will be expected to include better information for customers to help them make decisions about energy use and optimizing current energy availability (van Engelen and Collins 2010). Metreing also improves the technical management of a utility, allowing for accurate water balancing, the characterization of demand trends and easier identification of system failures.

### *Energy management*

One benefit of leakage management is improved energy efficiency for infrastructure assets (ie water can be pumped with more ease), however, additional energy gains can be attained with more direct actions. Since the efficiency with which a pump operates depends on size and years of service, energy costs can run up to several thousands of dollars per year as the horsepower of a pump increases, and its efficiency tends to decrease with age. Thus testing and benchmarking of pump stations can allow a city to gauge their performance and help reduce electricity consumption.

One method of testing is the Thermodynamic Method, which is based on the principle that water being pumped absorbs the heat transferred by a pump (ie efficiency loss). Given this, a pumps efficiency can be assessed by determining the difference between input and output temperatures of the water as well as pipe pressure (City of Ottawa 2013).

Energy efficiency can also be realised through renewable energy generation. The implementation of solar energy, for instance, is increasingly common either through their deployment for water pumping stations (eg India – see previous chapter) or installations at treatment facilities (eg San Diego). Despite perceptions that Norway is not suitable for solar power, the country may in fact be just as effective as Germany, and also has an advantage with the northern climate, which aids substantially with the efficiency of solar panels (Simmons 2012). A recent technological development that is being experimented with in numerous jurisdictions, including Oslo in the near future, is micro hydrokinetic turbines. A water turbine, by means of an electrical generator, uses the force of water to convert mechanical energy into electrical energy. As a result, water that is in constant flow regardless is now put to useful work. Four turbines, for instance, have been installed in a French drinking water supply network and have been able to produce 4.5 M kWh per year of electricity (KWR 2010).

Water utilities can also play a role in encouraging energy efficiency at the user end. Warm and hot water uses for cooking, showering, cleaning, etc. are "hotspots" of the water-energy nexus, so this part of the urban water system presents significant environmental benefits. Educational campaigns on the water-energy nexus, financial incentives for energy efficient appliances, and other initiatives can play a role.

## Methodology

The selected actions, which are analysed – demand-side (ie through end user) and supply-side system management interventions – aim to reduce the required water production volume. These actions involve leakage management, changes in water pricing and water reuse through greywater recycling and rainwater harvesting. Each of these can be considered to have a favourable likelihood for implementation over the selected 30 year timeframe. Leakage management is an inherent component of water asset management and significant budgets are allocated accordingly. Water metreing is an objective of the Urban Ecology Programme and can be expected to be increasingly implemented following in the lead of other municipalities (Jenssen 2012), although the exact extent in Oslo is still under discussion (Sægrov 2013). Greywater recycling has been demonstrated by the well-recognised Klosterenga project, which has been a successful experience (Ridderstolpe 2004) and represents an ambitious example of what is possible in Oslo. The prospect of rainwater harvesting increases as precipitation does likewise (as it is expected to in the coming years). Micro hydrokinetic turbines, as an energy management implementation, are a rapidly growing technology gaining increased attention across other jurisdictions.

Decreasing water demand is expected to assist with the City of Oslo in coping with threats to the security of its water source supply and to the reliability of the water system. Additional benefits that arise out of reduced water production include decreased operation and maintenance expenses, extended lifespans for current infrastructure, and the associated material and energy efficiencies. Evaluation of the environmental performance of the actions is based on impact categories involving water use and climate change (greenhouse gas emissions) through energy (eg electricity, diesel) and materials (eg treatment chemicals) flows. By comparing these actions to the baseline (business as usual), insight can be developed into how it can impact Oslo’s current system and how performance standards can be further improved upon. Considerations will be within the framework of a Scenario 0, which assumes no increase in population and water consumption. Against this backdrop, exploratory life cycle assessments and material flow analyses are carried out for each action item mentioned above.

The common starting point is based on 2012 operational data publicly reported by Oslo VAV. Specifically, the initial water production volume is considered as 101.2 M cubic m (Oslo VAV 2013). With respect to material and energy requirements, a directly proportional relationship is assumed for the chemicals and energy consumption for water treatment and pumping. The constant indicators are based on 2009 values: 97.2 g of chemicals and 0.342 kWh of electricity are required for each cubic m of water treated, while 1.09 kWh is required to pump one cubic m of water (Venkatesh 2012).

The greenhouse gas emission intensity for chemicals consumption due to water treatment in Oslo is 163.2 g CO2 e per cubic m of water, while that for electricity demands due to treatment and pumping, based on the Nordic grid mix, is 0.18 kg CO2 e per kWh (Venkatesh 2012). Further assumptions and simplifications for the interventions were necessary to perform the assessments, and these are discussed below.

### *Leakage management*

The current leakage rate is commonly recognised as 20 percent of the total water supplied, and leakages are taken to occur strictly within the pipeline network as reservoir leakages are considered negligible (Venkatesh 2012). The length of the distribution network is determined as 1,560 km of water mains (Oslo VAV 2013). The program for distribution network management involves pipeline rehabilitation and pressure management. The method of rehabilitation is slip lining with new plastic polyethylene pipes, which is the preferred method of the city (Venkatesh 2012). The average amounts of polyethylene materials and diesel energy consumed for each km of rehabilitation work are calculated from Venkatesh (2012).The target for pipeline rehabilitation is set as 1 percent of the distribution network annually for 30 years, which can realistically yield a total 6 percent reduction of the leakage volume in the initial year. Moreover, various pressure management tasks, manageable within the first 5 years, are expected to yield an additional 2 percent reduction of leakage volume in the initial year (Sægrov 2013). Greenhouse gas emission intensities for polyethylene and diesel fuel production are 2.33 kg per kg of material and 3.19 kg per litre of fuel, respectively (Venkatesh 2012).

### *Water metre installations*

A universal water metre installation program is considered beginning in 2015 and proceeding over a 20-year horizon until 2034. A 20-year time frame is reasonable for covering the entire city and is based on a metreing program in Sacramento, California which aims to install 110,000 water metres within two decades by 2025 (City of Sacramento 2013). 53,500 water metres would need to be installed in Oslo, and this figure is based on the number of household connections (Oslo VAV 2013). There is currently a negligible number of household water metres installed, precisely 1.53 percent of household connections (Jenssen 2012). Domestic water users are targeted because previous studies mentioned in preceding chapters indicate a high degree of impact on the urban water system from households. Moreover, water metering for all non-residential connections in Oslo is already mandatory (Jenssen 2012). Water metreing is currently optional for households, but this is can be expected to change according to the Oslo's Urban Ecology Programme and the trend of (mandatory) water metre programs in neighbouring municipalities.

Domestic water consumption accounts for approximately 45 percent of the total water consumption (Venkatesh 2011, Jenssen 2012). Thus, the calculated water consumption for each household connection is 851.2 cubic m per year. For every metre installed, household consumption decreases by 10 percent as has been documented by water metering programs in Norwegian municipalities, notably Trondheim (Norconsult AS 2012). Upon installation of a water metre, water consumption for that connection remains at the reduced rate indefinitely. The carbon footprint for each water metre is based on manufacturer's data and represents a best-case scenario at 0.915 kg CO2 e per water metre (Elster Group 2010).

### *Water reuse*

The implementation of greywater recycling systems in Oslo are based on a per capita water consumption of 180 litres per day (Norconsult AS 2012). In terms of specific domestic water uses and the proportion of greywater and blackwater, Norwegian data is indefinite. In general, 20-40 percent of water consumed in cities is for toilet flushing, and a study in Norway revealed 40 and 120 litres per day of blackwater and greywater, respectively (Jenssen 2002). Furthermore, newly built homes in Germany, Norway and Sweden have demonstrated greywater production of less than 100 litres per person per day (Ridderstolpe 2004). In the absence of refined Norwegian statistics, domestic water consumption is based on data derived from Danish households: 23 percent for toilets, 36 percent for bathrooms and 14 percent for laundry (Revitt, Eriksson et al. 2011). Water from kitchen sources is excluded from greywater recycling due to high matter content that requires careful levels of treatment.

Initial greywater programs in Germany during the mid-1990s began with the goal of supplying residential dwellings with about 100 persons with recycled greywater (Nolde 2005). Given the relative novelty of greywater recycling in Norway at present, this would make an ideal starting point. The greywater recycling systems are modelled after the biofilter/constructed wetland system at Klosterenga in Oslo, which serves 100 persons in 33 apartments. As such, this analysis considers the scaling up of similar systems city-wide in clusters of 100 residents, initially in the courtyards of multi-residential dwellings and in time they will serve single-family housing neighbourhoods of approximately 100 residents. A major benefit of the systems at Klosterenga is that it has a fairly compact land requirement of about 1 sq m per person, so land should not be a major hindrance. It is furthermore assumed that the footprint will be further minimised as know-how improves over time.

This clustered communal approach of collecting and treating greywater from several apartments and homes outside the residences is preferable over decentralised systems that treat water inside each home for several reasons. Firstly, they are easier to monitor and maintain, and do not depend on each household to maintain their own individual systems (ie filter cleaning), which would increase likelihoods of cross-contamination health risks or laziness and reverting back to conventional plumbing for non-potable uses. Oslo VAV or a public health agency can periodically maintain centralised systems in an efficient manner. Secondly, the centralised approach facilitates energy and material savings through natural treatment whereas individual in-home systems would likely require chemical disinfection to maximise the use of greywater volumes. Thirdly, the "pooling of resources" helps to ensure more consistent flows and less accumulation of stock. Individual household systems are likely to produce more greywater on a daily basis than what is required for toilet flushing, and this can be problematic since greywater decomposes quickly and can turn septic in about 24 hours (Prathapar, Ahmed et al. 2006).

Klosterenga treats water to swimming quality (Jenssen 2002) while minimising material and energy inputs through biofilter and constructed wetland. This is important since greywater intended for toilet flushing is also advised to undergo treatment (NSW Government 2008). The adopted approach for water savings is equal to the demand of non-potable end uses served (eg toilet flushing), provided that there is sufficient greywater yield. Thus this analysis makes use of this benefit by applying greywater for toilet flushing. The actual system in Klosterenga does not seem to do this but rather discharges to the natural environment (CMHC 2009). Any excess greywater that exceeds the required amount for toilet flushing is allocated to garden irrigation during the summer months and frost tapping[3] in the winter. The relative percentage for these uses (4.6 percent) is derived from future forecasts of water usage in Oslo (Norconsult AS 2012). Sufficiently treated greywater can also be used for laundry, but it is assumed that consumer perception will make this difficult to implement.

An additional water reuse scenario applies rainwater harvesting to supply domestic laundry demands. The intermittency of rain is considered here to appropriately suit the relatively infrequent laundering needs (ie weekly rather than daily). Thus, in homes served by the water reuse systems, per capita water demand will decrease by the amount required for laundry since potable water from Oslo VAV is no longer required. The captured rainwater will be pumped into the homes like the greywater, and after use will also be recycled for gardening and/or frost tapping. As a result, the sizes of the septic tanks do not change.

The material costs associated with both systems are embedded in the septic tanks. The constructed wetland is assumed to serve as the 'container' for treated water. Sizing of the septic tanks is based on:

$$C = (GW \times P + 2{,}000)$$

where the initial volume is 2,000 litres and the subsequent size of the tank in litres C is determined by adding the amount of daily greywater GW in litres per person multiplied by the population P to be served (UK Septic Tanks 2013). Fibreglass, polyethylene and concrete are the most common

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[3] allowing water to flow continuously at a minimum rate to prevent unlagged pipes freezing during winter (eg construction sites)

construction materials for septic tanks – polyethylene and concrete considered in this analysis. The greenhouse gas intensity for polyethylene is the same as that applied for pipe rehabilitation, with the weight (kg) having been obtained from manufacturer data (Tank Depot 2013). Stormwater flows for rainwater harvesting are expected to be managed by the constructed wetland, so no additional holding tanks are considered necessary.

The amount of greywater required for toilet flushing (and rainwater for laundry) will be pumped back into homes for domestic use. A best-case scenario would likely incur 0.67 kWh electricity per cubic m for a constructed wetland system (WECF 2011). Water for gardening and frost-tapping are assumed to require no pumping due to natural sloping for conveyance.

### *Energy efficiency*

Hydrokinetic turbines are relatively new, so municipalities are only beginning to experiment with the technology. Since many of the cases are in essence pilot projects, the number of installations per utility appears to be five turbines at most. Based on available data of the distribution network in Oslo, the power potential for one hydrokinetic turbine can be estimated, and is calculated with:

$$P = Q \times H \times 9.81 \times p_{turbine}$$

where P is the power output (kW), Q is the flow rate through the turbine (cubic m per sec), H is the effluent head (m), and $p_{turbine}$ is the overall turbine efficiency (KWR 2010). A conservative turbine efficiency value of 65 percent is assumed for this analysis (Corcoran, McNabola et al. 2012)

## Results

The interventions have been modelled on an individual basis, and their relative environmental impacts are presented below (Figures 16-17).

### *Leakage management*

The planned network optimisation program would rehabilitate 15.6 km of pipelines each year. To carry out this work, especially that of pipeline repairs, the annual material and energy costs incurred would be in the range of 234,067 kg of polyethylene pipes and 20,141 litres of diesel fuel. Over the course of the 30-year planning horizon the cumulative consumption amounts to 7 M kg of polyethylene pipes and 604,250 litres of diesel fuel.

In light of these costs, the combination of pipe rehabilitation and pressure management activities would reduce the loss of water by about 29.4 M cubic m over the considered timeframe. In addition to improved water resource efficiency, the associated savings with the leakage reductions would also reduce the consumption of chemicals as well as energy for both the treatment and pumping of water. In this case, over 2.8 M kg of chemicals and 10 M kWh of electricity could be saved in the treatment process. An additional savings of 32 M kWh of electricity would be achievable in the pumping and distribution network.

Regarding the environmental impact, assessed in terms of climate change potential, network rehabilitation would result in an increase of greenhouse gas emissions, specifically 5,925 t CO2 e. While the avoided emissions associated with water reductions would reduce greenhouse gas emissions by 12,363 t CO2 e, this would be balanced by the emissions incurred from the production and consumption of polyethylene and diesel fuel (18,288 t CO2 e). However, pipelines that have been adequately rehabilitated can provide benefits to water systems for many decades into the future, so the sustained emissions reduction from water efficiency should be kept in mind in spite of the one-time costs incurred for network renovations.

### *Change in water pricing*

Based on previous implementations of water metres in Norwegian households, water consumption has been observed to have decrease by 10 percent. In Oslo, water consumption in households with water metres installed would amount to 162 litres per capita per day. With universal coverage of the domestic sector in the city eventually reduces total water production to 95.5 M cubic m. Compared to baseline operations, this would achieve a total savings of 105.3 M cubic m in water production. In line with this, the associated cumulative savings in the treatment and pumping sub-systems are in the range of 10.2 M kg of chemicals, 36 M kWh of treatment energy, and 114 M kWh of pumping energy.

To realise these savings and the environmental benefits, the carbon footprint of each water metre has been factored in. As a best-case scenario, the greenhouse gas emissions associated with each water metre installed can be considered 0.915 kg CO2 e. To equip each household connection in Oslo, the cumulative impact is 48 t CO2 e. In light of the environmental benefits derived from reduced water consumption, this would be a worthwhile investment. Over the 30-year timeframe, the combined avoided greenhouse gas emissions from the production and consumption of chemicals and electricity would stand at 44,331 t CO2 e.

*Water reuse*

Figure 15 illustrates the corresponding reductions in per capital water consumption through the introduction of greywater recycling and rainwater harvesting systems. In the first instance, the implementation of greywater recycling (36 percent of consumption) is expected to fully replace the potable water demand currently required for toilet flushing (23 percent). As such, per capita consumption decreases to 138 litres per day, and the surplus greywater will further reduce water consumption currently allocated for gardening and frost-tapping by 23 litres per capita per day. In this scenario of greywater recycling, construction and implementation is modelled to gradually increase over the planning horizon as technical efficiencies increase with the technology. In sum, 615 greywater recycling systems serving approximately 61,500 residents can reduce water production by 28.5 M cubic m. This savings results in a drop in chemical consumption by 2.7 M kg and 40.8 M kWh of treatment and pumping energy.

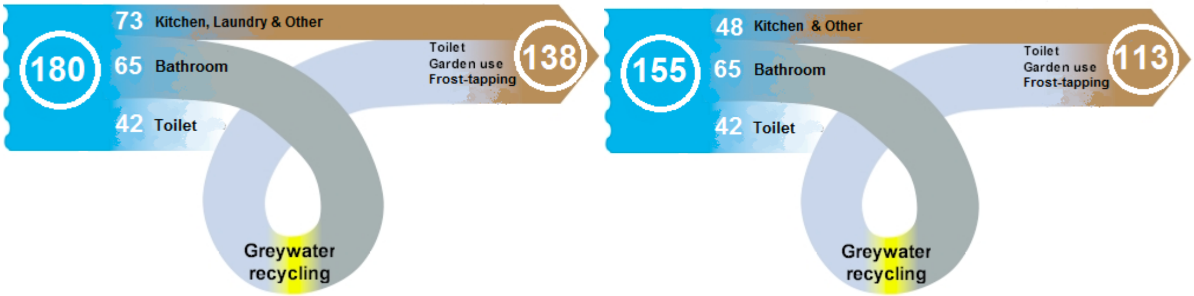

**Figure 15** Water consumption scenarios (litres per capita per day) with greywater recycling (l) and rainwater harvesting (r). Adapted from (Sankey Diagrams 2009).

To realise these savings, material and energy costs would be necessary as part of the septic holding tanks and electricity for water pumping into households. For each greywater recycling system, it is expected that a holding tank with a capacity of 2,906 gallons would be required. Based on market availability, two 1,500-gallon polyethylene tanks weighing 207.7 kg each are available, resulting in a cumulative consumption of 255,526 kg of materials. 619,551 kWh of electricity for greywater pumping back into households would be required over the same time frame.

All told, the prospective greywater recycling systems could result in a net reduction of greenhouse gas emissions. A cumulative savings of 12,018 t CO2 e would be possible keeping in mind that 706 t CO2 e would also be incurred assuming that the greywater technologies remain the same over time. The bulk of the greenhouse gas emissions (84 percent) is attributed to the production and consumption of construction materials, in the case polyethylene. Thus improving the sustainability of this particular greywater recycling vision would require reconfiguration of the system elements or choosing alternative holding tank materials.

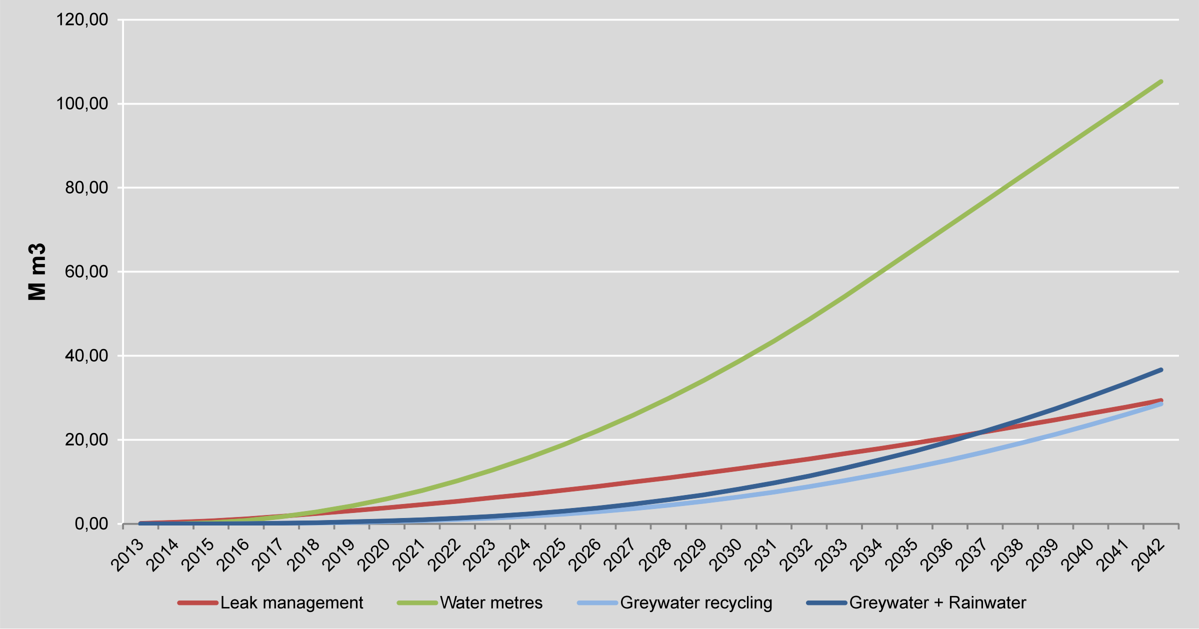

**Figure 16** Cumulative savings in annual water production for each intervention strategy

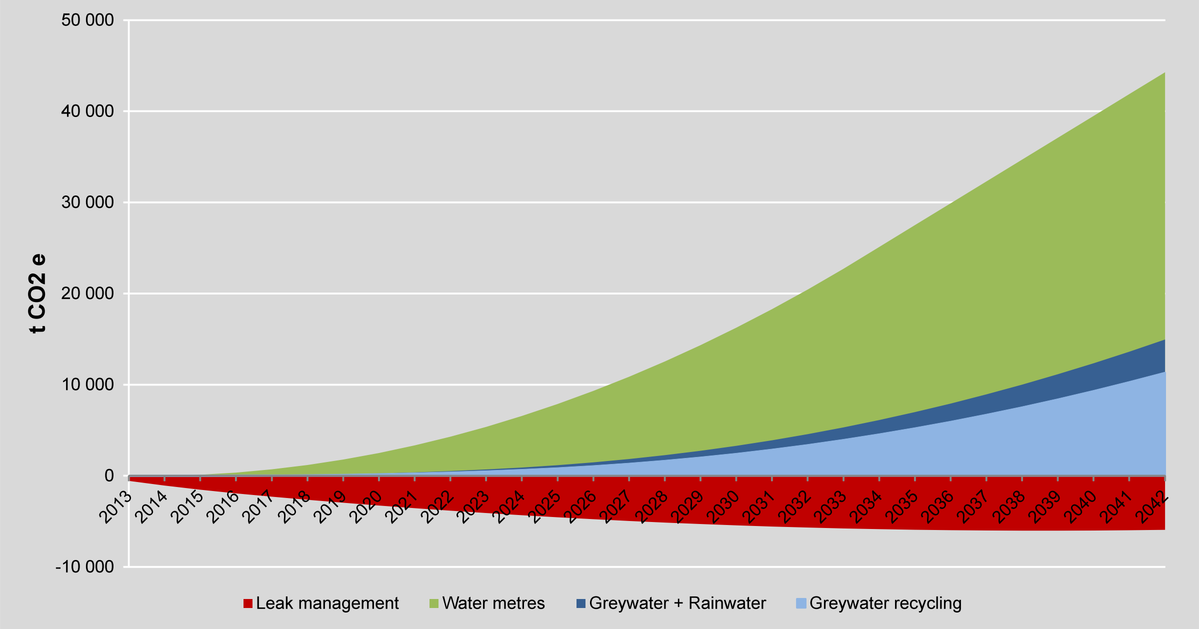

**Figure 17** Cumulative savings in annual greenhouse gas emissions for each intervention strategy

The alternative greywater recycling scenario that was considered concrete holding tanks in addition to the incorporation of rainwater harvesting. The use of stormwater was modelled to fully replace laundering requirements (25 litres per capita per day) thus resulting in a total demand of 113 litres per capita per day with the previous greywater configuration remaining in place. The amount of water saved through this setup equates to 36.7 M cubic m, which corresponds to 3.5 M kg treatment chemicals consumption and a combined 52.5 M kWh of electricity for treatment and pumping.

Concrete holding tanks were considered because of a reportedly lower carbon footprint (approximately half) over plastic (CPM Group 2012). The possibility for concrete to simultaneously absorb CO2 during its lifetime is an additional factor that improves its viability (Norden 2005), but in any case, a lower overall environmental impact can be realised through this scenario. Although more energy will be required to re-circulate greywater into households (996,669 kWh of electricity due to the additional rainwater flows), greenhouse gas emissions can be further reduced to 473 t CO2 e compared to the previous water reuse scenario. The cumulative avoided greenhouse gas emissions will also increase to 15,432 t CO2 e.

*Energy management*

Raw water is normally gravity-fed from Elvåga (195 m above sea level) into the Skullerud water treatment plant. The facility supplies 400 litres of water per second under normal circumstances, and partly distributes water by gravity to reservoirs situated 178 m above sea level (Oslo VAV 2008). Thus the potential power output for one micro hydroturbine outfitted at Skullerud based on a flow rate of 0.4 cubic m per second and a maximum height differential of 17 m is 43.4 kW. The annual efficiency gain would be in the order of 379 MWh, which translates to an offset of 68 t CO2 e.

# Discussion

The preliminary investigations conducted suggest that improvements to the sustainability of Oslo's urban water-energy nexus are possible. With a view towards environmental performance, it is evident that the individual actions on their own contribute to the goals of material and energy efficient flows and the reduction of greenhouse gas emissions to varying degrees. In some instances, significant benefits can be attained with relatively low technical obstacles as in the case of water metres. By contrast, this particular iteration leakage management planning showed an increase in overall greenhouse gas emissions. This demonstrates that individual interventions have their own respective effects on the metabolic dynamics of the urban water system. More importantly, considerations of the options in relation to each other, rather than in opposition to each other, can help to minimise their adverse impacts and potentially maximise the environmental gains.

Each of the actions that have been considered contributes appropriately to the resiliency of the upstream (and downstream) water system. Leakage management strengthens the rigidity of the distribution network and its long-term ability to withstand stresses that stem from operations and service demand. The universal installation of water metres, while contributing to the technical management of leakage reduction, also facilitates system resourcefulness by encouraging water consumers to make do with less. Water reuse schemes improve redundancy through the establishment of backup configurations of water supplies. The possibilities for energy efficiency savings are quite varied and permeate all stages and aspects of water system activities. But beyond the reduction of energy and embodied energy inputs, the application of alternative and renewable energy sources such as solar energy and hydrokinetic turbines can maintain system functionality and robustness while simultaneously minimising the externalities that are driving the development of threats and vulnerabilities.

With respect to the interventions with direct effects on water production flows, their combined potential for savings in water supply and greenhouse gas emissions are presented in Figures 18 and 19. Taken together, the interventions including rainwater harvesting show the potential for a cumulative saving of at least 171 M cubic m of water over the course of the 30-year time frame. In terms of reductions in greenhouse gas emissions, the three interventions would be able to save at least 53,317 t CO2 e over the same time frame compared to baseline operations.

As it is with asset management and infrastructure planning, a note must be made on cost considerations, which have not been incorporated into these preliminary environmental impact assessments. This would constitute a limitation into the practical feasibility of the proposed interventions and would be a required extension in the future course of directed work. However, in light of this, a few notes can be made.

The rehabilitation of pipelines is rarely carried out with the sole motive of leakage reduction since water quality improvements and performance reliability are also key drivers (Venkatesh 2012). As such, the high upfront environmental costs of network optimisation are expected to decrease over the long-run, and combined with the reductions in social costs (eg disruptions, time loss, loss of business, property damage) and operational costs (eg sewer damage, street body deterioration and reconstruction), the economic feasibility stands at a greater value.

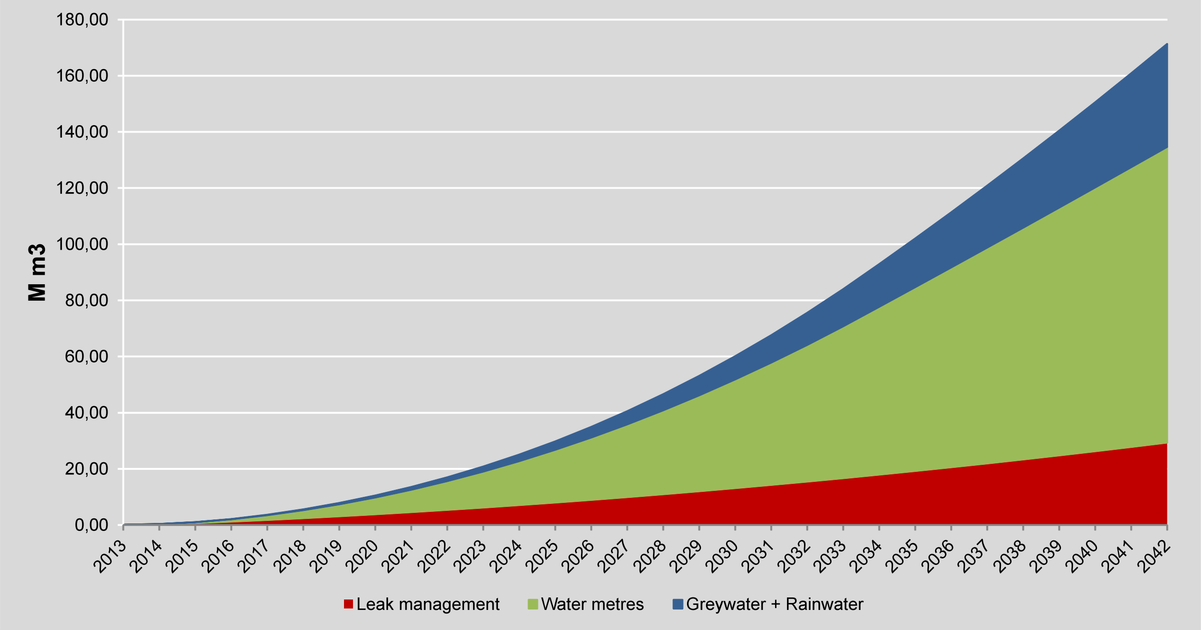

**Figure 18** Combined cumulative savings in annual water production for selected intervention strategies

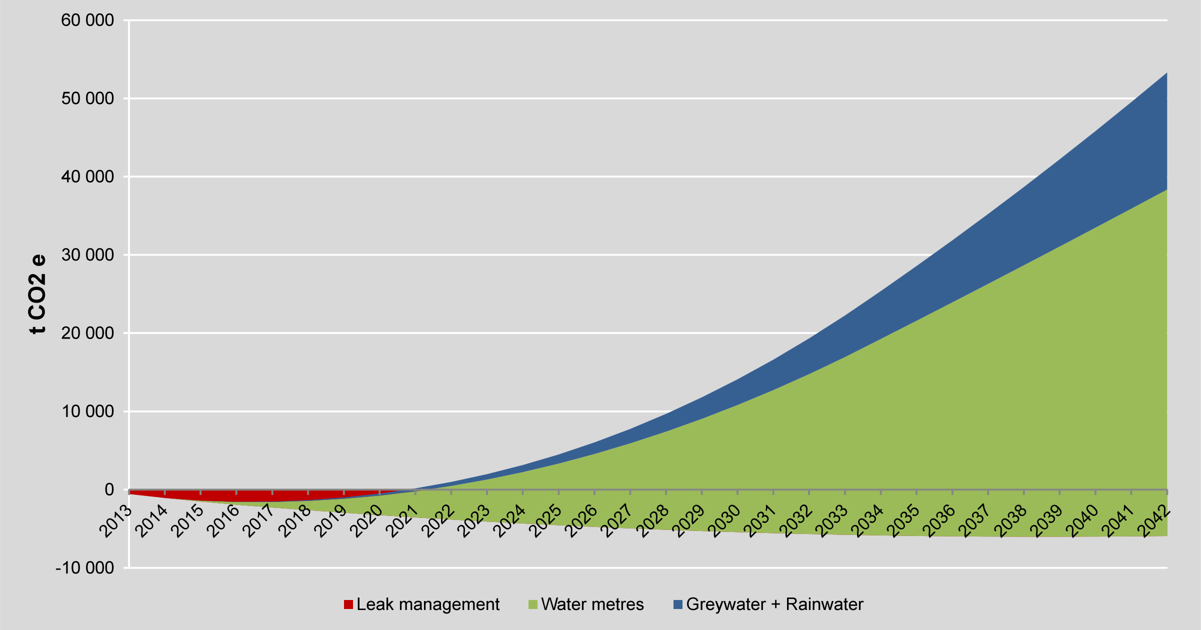

**Figure 19** Combined cumulative reductions in annual greenhouse gas emission for selected intervention strategies

The state of water metres have advanced significantly to become an established technology which is now cost-effective enough to be applied to collect, store and distribute real-time water consumption data (Cole and Rodney 2013). Thus the greatest barrier to universal implementation lies within the political realm and with public resistance to metre installations. However, the trend in neighbouring and other Norwegian municipalities indicate that such obstacles are not insurmountable, and indeed must be met in light of the low economic and environmental costs.

Greywater recycling was given preference over rainwater harvesting because the concept strikes at the core of the water-energy relationship; that is, increasing the productivity of water rather than reinforcing the single use setup whereby drinking quality water and its embodied investments is carelessly consumed and discarded. By cascading household wastewater at a low energetic cost and re-circulating it for adaptive uses, the benefits are equally cascaded at both the upstream and downstream systems through a reduction in flows from and to treatment facilities. With regards to decentralised concepts, financial costs are cited as main concerns particularly in regions with established infrastructure, which is why most applications are in developing regions of the world. Nevertheless, a full cost assessment would need to account for the benefits, which are difficult to monetise within the scope of this study. The benefits would entail a rise in property values due in part to increased wildlife and biodiversity, environmental health and more pleasant and scenic landscapes, and the potential for job creation through the maintenance and monitoring of greywater recycling systems. Given these additional benefits of water reuse in addition to their positive impacts on combined sewer overflows (Ridolfi 2009), which are a driving climate change concern in Norway, there is a strong case to be made for water reuse. In light of the potential for a Winter Olympics in Oslo during 2022 and an accompanying construction boom, the potential to seize the opportunity to showcase to the world a major step towards a new paradigm for urban water provision is imminent.

The implementation of energy efficiency improvements and renewable energy sources is a win-win proposition of water utilities. Despite likely high upfront financial costs, these would be tempered with payback potential through both reduced expenses and in compensation for energy supplied to the grid. Micro hydroturbines have great potential to improve the sustainability of water systems by converting water flows into electricity. The power potential was demonstrated for a possible application at Skullerud water treatment plant; however, numerous other candidate locations are abundant throughout the distribution network by virtue of its configuration in relation to the elevated water source. Other potential candidate locations or implementation would include the Grefsen tunnel and Nydals pipeline extending from Oset as well as at the wastewater treatment facilities where effluent release drop points can be harnessed.

### *Concluding remarks*

While not entirely immune to the effects of climate change, the position of Norway is rather enviable compared to other nations. Thus there is perhaps little impetus to push the boundaries of urban water services. Nevertheless, the combination of rising population and climate change are no less of a concern for the urban water system in Oslo as they are in other parts of the world. The contributions of the water system to global climate change and the opportunity for the utility to provide knowledge sharing and technology transfer to lower- and middle-income countries (to help ensure sustainable path dependency) by setting strong examples are strong reasons for robust intervention planning. The likelihood of the selected interventions is favourable due to a combination of inherent asset management principles, endorsements from high-level strategic urban management plans, domestic and international trends, successful pilot projects, and national climate change forecasts. The environmental performance of the individual interventions are varied and contribute in their own rights, but considered in conjunction and taken as a whole, they can offer more robust system sustainability and urban resilience solutions. Monetary analyses to complement exploratory environmental impact assessments are likely to indicate strong economic justifications.

# CHAPTER 05
# Conclusion

Rapid mass migration to cities and slow-developing climate change are the dual forces driving the concerns and vulnerabilities of urban system authorities. Rising populations are expected to increase demand for resource consumption, and the infrastructural services that cater to these needs is expected to likewise increase global greenhouse gas emissions thus reinforcing the climate change conundrum. Based on the role of water in human physiology, its historical importance to human settlements, and its embedded impacts in wider society (from the floorboards that are walked on to the cotton that is worn to the meat that is eaten) modern urban water systems will play a critical role in driving sustainable urban development.

In this thesis it was shown that conceptions of urban water services are shifting from the linear to the circular. Such a shift has actually been acknowledged for some time with life cycle, material flow and impact assessments of single urban water technologies and processes. However, a further evolution in thinking is evident by the uptake of multi-stage water-energy nexus studies and initiatives at the academic level in addition to other institutions including urban environmental departments, regional management authorities, non-governmental organisations, the military and multi-lateral world bodies. A combination of industrial ecology perspectives and the framing of sustainability in terms of the water-energy nexus also helped to determine why nexus relationships are divergent in urban areas. The analysis of four water systems yielded interlinkages and findings that show the need for collaboration of the water sector with its sectoral counterparts in pursuit of robust climate change adaptation policies and programs. Environmental analyses of interventions in Oslo also demonstrated that intra-collaboration and internal systems thinking is equally crucial to external cooperation. Considering the multiple stages of the urban water system itself (eg extraction, treatment, distribution and consumption) in conjunction provides a more insightful look into the relative environmental costs of efficiency gains, and that taken as a whole can yield relevant reductions in greenhouse gas emissions.

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# Appendices

## A

| GWh (Toronto, 2011) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct Requirements | Fossil Fuels | | | | | 149,85 | 149,85 |
| | Electricity | | 130,61 | 139,94 | 43,91 | 205,35 | 519,82 |
| | Heat | | | | | | 0,00 |
| B - Indirect Requirements | Fossil Fuels | | 3,37 | | | 11,63 | 15,00 |
| | Electricity | | 3,63 | | | 8,11 | 11,74 |
| | Heat | | 1,49 | | | 3,69 | 5,19 |
| C - Energy Generation | Fossil Fuels | | | | | | 0,00 |
| | Electricity | | | | | | 0,00 |
| | Heat | | | | | 111,16 | 111,16 |
| D - Avoided Consumption | Fossil Fuels | | | | | | 0,00 |
| | Electricity | | | | | | 0,00 |
| | Heat | | | | | | 0,00 |
| **Balance** | Fossil Fuels | | 3,37 | | | 161,47 | 164,85 |
| | Electricity | | 134,24 | 139,94 | 43,91 | 213,47 | 531,56 |
| | Heat | | 1,49 | | | 114,86 | 116,35 |
| | **TOTAL** | | **139,10** | **139,94** | **43,91** | **489,80** | **812,75** |

| GWh (Oslo, 2007) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct Requirements | Fossil Fuels | | 2,41 | | | 1,11 | 3,52 |
| | Electricity | | 22,80 | 15,20 | 5,80 | 29,65 | 73,45 |
| | Heat | | | | | | |
| B - Indirect Requirements | Fossil Fuels | | 0,53 | | | 3,76 | 4,29 |
| | Electricity | | 0,67 | | | 7,09 | 7,75 |
| | Heat | | 0,37 | | | 13,10 | 13,47 |
| C - Energy Generation | Fossil Fuels | | | | | | |
| | Electricity | | | | | 14,50 | 14,50 |
| | Heat | | | | | 56,40 | 56,40 |
| D - Avoided Consumption | Fossil Fuels | | | | | 2,40 | 2,40 |
| | Electricity | | | | | 1,93 | 1,93 |
| | Heat | | | | | 23,60 | 23,60 |
| **Balance** | Fossil Fuels | | 2,94 | | | 4,87 | 7,81 |
| | Electricity | | 23,47 | 15,20 | 5,80 | 51,24 | 95,70 |
| | Heat | | 0,37 | | | 69,50 | 69,87 |
| | **TOTAL** | - | **26,77** | **15,20** | **5,80** | **125,61** | **173,38** |

| GWh (Nantes, 2010) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct Requirements | Fossil Fuels | | 0,97 | | | | 0,97 |
| | Electricity | 2,70 | 11,00 | 9,20 | 4,12 | 22,20 | 49,22 |
| | Heat | | 0,84 | | | 0,80 | 1,64 |
| B - Indirect Requirements | Fossil Fuels | | 1,09 | | | 3,81 | 4,90 |
| | Electricity | | 1,88 | | | 0,28 | 2,16 |
| | Heat | | 0,57 | | | 0,19 | 0,76 |
| C - Energy Generation | Fossil Fuels | | | | | | - |
| | Electricity | | | | | | - |
| | Heat | | | | | | - |
| D - Avoided Consumption | Fossil Fuels | | | | | 1,37 | 1,37 |
| | Electricity | | | | | 1,06 | 1,06 |
| | Heat | | | | | 14,28 | 14,28 |
| **Balance** | Fossil Fuels | | 2,06 | | | 3,81 | 5,87 |
| | Electricity | 2,70 | 12,88 | 9,20 | 4,12 | 22,48 | 51,38 |
| | Heat | | 1,41 | | | 0,99 | 2,40 |
| | **TOTAL** | **2,70** | **16,35** | **9,20** | **4,12** | **27,28** | **59,65** |

| GWh (Torino, 2010) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct Requirements | Fossil Fuels | 1,70 | 1,70 | 1,70 | 1,70 | 1,70 | 8,50 |
| | Electricity | 5,53 | 58,56 | 71,13 | 5,21 | 47,25 | 187,68 |
| | Heat | | | | | | - |
| B - Indirect Requirements | Fossil Fuels | | 13,51 | | | 80,11 | 93,62 |
| | Electricity | | 14,49 | | | 25,16 | 39,65 |
| | Heat | | | | | | - |
| C - Energy Generation | Fossil Fuels | | | | | | - |
| | Electricity | | | | | 31,60 | 31,60 |
| | Heat | | | | | 38,30 | 38,30 |
| D - Avoided Consumption | Fossil Fuels | | | | | | - |
| | Electricity | 6,00 | | | | | 6,00 |
| | Heat | | | | | | - |
| **Balance** | Fossil Fuels | 1,70 | 15,21 | 1,70 | 1,70 | 81,81 | 102,12 |
| | Electricity | 5,53 | 73,05 | 71,13 | 5,21 | 104,01 | 258,93 |
| | Heat | | | | | 38,30 | 38,30 |
| | **TOTAL** | **7,23** | **88,26** | **72,83** | **6,91** | **224,12** | **399,35** |

| t CO2 e (Toronto, 2011) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct emissions | Non-biogenic | | | | | | |
| | Fossil fuels | | | | | 27 030,39 | 27 030,39 |
| B - Indirect emissions from direct consumption | Fossil fuels | | | | | 10 789,14 | 10 789,14 |
| | Electricity | | 13 061,16 | 13 994,10 | 4 391,16 | 20 535,45 | 51 981,87 |
| | Heat | | | | | | |
| C - Indirect emissions from indirect | GWP | | 4 470,78 | | | 14 099,43 | 18 570,21 |
| D - Avoided consumption | GWP | | | | | | |
| **Balance** | **Total** | | **17 531,94** | **13 994,10** | **4 391,16** | **72 454,41** | **108 371,61** |

| t CO2 e (Oslo, 2007) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct emissions | Non-biogenic | | | | | 2 538,19 | 2 538,19 |
| | Fossil fuels | | 867,60 | | | 399,60 | 1 267,20 |
| B - Indirect emissions from direct consumption | Fossil fuels | | 173,52 | | | 79,92 | 253,44 |
| | Electricity | | 1 071,60 | 714,40 | 272,60 | 1 393,55 | 3 452,15 |
| | Heat | | | | | | |
| C - Indirect emissions from indirect | GWP | | 950,32 | | | 16 706,84 | 17 657,15 |
| D - Avoided consumption | GWP | | | | | 40 829,07 | 40 829,07 |
| **Balance** | **Total** | | **3 063,04** | **714,40** | **272,60** | **21 118,09** | **25 168,13** |

| t CO2 e (Nantes, 2010) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct emissions | Non-biogenic | | | | | 2 573,00 | 2 573,00 |
| | Fossil fuels | | 349,20 | | | | 349,20 |
| B - Indirect emissions from direct consumption | Fossil fuels | | 69,84 | | | | 69,84 |
| | Electricity | 54,00 | 220,00 | 184,00 | 82,40 | 444,00 | 984,40 |
| | Heat | | 214,70 | | | 204,48 | 419,18 |
| C - Indirect emissions from indirect | GWP | | 3 957,93 | | | 5 198,25 | 9 156,18 |
| D - Avoided consumption | GWP | | | | | 16 677,84 | 16 677,84 |
| **Balance** | **Total** | **54,00** | **4 811,67** | **184,00** | **82,40** | **8 419,73** | **13 551,80** |

| t CO2 e (Torino, 2010) | | Raw Water Supply | Water Treatment | Distribution | Sewage Collection | WW Treatment | Balance |
|---|---|---|---|---|---|---|---|
| A - Direct emissions | Non-biogenic | | | | | | |
| | Fossil fuels | 397,00 | 1 687,00 | 397,00 | 397,00 | 397,00 | 3 275,00 |
| B - Indirect emissions from direct consumption | Fossil fuels | | | | | | |
| | Electricity | 2 938,00 | 31 098,00 | 37 772,00 | 2 767,00 | 25 090,00 | 99 665,00 |
| | Heat | | | | | | |
| C - Indirect emissions from indirect | GWP | | 7 555,00 | | | 10 979,00 | 18 534,00 |
| D - Avoided consumption | GWP | 3 186,00 | | | | 37,11 | 3 223,11 |
| **Balance** | **Total** | **3 335,00** | **40 340,00** | **38 169,00** | **3 164,00** | **36 466,00** | **121 474,00** |

# B

**Leakage management**

| Year | Water | | Treatment and pumping savings | | | Rehabilitation consumption | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Chemicals (kg) | T energy (kWh) | P energy (kWh) | Repair length (km) | Materials (kg) | Diesel (litres) |
| 2013 | 101.1 | 0.1 | 11,804.0 | 41,532.5 | 132,369.6 | 15.6 | 234,067.2 | 20,141.7 |
| 2014 | 101.0 | 0.2 | 23,537.1 | 82,815.8 | 263,945.0 | 15.6 | 234,067.2 | 20,141.7 |
| 2015 | 100.8 | 0.4 | 35,199.9 | 123,851.4 | 394,730.9 | 15.6 | 234,067.2 | 20,141.7 |
| 2016 | 100.7 | 0.5 | 46,792.6 | 164,640.7 | 524,732.1 | 15.6 | 234,067.2 | 20,141.7 |
| 2017 | 100.6 | 0.6 | 58,315.8 | 205,185.4 | 653,953.3 | 15.6 | 234,067.2 | 20,141.7 |
| 2018 | 100.6 | 0.6 | 62,133.9 | 218,619.1 | 696,768.6 | 15.6 | 234,067.2 | 20,141.7 |
| 2019 | 100.5 | 0.7 | 65,944.3 | 232,026.1 | 739,498.3 | 15.6 | 234,067.2 | 20,141.7 |
| 2020 | 100.5 | 0.7 | 69,747.0 | 245,406.2 | 782,142.5 | 15.6 | 234,067.2 | 20,141.7 |
| 2021 | 100.4 | 0.8 | 73,542.2 | 258,759.5 | 824,701.4 | 15.6 | 234,067.2 | 20,141.7 |
| 2022 | 100.4 | 0.8 | 77,329.8 | 272,086.2 | 867,175.2 | 15.6 | 234,067.2 | 20,141.7 |
| 2023 | 100.4 | 0.8 | 81,109.7 | 285,386.2 | 909,564.1 | 15.6 | 234,067.2 | 20,141.7 |
| 2024 | 100.3 | 0.9 | 84,882.2 | 298,659.5 | 951,868.1 | 15.6 | 234,067.2 | 20,141.7 |
| 2025 | 100.3 | 0.9 | 88,647.1 | 311,906.4 | 994,087.6 | 15.6 | 234,067.2 | 20,141.7 |
| 2026 | 100.2 | 1.0 | 92,404.4 | 325,126.7 | 1,036,222.6 | 15.6 | 234,067.2 | 20,141.7 |
| 2027 | 100.2 | 1.0 | 96,154.3 | 338,320.6 | 1,078,273.4 | 15.6 | 234,067.2 | 20,141.7 |
| 2028 | 100.2 | 1.0 | 99,896.6 | 351,488.2 | 1,120,240.0 | 15.6 | 234,067.2 | 20,141.7 |
| 2029 | 100.1 | 1.1 | 103,631.5 | 364,629.3 | 1,162,122.7 | 15.6 | 234,067.2 | 20,141.7 |
| 2030 | 100.1 | 1.1 | 107,358.9 | 377,744.2 | 1,203,921.7 | 15.6 | 234,067.2 | 20,141.7 |
| 2031 | 100.1 | 1.1 | 111,078.8 | 390,832.9 | 1,245,637.1 | 15.6 | 234,067.2 | 20,141.7 |
| 2032 | 100.0 | 1.2 | 114,791.3 | 403,895.4 | 1,287,269.0 | 15.6 | 234,067.2 | 20,141.7 |
| 2033 | 100.0 | 1.2 | 118,496.4 | 416,931.8 | 1,328,817.6 | 15.6 | 234,067.2 | 20,141.7 |
| 2034 | 99.9 | 1.3 | 122,194.1 | 429,942.1 | 1,370,283.2 | 15.6 | 234,067.2 | 20,141.7 |
| 2035 | 99.9 | 1.3 | 125,884.3 | 442,926.3 | 1,411,665.8 | 15.6 | 234,067.2 | 20,141.7 |
| 2036 | 99.9 | 1.3 | 129,567.2 | 455,884.7 | 1,452,965.7 | 15.6 | 234,067.2 | 20,141.7 |
| 2037 | 99.8 | 1.4 | 133,242.7 | 468,817.0 | 1,494,183.0 | 15.6 | 234,067.2 | 20,141.7 |
| 2038 | 99.8 | 1.4 | 136,910.9 | 481,723.6 | 1,535,317.8 | 15.6 | 234,067.2 | 20,141.7 |
| 2039 | 99.8 | 1.4 | 140,571.7 | 494,604.3 | 1,576,370.4 | 15.6 | 234,067.2 | 20,141.7 |
| 2040 | 99.7 | 1.5 | 144,225.3 | 507,459.2 | 1,617,340.8 | 15.6 | 234,067.2 | 20,141.7 |
| 2041 | 99.7 | 1.5 | 147,871.5 | 520,288.5 | 1,658,229.4 | 15.6 | 234,067.2 | 20,141.7 |
| 2042 | 99.6 | 1.6 | 151,510.4 | 533,092.1 | 1,699,036.1 | 15.6 | 234,067.2 | 20,141.7 |
| Total | 3,006.6 | 29.4 | 2,854,775.9 | 10,044,581.8 | 32,013,433.1 | 468.0 | 7,022,016.2 | 604,250.0 |

| Year | Water | | GHG emissions (kg CO2 e) | | | Avoided GHG emissions (kg CO2 e) | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Material | Diesel | Total | Chemical | Energy | Total |
| 2013 | 101.1 | 0.1 | 545,376.6 | 64,251.9 | 609,628.5 | 19,819.0 | 31,302.4 | 51,121.4 |
| 2014 | 101.0 | 0.2 | 545,376.6 | 64,251.9 | 609,628.5 | 39,519.1 | 62,416.9 | 101,936.0 |
| 2015 | 100.8 | 0.4 | 545,376.6 | 64,251.9 | 609,628.5 | 59,101.0 | 93,344.8 | 152,445.8 |
| 2016 | 100.7 | 0.5 | 545,376.6 | 64,251.9 | 609,628.5 | 78,565.4 | 124,087.1 | 202,652.5 |
| 2017 | 100.6 | 0.6 | 545,376.6 | 64,251.9 | 609,628.5 | 97,913.0 | 154,645.0 | 252,558.0 |
| 2018 | 100.6 | 0.6 | 545,376.6 | 64,251.9 | 609,628.5 | 104,323.5 | 164,769.8 | 269,093.3 |
| 2019 | 100.5 | 0.7 | 545,376.6 | 64,251.9 | 609,628.5 | 110,721.2 | 174,874.4 | 285,595.6 |
| 2020 | 100.5 | 0.7 | 545,376.6 | 64,251.9 | 609,628.5 | 117,106.1 | 184,958.8 | 302,064.9 |
| 2021 | 100.4 | 0.8 | 545,376.6 | 64,251.9 | 609,628.5 | 123,478.2 | 195,023.0 | 318,501.2 |
| 2022 | 100.4 | 0.8 | 545,376.6 | 64,251.9 | 609,628.5 | 129,837.6 | 205,067.0 | 334,904.7 |
| 2023 | 100.4 | 0.8 | 545,376.6 | 64,251.9 | 609,628.5 | 136,184.3 | 215,091.0 | 351,275.3 |
| 2024 | 100.3 | 0.9 | 545,376.6 | 64,251.9 | 609,628.5 | 142,518.2 | 225,095.0 | 367,613.2 |
| 2025 | 100.3 | 0.9 | 545,376.6 | 64,251.9 | 609,628.5 | 148,839.5 | 235,078.9 | 383,918.5 |
| 2026 | 100.2 | 1.0 | 545,376.6 | 64,251.9 | 609,628.5 | 155,148.2 | 245,042.9 | 400,191.1 |
| 2027 | 100.2 | 1.0 | 545,376.6 | 64,251.9 | 609,628.5 | 161,444.2 | 254,986.9 | 416,431.2 |
| 2028 | 100.2 | 1.0 | 545,376.6 | 64,251.9 | 609,628.5 | 167,727.7 | 264,911.1 | 432,638.8 |
| 2029 | 100.1 | 1.1 | 545,376.6 | 64,251.9 | 609,628.5 | 173,998.6 | 274,815.4 | 448,813.9 |
| 2030 | 100.1 | 1.1 | 545,376.6 | 64,251.9 | 609,628.5 | 180,256.9 | 284,699.9 | 464,956.8 |
| 2031 | 100.1 | 1.1 | 545,376.6 | 64,251.9 | 609,628.5 | 186,502.7 | 294,564.6 | 481,067.3 |
| 2032 | 100.0 | 1.2 | 545,376.6 | 64,251.9 | 609,628.5 | 192,736.1 | 304,409.6 | 497,145.6 |
| 2033 | 100.0 | 1.2 | 545,376.6 | 64,251.9 | 609,628.5 | 198,956.9 | 314,234.9 | 513,191.8 |
| 2034 | 99.9 | 1.3 | 545,376.6 | 64,251.9 | 609,628.5 | 205,165.3 | 324,040.6 | 529,205.9 |
| 2035 | 99.9 | 1.3 | 545,376.6 | 64,251.9 | 609,628.5 | 211,361.3 | 333,826.6 | 545,187.9 |
| 2036 | 99.9 | 1.3 | 545,376.6 | 64,251.9 | 609,628.5 | 217,545.0 | 343,593.1 | 561,138.0 |
| 2037 | 99.8 | 1.4 | 545,376.6 | 64,251.9 | 609,628.5 | 223,716.2 | 353,340.0 | 577,056.2 |
| 2038 | 99.8 | 1.4 | 545,376.6 | 64,251.9 | 609,628.5 | 229,875.1 | 363,067.4 | 592,942.6 |
| 2039 | 99.8 | 1.4 | 545,376.6 | 64,251.9 | 609,628.5 | 236,021.7 | 372,775.4 | 608,797.1 |
| 2040 | 99.7 | 1.5 | 545,376.6 | 64,251.9 | 609,628.5 | 242,156.0 | 382,464.0 | 624,620.0 |
| 2041 | 99.7 | 1.5 | 545,376.6 | 64,251.9 | 609,628.5 | 248,278.0 | 392,133.2 | 640,411.2 |
| 2042 | 99.6 | 1.6 | 545,376.6 | 64,251.9 | 609,628.5 | 254,387.8 | 401,783.1 | 656,170.9 |
| Total | 3,006.6 | 29.4 | 16,361,297.8 | 1,927,557.6 | 18,288,855.4 | 4,793,203.9 | 7,570,442.7 | 12,363,646.6 |

**Water metre installations**

| Year | Water | | Treatment and pumping savings | | | |
|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Chemicals (kg) | T energy (kWh) | P energy (kWh) | Metres installed |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 100.9 | 0.3 | 27,665.5 | 97,341.7 | 310,241.2 | 2,675.0 |
| 2016 | 100.6 | 0.6 | 55,331.1 | 194,683.5 | 620,482.5 | 2,675.0 |
| 2017 | 100.3 | 0.9 | 82,996.6 | 292,025.2 | 930,723.7 | 2,675.0 |
| 2018 | 100.1 | 1.1 | 110,662.2 | 389,367.0 | 1,240,965.0 | 2,675.0 |
| 2019 | 99.8 | 1.4 | 138,327.7 | 486,708.7 | 1,551,206.2 | 2,675.0 |
| 2020 | 99.5 | 1.7 | 165,993.3 | 584,050.5 | 1,861,447.5 | 2,675.0 |
| 2021 | 99.2 | 2.0 | 193,658.8 | 681,392.2 | 2,171,688.7 | 2,675.0 |
| 2022 | 98.9 | 2.3 | 221,324.4 | 778,734.0 | 2,481,930.0 | 2,675.0 |
| 2023 | 98.6 | 2.6 | 248,989.9 | 876,075.7 | 2,792,171.2 | 2,675.0 |
| 2024 | 98.4 | 2.8 | 276,655.5 | 973,417.5 | 3,102,412.5 | 2,675.0 |
| 2025 | 98.1 | 3.1 | 304,321.0 | 1,070,759.2 | 3,412,653.7 | 2,675.0 |
| 2026 | 97.8 | 3.4 | 331,986.6 | 1,168,101.0 | 3,722,895.0 | 2,675.0 |
| 2027 | 97.5 | 3.7 | 359,652.1 | 1,265,442.7 | 4,033,136.2 | 2,675.0 |
| 2028 | 97.2 | 4.0 | 387,317.7 | 1,362,784.5 | 4,343,377.5 | 2,675.0 |
| 2029 | 96.9 | 4.3 | 414,983.2 | 1,460,126.2 | 4,653,618.7 | 2,675.0 |
| 2030 | 96.6 | 4.6 | 442,648.8 | 1,557,468.0 | 4,963,860.0 | 2,675.0 |
| 2031 | 96.4 | 4.8 | 470,314.3 | 1,654,809.7 | 5,274,101.2 | 2,675.0 |
| 2032 | 96.1 | 5.1 | 497,979.9 | 1,752,151.5 | 5,584,342.5 | 2,675.0 |
| 2033 | 95.8 | 5.4 | 525,645.4 | 1,849,493.2 | 5,894,583.7 | 2,675.0 |
| 2034 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 2,675.0 |
| 2035 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2036 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2037 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2038 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2039 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2040 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2041 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| 2042 | 95.5 | 5.7 | 553,311.0 | 1,946,835.0 | 6,204,825.0 | 0.0 |
| Total | 2,930.7 | 105.3 | 10,236,253.5 | 36,016,447.5 | 114,789,262.5 | 53,500.0 |

| Year | Water | | GHG (kgCO2e) | Avoided GHG emissions (kg CO2 e) | | |
|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Water metres | Chemical | Energy | Total |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 100.9 | 0.3 | 2,447.6 | 46,450.8 | 73,364.9 | 119,815.7 |
| 2016 | 100.6 | 0.6 | 2,447.6 | 92,901.6 | 146,729.9 | 239,631.5 |
| 2017 | 100.3 | 0.9 | 2,447.6 | 139,352.4 | 220,094.8 | 359,447.2 |
| 2018 | 100.1 | 1.1 | 2,447.6 | 185,803.2 | 293,459.8 | 479,263.0 |
| 2019 | 99.8 | 1.4 | 2,447.6 | 232,254.0 | 366,824.7 | 599,078.7 |
| 2020 | 99.5 | 1.7 | 2,447.6 | 278,704.8 | 440,189.6 | 718,894.4 |
| 2021 | 99.2 | 2.0 | 2,447.6 | 325,155.6 | 513,554.6 | 838,710.2 |
| 2022 | 98.9 | 2.3 | 2,447.6 | 371,606.4 | 586,919.5 | 958,525.9 |
| 2023 | 98.6 | 2.6 | 2,447.6 | 418,057.2 | 660,284.5 | 1,078,341.7 |
| 2024 | 98.4 | 2.8 | 2,447.6 | 464,508.0 | 733,649.4 | 1,198,157.4 |
| 2025 | 98.1 | 3.1 | 2,447.6 | 510,958.8 | 807,014.3 | 1,317,973.1 |
| 2026 | 97.8 | 3.4 | 2,447.6 | 557,409.6 | 880,379.3 | 1,437,788.9 |
| 2027 | 97.5 | 3.7 | 2,447.6 | 603,860.4 | 953,744.2 | 1,557,604.6 |
| 2028 | 97.2 | 4.0 | 2,447.6 | 650,311.2 | 1,027,109.2 | 1,677,420.4 |
| 2029 | 96.9 | 4.3 | 2,447.6 | 696,762.0 | 1,100,474.1 | 1,797,236.1 |
| 2030 | 96.6 | 4.6 | 2,447.6 | 743,212.8 | 1,173,839.0 | 1,917,051.8 |
| 2031 | 96.4 | 4.8 | 2,447.6 | 789,663.6 | 1,247,204.0 | 2,036,867.6 |
| 2032 | 96.1 | 5.1 | 2,447.6 | 836,114.4 | 1,320,568.9 | 2,156,683.3 |
| 2033 | 95.8 | 5.4 | 2,447.6 | 882,565.2 | 1,393,933.9 | 2,276,499.1 |
| 2034 | 95.5 | 5.7 | 2,447.6 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2035 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2036 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2037 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2038 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2039 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2040 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2041 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| 2042 | 95.5 | 5.7 | 0.0 | 929,016.0 | 1,467,298.8 | 2,396,314.8 |
| Total | 2,930.7 | 105.3 | 48,952.5 | 17,186,796.0 | 27,145,027.8 | 44,331,823.8 |

**Greywater recycling**

| Year | Water | | Treatment and pumping savings | | | Greywater | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Chemicals (kg) | T energy (kWh) | P energy (kWh) | Systems | Materials (kg) | Energy (kWh) |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 101.2 | 0.0 | 1,677.6 | 5,902.6 | 18,812.3 | 5.0 | 2,077.5 | 5,037.0 |
| 2016 | 101.2 | 0.0 | 3,673.2 | 12,924.3 | 41,191.4 | 5.0 | 2,077.5 | 5,037.0 |
| 2017 | 101.1 | 0.1 | 5,668.8 | 19,946.0 | 63,570.4 | 5.0 | 2,077.5 | 5,037.0 |
| 2018 | 101.1 | 0.1 | 9,660.1 | 33,989.3 | 108,328.6 | 10.0 | 4,154.9 | 10,074.0 |
| 2019 | 101.1 | 0.1 | 13,651.4 | 48,032.7 | 153,086.7 | 10.0 | 4,154.9 | 10,074.0 |
| 2020 | 101.0 | 0.2 | 17,642.7 | 62,076.1 | 197,844.8 | 10.0 | 4,154.9 | 10,074.0 |
| 2021 | 101.0 | 0.2 | 21,633.9 | 76,119.5 | 242,602.9 | 10.0 | 4,154.9 | 10,074.0 |
| 2022 | 100.9 | 0.3 | 27,620.9 | 97,184.5 | 309,740.1 | 15.0 | 6,232.4 | 15,111.0 |
| 2023 | 100.9 | 0.3 | 33,607.8 | 118,249.6 | 376,877.3 | 15.0 | 6,232.4 | 15,111.0 |
| 2024 | 100.8 | 0.4 | 39,594.7 | 139,314.6 | 444,014.5 | 15.0 | 6,232.4 | 15,111.0 |
| 2025 | 100.7 | 0.5 | 49,572.9 | 174,423.1 | 555,909.8 | 25.0 | 10,387.3 | 25,185.0 |
| 2026 | 100.6 | 0.6 | 59,551.1 | 209,531.5 | 667,805.1 | 25.0 | 10,387.3 | 25,185.0 |
| 2027 | 100.5 | 0.7 | 69,529.2 | 244,640.0 | 779,700.4 | 25.0 | 10,387.3 | 25,185.0 |
| 2028 | 100.4 | 0.8 | 79,507.4 | 279,748.4 | 891,595.7 | 25.0 | 10,387.3 | 25,185.0 |
| 2029 | 100.3 | 0.9 | 89,485.6 | 314,856.8 | 1,003,491.1 | 25.0 | 10,387.3 | 25,185.0 |
| 2030 | 100.2 | 1.0 | 101,459.4 | 356,987.0 | 1,137,765.4 | 30.0 | 12,464.7 | 30,222.0 |
| 2031 | 100.0 | 1.2 | 113,433.3 | 399,117.1 | 1,272,039.8 | 30.0 | 12,464.7 | 30,222.0 |
| 2032 | 99.9 | 1.3 | 125,407.1 | 441,247.2 | 1,406,314.2 | 30.0 | 12,464.7 | 30,222.0 |
| 2033 | 99.8 | 1.4 | 137,380.9 | 483,377.3 | 1,540,588.6 | 30.0 | 12,464.7 | 30,222.0 |
| 2034 | 99.7 | 1.5 | 149,354.7 | 525,507.5 | 1,674,862.9 | 30.0 | 12,464.7 | 30,222.0 |
| 2035 | 99.5 | 1.7 | 161,328.6 | 567,637.6 | 1,809,137.3 | 30.0 | 12,464.7 | 30,222.0 |
| 2036 | 99.4 | 1.8 | 173,302.4 | 609,767.7 | 1,943,411.7 | 30.0 | 12,464.7 | 30,222.0 |
| 2037 | 99.3 | 1.9 | 185,276.2 | 651,897.8 | 2,077,686.1 | 30.0 | 12,464.7 | 30,222.0 |
| 2038 | 99.2 | 2.0 | 197,250.0 | 694,028.0 | 2,211,960.4 | 30.0 | 12,464.7 | 30,222.0 |
| 2039 | 99.0 | 2.2 | 209,223.9 | 736,158.1 | 2,346,234.8 | 30.0 | 12,464.7 | 30,222.0 |
| 2040 | 98.9 | 2.3 | 221,197.7 | 778,288.2 | 2,480,509.2 | 30.0 | 12,464.7 | 30,222.0 |
| 2041 | 98.8 | 2.4 | 233,171.5 | 820,418.3 | 2,614,783.6 | 30.0 | 12,464.7 | 30,222.0 |
| 2042 | 98.7 | 2.5 | 245,145.3 | 862,548.5 | 2,749,057.9 | 30.0 | 12,464.7 | 30,222.0 |
| Total | 3,007.5 | 28.5 | 2,775,008.6 | 9,763,919.0 | 31,118,923.1 | 615.0 | 255,526.7 | 619,551.0 |

| Year | Water | | GHG emissions (kgCO2e) | | | Avoided GHG emissions (kgCO2e) | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Materials | Energy | Total | Chemical | Energy | Total |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 101.2 | 0.0 | 4,840.5 | 906.7 | 5,747.1 | 2,816.7 | 4,448.7 | 7,265.3 |
| 2016 | 101.2 | 0.0 | 4,840.5 | 906.7 | 5,747.1 | 6,167.4 | 9,740.8 | 15,908.2 |
| 2017 | 101.1 | 0.1 | 4,840.5 | 906.7 | 5,747.1 | 9,518.1 | 15,032.9 | 24,551.0 |
| 2018 | 101.1 | 0.1 | 9,680.9 | 1,813.3 | 11,494.3 | 16,219.5 | 25,617.2 | 41,836.7 |
| 2019 | 101.1 | 0.1 | 9,680.9 | 1,813.3 | 11,494.3 | 22,920.9 | 36,201.5 | 59,122.4 |
| 2020 | 101.0 | 0.2 | 9,680.9 | 1,813.3 | 11,494.3 | 29,622.3 | 46,785.8 | 76,408.0 |
| 2021 | 101.0 | 0.2 | 9,680.9 | 1,813.3 | 11,494.3 | 36,323.7 | 57,370.0 | 93,693.7 |
| 2022 | 100.9 | 0.3 | 14,521.4 | 2,720.0 | 17,241.4 | 46,375.8 | 73,246.4 | 119,622.2 |
| 2023 | 100.9 | 0.3 | 14,521.4 | 2,720.0 | 17,241.4 | 56,427.9 | 89,122.8 | 145,550.7 |
| 2024 | 100.8 | 0.4 | 14,521.4 | 2,720.0 | 17,241.4 | 66,480.0 | 104,999.2 | 171,479.2 |
| 2025 | 100.7 | 0.5 | 24,202.3 | 4,533.3 | 28,735.6 | 83,233.5 | 131,459.9 | 214,693.4 |
| 2026 | 100.6 | 0.6 | 24,202.3 | 4,533.3 | 28,735.6 | 99,987.0 | 157,920.6 | 257,907.6 |
| 2027 | 100.5 | 0.7 | 24,202.3 | 4,533.3 | 28,735.6 | 116,740.5 | 184,381.3 | 301,121.7 |
| 2028 | 100.4 | 0.8 | 24,202.3 | 4,533.3 | 28,735.6 | 133,494.0 | 210,841.9 | 344,335.9 |
| 2029 | 100.3 | 0.9 | 24,202.3 | 4,533.3 | 28,735.6 | 150,247.5 | 237,302.6 | 387,550.1 |
| 2030 | 100.2 | 1.0 | 29,042.8 | 5,440.0 | 34,482.8 | 170,351.7 | 269,055.4 | 439,407.1 |
| 2031 | 100.0 | 1.2 | 29,042.8 | 5,440.0 | 34,482.8 | 190,455.9 | 300,808.2 | 491,264.1 |
| 2032 | 99.9 | 1.3 | 29,042.8 | 5,440.0 | 34,482.8 | 210,560.1 | 332,561.0 | 543,121.1 |
| 2033 | 99.8 | 1.4 | 29,042.8 | 5,440.0 | 34,482.8 | 230,664.3 | 364,313.9 | 594,978.1 |
| 2034 | 99.7 | 1.5 | 29,042.8 | 5,440.0 | 34,482.8 | 250,768.5 | 396,066.7 | 646,835.1 |
| 2035 | 99.5 | 1.7 | 29,042.8 | 5,440.0 | 34,482.8 | 270,872.7 | 427,819.5 | 698,692.1 |
| 2036 | 99.4 | 1.8 | 29,042.8 | 5,440.0 | 34,482.8 | 290,976.9 | 459,572.3 | 750,549.2 |
| 2037 | 99.3 | 1.9 | 29,042.8 | 5,440.0 | 34,482.8 | 311,081.1 | 491,325.1 | 802,406.2 |
| 2038 | 99.2 | 2.0 | 29,042.8 | 5,440.0 | 34,482.8 | 331,185.3 | 523,077.9 | 854,263.2 |
| 2039 | 99.0 | 2.2 | 29,042.8 | 5,440.0 | 34,482.8 | 351,289.5 | 554,830.7 | 906,120.2 |
| 2040 | 98.9 | 2.3 | 29,042.8 | 5,440.0 | 34,482.8 | 371,393.7 | 586,583.5 | 957,977.2 |
| 2041 | 98.8 | 2.4 | 29,042.8 | 5,440.0 | 34,482.8 | 391,497.9 | 618,336.3 | 1,009,834.2 |
| 2042 | 98.7 | 2.5 | 29,042.8 | 5,440.0 | 34,482.8 | 411,602.1 | 650,089.1 | 1,061,691.2 |
| Total | 3,007.5 | 28.5 | 595,377.3 | 111,519.2 | 706,896.5 | 4,659,273.6 | 7,358,911.6 | 12,018,185.2 |

**Greywater recycling and rainwater harvesting**

| Year | Water | | Treatment and pumping savings | | | Greywater | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Chemicals (kg) | T energy (kWh) | P energy (kWh) | Systems | Materials (kg) | Energy (kWh) |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 101.2 | 0.0 | 2,554.4 | 8,987.8 | 28,645.2 | 5.0 | 2,077.5 | 8,103.0 |
| 2016 | 101.1 | 0.1 | 5,108.8 | 17,975.5 | 57,290.4 | 5.0 | 2,077.5 | 8,103.0 |
| 2017 | 101.1 | 0.1 | 7,663.2 | 26,963.3 | 85,935.6 | 5.0 | 2,077.5 | 8,103.0 |
| 2018 | 101.1 | 0.1 | 12,772.1 | 44,938.8 | 143,226.0 | 10.0 | 4,154.9 | 16,206.0 |
| 2019 | 101.0 | 0.2 | 17,880.9 | 62,914.3 | 200,516.4 | 10.0 | 4,154.9 | 16,206.0 |
| 2020 | 101.0 | 0.2 | 22,989.7 | 80,889.8 | 257,806.8 | 10.0 | 4,154.9 | 16,206.0 |
| 2021 | 100.9 | 0.3 | 28,098.6 | 98,865.4 | 315,097.2 | 10.0 | 4,154.9 | 16,206.0 |
| 2022 | 100.8 | 0.4 | 35,761.8 | 125,828.6 | 401,032.8 | 15.0 | 6,232.4 | 24,309.0 |
| 2023 | 100.8 | 0.4 | 43,425.1 | 152,791.9 | 486,968.4 | 15.0 | 6,232.4 | 24,309.0 |
| 2024 | 100.7 | 0.5 | 51,088.3 | 179,755.2 | 572,904.0 | 15.0 | 6,232.4 | 24,309.0 |
| 2025 | 100.5 | 0.7 | 63,860.4 | 224,694.0 | 716,130.0 | 25.0 | 10,387.3 | 40,515.0 |
| 2026 | 100.4 | 0.8 | 76,632.5 | 269,632.8 | 859,356.0 | 25.0 | 10,387.3 | 40,515.0 |
| 2027 | 100.3 | 0.9 | 89,404.6 | 314,571.6 | 1,002,582.0 | 25.0 | 10,387.3 | 40,515.0 |
| 2028 | 100.1 | 1.1 | 102,176.6 | 359,510.4 | 1,145,808.0 | 25.0 | 10,387.3 | 40,515.0 |
| 2029 | 100.0 | 1.2 | 114,948.7 | 404,449.2 | 1,289,034.0 | 25.0 | 10,387.3 | 40,515.0 |
| 2030 | 99.9 | 1.3 | 130,275.2 | 458,375.8 | 1,460,905.2 | 30.0 | 12,464.7 | 48,618.0 |
| 2031 | 99.7 | 1.5 | 145,601.7 | 512,302.3 | 1,632,776.4 | 30.0 | 12,464.7 | 48,618.0 |
| 2032 | 99.5 | 1.7 | 160,928.2 | 566,228.9 | 1,804,647.6 | 30.0 | 12,464.7 | 48,618.0 |
| 2033 | 99.4 | 1.8 | 176,254.7 | 620,155.4 | 1,976,518.8 | 30.0 | 12,464.7 | 48,618.0 |
| 2034 | 99.2 | 2.0 | 191,581.2 | 674,082.0 | 2,148,390.0 | 30.0 | 12,464.7 | 48,618.0 |
| 2035 | 99.1 | 2.1 | 206,907.7 | 728,008.6 | 2,320,261.2 | 30.0 | 12,464.7 | 48,618.0 |
| 2036 | 98.9 | 2.3 | 222,234.2 | 781,935.1 | 2,492,132.4 | 30.0 | 12,464.7 | 48,618.0 |
| 2037 | 98.8 | 2.4 | 237,560.7 | 835,861.7 | 2,664,003.6 | 30.0 | 12,464.7 | 48,618.0 |
| 2038 | 98.6 | 2.6 | 252,887.2 | 889,788.2 | 2,835,874.8 | 30.0 | 12,464.7 | 48,618.0 |
| 2039 | 98.4 | 2.8 | 268,213.7 | 943,714.8 | 3,007,746.0 | 30.0 | 12,464.7 | 48,618.0 |
| 2040 | 98.3 | 2.9 | 283,540.2 | 997,641.4 | 3,179,617.2 | 30.0 | 12,464.7 | 48,618.0 |
| 2041 | 98.1 | 3.1 | 298,866.7 | 1,051,567.9 | 3,351,488.4 | 30.0 | 12,464.7 | 48,618.0 |
| 2042 | 98.0 | 3.2 | 314,193.2 | 1,105,494.5 | 3,523,359.6 | 30.0 | 12,464.7 | 48,618.0 |
| Total | 2,999.3 | 36.7 | 3,563,410.3 | 12,537,925.2 | 39,960,054.0 | 615.0 | 255,526.7 | 996,669.0 |

| Year | Water | | GHG emissions (kgCO2e) | | | Avoided GHG emissions (kgCO2e) | | |
|---|---|---|---|---|---|---|---|---|
| | Production (M m3) | Savings (M m3) | Materials | Energy | Total | Chemical | Energy | Total |
| 2013 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2014 | 101.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2015 | 101.2 | 0.0 | 2,389.1 | 1,458.5 | 3,847.6 | 4,288.9 | 6,773.9 | 11,062.8 |
| 2016 | 101.1 | 0.1 | 2,389.1 | 1,458.5 | 3,847.6 | 8,577.8 | 13,547.9 | 22,125.7 |
| 2017 | 101.1 | 0.1 | 2,389.1 | 1,458.5 | 3,847.6 | 12,866.7 | 20,321.8 | 33,188.5 |
| 2018 | 101.1 | 0.1 | 4,778.1 | 2,917.1 | 7,695.2 | 21,444.5 | 33,869.7 | 55,314.1 |
| 2019 | 101.0 | 0.2 | 4,778.1 | 2,917.1 | 7,695.2 | 30,022.3 | 47,417.5 | 77,439.8 |
| 2020 | 101.0 | 0.2 | 4,778.1 | 2,917.1 | 7,695.2 | 38,600.1 | 60,965.4 | 99,565.5 |
| 2021 | 100.9 | 0.3 | 4,778.1 | 2,917.1 | 7,695.2 | 47,177.9 | 74,513.3 | 121,691.1 |
| 2022 | 100.8 | 0.4 | 7,167.2 | 4,375.6 | 11,542.8 | 60,044.5 | 94,835.1 | 154,879.6 |
| 2023 | 100.8 | 0.4 | 7,167.2 | 4,375.6 | 11,542.8 | 72,911.2 | 115,156.9 | 188,068.1 |
| 2024 | 100.7 | 0.5 | 7,167.2 | 4,375.6 | 11,542.8 | 85,777.9 | 135,478.7 | 221,256.6 |
| 2025 | 100.5 | 0.7 | 11,945.4 | 7,292.7 | 19,238.1 | 107,222.4 | 169,348.3 | 276,570.7 |
| 2026 | 100.4 | 0.8 | 11,945.4 | 7,292.7 | 19,238.1 | 128,666.9 | 203,218.0 | 331,884.9 |
| 2027 | 100.3 | 0.9 | 11,945.4 | 7,292.7 | 19,238.1 | 150,111.4 | 237,087.6 | 387,199.0 |
| 2028 | 100.1 | 1.1 | 11,945.4 | 7,292.7 | 19,238.1 | 171,555.8 | 270,957.3 | 442,513.2 |
| 2029 | 100.0 | 1.2 | 11,945.4 | 7,292.7 | 19,238.1 | 193,000.3 | 304,827.0 | 497,827.3 |
| 2030 | 99.9 | 1.3 | 14,334.4 | 8,751.2 | 23,085.7 | 218,733.7 | 345,470.6 | 564,204.3 |
| 2031 | 99.7 | 1.5 | 14,334.4 | 8,751.2 | 23,085.7 | 244,467.1 | 386,114.2 | 630,581.2 |
| 2032 | 99.5 | 1.7 | 14,334.4 | 8,751.2 | 23,085.7 | 270,200.4 | 426,757.8 | 696,958.2 |
| 2033 | 99.4 | 1.8 | 14,334.4 | 8,751.2 | 23,085.7 | 295,933.8 | 467,401.4 | 763,335.2 |
| 2034 | 99.2 | 2.0 | 14,334.4 | 8,751.2 | 23,085.7 | 321,667.2 | 508,045.0 | 829,712.2 |
| 2035 | 99.1 | 2.1 | 14,334.4 | 8,751.2 | 23,085.7 | 347,400.6 | 548,688.6 | 896,089.1 |
| 2036 | 98.9 | 2.3 | 14,334.4 | 8,751.2 | 23,085.7 | 373,134.0 | 589,332.2 | 962,466.1 |
| 2037 | 98.8 | 2.4 | 14,334.4 | 8,751.2 | 23,085.7 | 398,867.3 | 629,975.8 | 1,028,843.1 |
| 2038 | 98.6 | 2.6 | 14,334.4 | 8,751.2 | 23,085.7 | 424,600.7 | 670,619.3 | 1,095,220.1 |
| 2039 | 98.4 | 2.8 | 14,334.4 | 8,751.2 | 23,085.7 | 450,334.1 | 711,262.9 | 1,161,597.0 |
| 2040 | 98.3 | 2.9 | 14,334.4 | 8,751.2 | 23,085.7 | 476,067.5 | 751,906.5 | 1,227,974.0 |
| 2041 | 98.1 | 3.1 | 14,334.4 | 8,751.2 | 23,085.7 | 501,800.8 | 792,550.1 | 1,294,351.0 |
| 2042 | 98.0 | 3.2 | 14,334.4 | 8,751.2 | 23,085.7 | 527,534.2 | 833,193.7 | 1,360,727.9 |
| Total | 2,999.3 | 36.7 | 293,855.7 | 179,400.4 | 473,256.2 | 5,983,009.9 | 9,449,636.3 | 15,432,646.2 |

An electronic appendix is available upon request.