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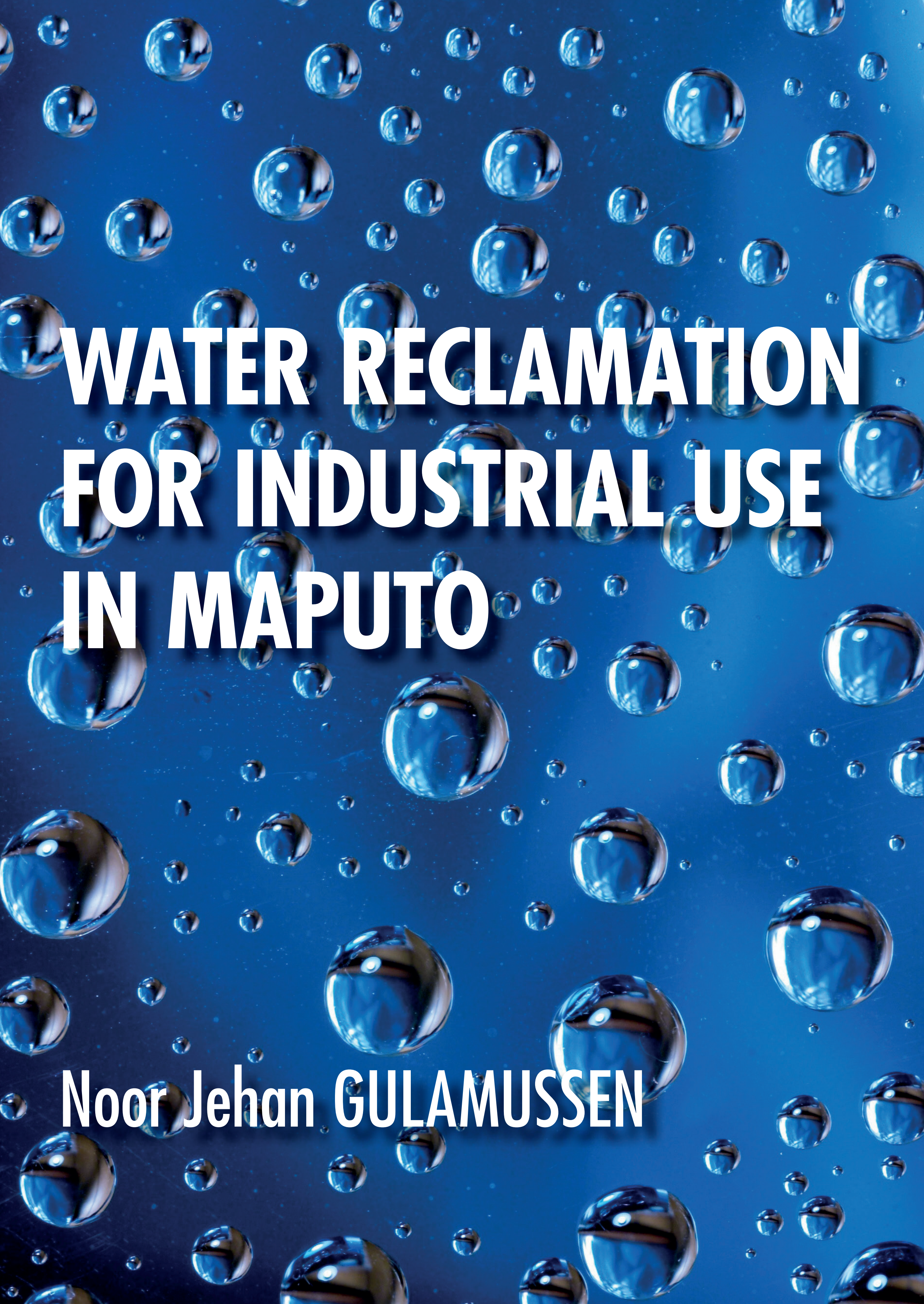

WATER RECLAMATION FOR INDUSTRIAL USE IN MAPUTO

Noor Jehan GULAMUSSEN

WATER RECLAMATION FOR INDUSTRIAL USE IN MAPUTO

WATER RECLAMATION FOR INDUSTRIAL USE IN MAPUTO

Dissertation

for the purpose of obtaining the degree of doctor

at Delft University of Technology

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Chair of Board for Doctorates

To be defended publicly on

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Keywords: Water reclamation; wastewater; industry; ceramic membranes; water treatment.

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List of abbreviations

BCI	Blue City Index
CBF	City Blueprint Framework
CMF	Ceramic micro-filtration
COD	Chemical Oxygen Demand
EPA	Environmental Protection Agency
FIETS	Financial, Institutional, Environmental, Technical, and Social
GCF	Governance Capacity Framework
GDP	Gross Domestic Product
IUWM	Integrated Urban Water Management
IW	Industrial Water
MBR	Membrane Bioreactors
PPP	Public-private partnerships
RW	Reclaimed Water
SA	Sodium Alginate
SEM	Scanning Electron microscopy
SSA	Sub-Saharan Africa
TPF	Trends and Pressures Framework
TPI	Trends and Pressure Index
TPP	Thermal Power Plant
UF	Ultrafiltration
UN	United Nations

USA	United States of America
WHO	World Health Organization
WRpi	Water Reclamation potential for industrial
WRpiF	Water Reclamation potential for industrial use Framework
WC	Water Cost
WT	Water Tariff
WW	Wastewater
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plant

Summary

As fresh water is becoming progressively scarce due to increasing demand, as a result of high population growth, rapid economic development and climate change, and stricter regulations on wastewater discharge are set, world-wide the interest in water reclamation increases. The potential for resource recovery from wastewater and sludge is largely untapped and in developing countries, and in particular in Sub-Saharan Africa (SSA), only a small portion of these waste streams is used in a planned and safe manner.

Compared to surface water, reclaimed wastewater can also be an attractive source to increase water availability, because of the low fluctuations of flow and water quality and its abundance in the urban environment. Recognizing the many applications and benefits of water reclamation, the purpose of this thesis was to evaluate the potential of water reclamation for industrial use with Maputo as case study.

First a review was performed to provide a frame of reference for the trends in water reclamation for industrial use, the effluent quality and the degree of reliability that may be required, and to identify challenges and impediments to implementation. The findings of this review showed that although some examples of water reclamation implementation for industrial use exist, the region is challenged by the need to develop a framework that can facilitate the integration of social and technological methodologies and help to introduce water reclamation in water allocation planning, including the development of specific legislation for industrial water use and disposal in countries where it is not practiced as in the case of Mozambique.

Second, a framework for assessment of water reclamation for industrial use potential was developed and tested for the case of Maputo. It was found that Maputo, amongst others, requires changes in the sanitation infrastructure to increase the sewerage system coverage, a larger gap between drinking water demand and supply, legislation that encourages the use of reclaimed water by industries (incentives), and a higher technological capability to successfully implement water reclamation projects.

Third, a pilot test on the use of wastewater treatment plant (WWTP) effluent for unreinforced concrete production for the construction industry showed that the compressive strength of blocks manufactured using WWTP effluent had a similar strength to the blocks produced using drinking water. Ammonium, phosphate (impurities found in the WWTP effluent) and chlorine (added for disinfection) were found not to have a negative effect on the strength of the blocks. Water absorption tests confirmed the results of the compressive strength, as lower humidity was found in cases of higher strength.

Fourth, the development of a novel application of ceramic microfiltration treatment, focusing on hardness removal of model WWTP effluent for recirculating cooling systems make-up water indicated that softening can be combined with ceramic microfiltration for post-treatment of secondarily treated wastewater for use in cooling systems. The study also demonstrated that inhibition of calcium carbonate precipitation occurred when inorganic substances, such as phosphate, and organic compounds were present in the water, while the fouling of the membranes, due to sodium alginate in water, was only slightly negatively affected when combined with softening.

The thesis ends with the conclusion that the city of Maputo has potential for introducing water reclamation in industries, requiring well-planned interventions that include the opportunity of optimizing the use of water in different industries and institutions existent in the city and the vicinity. We have demonstrated that the central WWTP of Maputo could be used to supply water for cooling systems at a thermal power plant and construction industries, located nearby. To turn it possible, participatory and collaborative practices of the co-creation concept should be explored together with pilot studies, governance capacity evaluation and promotion of public private partnerships.

Chapter 1

Introduction

Introduction

1.1. Background

Water scarcity can result from population growth, a high urbanization rate, economic development, climate change or unreliable water sources (WMO, 2021). This situation calls for diversification of measures to guaranty the sufficient availability of drinking water in both quantity and quality. Therefore, water managers can utilize tools such as water demand management, leakage control, securing natural sources by assuring safe discharges of effluents (water conservation, prevention of contamination), and water recycling and reclamation (Thivet and Fernandez, 2012). An approach that is gaining popularity is the use of treated municipal wastewater as a vital resource for agricultural, industrial and even domestic applications (Ahuja, 2014). Apart from increasing the water supply, it also protects, amongst others, the environment by treating the wastewater and thus avoiding direct discharges. The utilization of the municipal wastewater in a more sustainable manner also gives possibilities for recycling of other valuable compounds, such as nutrients (UNEP-GEC, 2004).

Water reclamation is practiced in many parts of the world, such as in Australia, China, Mediterranean countries, the Middle East, and the USA (Lazarova and Asano, 2013). Most industrial applications are located in northern Europe, northern America, Asia, Australia and South Africa (Angelakis and Gikas, 2014; Apostolidis et al., 2011; do Monte, 2007; Jiménez and Asano, 2008; Schaefer et al., 2004; Tare, 2011). However, water reclamation for industrial uses in Sub-Saharan Africa (SSA) countries, such as Mozambique, is hindered by proper planning of water supply, legislation, lack of finances, aged sanitation infrastructure with a low level of coverage, and expertise. Therefore, only a small portion of wastewater is used in a planned and safe manner, while the majority of the wastewater remains untreated, or partially treated, being only sometimes used in the informal (unregulated) irrigation sector (Janeiro et al., 2020).

1.2. Local context

Mozambique is located in the southern part of the eastern African coast. In 2023, the projections of the total population were 32.4 million with 34.7% living in cities (INE, 2023), and the population is projected to reach 38.9 million in 2030 (UNDP, 2015). The total available fresh surface water flow is about 216.5 km^3/year, of which about 46% is produced within the country, while the rest comes from upstream countries (Inguane et al., 2014). In fact, all major rivers in the southern part of Mozambique (Maputo, Umbeluzi, Incomati, Limpopo and Save) originate in neighbouring countries (Ashton and Turton, 2009). The combined average natural flow in the five mentioned river basins is about 11 km^3/year. This has been predicted to decrease to about 5 to 6 km^3/year in 2027, with increasing variability due to growing demands from riparian neighbours (Nepad, 2013) and resulting in reduced freshwater flows into the ocean (Ashton, 2003). With increasing industrial and urban development, the demand on the country's water resources is nearing the point where conventional supplies will soon be exceeded. Projections indicate that urban water demand will increase by about 40%, with industrial use being expected to augment by about 65% (GWP, 2013).

The capital city Maputo is situated in the water scarce southern part of Mozambique. De Lange, 2017 has estimated an annual increase of 7% and 3% in industrial water use for a scenario of progressive development and conservative development, respectively, in a situation where drinking water supply is limiting. In the meantime, the increasing water demand of other key sectors of the national economy, mainly agriculture, will, on the medium and long-term, also be limited in growth due to restricted water availability, particularly in the economically most developed southern and central regions (GWP, 2013). Climate change poses an additional threat to water security, because changes in precipitation, temperature and other climatic variables may hamper water availability in many regions.

Maputo city has a central wastewater treatment plant (WWTP) that is connected to a combined sewer system discharging about 10 % of the city buildings (Weststrate et al., 2019). However, less than half of the generated wastewater reaches the WWTP due to failures in the pumping stations. Part of the treated WWTP effluent is used for irrigation, while the majority is discharged to Infulene river and ends up in the ocean (Janeiro et al., 2020).

In the situation of insufficient availability of water, as is the case in Maputo city, competition between industrial and domestic uses is of a major concern, since both abstract from the same water sources. Water reclamation from municipal wastewater for industrial use is therefore a promising option to be considered (Tian et al., 2017). Increasing the industrial water supply security, applying water reclamation, will then increase the overall water supply security.

In addition, the potential reduction in raw water abstraction can increase water available for ecological flows and preserve the environmental health of waterways, wetlands, flora and fauna. It can also result in the reduction of the level of nutrients and other pollutants entering waterways and sensitive marine environments by reducing direct municipal wastewater discharges (Anderson, 2003). In addition, since in Mozambique access to sanitation services, with only 44% of the urban population having access to improved sanitation systems (Dietz et al., 2014), water reclamation can be an incentive for increasing the coverage of improved sanitation.

1.3. Research Description and problem statement

In order to contribute to the sustainability of the drinking water supply and to the use of alternative water sources for industry, the main objective of this thesis is to assess the potential for water reclamation for industrial use in Maputo, Mozambique.

For the purpose of this thesis, we considered, amongst others, the topology of the existent industries, the water requirements both in quality and quantity. For the identification of potential users, we focused on the largest piped water (=drinking water) users for applications that does not require a high-water quality, being mainly non-food industries. In the metropolitan area of Maputo region the manufacturing industry, with potential of using reclaimed water, is located in the industrial area of Matola, neighbouring Maputo city, having a potential for synergies within the industrial area, as also happens in other industrial areas world-wide (Rafaai et al., 2025). In Maputo city itself the electricity and construction industries were identified as potential users of reclaimed water. The map showing the locations of the construction companies and available wastewater sources is given in the **annex A** (Fausta, 2016).

Figure 1 shows the map of the location of the thermal power plant in relation the WWTP.

Figure 1: Location of the thermal power plant in relation to the WWTP of Maputo.

To study the feasibility for water reclamation in industries in SSA in general, and Maputo in specific, four main research questions were formulated:

1. What is the state of the art of water reclamation for industrial use in SSA?

2. How the potential for industrial water reclamation in cities could be assessed?

3. What are the water quality requirements for (unreinforced) concrete production for the construction industry?

4. How WWTP effluent could be treated for make-up water for cooling of a thermal power plant?

1.4. Thesis Outline

In the **chapter 2**, an overview of the global trends in water reclamation in SSA, with a focus on industrial use, is reviewed to derive lessons for implementation of water reclamation projects in this region.

Then a framework for identification of main gaps, opportunities and priorities for industrial water reclamation was developed and assessed for the case of Maputo, as described in **chapter 3**.

Chapter 4 presents a study of the use of reclaimed water for unreinforced concrete block production for the self-construction of houses, which is a major industrial water user in Maputo. The results of pilot experiment are presented to evaluate the possibilities of using (poorly) treated wastewater for the production of unreinforced concrete blocks.

Chapter 5 is dedicated to the development of a novel method of treatment of (model) WWTP effluent with ceramic micro filtration for application in water reclamation for industrial recirculating cooling systems with the focus on avoiding scale formation by removing hardness, in the presence of other fouling agents as organic matter and suspended solids.

Finally, the conclusions and outlook of the potential of industrial water reclamation in Maputo are discussed in **Chapter 6**.

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Chapter 2

Water Reclamation for Industrial Use in sub-Saharan Africa – A Critical Review

This chapter is based on:

Gulamussen, N. J., Arsénio, A. M., Matsinhe, N. P., and Rietveld, L. C. (2019). Water reclamation for industrial use in sub-Saharan Africa – a critical review. *Drink. Water Eng. Sci.*, *12*(2), 45-58. https://doi.org/10.5194/dwes-12-45-2019.

Water Reclamation for Industrial Use in sub-Saharan Africa – A Critical Review

Abstract

The increasing world population and growth of industrial development lead to growing water scarcity that, combined with deficient sanitation services, represent serious challenges, particularly in regions like sub-Saharan Africa. Water reclamation is a promising approach to reduce water scarcity, serving as a driving force for better sanitation services and protecting the environment by treating sewage and redistributing for the benefit of other water-dependent applications (e.g. industries).

This paper aims to give an overview of the global trends on water reclamation, with a focus on industrial use, and to derive lessons for implementation of water reclamation projects in Sub-Saharan Africa. Findings show that extensive experience exists in technology and management practices that can allow successful implementation of water reclamation projects in the region. Under the conditions of deficient sanitation services and low levels of technical expertise, the main challenge is to develop a framework that can facilitate the integration of social and technological methodologies and help to introduce water reclamation in water allocation planning, including the development of specific legislation for industrial water use and disposal.

2.1. Introduction

The importance of water reclamation as a way of supplementing water supply needs, improving sanitation services through wastewater treatment and disposal, and maintaining a sustainable environment is commonly acknowledged (Kennedy and Tsuchihashi, 2005; Lazarova et al., 2012, 2013; Miller, 2006; Yerri and Piratla, 2019). The use of reclaimed water increases the total available water supply, substituting drinking water where appropriate (Asano, 2005), and preserving the health of waterways, wetlands, flora, and fauna (Asano, 2005; Toze, 2006). In addition, reclaimed water, originating from sewage, contains nutrients; thus, if this water is used to irrigate agricultural land, less fertilizer is required for crop growth, therefore reducing the level of nutrients and other pollutants entering waterways and sensitive marine environments (Cornejo et al., 2016; Editorial, 2019; Eslasmain, 2016; Toze, 2006). Furthermore, reclaimed water can often be found near the point of use, reducing pumping costs and eliminating the need to negotiate with neighboring countries for increased water supplies (Lee and Tan, 2016; Smith, 2011). Using reclaimed water, scarcity, environmental pollution and human- health issues can be addressed and can positively impact the quality of the urban environment and lead to improved urban health (Rietveld et al., 2016; Salgot and Folch, 2018). There are a wide variety of water reclamation applications, including irrigation, industry water supply, non-potable urban uses, environmental and recreational enhancement, and even direct consumption (Angelakis and Gikas, 2014; Van der Bruggen, 2010; Lazarova et al., 2012).

The global practice of water reclamation in the world is growing (Chhipi-shrestha et al., 2019); the global reclamation capacity was projected to have increased from 33.7 million m^3/day in 2010 to 54.5 million m^3/day in 2015 (Eslasmain, 2016). Case studies also show that significant advances in water reclamation have occurred in arid regions including Australia, China, Mediterranean countries, the Middle East, and the US (Lazarova et al., 2013). In temperate regions, water reclamation is characterized by a fast development in particular for industrial applications, and in environmental and urban water reclamation (Lazarova et al., 2013; Rietveld et al., 2011; Agtmaal et al., 2007).

The expansion of water reclamation at the global scale has been driven by multiple factors: pressure on water resources derived from climate change (Nazari et al, 2012; Jiménez et al., 2010); water stress derived from population growth and, consequently, growth of cities that challenges the water resources and sanitation systems (Lautze et al., 2014); environmental and economic concerns that limit the use of other solutions to combat water scarcity, such as long distance water transfer, construction of large dams and desalination (GWI, 2010); and increased confidence in and reduced costs of membrane and disinfection technologies, which provide assurance of safety of reclaimed water blended into reservoirs or aquifers for potable uses (GWI, 2010).

In high income countries, the total water usage for industry corresponds to 41% of the total water demand, while in low income countries only 3% is used for industry (The World Bank, 2015). Although the industrial withdrawal tends to rise, estimated at 1.9 x 10^3 million m^3/day in 1995 to about 3.2 x 10^3 million m^3/day by 2025 (Holden, 2013), the rate of increase will slow down as the industries adopt water saving and water recycling practices. Globally, 20% of reclaimed water is used in industrial applications, competing with agriculture (70%) and municipal (10%) uses (GWI, 2010; Lautze et al., 2014).

Industrial water use can be grouped as cooling, boiler feed, and process water (Visvanathan, 1999). The uses are very diverse and include washing and rinsing, equipment operation, product transport, manufacturing and construction activities (Lautze et al., 2014; Vigneswaran and Sundaravadivel, 2009). Although cooling water is the most water demanding process in industry (EUROSTAT, 2014), with two-thirds of all industrial water being used for cooling (Lens et al., 2002), the percentage of reduction by using reclaimed water largely depends on the demand of the recirculating cooling system (Hunter, 2001).

Despite the great application potential in terms of water needs (Almeida et al., 2013), the market for reclaimed water for industry is still awaiting a wider implementation (Ordóñez et al., 2014). Information about the means, methods, and technologies for implementing water reclamation best practices in industry exist and are well known (Emanuel, 2010; NWRS, 2011), and this information can be used to define and refine technical water reclamation solutions in sub-Saharan Africa (WBCSD – IWA, 2009). Therefore, water reclamation for industrial use is herein reviewed, considering the global trends, water flow, and quality requirements for different uses and the possibility of using reclaimed water as an alternative for fresh surface or groundwater for industries in sub-Saharan Africa.

2.2. Global trends in water reclamation for industrial use

2.2.1. Driving forces for water reclamation

Water reclamation for industries is mostly driven by low availability of local water, either due to limited sources of water or intense competition for supply. Both factors are sometimes reflected by high industrial water tariffs (Jiménez-Cisneros, 2014). However, the major factors limiting the use of reclaimed water in industry are, among others, ensuring continuous operation without resulting in water shortage, meeting quality standards, producing at acceptable costs, and acceptability of the use of reclaimed water by industries (Toze, 2006; Ordóñez et al., 2014).

The dynamics of water reclamation for industrial use are also influenced by factors such as economic development priorities, environmental and climatic factors, social acceptance, and availability of financial resources (Lautze et al., 2014).

Table 1 presents general drivers for and main applications of water reclamation for industrial use in different regions of the world. In developed countries, aside from water scarcity, water reclamation for industrial use is driven by environmental concerns, with sewage treatment plant effluent typically utilized for purposes such as cooling, boiler feeds, condensing and steam production, firefighting, and dust mitigation; in developing countries water reclamation is primarily driven by water scarcity.

These drivers can thus be connected to the socio-economic context in which the projects are executed, but also to governmental support, public-private partnerships, stakeholder involvement, savings in water needs, and economic and environmental benefits.

Table 1: Regional variation in water reclamation for industrial application.

Region	Drivers	Main application(s)	References
Northern Europe	High industrial water demand in highly populated areas Resource efficiency Environmental concerns	Cooling	(Asano and Jimenez, 2008; USEPA, 1992; Ryan, 2016; Marecos do Monte, 2007; Angelakis and Gikas, 2014)
North America	Water scarcity Cost-effectiveness of reclaimed water and resource efficiency Environmental concerns	Process water, cooling, condensing and steam generation	(Asano and Jimenez, 2008; USEPA, 1992; Schaefer et al., 2004; C. Smith, 2015)
Asia	Water scarcity Political pressure	Cooling, washing and process water	(Asano and Jimenez, 2008; Indian Institutes of Technology, 2011; USEPA, 1992)
Australia	Water scarcity Environmental concerns	Cooling, boiler feed, firefighter, dust suppression	(Asano and Jimenez, 2008; USEPA, 1992; Apostolidis et al., 2011)
Southern Africa	Water scarcity	Cooling, mining and process water	(Indian Institute of Technology, 2011)

2.2.2. Socioeconomic and political context

The regional variations in water reclamation indicate that most projects, executed in industry, are centered in developed countries, where water use for industries is higher than in developing countries. There are a number of conditions in developing countries that impact the potential for water reclamation, such as lack of wastewater collection and inadequate treatment systems (Bendahmane, 1992). Despite this, severe water shortages and growing interest in ecological systems have led the city of Durban, South Africa, to implement water reclamation for several demanding industries (Jacobsen et al., 2013; Otoo et al., 2015).

Establishing effective and equitable management practices requires knowledge, expertise, and investment at political, institutional, and technical levels. In cases where governments were committed to minimize water shortage or protect the environment, the projects were successful (Lautze et al., 2014; Lazarova et al., 2013). Some actions required the development and application of regulatory actions with stringent influent requirements and tariffs to force industries to implement new technologies and strategies to use reclaimed water (Grobicki, 2008).

The city of Sydney experienced three severe droughts in the last two centuries, which challenged the government to improve the understanding of the potential impacts of climate change on water availability and demand. As a result, the city conducted studies in order to increase water reclamation and reduce demand (Water for Life, 2006).

In order to reduce the dependence on water imported from neighboring Malaysia, the government of Singapore secured the availability of funds and incentives for industries that use reclaimed water (Lee and Tan, 2016; PUB, 2014).

The state of Karnataka, India, also faces water shortages due to population growth and expansion of industrial activities (Government of Karnakata, 2012). Therefore, the state government planned the implementation of subsidies for up to 75% of the cost of equipment for water reclamation by “small and medium manufacturing enterprises” (Freedman and Enssle, 2015; Government of Karnakata, 2012).

2.2.3. Public-private partnerships and stakeholder involvement

One particular challenge is to reconcile the need for tariffs that encourage the use of reclaimed water with availability of financing for water reclamation projects (Molinos-Senante et al., 2013). Public-private partnerships (PPP) can offer a combination of cost and performance benefits that municipal and industrial clients require (Lloyd Owen, 2016). Lloyd Owen (2016), having evaluated 2,714 water projects, noted the existence of 72 water reclamation projects (for all applications) in 2014 under PPP covering 29.44 million people, with a total capacity of 11.80 million m^3/day and more than half of the projects located in areas of high-water stress.

The integration of all relevant institutions and stakeholders in the planning and design of water reclamation projects can reduce the risk of failure and increase the cost effectiveness of the projects (Lautze et al., 2014; Giurco et al., 2010). Lloyd Owen (2016) also showed that water reclamation projects had not ended before the deadline, which is in contrast with general water projects, indicating the complexity of implementing water reclamation schemes. Therefore, water reclamation opportunities must be identified and cost-efficiencies optimized by the stakeholders' involvement through synergy development and exploration of co-generation opportunities. If the end users' preferences are not considered during the planning phase, they may simply reject the plan, not be able to make full use of the provided water, or refuse to pay for the service (Lautze et al., 2014).

Historical survey data consistently show that the public tolerates and welcomes non-potable use of reclaimed water, particularly when there is lower risk of human contact, e.g. high levels of public acceptance of non-potable water use in industrial processing have been reported (Chen et al., 2015). Examples can be found in Australia and California, where the success is credited to the commitment of the projects to informing and educating the local community about the efficient water use and reclamation, thus creating a greater awareness on water shortage problems (Po et al., 2003).

2.2.4. Savings in water needs and economic, health and environmental benefits

Water reclamation for industry often produces considerable savings in fresh water and produces economic and environmental benefits (Lahnsteiner and Klegraf, 2005; UNEP, 2005).

In the city of St. Petersburg, Florida (USA), all wastewater is treated to a high standard. The reclaimed water is then used for irrigation and industrial cooling applications by thousands of customers, accounting for nearly half of the city's water needs. By substituting the potable water, the city has eliminated the need for expansion of its potable water supply system until the year 2030 with a cost savings of about 30 million US dollars (Grobicki, 2008; Lazarova et al., 2012).

By using reclaimed water, Durban industries reduced the costs of water supply; in particular, Mondi Paper Mill saves an amount equivalent to 3.5 million EUR/year. The project allowed Durban Metro Water Services to install and operate a new affordable distribution network for the townships while offering the industry cheap and high quality water (Mudgal et al., 2015).

The Panipat refinery in India enabled its expansion by implementing water reclamation, increasing the economic activity. The cost saving, by using reclaimed water, was 5,000-12,400 EUR/year, and the water demand decreased by 16,000 m^3/day. In addition, it had a positive environmental impact by reducing fresh water withdrawal by 7,000 m^3/day and by not discharging the sewage in the Yamuna canal (Anderson, 2003; Lazarova et al., 2013).

Another example is Dow Benelux's site at Terneuzen (the Netherlands). The effluent of the sewage treatment plant is treated by membrane filtration and used by the industry to generate steam, resulting in savings not only in water for domestic uses but also energy, with 65% less energy consumed at the facility compared to desalination of the same amount of seawater. This savings is equivalent with a decrease in CO_2 emission of 5,000 tonnes per year (Baker, 2008).

Discharge of untreated sewage can lead to adverse health effects. Besides the economic and environmental benefits, by using reclaimed water in industry, also negative public health effects are prevented (Kerstens et al., 2016).

2.3. Water use in industry

2.3.1. Water flow in industry

In the period 1997-2002, the water consumption by industries, in 10^3 million m^3/day, was 26.6 in Africa, 697.0 in Asia and the Pacific, 556.4 in Europe, 75.3 in Latin America and Caribbean, and 670.1 in North America, respectively. In Africa, only 5% of the total water use was industrial, whereas in sub-Saharan countries it was only 2% (12.1 million m^3/day) (Institute Water for Africa, 2016).

The most water demanding industries and their applications per tonne of product can be found in **Table 2**.

Table 2: Industrial water consumption for most water demanding industries. Adapted from Hunter (2001); Ranade and Bhandari (2014); Joint Research Council (2001); The European Commission (2003); Cooperman et al. (2012).

Type of industry	**Consumption**	**Most water demanding applications**
Thermal power plant	1.8 m^3/h/MW	Cooling
Paper	300-1,000 m^3/tonne of product	Cooling and boiler feed
Petroleum	10-300 m^3/tonne of product	Cooling
Chemical fertilizer	270 m^3/tonne of product	Cooling
Iron and steel	20-60 m^3/tonne of product	Cooling
Mining	40 m^3/tonne of ore	Process
Sugar	15 m^3/tonne of Sugar	Cooling
Textile	2-6 m^3/tonne of greasy wool	Cooling and Process

Thermoelectric power generation typically requires large quantities of cooling water, representing a major opportunity for reclaimed water providing that corrosion, biological, and scaling concerns are addressed. There are also opportunities for the use of reclaimed water in various production steps of some industries such as pulp and paper, chemical, textile, construction, petroleum and coal.

2.3.2. Water quality needs and required treatment for use of reclaimed water in non-food industry

Food industries require potable water even for cleaning purposes (Meneses et al., 2017). Treating sewage to potable quality requires advanced technology (Li et al., 2015) that, in most cases, is not available in developing countries (Bouabid and Louis, 2015). Furthermore, the public tends to be more skeptical towards the use of reclaimed water in food industries (Chen et al., 2015). Therefore, the focus of this paper is on non-food applications.

The main concern related to water quality, principally for boiler feed and cooling water, is the formation of precipitated impurities (scaling), corrosion, biological growth, fouling, and foaming. For this reason, industrial water for cooling and boiler feed should have a low hardness level, a low salt and suspended solids' concentration, low organic matter and nutrients, and in some cases, the absence of pathogenic microorganisms. The industrial water reclamation concerns and potential treatment processes are presented in **Table 3**.

Table 3: Industrial water reclamation concern and potential treatment (Sources: Asano, 1998; Cisneros, 2014; USEPA, 1992).

Concern	Problem description	Cause	Treatment process
Scaling	Hard deposits formed in cooling systems that reduce the efficiency of the heat exchanger	Inorganic compounds such as calcium, magnesium and silica	Chemicals for acidification; EDTA and polymeric inorganic phosphate; Lime softening; Ion exchange
Corrosion	Corrosion by increase in electrical conductivity, acidic conditions, and the presence of dissolved gases and certain metals with high oxidation state	Dissolved solids; pH; Ammonia	Corrosion inhibitors such as chromates, polyphosphates, zinc, and polysilicates
Biological growth	Growth of microorganisms, reducing heat transfer efficiency and water flow; Formation of corrosive by-products	Organic residues; Suspended solids; Ammonia; Phosphorus	Biocides such as chlorine, sodium hypochlorite and chlorine dioxide; Filtration
Clogging	Formation and settling of particulate matter that clogs equipment	Suspended solids and precipitates	Coagulation; Filtration

Cooling water requirements

Cooling is utilized for the operation of pumps and compressors vacuum systems, and steam turbine condensers (Hunter, 2001). Cooling systems can have different configurations but are mainly divided into once-through and recirculating systems.

Once-through cooling systems transfer process heat to water to cool the process equipment and then discharge the hot water after a single use (Asano, 1998) This system requires a large volume of water, but the quality requirements are generally not restrictive, and usually lake, river, and sea water is used with little or any treatment (Lens et al., 2002). The use of disinfected reclaimed water is also a convenient alternative whenever the industries are located near a wastewater outfall (USEPA, 2004; National Academy, 2012).

Recirculating cooling systems transfer the heat from the warmed water to the vapor so that the water can be reused to absorb process heat and recirculated for additional cycles (San Jose Environmental Service Department, 2002). Hot water is pumped at the top of the tower and released over packing material, where it is cooled when in contact with the cold air (Lens et al., 2002). Resulting hot moist air is released into the atmosphere, while the cooled water is collected into a reservoir at the bottom of the cooling tower, where it is returned into the recirculating system (Lens et al., 2002). In recirculating cooling systems, additional treatment, such as filtration, chemical precipitation, ion exchange, or reverse osmosis, can be necessary to avoid scaling (Asano and Jiménez, 1998). In some cases, only additional chemical treatment is necessary, e.g. to avoid foaming, to control corrosion, to disperse suspended solids, or to control biological growth (National Academy, 2012).

Boiler feed water requirements

Water to be used for boiler feed requires extensive treatment, with the quality requirements increasing with the operating pressure of the boiler. The water needs to be treated to remove inorganic constituents such as calcium, magnesium, silica, and aluminium that contribute to scale formation in boilers. Treatment should also control excessive alkalinity and high concentrations of potassium and sodium that can cause foaming as well as bicarbonate alkalinity that can lead to the release of carbon dioxide, which can increase the acidity in the steam and corrode the equipment (National Academy, 2012). To prevent corrosion, chloride, sulphate and sodium should be lower than 5 mg/L (Moed, 2015). Organics in reclaimed water can also cause foam and corrosion in boilers, which can be controlled by carbon adsorption, ion exchange, or corrosion inhibitors such as amines (USEPA 2012; Sensorex, 2016; Moed, 2015).

Process water requirements

Process water is needed for processes such as quenching reactions and washing (Lens et al., 2002). For mineral wash and transport in mineral and mining industries, the required treatment involves the removal of suspended solids and some organics. Secondary sewage treatment plant effluent may be acceptable for applications such as concrete manufacturing, but advanced treatment is needed for applications such as carpet dyeing because water used in textile manufacturing must be non-staining and organic matter could compromise the quality of the final product. Divalent metal cations cause problems in some of the dyeing processes that use soap, and nitrates and nitrites may also cause problems because of structural modification in azo-dyes (National Academy, 2012). Other industrial process uses require high quality water, e.g. water used to wash circuit boards in the electronics industry often requires reverse osmosis treatment for extensive salt removal. More specific examples of treatment requirements for process water in industries can be seen in **Table 4**.

Table 4: Examples of industries that use reclaimed water.

Industry	**Country (company)**	**Reclamation application**	**Water source**	**Treatment technology**	**Reference**
Power plant	Turkey	Boiler feed	Sewage	UF, activated Carbon filter, RO, and IEX	(Tanik et al., 1996)
	Mexico (Villa des Reyes)	Cooling	Wastewater	Screening and advanced primary treatment, secondary treatment by activated sludge with N removal and tertiary treatment with lime softening, sand filtration, IEX, and chlorine disinfection	(Lazarova et al., 2013)
	US –Texas (Palo Verde Nuclear)	Cooling	Sewage	Secondary treatment, followed by biological nitrification, lime and soda ash addition for softening and phosphorus removal, filtration, and chlorination	(Asano and Visvanathan, 2001)
Petrochemical	India (Panipat)	Boiler feed	Industrial wastewater	Solid contact clarification, pressure sand filtration, UF, RO and IEX in mixed bed filters	(Lahnsteiner and Mittal, 2010)
	California (RARE)	Boiler feed and cooling	Sewage	Secondary effluent is pretreated by MF and then treated by RO	(Lazarova et al., 2013)

Table 4 (cont.): Examples of industries that use reclaimed water.

Industry	Country (company)	Reclamation application	Water source	Treatment technology	Reference
Refinery	US (Chevron under ECLWRF)	Boiler feed	Sewage	Secondary effluent treated by RO	(GWI, 2010)
	India (Madras refinery)	Boiler make-up	Wastewater	Additional secondary biological treatment, chemically-aided settling, pressure filtration, ammonia Stripping, carbonation, clarification, pressure filtration, chlorination, sodium bisulfate dosing, multimedia filtration, cartridge Filtration, RO	(Indian Institutes of Technology, 2011; Lahnsteiner and Mittal, 2010)
Pulp and paper	South Africa (Mondi Paper Mill)	Cooling and process water	Industrial wastewater	UF, IEX, and RO	(Visvanathan and Asano, 2009)
	Brazil (Indústria CPBR)	Cooling and process water	Wastewater	Tertiary UF system	(Kossar, 2013)
	China (Taian Baichuan Paper)	Cooling	Wastewater	Two-stage activated sludge plant with tertiary sand filtration and chlorination	(Lahnsteiner and Klegraf, 2005)
Wafer fabrication	Singapore (Fabs)	Cooling and process water	Sewage	MF, RO, and UV	(PUB, 2014)
Chemical	Germany (DuPont production Centre)	Process water for fiber production and boiler feed water	Industrial wastewater	Biological pre-treatment including nitrogen and phosphorous removal and then tertiary filtration with UF, activated carbon adsorption, UV, RO and IEX	(Lahnsteiner and Klegraf, 2005)

2.3.3. Cost comparison of treatment technology options for water reclamation

Most of the existing water reclamation schemes use effluent from the secondary sewage treatment processes for further purification in tertiary or advanced treatment units (**Table 4**), resulting in additional costs for installation and operation. Other constraints such as land acquisition for building sites, distance between the production site and the consumers, and requirement to install a dual distribution system or retrofitting, also highly influence the capital and operation and maintenance costs. The separate distribution system can involve more than 70% of the overall costs for reclamation, depending on site-specific conditions (Lazarova, 2005).

Among the tertiary treatments, polishing pond treatment is the most simple and unsophisticated but has proven to be a competitive, efficient solution for small aggregates (project size flow of 3,000 m^3/day and 15,000 population equivalent) (Lazarova, 2005). The construction of filtration as a tertiary treatment unit result in a two- to three-fold increase in the capital and operating costs compared to the disinfection processes. For project sizes more than 7,500 m^3/day (50,000 population equivalent), the costs for UV treatment or chlorination for disinfection become comparable to maturation ponds. The cost difference between UV irradiation and ozonation decreases with plant size. For disinfection processes, the variable costs are high compared to the fixed costs, e.g. for UV irradiation, the variable costs associated with lamp replacement and cleaning are about 45–50% of the total annual costs (Indian Institute of Technology, 2011), while variable costs associated with chemical use can increase up to 50–70% for chlorination and ozonation, respectively, for small to large water reclamation schemes (Lazarova, 2005). Use of secondary to tertiary processes for treatment of sewage to a high level, for water reclamation can be energy intensive. Energy costs are only about 2–5% of the variable costs for chlorination but can be 15 and 35% of the total variable costs for UV irradiation and ozonation, respectively (Indian Institute of Technology, 2011).

The costs of membrane filtration (micro- and ultra-filtration) are significantly higher compared to the other disinfection processes. The widespread application of membrane bioreactors (MBRs), despite all the process advantages, is constrained by the high costs of membranes aside from high operation and maintenance costs due to fouling but has as an advantage in terms of treatment performance. Compared to the conventional activated sludge process, the overall costs for membrane bioreactors are up to 20% and 50% higher, depending on plant size (Indian Institute of Technology, 2011).

2.4. Water scarcity in sub-Saharan Africa

Water scarcity in sub-Saharan Africa is highly influenced by increased demand (UN WATER/AFRICA, 2009); insufficient water resource management including water losses due to poor operation and maintenance, below-cost recovery tariffs, and low collection rates (IMF, 2015); lack of infrastructure, financial resources and skills (UN WATER/AFRICA, 2009); and climate change (Conway et al., 2015).

2.4.1. Water availability and climate change

Sub-Saharan Africa has an abundance of water year-round in the humid and semi-humid parts of central Africa (UN WATER/AFRICA, 2009). However, many sub-Saharan African countries have relatively limited access to water resources (IMF, 2015). In the large semi-arid and arid areas of the southern sub-region, there is an unpredictable temporal and spatial variability of rainfall (Van Koppen, 2003; UN WATER/AFRICA, 2009). Great disparities also exist within countries – whereas in northern/central Mozambique the precipitation is almost 2,000 mm/year, it is less than 800 mm/year in the southern region (Tadross and Johnston, 2012), with all rainfall being restricted to the period between November and April. Due to high rates of evaporation, in the southern part of Africa, renewable water resources – average availability of surface water and groundwater – constitute only 9% of the total water available (AMCOW, 2012). Furthermore, historical data show that in the past 20 years, available freshwater resources in Africa have greatly decreased due to severe and prolonged droughts (Donkor and Wolde, 2001). Also, several countries report that the quality of water resources is deteriorating due to pollution resulting from industries, urban runoff, sewerage, and agro-chemicals (IMF 2015; Donkor and Wolde, 2001).

Climate change poses an additional threat to water security in sub-Saharan Africa; changes in precipitation and temperature may lead to changes in water availability due to the fact that annual precipitation, soil moisture, and runoff are likely to decrease while temperature increases evaporative demand (Conway et al., 2015). In addition, it is expected that rainfall will drop by 10% by 2050, leading to major water shortages (de Wit, 2006). According to most climate models, many southern African countries will warm up more than the global mean, with annual mean temperature rising by 2 to 3°C in most cases (Conway et al., 2015).

2.4.2. Water demand

Water demand in Africa has been increasing as a consequence of rapid population growth (UN WATER/AFRICA, 2009), expanding urbanization (The World Bank, 2011), and increased economic development (UN WATER/AFRICA, 2009). In the continent, industrial water demand represents 6% of the total water withdrawal, followed by domestic with 9% and agriculture with 85% (AMCOW, 2012). Most water demand from industries in sub-Saharan Africa countries comes from mining and metallurgy, particularly smelting and refining. For example, In Mozambique, coal mining was estimated to produce 8.42 million tonnes (Yager, 2016), which can be translated in a total water consumption of 0.55-1.36 million m^3/day (**Table 2**). Electricity production from thermal power plants (66 GW, Jingura and Kamusoko, 2017) in sub-Saharan Africa is estimated to consume around 2.85 million m^3/day **(Table 2**), whereas sugar production was estimated at 760 million tonnes in 2013 (Hess et al., 2016); the water involved in production, not including irrigation, was equivalent to 312.33 million m^3/day (**Table 2**). This development of more water-intensive activities has put stress on existing water infrastructure (IMF, 2015), and this is expected to increase in the near future (Holden, 2013).

2.4.3. Water resources management

All continental Sub-Saharan African countries share at least one international water basin (UN WATER/AFRICA, 2009), and often this situation leads to disputes, with the downstream countries being the most affected (Ashton, 2003).

Extensive upstream usage of the Umbeluzi and Incomati rivers for irrigation and industrial use in South Africa and Swaziland have impacted water supply to the city of Maputo, capital of Mozambique (Van der Watt, 2003). A very similar situation is also encountered at the Limpopo river where excessive abstraction, 1,173 million m^3 in 1980 and 1,723 million m^3 in 2000, from a total of 5,280 million m^3, in South Africa, has originated in reduced freshwater flow into the ocean in Mozambique, damaging the ecosystems and leading to saline intrusion (Ashton, 2003).

The shared nature of water resources in Africa, with more than 80 shared river basins and lakes and at least 60 transboundary aquifer systems, led to the establishment of various entities at national, sub-regional and regional levels for promotion of sustainable water resources management. Better management and development of water resources has also recognized in 2002 during the Johannesburg World Summit on Sustainable Development. Due to scarcity in this region, there is a need to pursue and adapt, in line with the Africa Water Vision 2025 (UN WATER/AFRICA, 2009), more sustainable approaches for use and management of water resources, integrating aspects of water quantity and quality, surface and groundwater, climate change, and cultural aspects (Setegn and Donoso, 2015).

2.4.4. Lack of infrastructure, financial resources and skills

The lack of storage, treatment, and piped water infrastructure can, even with abundant natural water resources, result in water not being utilized neither effectively nor efficiently across many African countries (ACPC, 2013). As the costs of building new water infrastructure increase, together with the higher costs of operating and maintaining existing water infrastructure, funding for required investments in the sector becomes more difficult (Deloitte, 2016). Also the water quality of the sources for water supply is highly affected by untreated discharges due to improper sanitation (World Bank, 2011).

The most common types of sanitation infrastructure in many African cities are pit latrines and septic tanks, covering 60-100% of the population (Nansubuga et al., 2016). In sub-Saharan Africa, only Angola, Botswana, Cape Verde, Guinea Equatorial, and South Africa have more than 70% coverage of improved sanitation – one that hygienically separates human excreta from human contact – with an average of 40% in 2015 (WHO/UNICEF, 2015). Furthermore, even the few existing central infrastructure systems in the region are generally not functioning at full capacity due to lack of regular maintenance (Bahri et al., 2008). These very low levels of wastewater treatment have high negative impacts on receiving water bodies (Arsénio et al., 2018; Jacobsen et al., 2013) and on the health of the urban populations (Duflo et al., 2012).

African countries struggle to provide water and sanitation services mostly due to inefficiency in utilization of financial resources. In addition, misguided priorities in project development and infrastructure planning processes occur, where feasibility studies give more emphasis on technical feasibility rather than on financial and institutional issues that are equally important or, in some cases, should precede the technical ones. Furthermore, projects in their conceptual stage do not always consider benefit maximization of the economic activities for where they are allocated such as water storage, power generation, water reclamation applications, existing water supply systems, and tourism. Tandi and Earle (2015) stated, therefore, that water-related infrastructure would be stronger if projects were conceptualized to serve multiple purposes.

2.4.5. Possible solutions for alleviation of water scarcity

The status quo regarding water and sanitation services has resulted to be insufficient, with many sub-Saharan countries presently experiencing physical water scarcity (Ashton and Turton, 2009; Wandiga, 2014), and with almost all countries expected to be in a state of water-stress or scarcity within the next decade (UNEP, 2008).

The challenges could be overcome by implementing a combination of water demand management approaches together with the use of other alternative water sources.

Water demand management approaches have been proposed with the aim to conserve water by influencing its demand. This involves the application of selective incentives to promote efficient and equitable use of water. However, in urban centers of southern Africa, water demand management tends to fail due to lack of data and a comprehensive information system to aid decision-making (Gumbo et al., 2003).

There is a major technical and organizational challenge for countries to launch rainwater harvesting and water conservation programs (Bixio et al., 2008), minimizing non-revenue water through improved management and efficient use (Rached et al., 1996), implementing water reclamation schemes (Bixio et al., 2005), studying and developing other sources such as groundwater (Pavelic et al., 2012), seawater (Frost and Sulivan, 2008) and (managed) aquifer recharge (Tredoux et al., 2002). Where feasible, transfer of water from those regions with excess water to the water-deficient regions can also be an option (Setegn and Donoso, 2015).

Nansubuga et al. (2016) argued that in particular, resource recovery, e.g. through water reclamation programs, is a pivotal strategy for wastewater management in sub-Saharan Africa.

2.5. Discussion

2.5.1. Development of water reclamation projects for industrial use

The potential for water reclamation around the world is high since sewage is available, technology and legislation regarding water savings exist, and people/industries are potentially interested. Projects implemented around the world illustrate the existence of functional methodologies for water reclamation and strategies and programs, acknowledging the beneficial role of water reclamation (Salgot and Huertas, 2006).

Although the driving forces for water reclamation differ, according to the socioeconomic context or the circumstances that lead to the successful implementation of a project, it can be noted that it is potentially possible to combine different experiences and create a baseline that can help to implement new projects. In this way, water reclamation for industries can play an important role in addressing water scarcity, giving industries the responsibility of not competing with the available water resources for domestic use and, in many cases, resulting in financial benefits (Grobicki, 2008). By using reclaimed water in industry, additional water will be available for drinking and other domestic purposes. From an economic perspective, it is important to have a clear view on the purpose of evaluating the costs of water reclamation installations. This can be focused on determining the charges to water users, the ways to finance the project, or assessing the wider economic performance of the investment, including the value of environmental impacts (Indian Institute of Technology, 2011).

From a social point of view, there is a need to examine the public attitude towards the idea of using reclaimed water. Although there are not many examples where industries reject the idea of reclaiming water, a low adoption rate was found in Thailand; despite the country's intention for industries to adopt water reclamation practices, only 10.5% of the industries included in the survey accepted to reclaim the treated wastewater (Visvanathan and Cippe, 2000).

Understanding the drivers for and against water reclamation can facilitate efforts to meet associated policy goals. In Europe, the Urban Wastewater Treatment Directive (91/271/EEC) advises the use of reclaimed water "where appropriate," but the "appropriateness" is not defined (Hochstrat et al., 2006). Similarly, in 2007 the Australian federal government set a national target to reclaim 30% of Australia's sewage by 2015 (Marsden Jacob Associates, 2008) but did not articulate selection criteria for prioritizing investments. Given the lack of clear criteria, many different factors can influence whether or not water reclamation projects are actually implemented.

2.5.2. Potential for successful implementation of water reclamation for industries in sub-Saharan Africa

In literature, information about water reclamation schemes in sub-Saharan Africa is scarce. Most of the examples of reclaimed water are related to agriculture (Jiménez et al., 2010), with the exception of Namibia, directly producing drinking water from treated wastewater (Lahnsteiner and Lempert, 2007), and South Africa using water reclamation for some industries (**Table 4**) (Eckart et al., 2011; Adewumi et al., 2010). Even data of produced wastewater reported in this region include only a few countries. E.g. in the period 2008 to 2012 only 13 of the 48 countries have partial reported volumes (Fao (Aquastat), 2012) and only three countries, Senegal, Seychelles and South Africa, have complete information on wastewater generation, treatment and reclaimed water available (Sato et al., 2013).

Water reclamation in industry is already practiced around the world, supported by advanced treatment technologies. However, reclaimed water is still not extensively explored as an alternative reliable source of water supply in sub-Saharan countries. The slow adoption reveals that the controversy around reclaimed water extends beyond just engineering and economics; many additional barriers such as governance issues, lack of infrastructure, financial resources, and technical skills for operation and maintenance must be overcome to reclaim water for industry in this region.

One of these barriers is that water is underpriced, and most companies are subsidized by municipal or regional authorities (Banerjee et al., 2008). This situation leads to inefficient use of already scarce water resources and negatively influences the market for water reclamation initiatives. Subsidized prices not only tend to discourage proper use of water among those who often could afford to pay more but may also reduce the incentive for investment in sewage treatment and water reclamation. However, the example of eThekwini, where the concept of "water fit for purpose" has been implemented in the city of Durban, South Africa, shows that water reclamation in industry can be an alternative to respond to a conflict between water demand for domestic use and economic development under conditions of water scarcity (Adewumi et al., 2010).

The possibilities for the use of reclaimed water in industry should mainly be explored for mineral extraction, cooling in thermal power plants, and in other non-food manufacturing industries such as metal processing (aluminium, coper, iron and steel), paper, textile, chemicals and construction. According to **Table 4**, these industries especially use water for cooling processes and as boiler makeup and in the case of minerals and construction, water is used for washing and processes, respectively.

Future infrastructure developments should include the design of systems that allow for the implementation of water reclamation with appropriate solutions for the local conditions. Particularly in sub-Saharan Africa, the selection of the treatment technology according to local experience and skills is important (Adewumi et al., 2010), including plans that allow for closing cycles, resource recovery, and synergy options. The design of these systems should comprise a multi-objective optimization methodology for efficient use of resources (Jacobsen et al., 2013).

In addition, infrastructure planning, including sanitary infrastructure and industrial parks, should consider technological options taking into account all potential sources of water as a water resource appropriately matched to its end use and involving all stakeholders over the planning cycles. This means that additional costs have to be considered, and not only the water utility(ies) should be included in the planning process (WERF, 2010).

Finally, an appropriate business model for industrial use of water, including all aspects of sustainability in water use, should be considered.

Industrial water users are firstly concerned with profitability and operating sustainability of their businesses (WBCSD – IWA, 2009). Therefore, when planning to implement water reclamation programs, the main factors that hinder the use of this water (e.g. water quantity and quality requirements, techno-economic considerations, service reliability, and risk assurance) should be considered. The most decisive factors are the availability of water resources, their accessibility, the distance between the production and the point of use, and the existence of treatment facilities. Other major factors include the general infrastructure, climatic conditions, other economic sectors (such as industry, tourism etc.), institutional landscape (governmental, private), policy and strategy in the water sector, enforcement of legislation, general income level of the population, existing water tariff structures, and/or governmental subsidies (FEMIP, 2009).

2.6. Concluding remarks

The implementation of water reclamation in sub-Saharan Africa is lagging behind. Factors such as the increased demand for water, coupled with increased water stress, water scarcity, climate change and compliance measures towards environmental legislation, are likely to be drivers for use of reclaimed water in industries.

However, the Sub-Saharan African region is characterized as not only water, but also data and information scarce, given a lack of well-developed sewer infrastructure and a low level of education on aspects related to water reclamation, usually with low water tariffs and legislation that, in most countries, is not being enforced. Therefore, the crucial steps to implement water reclamation should involve further practical research both on technical and governance aspects.

Industries with potential for use of reclaimed water should be identified, and the industrial water use locations and patterns should be evaluated. In addition, sewage flows available for reclamation should be identified to find links for incorporation of water reclamation in urban and industrial planning. Furthermore, the required water quality for industrial applications, compared to the quality of sewage, or effluents of wastewater treatment plants, should be determined to be able to design appropriate (low cost) water treatment solutions for water reclamation for industrial purposes.

Parallel to the technical challenges, possibilities for changing legislation or introducing of new policies where they do not exist should be assessed, next to the adoption of alternative financial structures and subsidies that support water reclamation. In particular, the involvement of stakeholders should be analyzed to study the acceptance of water reclamation for industrial uses and the inclusion of water reclamation options in integrated water and sanitation infrastructure planning.

This together will, at the end, lead to a higher availability of water for both domestic and industrial purposes, increasing the chances for economic growth and growth of urban health and well-being.

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Chapter 3

Assessing Water Reclamation Potential for Industrial Use in Cities: Identifying Gaps, Opportunities and Priorities for Water Reclamation in Maputo

This chapter is based on:

Gulamussen, N. J., Arsénio, A. M., Koop S. H. A., van Leeuwen, C. J., and Rietveld, L. C. (2025). Assessing water reclamation potential for industrial use in cities: Identifying gaps, opportunities and priorities for water reclamation in Maputo (to be submitted).

Assessing Water Reclamation Potential for Industrial Use in Cities: Identifying Gaps, Opportunities and Priorities for Water Reclamation in Maputo

Abstract

This study particularly addresses the potential of water reclamation practices for industrial use to alleviate urban water stress. Through a case study of the city of Maputo, Mozambique, an applicable method was developed for cities to assess the water reclamation potential. Based on the City Blueprint Framework additional indicators were developed to better address for water reclamation for industrial. The indicators were developed to be easy to understand, timely and relevant, and with minimal computation efforts. By applying this newly developed assessment the main gaps, opportunities and priorities were identified for Maputo. Overall, we, amongst others, found that sanitation infrastructure and wastewater treatment are key priorities for increased wastewater reclamation for industrial use, as almost 90% for of the city's population rely on on-site sanitation and less than 20% of the generated wastewater is treated at a central treatment plant. However, the city's industry is relatively close to the sewage water sources, which, on the other hand, is an opportunity to reclaim wastewater for purposes that require less stringent water quality such as cooling processes. The potential savings in water consumption at reduced overall costs of water reclamation, may, thus, pose a promising solution to increase Maputo's water sustainability.

3.1. Introduction

Fresh water is progressively becoming scarce, mainly due to increasing water demand as a result of increasing population, economic growth, changing use patterns; water pollution and climate change (Schewe et al., 2014; WWAP, 2015, 2018). Global water demand increases at a rate of 1% a year with industrial and domestic water demand expected to increase faster than for agriculture (WWAP, 2018), also as a result of the fast urbanization (Cox, 2020). In addition, cities face several environmental challenges, e.g. related to the generated wastewater that, if not managed properly, often ends up in the environment, polluting the water sources and causing health problems (Kerstens et al., 2016). In low and middle income countries, where public infrastructure is frequently under-developed (Deng, et al., 2017) and policies, to ensure that the benefits of urban living are equitably shared (UNDESA, 2015), are not consequently implemented, inadequate water management accelerates the depletion of surface water and groundwater resources (Deng et al., 2017).

In order to adapt to these challenges, the role of integrated urban water management (IUWM) has become pivotal. From the on-the-ground experience of practitioners several empirical concepts of IUWM were built up (Savenije and Van der Zaag, 2008). One of the widely accepted is the definition by the Global Water Partnership: 'a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (IWA, 2024). Establishing effective and equitable urban water management practices within IUWM, requires knowledge, expertise, and investment at political level, and, at the same time, to be sustainable, should combine all related aspects, i.e., financial, institutional, environmental, technical, and social (FIETS), while considering the whole urban cycle (DWA, 2013). To assist long-term IUWM strategies for cities, some models, such as the City Blueprint Approach have been developed (Van Leeuwen et al., 2016), which consists of three complementary methodologies, (1) the Trends and Pressures Framework (TPF), (2) the City Blueprint Framework (CBF) and (3) the water Governance Capacity Framework (GCF).

The TPF consists of a set of general social, environmental, and financial indicators that may affect water management and allow to identify the main challenges that a city face. CBF provides cities with a quick and useful snapshot of the performance of their urban water management, management of solid waste, and climate adaptation measures (Koop and van Leeuwen, 2015). In 2020, more than 125 municipalities and regions in more than 50 countries had been assessed, creating a platform in which cities can share their best practices and learn from each other (Koop et al., 2022). The GCF analyses the governance conditions for addressing the challenges of managing long-term, complex, uncertain, and imperfectly known risks associated to water management. It provides tools for an iterative process that requires governance capacity to find integrated long-term solutions that are supported by flexible intermittent targets to anticipate changing situations and adapt to emerging barriers (Koop et al., 2017).

However, the implementation of IUWM is not an easy task, especially in African countries, where the implementation is challenged by a complex set of factors, including technical and social aspects affecting water management (Bahri et al., 2016). Therefore, some authors (Hyde et al., 2005; Tkach and Simonovic, 1997; Zarghami, 2010) have suggested the use of, amongst others, multi-criteria decision-making tools to evaluate alternatives for future water resources' use through adaptive management (Almeida et al., 2013). The adaptive management strategies may vary according to the socio-political context, resulting in a need for continuous improvement in the used methodologies.

Water reclamation, as one of the adaptive urban water management strategies, whereby sewage water is treated and used for other than domestic applications, being mainly industrial (and agricultural) use, is nowadays considered to be an important component of IUWM (Furlong et al., 2019). Therefore, in typically water-stressed countries such as Australia, Israel, Singapore and the US State of California, water reclamation strategies have already been developed and implemented (Hochstrat et al., 2006). Although many examples of water reclamation exist and the science and technology have developed to a point that it is possible to treat wastewater to any required quality, in many countries in Sub-Saharan Africa water reclamation is not (officially) implemented yet (Gulamussen et al., 2019). Therefore, in order to determine the role water reclamation could play in IUWM, especially for industrial use in Sub-Saharan Africa, an estimation of the water reclamation potential in these countries is essential.

Previous studies on the estimation of water reclamation potential focussed on developing and optimizing water treatment processes and systems for sustainable use of treated wastewater (Baresel et al., 2015), or on the assessment of the amount of available reclaimed water and its potential impacts on the water environment and economy (Xiang et al., 2015), using life cycle analyses, cost benefit analyses and water resources-environment-economic management models. Some other studies have identified the key challenges that limit water reclamation

(Esposito et al., 2005). However, these water reclamation potential estimates have been presented without reference to quantification methods applied to allow replication to other regions (Barbagallo et al., 2001; NRDC, 2014).

Implementation of water reclamation projects for industrial use, requires the evaluation of specific, techno-economic and environmental conditions, such as water availability and demand, quality requirements, service reliability, and risk assurance (Gulamussen et al. 2018). The most decisive technical factors are the availability of alternative (i.e., domestic wastewater) resources, their accessibility, the distance between the production and the point of use, and the existence of treatment facilities. Other major factors include the condition of the available infrastructure, climatic conditions, the demand from industry, general income level of the population, existing water tariff structures, and/or governmental subsidies (FEMIP, 2009).

In order to assess the potentials, in terms of techno-economic and environmental conditions for implementation of water reclamation for industrial use, we therefore developed a Water Reclamation potential for industrial use Framework (WRpiF), using the principles of the City Blueprint Approach with a set of indicators that are related to the objective proposed to attain. We then applied the framework to a case in the city of Maputo, Mozambique, with the final goal of finding the enabling factors that can boost the use of this adaptive measure for the improvement of IUWM. We combined the framework with the state-of-the-art TPF and CBF to give a general picture of the current IUWM situation of Maputo city.

3.2. Methods

3.2.1. Description of the case study: Maputo city

Maputo is located in the southern part of Mozambique (**Figure 1**). The city grows at a rapid rate as the result of high birth rates and migration. According to the latest data from the National Statistics Institute (INE, 2017), the population of Maputo city was about 1.3 million in 2017. Mozambique’s economy has expanded rapidly over the last decade with an annual Gross Domestic Product (GDP) growth between 5% and 7% (Economics, 2024). However, the

GDP has slowed down, due to the impact of two major cyclones in 2019 and the COVID-19 pandemic in 2020-2022. Growth and improvements in living standards have not evenly been spread across the country, mainly affecting urban areas and areas in the southern part of the country, where Maputo is located. As a coastal country, Mozambique relies heavily on international water resources, with many of the larger rivers originating from outside the country. Water resources are also unevenly distributed across the country, with the greatest limitations in the most developed southern part of the country (SWP, 2021). The southern basins are characterized by low runoff coefficients, deep saline intrusion in the river mouths (reaching up to 50 km inland), wide and shallow rivers, and valleys with low storage, high evaporation losses and large flood-prone areas. The country is vulnerable to climate change and its related effects on water resources: recurrent droughts, affecting the replenishment of reservoirs and aquifers, and floods. Groundwater sources for the coastal cities are also affected by saline intrusion (Manjate et al., 2023).

Figure 1: Maputo location (Wikipedia).

In Maputo city, piped drinking water is supplied by the Pequenos Libombos and Corrumana dams from Umbeluzi and Incomati rivers (Bhatt, 2014). About 50% of Greater Maputo's population (the expanded city including the municipalities of Maputo and Matola and the districts of Boane, Marracuene and Muamba with over 2 million people) depends on drinking water provided by small-scale water providers, in the fringe of the city (USAID, 2015). These providers extract groundwater from a superficial semi-confined aquifer, $10-20\ m$ deep and distribute water through small-scale water supply networks (Marques Arsénio et al., 2018; Schwartz et al., 2015). However, many boreholes are contaminated by onsite sanitation, displaying high nitrate concentration levels, above WHO's threshold of $50\ mg\ L^{-1}$, and sometimes even up to $250\ mg\ L^{-1}$ (Bhatt, 2014; Marques Arsénio et al., 2018), attributed to poor faecal sludge management.

The residents living in Greater Maputo rely to the same extent on poor quality, onsite sanitation as residents in many other cities in sub-Saharan Africa. Onsite facilities have mainly been constructed and emptied by private providers, residents and civil based organisations (Capone et al., 2020; Weststrate et al., 2019). An estimated 37% of the population in the municipality of Maputo uses facilities connected to septic tanks and 53% of the population use pit latrines (WSP, 2014). About 10 % of the population, living in the city, is connected to a sewer system that collects the municipal wastewater (Rietveld et al., 2016). However, less than 50% of the collected wastewater reaches the wastewater treatment plant (WWTP), consisting of stabilization ponds.

3.2.2. Trends and Pressures and City Blueprint framework

With the TPF we analysed the factors that may compete with or are in favour of IUWM and helped in identifying the main challenges that Maputo city face. The TPF comprises of twelve social, environmental, and financial indicators that may affect water management, but can hardly be influenced by local authorities in such a way that the most urgent challenges hinder the implementation of others. The TPF includes the following indicators (Koop and van Leeuwen, 2015): urbanization rate, burden of disease, education rate, political instability, water scarcity, flood risk, water quality, heat risk, economic pressure, unemployment rate, poverty rate and inflation rate. Each indicator has been scaled from 0 to 4 points, where a higher score represents a higher urban pressure or concern. The following ordinal classes, expressed as ‘degree of concern’, have been used: 0–0.5 points (no concern), 0.5–1.5 (little concern), 1.5–2.5 (medium concern), 2.5–3.5 (concern) and 3.5–4 (great concern). For the seven indicators and sub-indicators a scoring method, based on international quantitative standards such as the World Bank, the World Health Organisation, and the Food and Agricultural Organization database Aquastat, was proposed (Koop and van Leeuwen, 2015). For Maputo city the data for the social indicators were collected from the United States' Central Intelligence Agency world factbook, WHO, UNICEF and Global Economy data bases. For the environmental indicators, the sources included, Aquastat, International Groundwater Resources Assessment Centre, and local reports. For the financial indicators, European Innovation partnership, International Monetary Fund and World Bank reports were consulted. The scores were assessed using the ranking of the city amongst all available country scores. These scores are not normative and only provide an indication of the urban pressures with respect to global trends. Detailed information on the scoring methods is provided in (EIPWater, 2016). Finally, the Trends and Pressure Index (TPI; the arithmetic mean of all twelve TPF indicators) was calculated. Further details on the data sources, calculation methods and scaling methods and limitations of the TPF have been provided by Koop and van Leeuwen (2015).

The CBF helps to’ communicate the performance of the city’s urban water cycle services and exchange experiences, select appropriate water supply and sanitation strategies, develop technical and non-technical options as future alternatives for the water cycle, where several possible changes in the use of technology, space and socio-economic scenarios can be introduced, and, finally, to select measures, including an evaluation of their costs and benefits under different developments scenarios, and how to integrate these in long-term planning on urban investments’ (van Leeuwen, et al., 2012).The CBF consists of 25 performance indicators that are scored from 0 (very poor performance) to 10 (excellent performance). They are distributed within seven groups including water quality (secondary WWT, tertiary WWT, ground water quality), solid waste treatment (solid waste collected, solid waste recycled, solid waste energy recovered), basic water services (access to drinking water, access to sanitation, drinking water quality), wastewater treatment (nutrients recovery, energy recovery, sewage sludge recycling, WWT energy efficiency), infrastructure (stormwater separation, average age sewer, water system leakage, operation cost recovery), climate robustness (green space, climate adaptation, drinking water consumption, climate robust building) and governance (management and action plans, public participation, water efficiency measures, attractiveness). The data were gathered by means of a questionnaire and by using publicly available data. The Blue City Index (BCI) is the arithmetic mean of the 25 indicators. Detailed information on the scoring methods of all CBF indicators is provided in (EIPWater, 2016). Further details on the data sources, calculation methods and scaling methods and limitations of the CBF have also been provided by Koop and van Leeuwen (2015). Sources of information for Maputo city included masterplans, national reports, and published articles.

3.2.3. Development of Water Reclamation potential for industrial use Framework

For the development of the WRpiF, we identified three key factors within the FIETS sustainability structure, specific for the implementation of water reclamation for industrial use, being the financial, environmental and technical ones (DWA, 2013). These factors were expressed in, in total, nine indicators which helped to formulate the steps to take, to confidently and successfully move towards sustainable water use through water reclamation.

The proposed indicators have direct impact on the operation of WWTPs and on stimulation of industries to use reclaimed water to alleviate water scarcity and are assumed to be essential for characterizing current conditions, tracking the outcomes of taken actions, and assessing progress towards overall goals of influencing the use of reclaimed water by industries. The selection of the indicators effectively determines the “lens” through which one views the system and is, therefore, important in influencing decisions by governments and industries (EPA, 2012). The scoring methodology follows the scale from 0 to 4 points, where a higher score indicates a higher potential for the implementation of water reclamation for industries in the WRpiF. The water reclamation implementation potential index (WRipI), being the average score, is classified as of low potential when the average is below 1.5, medium potential when between 1.5 and 2.5 and high potential when the average score is higher than 2.5.

Financial factor

There is a wide range of drivers and hindrances that affect the analysis of costs and benefits of water reclamation, and ultimately, the implementation of water reclamation projects. The relatively high costs of the required infrastructure (especially the transport infrastructure) have been identified as major barriers for implementation of water reclamation (Morris et al., 2021).

In addition, the price of the water from a conventional drinking water supply system can greatly impact the implementation of water reclamation by industries. The price of supplied (drinking) water hardly equals its value and rarely covers its costs (Grafton, Chu, and Wyrwoll, 2020), especially in sub-Saharan Africa. Therefore, the three following indicators were proposed for the financial factor of the WRpiF: the (drinking) water tariff applied for industries in relation to the real costs of drinking water, reclaimed water costs in relation to the real costs of existing (drinking) water supply, and the incentives that governments give to stimulate industries to implement water reclamation.

Indicator 1. Drinking water costs in relation to tariff

The indicator "Drinking water costs in relation to tariff" shows the relation between the tariff of the water supplied by the water supply company to the industry (WT) and the real costs for the production, transport, and distribution of (drinking/piped) water (WC), including both CAPEX and OPEX (expressed in €/m^3). In case the water tariff is too low compared to the real costs it means that the drinking water is under-priced, which may discourage the industry to use alternative water sources. The drinking water tariff can be retrieved from water supply companies. The real costs of water can be obtained from international benchmark or by the governmental agencies that deal with water supply management. The scoring of the indicator is presented in **Table 1**.

Table 1: Scoring of the indicator drinking water cost in relation to water tariff.

Condition	Score
WT/WC < 0.25	0
0.25 <WT/WC < 0.5	1
0.5 <WT/WC < 0.75	2
0.75 <WT/WC < 1	3
WT/WC > 1	4

For Maputo, the data was collected from a published bulletin, indicating the water tariff by sectors and the calculation of the real costs from the water supply company "'Águas da Região Metropolitana de Maputo" (AdRMM) (Boletim da República, 2012).

Indicator 2. Reclaimed water costs versus drinking water costs

The indicator is based on the ratio between the average costs for reclaimed water (RW), including additional treatment and transport minus the saving on discharge fees of the effluent from a WWTP, for use in industry, and the real costs for drinking water production, transport, and distribution, based on CAPEX and OPEX (WC). It is expected that if the costs of reclaimed water are low compared to the costs of drinking water, the implementation of water reclamation is favoured. The costs of reclaimed water can be calculated based on the quality of water required, in terms of additional treatment, and transport. The discharge fees can be obtained from the WWTP management. The scoring of the indicator is presented in the **Table 2.**

Table 2: Scoring of the indicator reclaimed water cost versus drinking water cost.

Condition	Score
RW/WC > 1	0
0.75 < RW/WC < 1	1
0.5 < RW/WC < 0.75	2
0.25 < RW/WC < 0.5	3
RW/WC< 0.25	4

In Maputo, in the vicinity of the WWTP, there are two potential industrial users of reclaimed water, of which one is for cooling systems and the other is for construction industry. It was assumed here that additional treatment should consist of only ultra filtration of the effluent.

Indicator 3. Incentives

Incentives shape the behaviour of individuals (stakeholders) and include penalties and promise of rewards. In many places where water reclamation is successfully implemented, it is observed that there is a coherent regulatory regime. Jurisdictions where water policy is overseen by a centralized water authority—e.g., Singapore, Israel, Tunisia—or delegated to specialized basin-level authorities—e.g., Florida—have particularly been successful at encouraging water reclamation. Institutional organization, planning, and knowledge sharing in these jurisdictions have led to more effective regulatory development, which in turn creates greater demand for incentives (Maniam, 2022).

The scoring of the incentives' indicator assumes that the more measures that act as incentive for water reclamation are in place the higher the potential for water reclamation. Those measures are related to existence of legislation, public awareness, incentives and government procurement that address various aspects as explained by (Freedman and Enssle, 2015), see **Annex B**.

A higher score is attributed to the number of measures in place. The scoring is presented in the **Table 3**. For Maputo the data was obtained from national available documents, such as the water low and the Maputo sanitation master plan (Boletim da Republica, 1991; MOPHRH, 2015).

Table 3: Score of the indicator incentives.

Condition	**score**
No measures in place	0
2 measures in place	1
3 measures in place	2
4 measures in place	3
More than 5 measures in place	4

Environmental factor

A strict financial analysis may not be sufficient to capture the potential benefits of a water reclamation project. The decision on implementing water reclamation is not only based on the projected benefits exceeding costs, but also on other benefits that it can bring, such as watershed protection, local economic development, and improvement of public health (Miller, 2006).

Drivers for water reclamation in industrial settings could also be the low availability of local water and the negative impact of water shortages on the environment. Low availability can be either due to limited sources of water or intense competition for supply, leading to water scarcity. In addition, more and more, governments and the UN Sustainable Development Goals are concerned by the fact that discharge of untreated sewage can lead to damage to the environment and to adverse health effects (Wear et al,, 2021). Using reclaimed water in industry can bring environmental benefits and prevents negative public health effects. Here, the water demand - supply gap (indicating water scarcity), environmental water quality and the coverage of improved sanitation over the population (both indicating environmental degradation) were proposed as environmental indicators.

Indicator 4. Water demand - supply gap

The determination of the demand - supply gap for water in a city requires historical data and expert judgement. The expected water flow in time is then projected for both supply and demand over a chosen period. The gap between supply and demand intensifies as demand increases, and/or as the water supply source is limited or is affected by decreasing flows, and/or as the sources are at low water quality, and/or as there is a stagnation in investments in new infrastructure (UNWater, 2024). Because water demand and supply can fluctuate over the years, it is necessary to establish a series of confidence intervals. The confidence intervals can be established by statistical analysis of past years' per capita water demand and supply. Since the demand - supply gap is most relevant when demand is smaller than supply, in the scoring of mainly the values of the ratio between demand and supply between 0 and 1 were considered. The calculation method is presented in the **Annex C**.

The scoring was based on the classification of the fraction of the demand (fd) covered by the available water supply as presented in the **Table 4**, where, for implementation of water reclamation, a high scoring will be observed for the city with (extreme) shortage, and thus a high incentive for the use of reclaimed water for industrial purposes.

Table 4: Score of the indicator demand-supply gap.

Range of fraction of demand covered (fd)	Level of Water Shortage	score
$fd > 1$	Surplus	0
$0.75 < fd \le 1$	Slight shortage	1
$0.5 < fd \le 0.75$	Moderate shortage	2
$0.25 < fd \le 0.5$	Serious shortage	3
$0 < fd \le 0.25$	Extreme shortage	4

Indicator 5. Proportion of water with good (environmental) water quality

The water quality of the urban water sources was considered as the proportion of water with good water quality in relation to all available water resources. "Good" here indicates a water quality that does not damage ecosystem functions or human health according to core ambient water quality parameter groups that are globally relevant. Overall water quality is estimated based on an index, using measurements of five water quality parameters that represent the most common pressures related to organic matter, ions dissolved in water, nutrients, and acidification, which inform on major water quality impairments present in many parts of the world (UNWater, 2018):

- oxygen (surface water);
- salinity (surface water and groundwater);
- nitrogen (surface water and groundwater);
- phosphorus (surface water);
- acidification (surface water and groundwater).

The methodology calls for *in-situ* measurements of these water quality parameter groups of the water bodies in the study area, receiving WWTP effluent and/or direct municipal wastewater discharges. The measured values are then compared to national target levels for the different parameters, and if values meet targets 80 % or more of the time, the water body is classified as good (UNWater, 2018).

Once the benefits of water reclamation is preservation of the environment, the more that it is found that the water is of bad quality, the more favourable water reclamation for industrial use could be and thus the higher the score is (**Table 5**).

Table 5: Scoring of the indicator proportion of bodies of water with good ambient water quality.

Proportion of bodies of water with good water quality (%)	**score**
81-100	0
61-80	1
41-60	2
21-40	3
0 -20	4

For Maputo the available data correspond to measurement of the pH, Electrical Conductivity (EC) and nitrogen in groundwater for the period from 2011 to 2016 (raw data) and measurements of the core parameters in groundwater in 2019 (Tamele et al. 2019); measurements of water quality of Infulene river, the receiving water body for the WWTP effluent, for pH, EC, nitrates and phosphates in 2022 (Rodrigues, 2023).

Indicator 6. Proportion of population using flush-toilets

The proportion of population using sanitation through flush-toilets for human excreta disposal in the dwelling or immediate vicinity will positively impact the environment (and human health). In the meantime, the existence of these sanitation facilities can be an indication for possibilities of conveyance of municipal wastewater, preventing further pollution and increasing the potential for water reclamation for industrial use. A high coverage will thus positively impact water reclamation (**Table 6**). For Maputo the data is collected from (UNESCO, 2021).

Table 6: Score of the indicator proportion of population using improved sanitation.

Population using sanitation with flush-toilet (%)	**Score**
0-20	0
21-40	1
41-60	2
61-80	3
81-100	4

Technical Factor

Essential for the implementation of water reclamation for industry is the availability of an alternative water source, being municipal WWTP effluent. Various technical boundary conditions must be in place to be able to collect the municipal WWTP effluent, (post)treat it and transport it to industry. Basic technical prerequisites are the amount of water centrally collected from the city, the relation with the industrial needs and the technical capacity to operate the facilities in a proper manner (Maniam et al., 2022). Therefore, the following indicators were formulated.

Indicator 7. Sewerage system coverage

The existence and scale of collected sewage and a central WWTP effluent in a city or region forms a basic condition for the availability of water for reclamation. The existence of a sewer system is then a prerequisite to collect the water and treat it for use in industry.

In cities, with absence of a sewer system, the extent of use of reclaimed water for industrial application will probably be low, while where sewer systems exist, WWTPs can produce large flows of treated sewage for potential reclamation. The flows of generated water that can be conveyed in a city will thus define its source generation capacity. The score for sewer coverage is presented on **Table 7**. The data can be obtained from city sanitation information sources, as was done for the Maputo case study (MOPH, 2015).

Table 7: Score of the indicator sewerage system coverage.

Scale	**score**
Absence of sewerage system	0
Sewerage system existent and coverage less than 20% of the population	1
Sewerage system existent and coverage between 20 and 40% of the population	2
Sewerage system existent and between 40 and 60% of the population	3
Sewerage system existent and coverage more than 60% of the population	4

Indicator 8. Proportion of centrally collected wastewater in relation to water needed for industries

In addition, the ratio between the available treated wastewater (WW) for reclamation and the industrial water (IW), demand was assumed to contribute to the implementation of water reclamation.

If a central wastewater system exists in a city, the flow of collected wastewater can be calculated and related to the needs of potential industries in the surroundings. The quantification of water demand by industries requires a mapping of the main industries with potential for reclamation.

The more (treated) wastewater is relatively available, the better the condition for the implementation of water reclamation is (**Table 8**). The data of the flows of wastewater was obtained from literature (van Esch and van Ramshorst, 2014) and the demand for industries was calculated based on the main industrial applications in the surroundings of the Infulene WWTP.

Table 8: Score of the indicator proportion of centrally collected wastewater in relation to water needed for industries.

Condition	Score
WW/IW < 0.25	0
0.25 < WW/IW < 0.5	1
0.5 < WW/IW < 0.75	2
0.75 < WW/IW < 1	3
WW/IW > 1	4

Indicator 9. Technological capability

Technological capability comprises 'the body of practical and theoretical knowledge, procedures, experience, methods and physical equipment and devices' (Ahmad et al., 2014), necessary to 'design and develop new processes and products, and to upgrade knowledge and skills on the physical environment and transforming the knowledge into instructions and designs for efficient creation of the desired performance' (Wang et al., 2006). Several measurements on national technological capabilities have been developed. The World Economic Forum, the UN Development Program, the UN Industrial Development Organisation, and the RAND Corporation institutions e.g., measure technological capability (Archibugi and Coco, 2004). The varying nature of technology makes it difficult to aggregate its heterogeneous aspects and components into a single meaningful indicator. Archibugi and Coco (2005) have compared the similarities and differences between the various methodological approaches; and then tested the consistency. They have found that one of the key characteristics is that they are far from being uniformly distributed across countries, regions and firms and the various research teams are interested in slightly different aspects of technological change. Therefore, the same authors have proposed an index of technological capabilities, ArCo, for various countries.

The ArCo Technological Index is calculated considering three index categories, technology creation, actual technology infrastructures and actual human skills from eight subindexes, patents, scientific articles, internet penetration, telephone penetration, electricity consumption, tertiary science and engineering enrolment, mean years of schooling and literacy rate. More details of the calculation can be found in (Archibugi and Coco, 2004).

The ArCo Technology Index divide the countries in four groups:

- leaders (from 1 to 25 ranking);
- potential leaders (from 26 to 50);
- latecomers (from 51 to 111);
- marginalized (from 112 to 162).

The last two groups have a large spacing and therefore were here divided into three by introducing an additional group, so that our scoring is more uniform and distributed as follows:

- leaders (from 1 to 25 ranking);
- potential leaders (from 26 to 50);
- comers (from 51 to 81);
- latecomers (from 82 to 112);
- marginalized (from 112 to 162).

The scoring was based on the groups classification as presented in **Table 9**. The data for Maputo was obtained from the Mozambican calculated index by (Archibugi and Coco, 2004).

Table 9: Scoring of the indicator technological capability.

Group	ArCo Index	Score
Marginalised	< 0.22	0
Latecomers	0.28 - 0.23	1
comers	0.38 – 0.28	2
Potential leaders	0.51 - 0.39	3
Leaders	0.87 - 0.52	4

3.3. Results

3.3.1. Analysis of Trends and Pressures Framework of Maputo city

In order to identify the main challenges that Maputo face related to water management, the trends and pressures on IUWM were assessed, in accordance with the methodology proposed by Koop and Van Leeuwen (2015). After the TPF-analysis was carried out for Maputo, the scores were classified into five ordinal classes, varying from no concern to great concern, for each of these 12 TPF indicators as shown in **Figure 1** and the Trends and Pressure Index calculated to be 3.1.

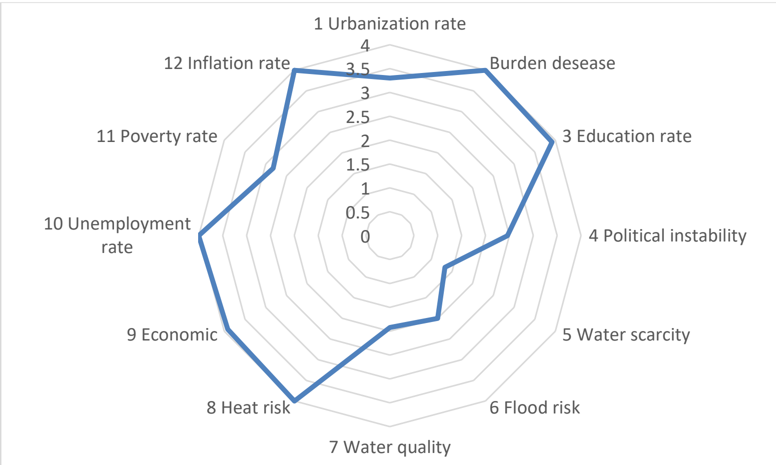

Figure 2: Trends and pressures for the city of Maputo on IUWM.

3.3.2. Analysis of City Blueprint Framework of Maputo

To determine the performance of Maputo's IUWM, management of solid waste, and climate adaptation measures, the CBF was assessed. The CBF scores for each of the 25 indicators ranging from 0 at the centre of the circle increasing outwards to 10 are presented in **Figure 3**. Based on an assessment of data from various sources, the average of the 25 City Blueprint indicators, i.e., the BCI, for Maputo was calculated to be 1.8. For calculations see **Annex D**.

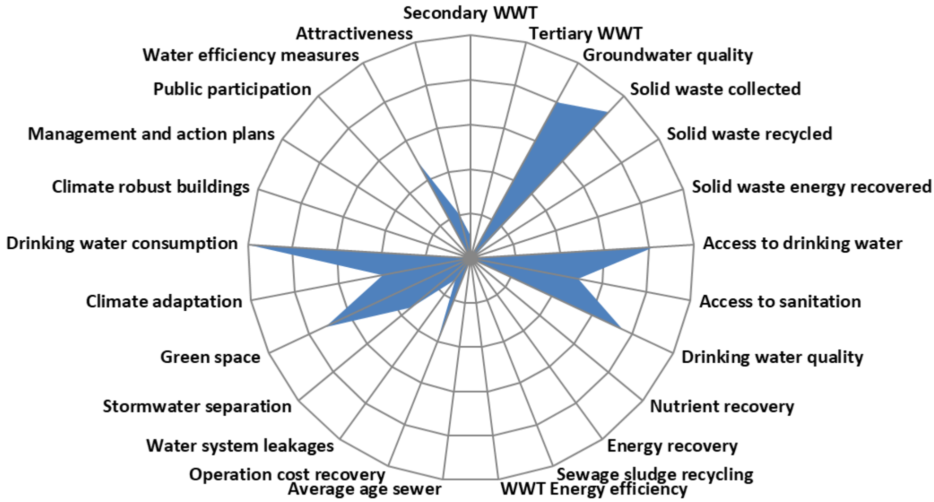

Figure 3: Representation of the City blueprint of Maputo.

3.3.3. Analysis of Water Reclamation potential for industrial use

With the WRpiF the potential for implementation of water reclamation for industrial use in Maputo city was evaluated in terms of the techno-economic and environmental conditions, based on nine indicators, as described in the Methods section.

1. Drinking water costs in relation to tariff

In the water tariff for industrial use in Maputo there are distinct prices according to the quantity supplied to industries. For calculation we considered the average price of WT = 59.36 MZN/m^3 (€ 0.87) (Boletim da Republica, 2021). The real water costs vary yearly, while the average cost between 2018 and 2022 was WC = 85.07 MZN/m^3 (€ 1.25). This resulted in a score of 2 according to **Table 1**.

2. *Reclaimed water costs versus drinking water costs*

In Maputo, there are two main applications of treated wastewater located close to central WWTP: a cooling system of a Central Power plant, and various concrete producing industries. We calculated the cost of reclaimed water based on the application that require the highest water quality, using ultrafiltration (UF) as post-treatment. Pérez et al. (2022) have calculated the cost of UF treatment, which can be suitable for water reclamation in cooling systems, in a scenario of a feed flow rate of 25 m^3/h, to be around 0.30 €/m^3. Additional investments are also required to convey the treated wastewater to these industries. The costs of pipeline construction vary from 200,000 per km up to 1 million USD per Km (SCMO, 2019). We assumed a baseline of 250,000 €/km with a length of around 2.0 km, and thus a calculated price of 0.38 €/m^3, considering that the Thermal Power Plant requires 30 m^3/h and a return investment period of 5 years. The total cost of supply reclaimed water for cooling purposes is then approximately 0.68 €/m^3. The ratio is 0.68 / 1.25 = 0.54 which gave the score 3 (**Table 2).**

3. *Incentives*

In Mozambique the tax for industrial water is higher than for domestic use and recently a pricing tax for the discharge of water containing contaminants in water courses was introduced. These two measures represent incentives for water reclamation. From the scoring presented in the Methods chapter (**Table 3**), the score for Maputo was thus 1.

4. *Water demand – supply gap*

In 2024 the projected ratio between supply and demand in the central part of the city of Maputo was fd = 1.3 (see **annex C**) with a tendency to decrease in the coming years, because of increasing demand and stagnant supply. However, in 2024 Maputo had a surplus of supplied drinking water and therefore a score of 0 was given (**Table 4**).

5. *Proportion of water with good (environmental) water quality*

The results of the studies mentioned in the Methods chapter, indicate that in some areas in Maputo, the water has high concentrations of nitrates, indicating pollution by latrines and septic tanks, and a high electrical conductivity, indicating areas of salt intrusion. Available data of measurements of pH and EC in groundwater (from 29 boreholes) indicate that 46 % of measured values of electrical conductivity exceeded the national limits for human consumption. Tamele at al. (2019) have presented results of electrical conductivity, total dissolved solids, chloride and sodium with 30 % of samples with values above the limit and 50% of the values of nitrates above the limit. The Infulene river was found to have a low water quality index, a bad quality in the rainy season and very bad quality in the dry season (Rodrigues, 2023). We estimated that the proportion of bodies with good water quality fit in the range of 21 to 40 %. The scoring for this indicator was therefore 3 (**Table 5**).

6. *Proportion of population using flush toilets*

The proportion of population using flush toilets in Maputo is about 70% of the population (UNESCO, 2021) with will give a score of 1 (**Table 6**).

7. *Sewerage system coverage*

Literature indicate that that Maputo city's sewerage coverage is only 5 – 10% of the population (Rietveld et al., 2016) which gave a score of 1 according to **Table 7**.

8. *Proportion of centrally collected wastewater in relation to water needed for industries*

In Maputo there is one central WWTP that treats about 4000 m^3/day of water (van Esch and van Ramshorst, 2014). The quantified volume of water demand for industries with potential for reclaiming this water, in the vicinity of the central WWTP is distributed as 15 % for cooling systems (720 m^3/day for the TPP thermal power plant), 85% for construction industry (4000 m³/day) (Fausta, 2016). The total demand for industrial application is therefore higher than the available treated wastewater, considering only the main applications and excluding the water used for agricultural purposes, giving a score of 3 (**Table 8**).

9. Technological capability

For Maputo we used the ArCo index for the entire country of Mozambique of the data published in 2004 that placed Mozambique in the 148th position with an ArCo index of 0.098. Mozambique was thus considered to be in the group of marginalised countries (Archibugi and Coco, 2004), with a score of 0 (**Table 9**). The results of the WRpiF are summarised in **Figure 4** .

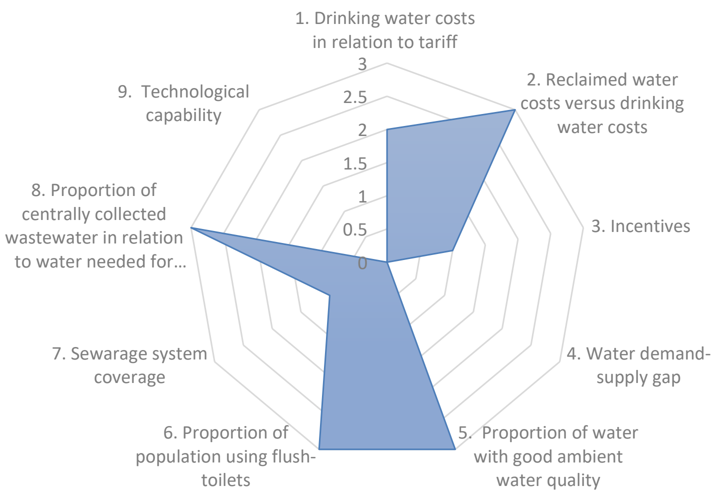

Figure 4: Representation WRpiF for Maputo city.

3.4. Discussion

To identify the gaps, opportunities and priorities for implementation of water reclamation for industrial use in Maputo, first the TPF and CBF were used.

From the TPF analysis, it can be observed that Maputo faces high social and financial challenges. The social indicators urbanization rate, disease burden and education rate and all financial indicators scored > 3, indicating areas of major concern and providing the context within which the water managers of the city of Maputo must operate. From the analysis it can also be observed that the main environmental challenge is the heat risk.

The low score in the BCI, which places Maputo in the category of cities lacking basic water services, is partially explained by lack of central sanitation infrastructures. Only a small part of the city is covered by a sewerage system and has limited access to fecal sludge management services (Marques Arsénio et al., 2018). In addition, less than 10% of the generated wastewater is potentially treated at a central treatment plant (Rietveld et al., 2016). While the indicators of drinking water and solid waste collected is good, the areas that need improvement include solid waste recycling and energy recovery, nutrients recovery, sewage sludge recycling, WWT energy efficiency, water system leakage, storm water separation, climate adaptation, management action plans, secondary and tertiary WWT and water efficiency measures (**Figure 3**).

Similar to Maputo, cities with high social pressures observed by high urbanisation rates, such as Jakarta and Manila, tend to have also high financial and environmental pressures from water scarcity, pollution, flooding and heat risk (Rahmasary et al., 2019). Cities with high social, environmental and financial pressures were found to have lower IUWM performances (Rahmasary et al., 2019), indicated by a low BCI. The BCI of Maputo (1.8) was found to be comparable to the cities of Belem, Kilamba Kiaxi, Jakarta, Dar-es-Salam, and Quito (Rahmasary et al., 2019), all lacking of basic IUWM services.

The WRpi was assessed in terms of the techno-economic and environmental conditions. From the WRpi assessment it can be concluded that the opportunities for water reclamation for industrial use in Maputo are mainly hampered by the present (on average) low demand - supply gap, the low technological capability, the low sewerage coverage, and the low number of incentives to reclaim wastewater for industrial use. However, Maputo also cyclically experiences prolongated periods of droughts, where temporarily the demand – supply gap seriously increases, e.g. as experienced by the end of 2016. After three consecutive years of rainfall below average and higher evaporation rates in the Umbeluzi River, water levels in the Pequenos Libombos dam, the primary source of drinking water for the city, even dropped below 20 percent. Therefore, a water rationing scheme was implemented under which each neighbourhood was to be supplied every other day (Rusca et al., 2021). Further, although the sewered areas are still small and only one central WWTP exists, 70 % of the population has improved sanitation, which can be a starting point for central sewage collection, requiring additional investment. Although the flow of centrally collected and treated municipal wastewater was calculated to be low compared to the industrial needs in the neighbourhood of the WWTP, in 2024 investments have been done to increase the sewerage coverage and the central WWTP capacity as a result of the implementation of the sanitation and drainage master plan for the Greater Maputo Metropolitan Area (MOPHRH, 2015).

Finally, the tariff of industrial water is relatively high, and the real costs of reclaimed water was calculated to be low, which could encourage the use of reclaimed water for industrial use.

The combined assessment within the TPF, CBF and the WRpiF gives a good overview of the strengths and weaknesses within IUWM of the city of Maputo in general and the potential for water reclamation for industrial use in specific. Although the global overall conclusion maybe that in Maputo city, as an example of a city or metropole in Sub-Saharan Africa, the circumstances are not totally favourable for water reclamation and much have to be done to improve the IUWM situation, some opportunities for the implementation of water reclamation in the industrial setting exist.

3.5. Conclusions

Using a CBF approach we identified the main challenges that Maputo face in IUWM and we introduced and assessed some key factors, specific for the implementation of water reclamation for industrial use in Maputo city, which permitted us to conclude that:

- The main challenges that city of Maputo face in IUWM are the burden diseases, education, and financial deficiencies.
- Maputo lacks basic water services with deficiencies in sanitation, solid waste recycling and energy recovery, nutrients recovery, sewage sludge recycling, wastewater treatment energy efficiency, water system leakage, storm water separation, climate adaptation, management action plans, secondary and tertiary wastewater treatment and water efficiency measures.
- The overall potential for water reclamation Maputo can at the moment (2024) be considered high when considering the costs of water reclamation for industrial use in comparison to the real cost of drinking water supply, the environmental water quality in the city, and the available treated wastewater in the city.
- However, to increase the potential for water reclamation for industrial use, changes in the sanitation infrastructure to increase the sewerage system coverage, a larger gap between drinking water demand and supply, legislation that encourage the use of reclaimed water by the industries (incentives), and higher technological capability are required.

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Chapter 4

Use of Reclaimed Water for Unreinforced Concrete Block Production for the Self-Construction of Houses

This chapter is based on:

Gulamussen, N. J., Arsénio, A. M., Matsinhe, N. P., Manjate, R. S., and Rietveld, L. C. (2021). Use of reclaimed water for unreinforced concrete block production for the self-construction of houses. *Water Reuse*, *11*(4), 690-704. https://doi.org/10.2166/wrd.2021.031.

Use of Reclaimed Water for Unreinforced Concrete Block Production for the Self-Construction of Houses

Abstract

Experiments were conducted to evaluate the possibilities of using treated wastewater for production of un-reinforced concrete blocks. Compressive strength, water absorption and morphology tests of concrete blocks, produced from different make-ups of mixing water; drinking water, drinking water spiked with ammonium and phosphate, and the effluent of the city's wastewater treatment plant, were evaluated. Results showed that the compressive strength of blocks manufactured using treated wastewater was as high as of the blocks produced using drinking water. Ammonium, phosphate and chlorine were found not to have a negative effect on the strength of the blocks. Water absorption tests confirmed the results of the compressive strength, as lower humidity was found in cases of higher strength. In the process of cement hydration, crystals of calcium silicate and calcium hydroxide were observed by morphology tests. From the variability in the results, it could be concluded that the quality of the mixing water was not the only factor that influenced the strength of the un-reinforced concrete blocks. The observed differences in strength could e.g. also be attributed to the manufacturing process.

4.1 Introduction

The use of reclaimed water, whereby treated wastewater is used for non-potable applications, is encouraged in situations where the demand for water is higher than the availability (Otoo *et al.*, 2015). The agricultural sector, as the main water user, accounting for 70% of global consumption, has a great potential, also in the context of Sub-Saharan Africa (Janeiro *et al.*, 2020). However, industries are the second major users of water around the world, accounting for nearly 19% of the total abstracted water flows (Flörke *et al.*, 2013), with the construction industry, with nearly 9% of that volume, being an important sector. In the construction industry, water is largely used for concrete production and curing, and, to a minor extent, for washing concrete mixers and concrete mixing trucks (Asadollahfardi *et al.,* 2016). A volume of 0.7 − 2.2 m^3 of water is needed to produce 1 m^3 of concrete (Mack-Vergara and John, 2017), with drinking water being the common source (Neville, 2011).

In the case of severe water shortages, as in Maputo, Mozambique, alternative, low cost, water sources for concrete manufacturing industries should thus be identified (Ofori, 2007). These industries are often located relatively close to wastewater sources, making it an attractive source because of the reduced transport costs. Moreover, concrete production might allow for the use of a lower quality than drinking water. Finally, in a city served by poor sanitation services for most of its population (Arsénio *et al.,* 2018; Bäuerl *et al.,* 2015; Rietveld *et al.,* 2016), water reclamation can be envisaged as a driving force to improve the city's sanitation services (Gulamussen *et al.,* 2019).

Previous studies around the world have shown the possibility of using non-potable water for concrete production, particularly treated wastewater (Kucche *et al.,* 2015). However, when using water for producing and curing concrete, impurities in mixing water such as ammonium, sulphate, chloride, phosphate (Kerkhoff, 2007) can affect the setting time, strength and the durability of the concrete (Asadollahfardi *et al.,* 2016). In addition, concerns about the safety of the workers can exist, resulting from exposure to pathogenic micro-organisms, when using reclaimed water (Silva and Naik, 2010). Various authors have evaluated the use of non-potable water in concrete manufacturing, with different, and sometimes contradicting, conclusions. For example, studies by Nikhil (2014) and Obi Lawrence (2016), using different water sources to produce concrete samples, have indicated that the 28-days compressive strength of concrete samples produced with drinking water was significantly higher than that produced using wastewater, runoff water and salty water. However, Al-Ghusain and Terro (2003), Silva and Naik (2010), Asadollahfardi et al. (2016), and Shrilatha et al. (2017) did not find differences in compressive strength between concrete produced with drinking and treated wastewater. Tay and Yip (1987) found that the use of treated industrial wastewater, by means of coagulation- flocculation, sedimentation, filtration, aeration, and chlorination, even improved concrete properties, in particular the compressive strength of the concrete. The presented studies, so far, did not include un-reinforced concrete blocks for self-construction of houses, which is an important industry in developing countries (Ofori, 2007).

Since ammonium and phosphate are abundantly present in wastewater treatment plant (WWTP) effluents and are known compounds that could potentially affect concrete production, and the probable need for water disinfection, in this work, the influence of ammonium, phosphate and chlorine on the quality of locally produced (un-reinforced) concrete blocks for house construction was investigated in the context of the Sub-Saharan country Mozambique, with the support of a local construction company.

The quality of the blocks was assessed by their strength and water absorption, and, for confirmation of the products formed during the hydration of cement that can confer durability of the blocks, the type of crystals that were formed was analysed by Scanning Electron microscopy (SEM) images.

4.2. Methods

4.2.1. Experimental set-up

The experimental studies covered the sampling of the effluent of the Maputo WWTP for the determination of the physical-chemical parameters of potential make-up water for concrete production, manufacturing of concrete blocks using different make-ups of mixing water (WWTP effluent treated with chlorine, drinking water and drinking water with various concentrations of ammonium, phosphate and chlorine), and evaluation of properties such as strength and durability of produced blocks by measurements of compressive strength, water absorption and imaging for morphology determination.

Water quality tests were performed at the laboratory of Sanitary Engineering of the Eduardo Mondlane University (UEM). Tested blocks were produced at a local construction company, BRICOM. Compressive strength and water absorption percentages were measured at the Laboratory of Engineering of Mozambique, and morphology tests were executed at the Chemistry Department of UEM.

The results from the compressive strength tests were then analyzed statistically by t-tests for comparing two means with the same variance for the results of blocks produced with drinking water and WWTP effluent and by observation of bar graphs plots and SEM images.

4.2.2. Wastewater characterization

Samples of WWTP effluent were collected at the Maputo WWTP on a weekly basis during a period of two months. The pH was measured in the field. Methods used for laboratory tests are resumed in Table 1.

Table 1: Methods for physical-chemical analyses.

Parameter	**Method**	**Reference**
Sugar	Lane-Eynon	(Silva et al., 2003)
Alcalis (Na_2O)	Flame photometer	(Standard Methods for the Examination of Water and Wastewater, 1999)
Chloride	Test kits mercury thiocyanate 4500-Cl^- E APHA	(Standard Methods for the Examination of Water and Wastewater, 1999)
COD	Reflux colorimetry 5220-COD D	(Standard Methods for the Examination of Water and Wastewater, 1999)
Phosphates as P_2O_5	Test kits ascorbic acid 4500-P E APHA	(Standard Methods for the Examination of Water and Wastewater, 1999)
Nitrates	Test kits 3,5-dimetil phenol 4500-NO3- E APHA	(Standard Methods for the Examination of Water and Wastewater, 1999)
pH	pH-meter 3010 WTW	(Standard Methods for the Examination of Water and Wastewater, 1999)
Total solids	Gravimetric	(Standard Methods for the Examination of Water and Wastewater, 1999)
Ammonia –N	Test kits HACH TNT 835	(Standard Methods for the Examination of Water and Wastewater, 1999)
Sulfates	Turbidity meter 4500- SO_4^{2-} E APHA	(Standard Methods for the Examination of Water and Wastewater, 1999)
Color	Visual	(BS EN 1008 2002)
Foam vanishing time	Visual	(BS EN 1008 2002)
Presence of oil and grease	Visual	(BS EN 1008 2002)
Odor	Sensorial	(BS EN 1008 2002)

4.2.3. Conditions for concrete blocks testing

Various batches were prepared using the conditions given in **Table 2**. The used concentrations of phosphate and ammonium were selected based on the concentrations that could be found in the WWTP effluent. The chlorine concentration (as $Ca(ClO)_2$, used to disinfect the effluent from the WWTP was based on EPA's onsite manual (EPA 2002), being 40 mg/L. In addition, to further determine the threshold levels (i.e. minimum concentration of the substances that could be present in water without effect) by plotting the calibration curves for each parameter, the concentrations of the above mentioned parameters were $10 - 40\ mg/L$ for chlorine, $20 - 120\ mg/L$ for ammonium and $30 - 120\ mg/L$ for phosphate, respectively.

Table 2: Conditions for concrete blocks testing.

Batch	Conditions
1	Drinking water (DW)
2	Drinking water + ammonium (80 mg/L) ($DW+NH_4^+$)
3	Drinking water + phosphate (60 mg/L) ($DW+PO_4^{3-}$)
4	Drinking water + ammonium (80 mg/L) and phosphate (60 mg/L) ($DW+NH_4^++PO_4^{3-}$)
5	Drinking water + ammonium (80 mg/L) and phosphate (60 mg/L) + chlorine (40 mg/L) ($DW+NH_4^++PO_4^{3-}+Cl_2$)
6	WWTP effluent (WW)
7	WWTP effluent + chlorine (40 mg/L) ($WW+Cl_2$)
8	Drinking water + chlorine (40 mg/L) ($DW+Cl_2$)

4.2.4. Block manufacturing

In Mozambique M15 blocks (400 mm length, 200 mm height and 150 mm width, see **Figure 1**) are commonly used for self-construction of houses. For the laboratory tests, similar blocks were manufactured, with a proportion of cement: gravel: coarse sand: fine sand of 1:1.14:0.75:0.75, respectively, as normally used for the production of M15 blocks. The mixing was done using the mixer and vibrational press presented in **Figure 2A**. The blocks were then wrapped in plastic to keep the moisture for curing for 2, 7,14 and 28 days (**Figure 2B**).

Most of the parameters, apart from water quality, that also can affect the quality of the blocks, such as accurate weighing of aggregates and water added, dryness of the aggregate, weather conditions (temperature and precipitation) (Orozco *et al.,* 2018), were not controlled on purpose, as we wanted to simulate real conditions of normal blocks' production.

Figure 1: Photo of an M15 block**.**

Figure 2: A: the equipment used to mix and mold the M15 concrete blocks. B: the blocks wrapped in plastic to keep the moisture.

4.2.5. Block testing

The blocks were tested on their compressive strength, water absorption and morphology, according to the experimental design presented in **Table 3**.

Compressive tests were performed using the Mozambican national standard NM 355/2011 (INNOQ, 2011b), which consists of placing the block between compressive plates parallel to the surface. The specifications of the apparatus and the procedure are in accordance with the standard method ASTM C140 – 11a (C140-11aAS 2012). The blocks were then compressed at a rate of 15 kN/min. The maximum load was recorded along with stress-strain data. All tests were performed using a press Kingtest, model Pat2001.

Water absorption of the blocks can give an indication for the durability and permeability of the concrete, with a higher absorption implying lower durability (Zhang and Zong, 2014). It measures the volume of water-accessible pores in the concrete (Raza *et al.*, 2020). In the process of block production, during cement hydration, calcium silicate hydrate ($C - S - H$) gel is formed (Neville, 2011). A more compact $C - S - H$ gel increases strength and lowers permeability and water absorption by virtue of the elimination of continuous capillaries (McCarter *et al.*, 1992). Water absorption is thus also a good surrogate indicator for concrete durability (Misra *et al.*, 2007). Water absorption tests were performed using the Mozambican national standard NM 355/2011 (INNOQ, 2011b), which consists of drying a specimen to a constant weight, weighing it, immersing it in water for 24 hours, and weighing it again. The weighing was performed with a Karen balance with maximum capacity of 60 kg and a precision of 0.014 kg, as indicated by the manufacturer. The results were presented as a percentage of water absorption by the blocks.

Finally, pore structure and morphology also affects concrete durability (McCarter *et al.*, 1992). Three types of morphology can result from mixing cement with water and the amounts and characteristics of the principal solid phases in the hydrated cement paste, which were measured with SEM (Jeol, Model JSM-IT100), are as follows (Mehta and Monteiro, 2006):

- Calcium silicate hydrate ($C - S - H$) or tobermorite;
- Calcium hydroxide or portlandite;
- Calcium sulfoaluminates hydrates or ettringite.

Table 3: Experimental design of the experiments in Mozambique. W - water absorption. C - Compression resistance. M – Morphology.

	Drinking water			**Spiked drinking water (ammonium and/or phosphate)**			**Effluent of WWTP**			**Effluent WWTP with chlorine**		
After 3 days	C			C			C			C		
After 7 days	C			C			C			C		
After 14 days	C			C			C			C		
After 28 days	W	C	M	W	C	M	W	C	M	W	C	M

4.2.6. Methods of data analysis

The results were presented considering a confidence limit of 95% taking the following into account:

- Three replicates for the laboratory tests for compressive strength;
- Three samples at each of the two discharge points of the WWTP;
- Twelve replicates for compressive strength testing during field experiments where blocks were produced with drinking water and effluent of WWTP;
- Six replicates for compressive strength testing of field experiments with blocks produced with drinking water spiked with ammonium, phosphate and WWTP effluent with chlorine;
- Three replicates for water absorption during field experiments for each mixture.

For comparison of the results of the compressive tests of the blocks, produced with drinking water and WWTP effluent at 28-day curing time, first the variances of the two groups of results were compared, using the *Fisher test* where the calculated F_{cal}, according to **Equation 1**, was compared with the critical tabulated value of F_{crit} for $n_1 - 1$ and $n_2 - 1$ degrees of freedom and level of significance of 95% to choose the appropriate *t-test*. Afterwards a *t-test* for comparison of two means with equal variance was used according to **Equation 2** to calculate the t_{cal} which is compared with the tabulated t_{crit} for $n_1 + n_2 - 2$ degrees of freedom, for two tailed test and 95% of level of significance (Miller and Miller, 2010).

$$F_{cal} = {s_2^2}/{s_1^2}. \qquad [1]$$

$$t_{cal} = {\bar{x}_1 - \bar{x}_2}\Big/{s\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}}. \qquad [2]$$

Where $\bar{x}_1$ and $\bar{x}_2$ are the mean results of compressive strength for drinking and WWTP effluent, s_1 and s_2 are standard deviations of compressive strength for drinking and WWTP effluent, n_1 and n_2 are the number of replicates of compressive strength for drinking and treated wastewater, and s is calculated from **Equation 3**.

$$s^2 = {(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}\Big/{(n_1 + n_2 - 2)}. \qquad [3]$$

The tested null hypothesis was: if the calculated value of $t > critical\ t$ with $n1 + n2 - 2$ degrees of freedom, 95% of significance level and $2 - tailed$, there is a significant difference between the means of the two groups of results.

The Coefficient of Variation (CV) of compressive strength were calculated using **Equation 4** to estimate the variability of the results.

$$CV\ (\%) = {s}/{\bar{x}} \times 100\%, \qquad [4]$$

where s is the standard deviation and $\bar{x}$ is the mean result.

4.3. Results and Discussion

4.3.1. Quality of wastewater treatment effluent of Maputo

Table 4 depicts the quality parameters of WWTP effluent of Maputo, Mozambique. This effluent, according to the standards (BS EN 1008 2002) and (‘ASTM 1602/C1602M :Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete’ 2012), was found to comply with concrete production standards for most of the important quality parameters, except for oil and grease and foam vanishing time. Compared to secondary treated wastewater used by Arooj *et al*. (2020) for concrete production and obtained from a WWTP, Maputo's WWTP effluent showed higher concentrations of sulfate and total solids and lower concentrations of chloride and COD, but all values were within the maximum permissible limits (**Table 4**). Swami et al. (2015) found higher concentrations of total solids, pH, sulfates and alkalinity, and a lower concentration of chloride compared to this study, using extended aeration for treatment of domestic wastewater, and alkalinity was above maximum permissible limits (**Table 4**).

Table 4: Quality of WWTP effluent and limits for concrete production according to norm BS EN 1008 (2002) and ASTM C1602/C1602M (2012).

Parameter	**Measured value**	**BS EN 1008 (2002)**	**ASTM C1602/C1602M (2012)**
Sugar (mg/L)	< 50	100	No Limit
Alcalis (Na_2O) (mg/L)	253,62 ± 20,93	1500	600
Chloride (mg/L)	281,03 ± 83,40	1000	500
COD (mg/L)	217,04 ± 92,66	500	No Limit
Phosphates as P_2O_5 (mg/L)	62,74 ± 6,42	100	No Limit
Nitrates (mg/L)	0,79 ±0,44	500	No Limit
pH	7,08 ± 0.08	≥4	6.5-8.5
Total solids (mg/L)	873,90 ± 29,40	2000	50000
Ammonia-N (mg/L)	58,58 ± 3,92	No Limit	No Limit
Sulfates (mg/L)	21,48 ± 15,47	2000	3000
Color	Gray	Colorless or pale yellow	No Limit
Foam vanishing time	After 6 min	After 2 min	No Limit
Presence of oil and grease	Oil and grease visible	Not apparent	No Limit
Odor	Characteristic of oil	Odorless or similar to potable water	No Limit

4.3.2. Compressive strength of M15 blocks

The compressive strength tests of the blocks, using different make-up waters, are depicted in **Figure 3**.

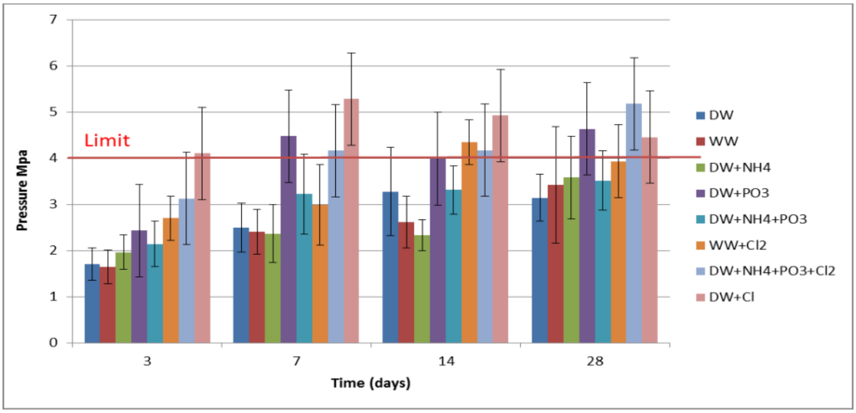

Figure 3: Compressive strength of blocks produced with drinking water, spiked drinking water and treated wastewater, with the indication of the strength limit (4 MPa) according to norm NM 354 2011(INNOQ 2011a).

Overall, the strength of the concrete increased as a function of curing time, which is in accordance with literature (Piplewar *et al.*, 2014; Uddin *et al.*, 2012), except for the conditions where chlorine was used in the absence of phosphate and ammonium. There, a higher compressive strength was observed at 7th and 14th days curing time and decreased at 28 days. Chlorine is added as $Ca(ClO)_2$ which reacts with water to form $HClO$ and $CaCl_2$. The chloride ions can be bound chemically in compounds like Friedel's salt (calcium chloroaluminate hydrate) or adsorbed physically at the surface of cement hydration product (Pargar *et al.*, 2017). $CaCl_2$ has been known to accelerate both the setting and hardening of Portland cement concrete, the effect of strength decreases with time and the final strength can be reduced due to the formation of chloroaluminate hydrates, which is responsible for the concrete softening. However, it can also partially inhibit the cracking caused by drying and sorption induced microcracking in the concrete system (Kishar *et al.*, 2013).

Blocks produced with drinking water with phosphate and drinking water with chlorine showed a large increase in strength from the 3rd to the 7th day. Blocks produced with drinking water with chlorine had already the required strength for use in self- construction on the 3rd day of curing. The rapid increase in strength can be explained by the capacity of chloride and phosphate ions which have quick setting capability to be adsorbed in calcium silicate hydrates ($C-S-H$), forming hydroxyapatite and calcium chloroaluminate, respectively, which are highly insoluble (Naus *et al*., 2008).

Comparing blocks produced with drinking water with the other make-up waters at 28 days of curing time, it was found that the addition of ammonium, phosphate, to the same concentrations found in WWTP effluent, and chlorine at a concentration of 40 mg/L, even increased the strength of the blocks. The strength of the blocks produced with drinking water with additional phosphate and ammonium was at the same level as that of the blocks produced with WWTP effluent. The highest strength was obtained when drinking water was used with a combination of ammonium, phosphate and chlorine.

According to the Mozambican norm NM354:2011, M15 blocks must have a resistance above 4 MPa at 28 days of curing time in order to be classified as "Category B with a structural function" for use in masonry elements above ground level for buildings of at most two floors. Only the blocks produced with drinking water with phosphate, drinking water with chlorine, WWTP effluent with chlorine and drinking water with a mixture of ammonium, phosphate and chlorine can, on average, be considered of the Category B. However, when comparing blocks produced with drinking water with blocks produced with WWTP effluent, the t-test (using **Equation 2**, was 0.11 and the critical t was 2.09) did not show a significant difference. These results are in accordance with the results of Arooj *et al*.(2020), Manjunatha and Dhanraj (2017), Asadollahfardi *et al*. (2016) and M.Ghrair and Al-Machaqbeh (2016), who found that treated wastewater using various treatment methods is suitable for concrete production.

Although the parameter oil and grease and foam vanishing time did not comply with concrete production standards, no adverse effect were detected during the experiment.

High variations in compressive strength (see the error bars in **Figure 3** and CV of more than 50% of the results higher than 20%, see **Table 5**) were observed, which indicates that another important factor when manufacturing concrete blocks was probably the manufacturing process rather than the quality of the used water as found by Orozco *et al*. (2018) in their study.

Table 5: Coefficient of variation (%) of compressive test results.

CV %								
Curing time	**DW**	**WW**	**DW+NH_4**	**DW+PO_3**	**DW+NH_4+PO_3**	**WW+Cl_2**	**DW+NH_4 +PO_3+Cl_2**	**DW+Cl_2**
3	21	22	19	15	23	18	28	5
7	21	20	27	15	27	29	23	20
14	29	21	14	28	16	11	25	6
28	16	37	25	25	18	20	13	22

After increasing the concentrations of ammonium, phosphate and chlorine in the make-up water, see Figures 4 **- 6**, the curing time of the blocks showed different trends. The blocks produced with drinking water and ammonium did not reach the required compressive strength, while the blocks produced with drinking water with phosphate and chlorine achieved the required compressive strength at 7th and 14th days, respectively. This is in accordance with the results of Kucche *et al*. (2015) who found that impurities (organic and inorganic compounds) in water react differently affecting the setting time and the compressive strength, also depending on their concentration. The lower strength of blocks produced with drinking water containing ammonium ($pK_a = 9.24$) (Vogel, A. I., and Mendham 2000) can be explained by the fact that at the considered concentrations the water is acidic with pH varying from 5.7 to 6.0. Since, during the process of concrete hardening, silicates and lime ($Ca(OH)_2$ crystals are formed, water of a pH lower than 6.5 can attack concrete by dissolving and removing part of the hydrated cement paste and leaving a soft and weak mass. Because the acidity increases with increasing ammonium concentration, the decline of the strength was observed from concentrations of 80 mg/L to 120 mg/L.

The compressive strength values at 28 days indicate that the highest strength of the blocks was obtained at concentrations of 80, 30 and 30 mg/L, for ammonium, phosphate and chlorine, respectively.

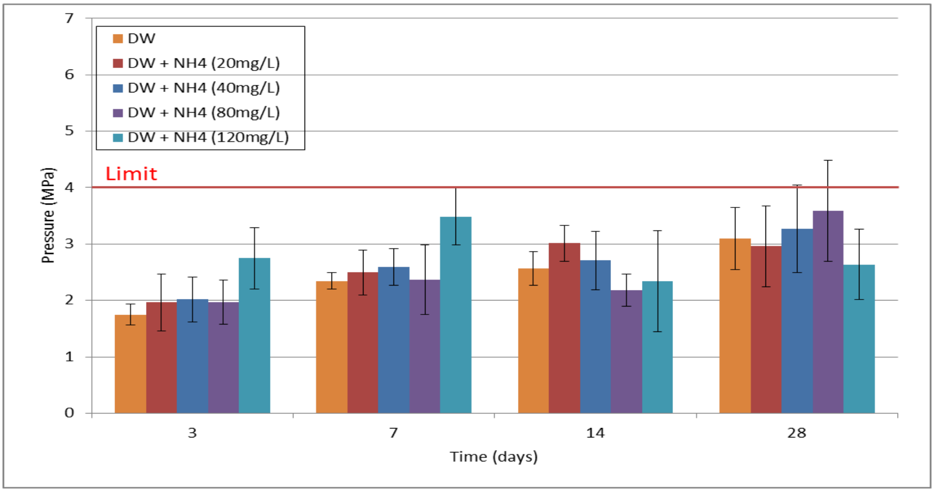

Figure 4: Compressive strength of blocks produced with increasing concentration of ammonium, with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

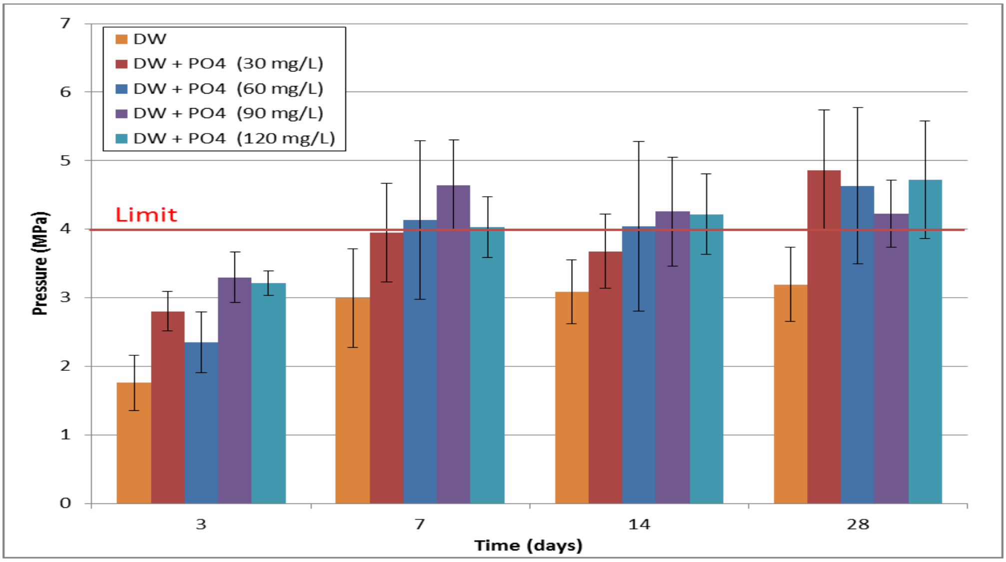

Figure 5: Compressive strength of blocks produced with increasing concentrations of phosphate with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

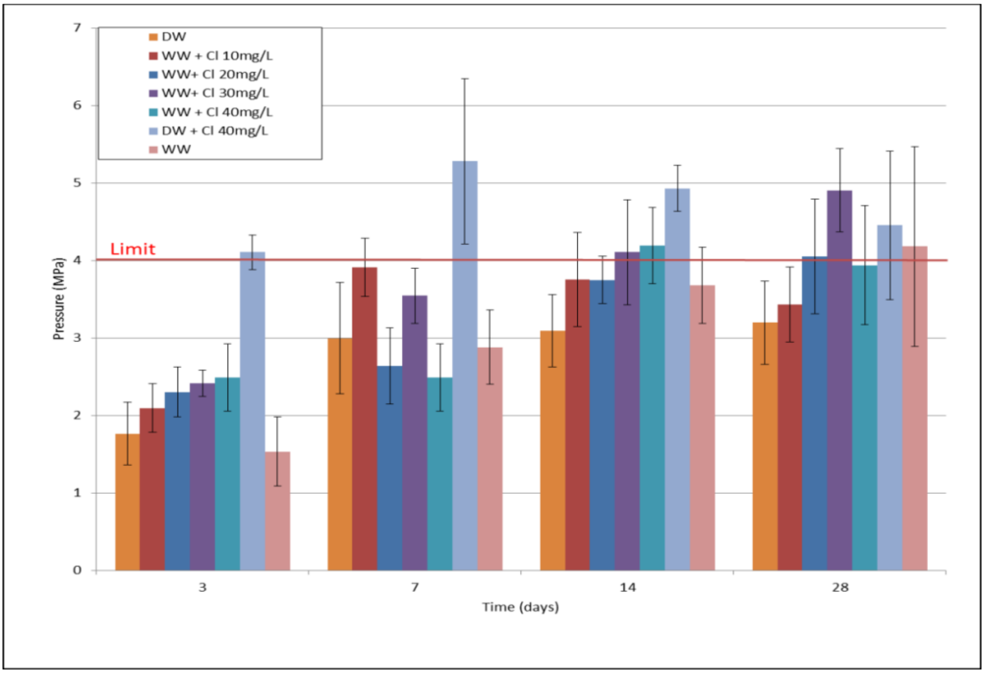

Figure 6: Compressive strength of chlorine at different concentrations with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

4.3.3. Water absorption tests of M15 blocks

Water absorption is a durability parameter of concrete. High water absorption causes corrosion of reinforcement and allows harmful chemicals to penetrate into the concrete and possibly react with the ingredients of the cement, thus changing the properties of the concrete (Raza *et al.*, 2020).

According to the Mozambican norm NM354:2011 non-reinforced blocks can be considered of category B when the percentage of water absorption is less than 10%, which was confirmed for all samples, as can be seen in **Figure 7** and **8**. The results confirm that the conditions that gave the highest durability (and thus the lowest water absorption) were drinking water with phosphate and drinking water with a mixture of ammonium, phosphate and chlorine. Considering the inverse relation between strength and humidity (Mehta and Monteiro, 2006), it was found that the concrete blocks made of drinking water with ammonium and phosphate (with lowest humidity at concentrations of 80 mg/L and 60 mg/L, respectively) were the most durable. Water containing ammonium is acidic which can attack concrete but the attack depends on the ability of hydrogen ions to be diffused trough the cement gel ($C-S-H$), after which $Ca(OH)_2$ have been leached out (Lea, 1965; Neville, 1987). Additionally, ammonium chloride salts present in the mixing water, interacts with $Ca(OH)_2$, which is included in the pores and forms $CaCl_2$ and volatile NH_3. Quick removal of NH_3 will adversely affect the concrete (Yilmaz *et al.*, 2002). $Ca(OH)_2$ appears in relatively large crystals and they will leave larger voids after being leached, resulting in a greater impact on the compressive strength and durability. The diffusivity of ammonia reduces along the process (Tyra *et al.*, 2001) and counteracts the voids, created by the leaching of lime, creating the opportunity to rearrange the microstructure of the hardened paste, reduce the pores in the structure and, therefore, reduce the possibility of water absorption. The low humidity of the produced blocks with drinking water and phosphate probably results from the formation of a dense coating of hydroxyapatite, as a result of the reaction of $C-S-H$ and phosphate, which reduces the water penetration.

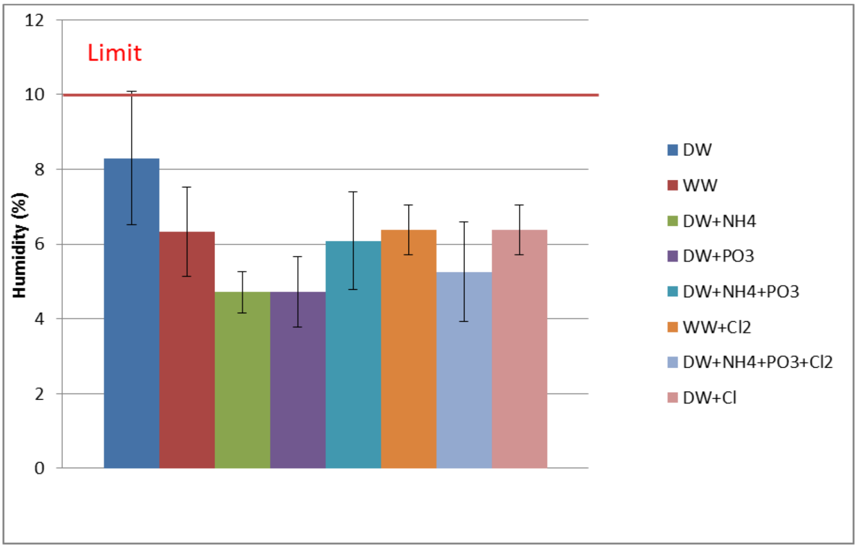

Figure 7: Water absorption of blocks produced with drinking water, spiked drinking water and WWTP effluent, with the indication of the Limit according to norm NM 354 2011 (INNOQ 2011a).

With increasing concentrations of the targeted compounds, different trends in water absorption were observed (**Figure 8**), while for ammonium the humidity decreased with increasing concentration, phosphate and chlorine did not show any trend. In solids, there exists a fundamental inverse relationship between porosity and strength, but sometimes this is not observed because of the presence of microcracks in the interfacial transition zone between the coarse aggregate and concrete matrix (Mehta and Monteiro, 2006). This porous zone, where cracks often originate, prevents efficient load transfer between the coarse aggregate and the cement mortar (Neville, 1987). This can be the reason why differences in behaviour are observed when analysing various compounds.

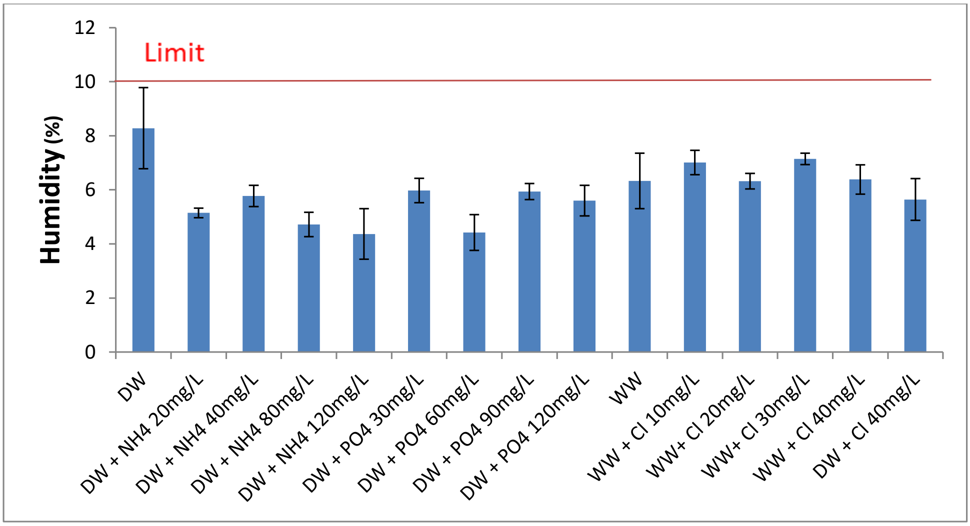

Figure 8: Water absorption of blocks made with increasing concentration of ammonium, phosphate and chlorine with the indication of the Limit according to norm NM 354 2011 (INNOQ 2011a).

Blocks characterization with SEM

The types of the formed minerals and their relative percentages, influence the quality of the produced concrete blocks and thus could confirm the strength and durability of the concrete. Depending on the added water mixtures to produce concrete blocks, different and complex microstructures are formed.

In concrete blocks produced with drinking water spherical crystals of $C-S-H$ (tobermorite) were observed, rounded by blue circle, and long needless crystals of ettringite, in red circles (**Figure 9**). As result of the interaction between calcium, sulfate, aluminate and hydroxyl ions, present on cement, and aggregates that get saturated in water forming small fibrous crystals, tobermorite that makes 50 to 60% of the volume of solids in a completely hydrated Portland cement paste and is the most important phase determining the properties of the paste, while ettringite occupies 15 to 20% of the solid volume in the hydrated paste and, therefore, plays only a minor role in the microstructure-property relationships. During the early stages of hydration the sulfate/alumina ionic ratio of the solution phase favors the formation of trisulfate hydrate, which forms these needle-shaped prismatic crystals of ettringite (Mehta and Monteiro, 2006).

In the blocks made with WWTP effluent (**Figure 10**) crystals of apatite (phosphate mineral), portlandite (calcium hydroxide mineral), in yellow circle, and tobermorite (red circle) were observed. Portlandite constitutes 20 to 25% of the volume of solids in the hydrated paste. It tends to form large crystals with a distinctive hexagonal-prism morphology like the ones presented in yellow circle.

In blocks made with WWTP effluent with chlorine mainly ettringite crystals were observed (red circle, **Figure 11**). The WWTP effluent have a mean chloride concentration of 281 mg/L (**Table 4**), which is increased by addition of $Ca(ClO)_2$. Friedel's salt is the main reaction product of chemical binding of chloride ions in concrete. It is formed due to the reaction between the chloride ions and hydration products. It is assumed that all aluminate hydrates transform to Friedel's salt with increasing chloride concentration in the pore solution (Birnin-Yauri and Glasser, 1998). In general, the tendency of sulfate ions to bind in hydration products is higher than that of chloride and hydroxide. However, the concentration of sulfate ions in the pore solution of mature (28 days) cement paste is low compared to chloride. Therefore, chloride ions can react with the aluminate compounds to form Friedel's salt. Even the sulfate-containing hydration products convert to Friedel's salt if the chloride concentration in the pore solution is sufficiently high (Pargar *et al.,* 2017) The formation of ettringite in the fresh, concrete is the mechanism that controls stiffening and improve strength development, and also reduce drying shrinkage. This can be the reason why an increase in the strength of the concrete is observed when chlorine is used.

Blocks made with phosphate looked more compact and thus were more durable (**Figure 7**). This can be explained by the presence of crystals of tobermorite (blue circle) and apatite (red circle) in **Figure 12**. These calcium salts are highly insoluble and therefore readily form a dense coating in the vicinity of hydrating cement particles creating a compact structure of hydroxyapatite (Naus *et al.,* 2008). It is expected that hydroxyapatite is formed as product of the reaction of phosphate ion and $C-S-H$ and this is the expected morphology.

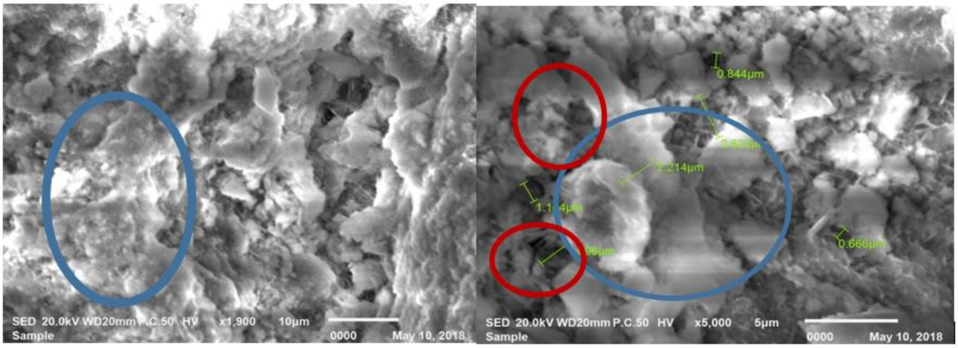

Figure 9: SEM images of blocks produced with drinking water (DW).

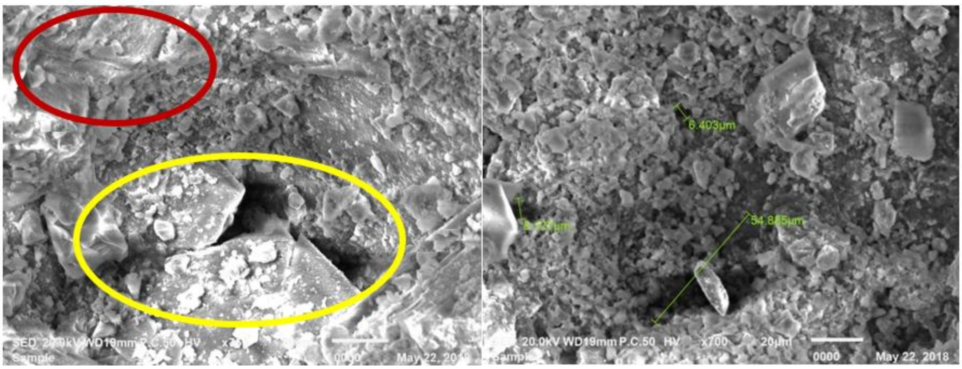

Figure 10: SEM images of blocks produced with wastewater (WW).

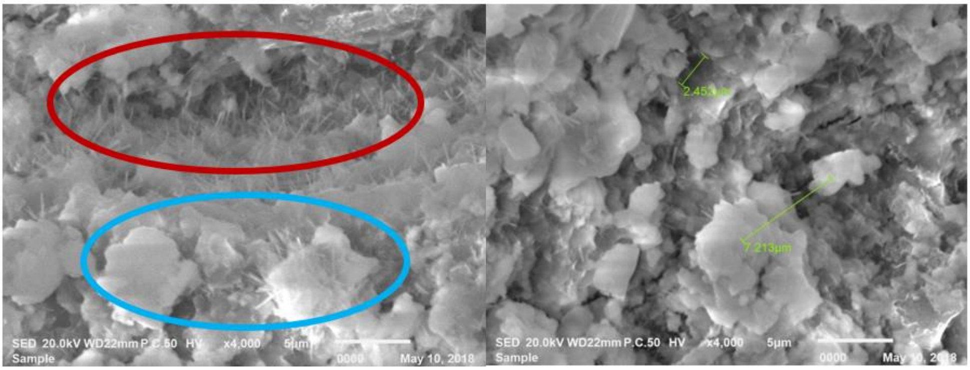

Figure 11: SEM images of blocks produced with chlorinated wastewater ($WW+Cl_2$).

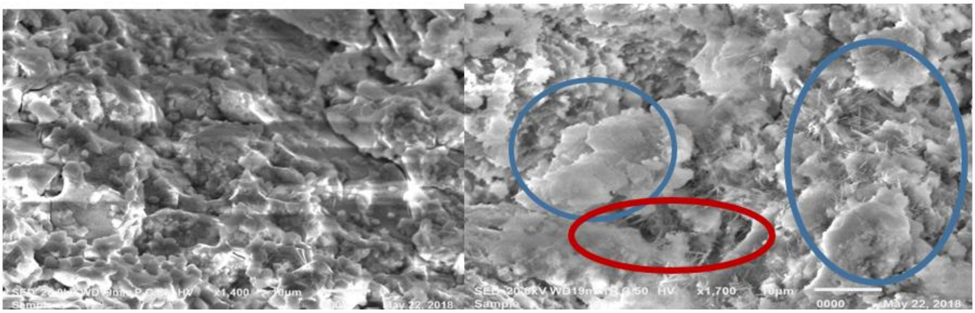

Figure 12: SEM images of blocks made with phosphate added to drinking water ($DW+PO_4$).

4.4. Conclusions

Field experiments were conducted to evaluate the possibility of using WWTP effluent for concrete production in low-cost applications, in particular of M15 blocks that are commonly used during self-construction of houses in Mozambique.

The water quality experiments showed that the parameters foam vanishing time, oil and grease and oily characteristic odour did not comply with the limits for concrete production, but they did not affect the strength and durability of produced blocks. These parameters are therefore not expected to limit the use of reclaimed water for blocks production.

From the experiments it was concluded that the strength and durability of M15 blocks produced with WWTP effluent did not show a significant difference with blocks produced with drinking water. The quality of reclaimed water for concrete mixing was thus sufficient for adequate strength development, and related water absorption and crystal formation. In addition, considering other makeup water, where drinking water was spiked with phosphate, ammonium and chlorine, the impurities had a slightly positive effect on concrete blocks manufacturing. However, it could also be concluded that the results were highly variable, indicating that the quality of the mixing water was not the only factor that influenced the strength of the M15 blocks, but could also be attributed to the manufacturing process.

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Chapter 5

Softening with Ceramic Micro-Filtration for Application on Water Reclamation for Industrial Recirculating Cooling Systems

This chapter is based on:

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Softening with Ceramic Micro-Filtration for Application on Water Reclamation for Industrial Recirculating Cooling Systems

Abstract

There is global need for optimizing the use of water that results from the increasing demand due to industrial development, population growth, climate change and pollution of natural water resources. One of the solutions is to use reclaimed water in industrial applications that does not require water of potable quality, such as cooling water. However, for cooling water, (treated) wastewater has a too high hardness, apart from a high load of suspended solids and organic matter. Therefore, a combination of softening with ceramic micro-filtration was proposed for treating wastewater treatment effluent, containing fouling agents, for potential use in industrial cooling systems. The effectiveness of the softening process of model treated wastewater with calcium hydroxide in the presence of phosphate and sodium alginate was first evaluated using jar tests. Furthermore, membrane fouling was studied when filtering the softened water. The results showed that inhibition of calcium carbonate precipitation occurs when inorganic substances, such as phosphate, and organic compounds were present in the water. The fouling of the membranes, due to sodium alginate in water was only slightly negatively affected when combined with softening and phosphate. This combination of treatment could therefore be potentially useful for post-treatment of secondary effluent for use in cooling systems.

5.1. Introduction

Water shortage in arid and semi-arid areas are drivers for the use of reclaimed water in industry (Gulamussen et al., 2019), because the high costs of advanced treatment processes for contaminant removal can be justified by the high value of reclaimed water compared with the use of the scarce natural water sources (UNEP, 2015).

A number of power plants in the US have already used secondary-treated municipal wastewater treatment plant (WWTP) effluent as makeup water in their recirculating cooling water (Difilippo, 2008; Ehrhardt et al., 1986). However, since WWTP effluent usually contains considerable concentrations of hardness, phosphate, ammonia, dissolved solids, and organic matter, compared to the concentrations in e.g. fresh surface water, extensive treatment is needed (Li et al., 2011).

A cooling system relies on water as a heat transfer medium and is the most water demanding process in industry (EUROSTAT, 2014). Water is utilized for the cooling of pumps and compressors of vacuum systems, and steam turbine condensers. Cooling systems can have different configurations but are mainly divided into once-through and recirculating systems (Veil, 2007). Once-through cooling systems transfer process heat to water to cool the process equipment and then discharge the hot water after a single use. This system requires a large volume of water, and usually lake, river, and sea water is used with little or no treatment (Lens et al., 2002). Recirculating cooling systems transfer the heat from warmed water to vapor so that the water can be reused to absorb process heat and recirculated for additional cycles (Joint Research Council, 2001; San Jose Environmental Service Department, 2002). However, as evaporation occurs, the concentration of mineral salts increases, and, when the concentration of mineral salts exceeds their solubility, scale formation on heat exchange surfaces may occur. The level of dissolved solids (mineral salts) is controlled by discharging part of the recirculating water, called blowdown water, from the system and replenishing this volume with fresh make up water. Previous studies have shown that the major mineral scales, formed in recirculating cooling systems using WWTP effluent as make-up water, are calcium carbonate and, to a lesser extent, calcium phosphate (Li et al., 2011). To avoid scale formation, hardness in the make-up water should be lower than 1.25 $mmol/L$ (Mech Co., 1994), and, therefore, when using WWTP effluent as cooling water make-up water, additional treatment, such as filtration, chemical precipitation, ion exchange, or reverse osmosis, may be necessary (Asano and Jiménez, 1998).

Ceramic micro-filtration (CMF) is a potential treatment alternative for water reclamation (Kramer et al., 2015). Ceramic membranes, compared to the mostly used polymeric membranes, are robust, have a high mechanical strength (Manohar, 2012), a high chemical and thermal resistance (Hu et al., 2018), high membrane porosity, membrane permeability and a homogeneous distribution of narrow pores (Pérez-Gálvez et al., 2011). Ceramic membranes can also be used at a higher flux compared to polymeric microfiltration membranes and therefore reduce the membrane surface area that is needed for the same quantity of wastewater (Mouratib et al, 2020). Ceramic membranes are also expected not to be damaged by high pressure, high temperatures or chemicals, enabling e.g. vigorous chemical cleaning of the membrane (Pérez-Gálvez et al., 2011). Other benefits are the long life of the membrane and the recyclability of the membrane material (Lee et al., 2015; Manohar, 2012). The disadvantage of ceramic membranes is their relatively high costs compared to polymeric membranes, which thus should be compensated by the mentioned advantages (Aryanti et al., 2020).

MF are low pressure-driven separation processes that are less energy-intensive than traditional treatment methods (Lee et al., 2015). They can be used to remove microorganisms and suspended or colloidal particles. However, they do not remove dissolved substances (Ha, 2013). Nevertheless, previous studies have shown that softening can be promoted, by precipitation of calcium ions (Ca^{2+}), in a membrane system (Heinsbroek, 2016; Pokrovsky, 1998). By dosing a base, calcium carbonate particles are formed, and these inorganic particles can be removed from the water by the membrane filtration. The findings showed that in a system containing Ca^{2+} and bicarbonate better softening was achieved in the absence of phosphate (${PO_4}^{3-}$), due to the inhibitive effect of ${PO_4}^{3-}$on calcium carbonate crystal growth. On the other hand, it is known that calcium promotes complexation of organic matter, influencing the rate of flux decline in membranes (Katsoufidou et al., 2007).

Therefore, in this work, attention was given to the development of a novel application of CMF treatment, focusing on hardness removal of model WWTP effluent, containing, fouling agents, agents such us Ca^{2+}, Mg^{2+}, ${HCO_3}^-$, organic matter, among, normally present in WWTP effluent. The effectiveness of calcium hydroxide ($Ca(OH)_2$) as softening agent was studied during softening with CMF membranes in the presence of ${PO_4}^{3-}$. In addition, the effect of organic compounds on the softening process was analyzed using model water with sodium alginate (SA).

5.2. Materials and Methods

5.2.1. Experimental set-up

To study the precipitation of calcium carbonate followed by CMF, in the presence of potential interfering inorganic and organic substances, two configurations were used:

1. Jar tests to rapidly evaluate the effectiveness of the softening agent in the presence of ${PO_4}^{3-}$ and SA. Solutions containing Ca^{2+}, ${HCO_3}^{-}$, ${PO_4}^{3-}$ and SA were prepared in demineralised water.
2. Membrane tests, to study the performance of the membrane when filtering precipitated calcium carbonate in combination with ${PO_4}^{3-}$ and SA, all prepared with demineralised water.

$Ca(OH)_2$ in suspension, a common base employed in the softening process (Ratnayaka et al., 2009), was used in this work.

The concentrations of Ca^{2+} ($1.5 - 3\ mmol/L$), ${PO_4}^{3-}$ ($0.1\ mmol/L$), used during the experiments, represent the values found in WWTP effluent (Dudziak and Kudlek, 2019; Kramer, 2019; Lei et al., 2019). The concentration of SA that was previously used to simulate organic substances' concentration in non-treated domestic wastewater is about $0.8\ g/L$ (Kramer, 2019; Charfy, 2021; Arndt et al., 2016). However, to avoid too rapid clogging, here, half of the concentration ($0.4\ g/L$) was used during the experiments.

A chemical cleaning with citric acid (1.5 %) and chlorine (0.1 %) was performed after the first set of membrane experiments and then after each membrane experiment (according to protocols presented in the sections below), and all experiments were executed in duplicate.

5.2.2. Jar tests

To study the differences between the conditions, with and without ${PO_4}^{3-}$ and SA, precipitation tests were performed in jars. **Table 1** presents the tested conditions. For each condition, samples were collected and filtered over a 0.45 μm pore filter (Whatman, Germany) for determination of the remaining Ca^{2+} concentration using ion chromatography (IC, ProfIC 15–AnCat ion chromatograph Metrohm 881 anion). An A Supp 150/4.0 anion column was used with 3.2 $mmol/L$ Na_2CO_3 and 1 $mmol/L$ $NaHCO_3$ eluent. To calibrate the IC, 6 standard solutions of Ca^{2+} (0.0025, 0.025, 0.25, 1.25, 2.5 and 3.75 $mmol/L$) were used. Due to the inhibitive nature of ${PO_4}^{3-}$, its effect was further analyzed considering different dosings of $Ca(OH)_2$ (1.5 and 2.5 $mmol/L$).

Table 1: Jar tests softening conditions.

Experiments	Ca^{2+} $(mmol/L)$	${HCO_3}^-$ $(mmol/L)$	$Ca(OH)_2$ $(mmol/L)$	${PO_4}^{3-}$ $(mmol/L)$	**Sodium Alginate** (g/L)
A1	3	6	1.5	0	0
A2	3	6	2.5	0	0
A3	3	6	0	0	0.4
A4	3	6	0	0.1	0.4
A5	3	6	1.5	0.1	0
A6	3	6	2.5	0.1	0
A7	3	6	1.5	0	0.4
A8	3	6	2.5	0	0.4
A9	3	6	1.5	0.1	0.4
A10	3	6	2.5	0.1	0.4

5.2.3. Membrane tests

Effect of softening agent on fouling

The setup depicted in **Figure 1** was used for in-line base and in tank dosing's from a neutralization tank to the membrane system. The first two experiments consisted of:

- B1 Filtration of the solution containing only a mixture of 3 $mmol/L$ of Ca^{2+} and 6 $mmol/L$ of $HCO_3{}^-$ to draw the base line and confirm that there is no retention of Ca^{2+} on the membrane;
- B2 Filtration of the solution containing a mixture of 3 $mmol/L$ of Ca^{2+} and 6 $mmol/L$ of $HCO_3{}^-$ with constant dosage of $Ca(OH)_2$ (2.5$mmol/L$) to remove the hardness.

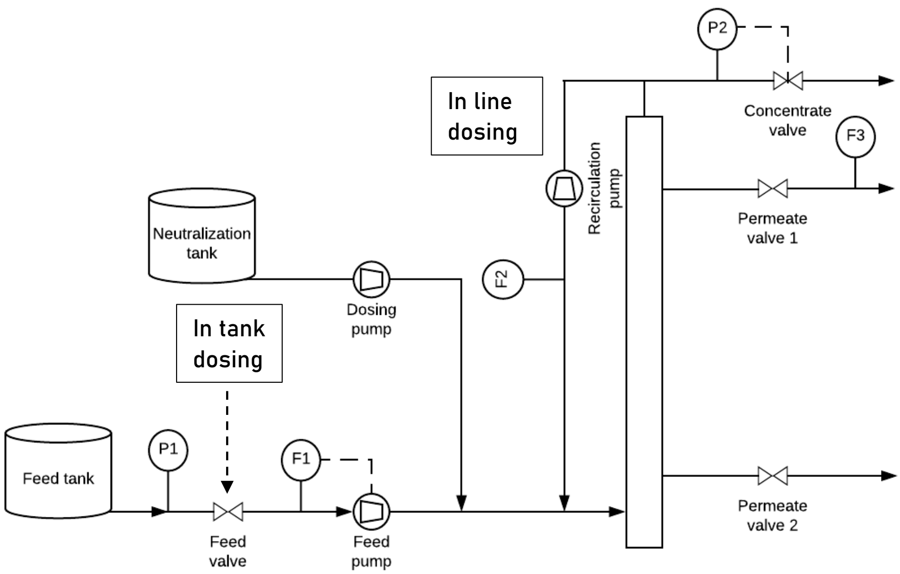

Figure 1: Schematic representation of the Ceramic Micro Filtration (CMF) setup. F1: feed flow meter (0-300 L/h ± 1 L/h). F2: recycle flow meter (0-1000 L/h). F3: permeate flow meter (0-30 L/h). P1: pressure meter (0-20 ± 0.1 bar). P2: pressure meter (0-20 ± 0.1bar).

The feed flow was $25 - 30\ L/h$ at a constant (transmembrane) pressure of 2 bar and the dosing pump constantly added 3 L/h of $Ca(OH)_2$ with a concentration of 22.73 $mmol/L$

$Ca(OH)_2$, which resulted in a concentration of 2.5 $mmol/L$ $Ca(OH)_2$ in the feed flow. The recovery fluctuated around $75 - 80\%$. The specification of the used membranes is presented in **Table 2**.

Table 2: Ceramic Micro Filtration (CMF) membrane specification (Inopor GmbH).

Material	**Al_2O_3**
Surface area	0.11 m^2
Diameter of membrane	25.4 mm
Diameter of tubes	7 mm
Number of tubes	4
Length	1200 mm
Direction of flow	Crossflow
Nominal permeability at 1 bar	25 $L/h/m^2$
Pore size	0.1 μm

For each experiment, samples of the feed water, permeate and concentrate flow were taken in duplicate at three moments during the tests, after 15 min, 1 h and at the end of the experiment, respectively. The samples were analyzed for the concentration of Ca^{2+} using IC. No flux decline was observed during the two experiments.

After the first set of experiments, the configuration was changed from in-line dosing to in-tank precipitation, where the base was added in the influent tank for the rest of the experiments.

Individual effect of sodium alginate, calcium and softening on membrane fouling

The following set of experiments consisted of evaluating the fouling of CMF in the presence of SA, $Ca^{2+}$and $HCO_3{}^{-}$ with and without the addition of $Ca(OH)_2$ using membranes in the same condition, leading to a similar initial flux. The tested conditions are presented in **Table 3**.

Table 3: Effect of sodium alginate and calcium and softening on fouling.

Experiments	Ca^{2+} (mmol/L)	$HCO_3{}^{-}$ (mmol/L)	$Ca(OH)_2$ (mmol/L)	$PO_4{}^{3-}$ (mmol/L)	Sodium Alginate (g/L)
C1	3	6	0	0	0.4
C2	3	6	1.5	0	0.4

For the experiments, the cleaning followed the same procedure as described in the previous section, however, substituting the citric acid by a solution of sodium hypochlorite 0.1% to better remove the organic fouling (Kramer, 2019).

Combined effect of sodium alginate, phosphate and softening on fouling

The last set of experiments consisted of evaluating the fouling of CMF in the presence of Ca^{2+}, $HCO_3{}^{-}$, $PO_4{}^{3-}$and SA, with the addition of $Ca(OH)_2$, compared to a solution consisting of SA only, using membranes in the same condition leading to a similar initial flux. The tested conditions are presented in. **Table 4**.

Table 4: Effect of organic compounds on softening.

Experiments	**Ca^{2+} (mmol/L)**	**HCO_3^- (mmol/L)**	**$Ca(OH)_2$ (mmol/L)**	**PO_4^{3-} (mmol/L)**	**Sodium Alginate (g/L)**
D1	0	0	0	0	0.4
D2	3	6	1.5	0.1	0.4

For the experiments, the cleaning followed the same procedure as described in the previous section.

Flux recovery

During the membrane experiments in the presence of organic fouling (SA), the initial flux varied, indicating that some irreversible fouling occurred during filtration and/or the cleaning protocol did not function efficiently. The membrane flux recovery is the ratio of pure water flux after a filtration and cleaning process, J_{pwfn}, to the pure water flux of the first filtration, J_{pwf1}, after either hydraulic or chemical washing.

The flux recovery is calculated using Equation **1** below:

$$\boldsymbol{R} = {}^{J_{pwfn}}\!/_{J_{pwf1}} \quad [1]$$

5.3. Results

5.3.1. Jar tests of softening process and influence of PO_4^{3-} and organic compounds

Effect of $Ca(OH)_2$ as softening agent

Figure 2 shows the results of the remaining Ca^{2+} after the precipitation with $Ca(OH)_2$. When the concentration of $Ca(OH)_2$ was low (1.5 $mmol/L$), the removal was relatively high as, with the addition of 1.5 $mmol/L$, it was expected that the concentration of Ca^{2+} would be reduced to half (from 3 to 1.5 $mmol/L$). The fact that $Ca(OH)_2$ is partially soluble ($Kps = 5.5\ x\ 10-6$) (Kellner et al., 2004), and added to the water as a suspension enhanced the nucleation and stimulated the crystallization process and probably the original solution was already somewhat supersaturated with $CaCO_3$ (Spanos and Koutsoukos, 1998). When the concentration of $Ca(OH)_2$ was increased to 2.5 $mmol/L$ the removal increased, but not linearly. Two explanations can be given: 1) At low supersaturation the nucleation mechanism is heterogeneous, whereas at higher supersaturation homogeneous nucleation prevails (Van Driessche et al.,2017). The homogeneous nucleation results in an increasing number of formed nuclei. These nuclei have a relatively lower chance to grow to large crystals compared to the growth of a lower number of formed nuclei during heterogeneous crystallization (El-Shall et al., 2002). Therefore, precipitation is hampered with excessive increasing $Ca(OH)_2$ concentration. 2) A $CaCO_3$ film is developed on the $Ca(OH)_2$ particles and eventually will be, partially or completely, enclosed. This film can inhibit $Ca(OH)_2$ from dissolving any further by a layer of $CaCO_3$ that is formed on the surface of a particle in water, which is called the dissolve-precipitate mechanism (Van Eekeren et al., 1994).

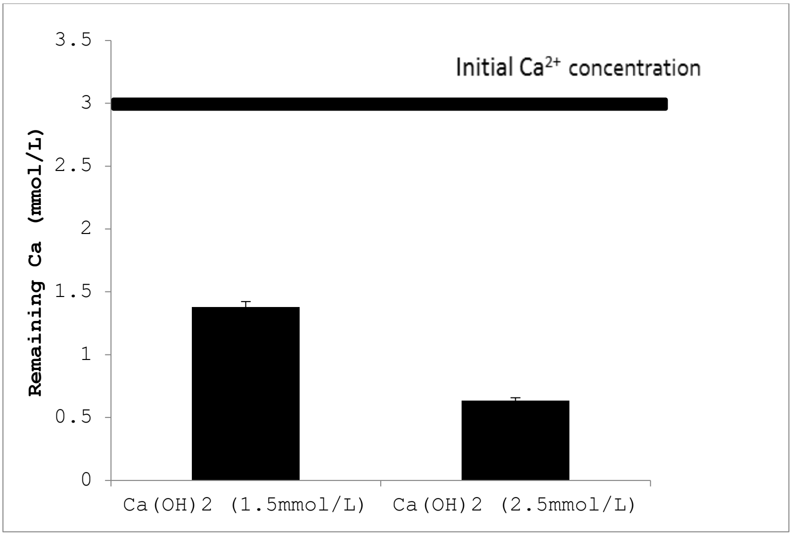

Figure 2: Calcium removal with calcium hydroxide.

Effect of phosphate and sodium alginate on softening

Both $PO_4{}^{3-}$ and SA inhibited precipitation of $CaCO_3$ (**Figure 3**). Inhibition by SA was observed only when the concentration of $Ca(OH)_2$ was increased to 2.5 $mmol/L$ (**Figure 3**). With a lower dosage of $Ca(OH)_2$ (1.5 $mmol/L$) the inhibition was dominated by the presence of

${PO_4}^{3-}$ rather than by SA, when considered separately. This was also found earlier, where, when growth of $CaCO_3$ took place in the presence of ${PO_4}^{3-}$ interfered with the $CaCO_3$ crystal growth process, because of interactions with the lattice ions of $CaCO_3$ at the respective active crystal growth sites (Tadier et al., 2017).

Two processes have been accepted to explain the mechanisms of potential inhibition by organic molecules. First is the formation of chelate complexes of dissolved Ca^{2+} ions with organic molecules, which results in the reduction of effective supersaturation of $CaCO_3$, thereby decreasing the rate of nucleation and crystal growth, depending on the saturation state (Sundarrajan et al., 2012). Second is the adsorption of organic compounds on the specific surface of the $CaCO_3$ crystals. The active growth sites on the $CaCO_3$ surface may be blocked by the adsorption reactions, thus preventing the further growth of the crystals of $CaCO_3$ (Kawano and Tokonami, 2014; Haidari et al., 2019). The negative charge of SA, due to deprotonated carboxylic functional groups, may then induce repulsive inter- and intramolecular electrostatic forces decreasing the chances of $CaCO_3$ precipitation (Katsoufidou et al., 2007).

When phosphate and SA were considered simultaneously, the precipitation of Ca^{2+} was less influenced compared to the condition where ${PO_4}^{3-}$ was considered separately, especially when the concentration of $Ca(OH)_2$ was 1.5 $mmmol/L$. The chelate complexes formed after addition of SA may thus have masked Ca^{2+} and inactivated the interaction between of Ca^{2+} and ${PO_4}^{3-}$ (Sundarrajan et al., 2012).

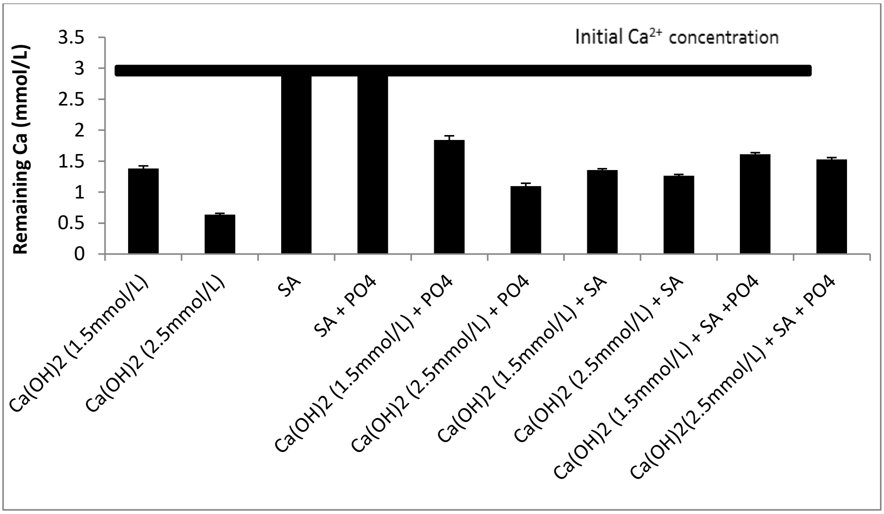

Figure 3: Effect of phosphate and sodium alginate in softening with calcium hydroxide.

Extent of inhibition effect of phosphate

From **Figure 4**, it can be observed that when increasing the concentration of ${PO_4}^{3-}$ from 0.05 to 0.15 $mmol/L$ a small increase in inhibition of $CaCO_3$ precipitation was observed, but it slightly was reduced when 0.2 $mmol/L$ of ${PO_4}^{3-}$ was added. Further, when the concentration of $Ca(OH)_2$ was increased from 1.5 to 2.5 $mmol/L$ the effect of ${PO_4}^{3-}$ was similar. Gebauer at al. (2009) studied the role of additives in $CaCO_3$ precipitation and also found that the addition of 10 mg/L sodium triphosphate (about 0.1 $mmol/L$) solution performed only slightly weaker than an addition of 100 mg/L sodium triphosphate (1 $mmol/L$). Therefore, it suggests that the mechanism of colloidal stability of the intermediate cluster structures is the most relevant in suppressing nucleation in this system, and not the stoichiometric binding events (as expected by an ion-binding-like mechanism).

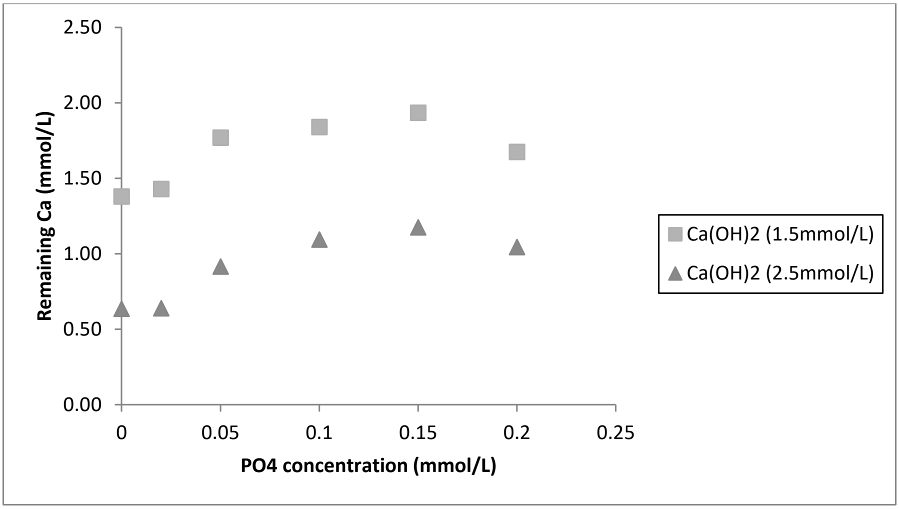

Figure 4: Inhibition effect of PO_4^{3-} on precipitation of $CaCO_3$.

5.3.2. Ceramic membrane tests results

Effect of softening on fouling

During the CMF tests without adding a base, the IC results (**Table 4**) showed a constant Ca^{2+} feed concentration of 1.6 $mmol/L$. The first two samples of the retentate were not taken because too little retentate was produced. The retentate showed values that were approximately 0.1 $mmol/L$ lower than the feed. Since in this experiment the base was not added, no difference in concentration was expected from the collected samples, since the pores of the CMF are too large to retain dissolved salts (i.e. $Ca(HO_3)_2$) without previous precipitation (Serhiienko et al., 2020), which was confirmed by the obtained results.

In the experiment with the addition of $Ca(OH)_2$, the Ca^{2+} concentration in the feed flow was around 1.9 $mmol/L$ (**Table 5**). The chemical dosing in this experiment was 2.5 $mmol/L$ of $Ca(OH)_2$, directly dosed into the feed flow. The Ca^{2+} concentration in the retentate decreased to a value of 0.5 $mmol/L$ and, near the end of the experiment, and even reached a concentration of less than 0.1 $mmol/L$, having precipitated 1.4 to 1.8 $mmol/L$. Since the base was stoichiometrically overdosed, it was to be expected that almost all Ca^{2+} would be removed by precipitation. These results were in accordance with the results of the jar tests, where we found that when increasing the concentration of $Ca(OH)_2$ to $2.5\,mmol/L$ a substantial removal of Ca^{2+} was observed. The results were also in accordance with the results of Zeppenfeld (2010) and Heinsbroek (2016), who found that with increasing the carbonate concentration, promoted by addition of the base, and, thereby increasing supersaturation, the rate constant increased linearly and consequently increased the Ca^{2+} removal.

During the experiment the flux built up rapidly in the first few minutes of the test, but stayed around a constant value (of 190 $L/m^2/h$) for the rest of the experiment, which is represented by the example in **Figure 5**, indicating that scaling of the membrane did not occur during the experiment (Heinsbroek, 2016).

Table 5: Calcium concentrations in the feed, permeate and concentrate samples.

	Ca^{2+} Feed (mmol/L)	**Ca^{2+} Permeate (mmol/L)**			**Ca^{2+} Retentate (mmol/L)**		
Time (hours)	-	0.25	1	6	0.25	1	6
Baseline	1.62	1.54	1.65	1.61	-	1.49	1.47
Added Ca $(OH)_2$ (2.5mM)	1.92	0.48	0.51	0.07	0.44	0.53	0.13

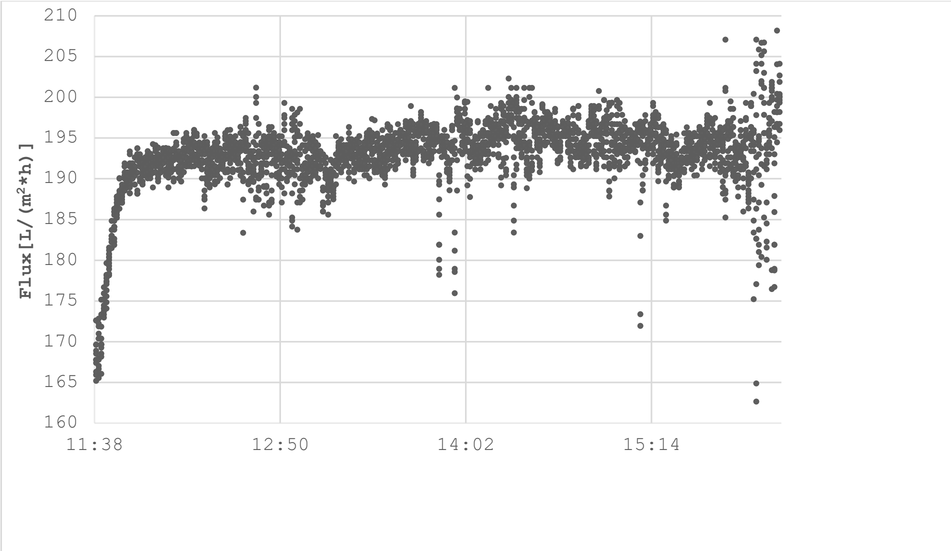

Figure 5. Membrane performance of the softening with calcium hydroxide.

Individual effect of sodium alginate, calcium and softening agent on fouling

When filtering a solution with Ca^{2+}, bicarbonate and 0.4 g/L of SA, the initial retentate flux was 270 $L/m^2/h$, and pronouncedly decreased, and reached a flux of about 50 $L/m^2/h$ in more than 30 min (experiment C1) (**Figure 6**). The accentuated decrease in the retentate flux can be explained by the complexation of Ca^{2+} with alginate, forming a compacted gel layer on the membrane surface. Compression of the electric double layers of the alginate on the membrane results in a lower electrostatic repulsion and a denser fouling layer with a higher absolute resistance (Brink et al., 2009; van de Ven et al., 2008). Not much difference (the flux also reached 50 $L/m^2/h$ in more than 30 min) was observed when 1.5 $mmol/L$ $Ca(OH)_2$ was added to the previous mixture (experiment C2). From the jar tests it was observed that, in the presence of SA, about 50% of Ca^{2+} was removed, and apparently, this removal did not influence the performance of the membrane, e.g. through scaling.

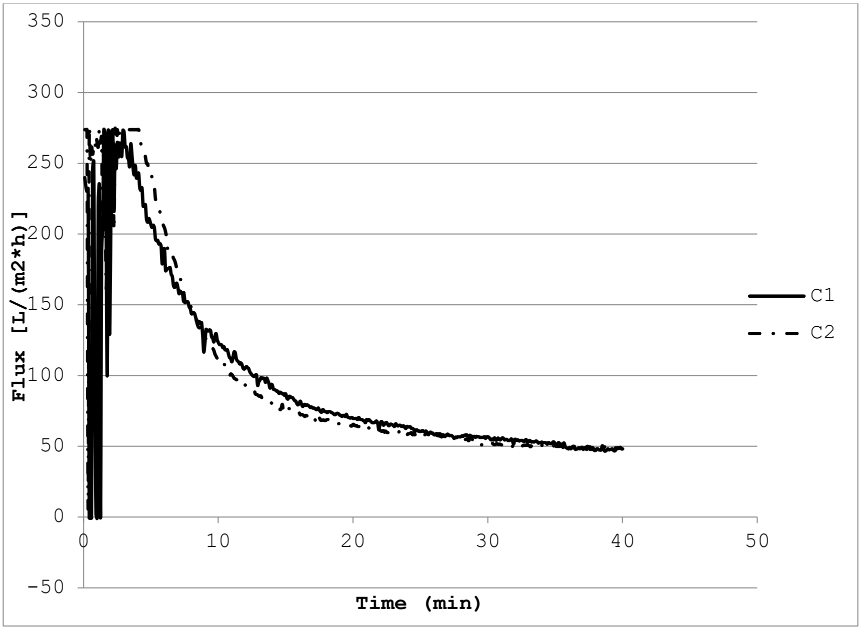

Figure 6. Membrane performance for the effect of sodium alginate, calcium and softening agent on fouling.

Combined effect of sodium alginate, calcium, phosphate and softening agent on fouling

During experiment D1, where a solution containing only $0.4 g/L$ SA was filtered, it took around 10 min to lower the retentate flux from 150 $L/(m^2 \times h)$ to about 80 $L/(m^2 \times h)$ 2/3 (**Figure** 7) and then stayed more or less constant. In all experiments a steep decline in permeability at the beginning of filtration was observed and is was probably caused by the loading effect (Abdelrasoul, 2013), being a direct interaction between the membrane surface and the alginate molecules that could then create a firm fouling layer. This interaction is mostly dominated by adsorption of foulant to the membrane surface which will lead to the pore constriction (Katsoufidou et al., 2007).

A similar behaviour was observed when dosing $Ca(OH)_2$ in the presence of SA, Ca^{2+}, $HCO_3{}^{-}$, $PO_4{}^{3-}$ (D2), although the final flux further decreased to about 60 $L/(m^2 \times h)$. This could be explained by the complexation of Ca^{2+} with alginate, forming a compacted gel layer on the membrane surface and some scaling of $CaCO_3$ on the surface or in the pores (Hashino, et al., 2011). Although flux decline was low compared to the first experiment it is likely the Ca^{2+} removal was negatively affected, as was observed during the jar tests.

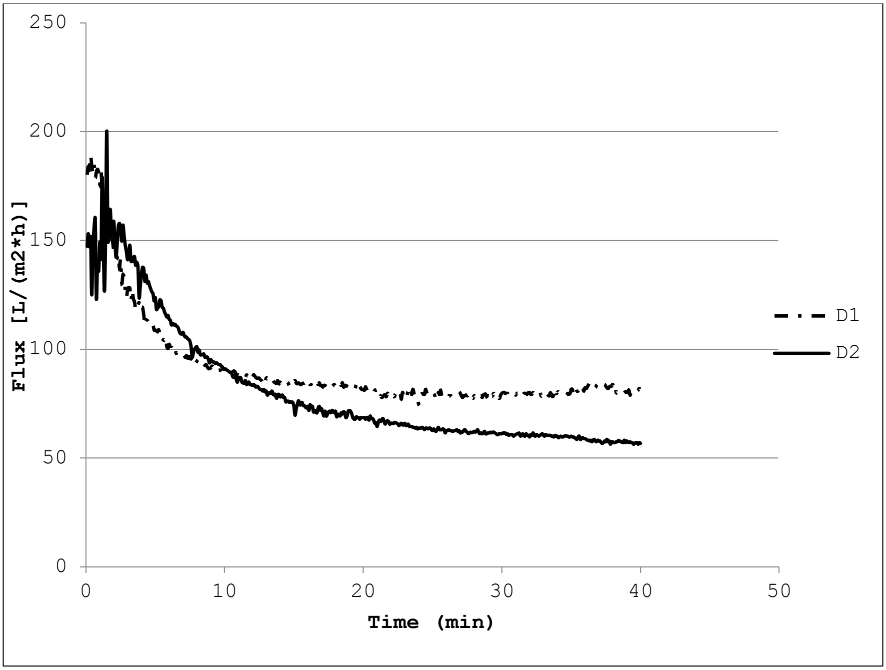

Figure 7: Membrane performance for combined effect of sodium alginate, calcium, phosphate and softening agent on fouling.

Flux recovery results

From **Figure 6** and **Figure 7** it can be observed that the initial flux declined from 270 to 200 $L/m^2/h$, being a flux recovery of 74 %. These results are in accordance with the first set of experiments (**Figure 5**) with recoveries between 75 and 80%. Katsoufidou et al. (2008) also analyzed fouling of membranes with SA and found that the fouling was due to two mechanisms; (1) a rapid irreversible fouling due to internal pore constriction, followed by (2) cake development on the membrane surface, which becomes the dominant fouling mechanism when calcium concentration increases. This may explain the fact that we observed a low flux recovery in the last experiments.

5.4. Conclusion

A novel method of treatment of model WWTP effluent with ceramic micro-filtration (CMF) for the use in cooling systems was developed, with the focus on scale formation by removing hardness, in the presence of other fouling agents as organic matter. The effectiveness of $Ca(OH)_2$ as softening agent was studied using jar tests and the effect of organic compounds on the softening process was analysed using model water with SA. During CMF tests the effect on fouling (through flux decline) was studied.

It was found that ${PO_4}^{3-}$ inhibited the precipitation of $CaCO_3$, when using $Ca(OH)_2$ as softening agent. In conditions where ${PO_4}^{3-}$ was present, the concentration of $Ca(OH)_2$ should be increased to compensate for the precipitation of ${PO_4}^{3-}$ and the inhibition of the calcite crystallisation process. Organic compounds also affected the removal of Ca^{2+} on the softening process, although in the presence of ${PO_4}^{3-}$ the alginate inhibition of the crystallisation process was reduced.

Finally, it was concluded that fouling of the membranes due to sodium alginate in water was only slightly negatively affected by ${PO_4}^{3-}$ and when combined with softening.

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Chapter 6

Conclusions and Outlook of the Potential of Industrial Water Reclamation in Maputo

Conclusions and Outlook of the Potential of Industrial Water Reclamation in Maputo

6.1. Conclusions

6.1.1. Overall conclusion on water reclamation for industrial use in SSA

In this thesis the potential of water reclamation for industries in the context of sub-Saharan Africa (SSA) was studied and Maputo city was used as a case study. First the conditions for implementation of water reclamation in an industrial setting in the region were analysed in a literature review, considering existent projects and examples from around the world. Then a framework for identification of the gaps, priorities and opportunities for implementation of water reclamation industries was developed and tested for the case of Maputo. Finally, two industrial applications were studied:

- ✓ The use of treated wastewater for the production of unreinforced concrete blocks for house construction;
- ✓ The development of a novel method of treatment of (model) WWTP effluent with ceramic micro filtration for application in water reclamation for industrial recirculating cooling systems with the focus on avoiding scale formation by removing hardness, in the presence of other fouling agents as organic matter, nutrients and suspended solids.

From the literature review, with the limited available information, it can be concluded, that in SSA the use of water reclamation is low. However, the water scarcity in SSA, the increasing water demand, and the existence of industries that can use water reclamation forms a potential for the use of reclaimed water in SSA in general and for Maputo, Mozambique, in specific. Gaps in the planning of water and sanitation infrastructure, incentives from the government for the use of reclaimed water, technological capability and financial resources were identified as the main barriers for implementation. In the case study of Maputo city two main options were identified that have a relatively high potential for using reclaimed water, since they need a relatively low water quality, they are located in the vicinity of the wastewater treatment plant (WWTP) and they now use large amounts of piped drinking water. These industries are construction firms, and a thermal power plant. The effluent from the WWTP of Maputo, with relatively low quality, can almost directly be utilized for blocks' production in the construction industry, only requiring an additional disinfection step. In addition, the WWTP effluent could be further treated, e.g. using ceramic microfiltration combined with a softening process, to be used for cooling purposes. Specific conclusions of the various chapters of the thesis are highlighted in the following.

6.1.2. State of water reclamation for industrial use in SSA

In chapter 2 a review is presented on the implementation of water reclamation in SSA. It has been concluded that, in this region, few examples exist referring to the use of reclaimed water in industry. The following possible reasons have been identified: the under-developed sewer infrastructure, the low concern related to the benefits of the use of reclaimed water, and pricing and legislation that do not create incentives for implementation of water reclamation in industries. Therefore, research on technologies and governance is required to determine the enabling conditions and thus facilitate the implementation.

6.1.3. Identifying gaps, opportunity and priorities for water reclamation in cities

Trends and Pressures, the City Blueprint of Maputo and financial, technical and environmental factors, translated into indicators, were used to assess the potential for water reclamation with as a case study Maputo city. It has been concluded that Maputo lacks basic water services that, amongst others, include deficiencies in sanitation systems, water system leakage, storm water separation, climate adaptation, water management action plans, secondary and tertiary wastewater treatment and water efficiency measures. However, the industrial water demand related to the available reclaimed water, and the water pricing, measured by the reclaimed water to drinking water costs ratio, could favour the implementation of water reclamation, although factors that include technological capability, incentives and sewerage coverage require considerable improvements.

6.1.4. The use of reclaimed water for production of unreinforced concrete blocks

WWTP effluent of Maputo was used to produce so-called M15 concrete blocks, commonly used for (self-) construction of houses in Maputo. Although from the water quality assessment it was concluded that some parameters did not comply with the limits for concrete production, they did not affect the strength and durability of the produced blocks, compared to the blocks produced with drinking water. The quality of reclaimed water for concrete mixing was thus sufficient for adequate strength development, and related water absorption and crystal formation. Parallel to the real conditions' experiments, the influence of other impurities such as phosphate, nitrate and chlorine was evaluated using spiked drinking water with known concentrations of these impurities. The impurities had a slightly positive effect on concrete blocks manufacturing. However, due to the high variability of the results, this was not conclusive. The high variability may indicate that the quality of the mixing water was not the only factor that influenced the strength of the M15 blocks and could also be attributed to the manufacturing process of the blocks.

6.1.5. Softening with ceramic membrane for use in recirculating cooling systems

The effectiveness of dosing calcium hydroxide ($Ca(OH)_2$) as softening agent to ceramic microfiltration membranes, in the presence of phosphate and of organic compounds, using model water with sodium alginate, was studied. It was found that hardness removal could be achieved, although phosphate and organic compounds inhibited the crystallization process of calcium carbonate and thus the removal of hardness, also, negatively affecting the membrane due to fouling.

6.2. Outlook

From the presented studies, it can be concluded that the feasibility of water reclamation from WWTP effluent for industrial use, in the context of SSA, could be achieved when solving existent challenges, such us the low institutional capacity and even the acceptance around reclaimed water that extends beyond just engineering and economics. In addition, barriers in governance, limits in infrastructure, financial resources, and technical skills for operation and maintenance must be overcome.

However, a main bottleneck is the lack of experience (both in governance and technology) on the topic of water reclamation for industrial use, making implementation risk-full. Therefore, to address the challenges that affect and impact the many stakeholders involved in the implementation of water reclamation in industry, participatory and collaborative practices of the co-creation concept should be further explored together with pilot studies, governance capacity evaluation and other related projects.

6.2.1. Co-creation program for implementation of water reclamation in industries in Maputo

Water reclamation as essential part of the integrated water resources management requires the use of enabling engagement with expertise from across disciplinary fields, e.g. engineers, social scientists and technologists, and organizational silos, such as governmental agencies in the water sector, investors and legal institutions.

The co-creation process should be built on the following principles of competence, sustainability, support for the outcome, validating ideas, and information exchange and transparency (Medema et al., 2017). In addition, effective co-creation requires an organizational structure with defined roles of each intervenient. Therefore, it is important to evaluate the third parties which in this case can be the industries with potential for using water reclamation, private sector interested in providing the treated wastewater and the entities responsible for the management of wastewater in the city, once considering engaging innovation/proposed program.

For the case of Maputo, therefore, a mapping of all stakeholders has been conducted, focussing on the use of reclaimed water from the Infulene WWTP for the main industrial applications identified in this thesis, being for the production of unreinforced concrete blocks and as make up water for the cooling systems of the thermal power plant.

First, all necessary parties have been listed; second, they have been characterized according to their importance in the project (essential and interested, essential and not interested, not essential but interested and only beneficiaries); third, strategies have been formulated for moving the essential and not interested to the group of the interested. From this stakeholder analysis, third parties have been identified with vested interest in water reclamation for industrial use.

6.2.2. Governance aspects

In 2018 an action plan for implementation of Sustainable Development Goals in water and sanitation sector was published (BR, 2018). The fragility of the sanitation institutional framework was recognised by the fact that responsibilities in the sanitation sector is fragmented and distributed within governmental entities, both centrally and at local level, which makes it difficult to have a proper coordination and coherent interventions. Therefore, in this action plan, the strengthening of the institutional framework was proposed by stablishing a single, central and intersectoral coordination, with strong methodologically oriented capabilities.

The sanitation and hygiene sector in Mozambique has then set up an intersectoral cooperation team that works in information sharing and harmonization of investment in sanitation programmes. In parallel the Mozambican Water and Sanitation Group was established, a forum for consultation, technical discussions, and recommendations in support of the country's Governmental efforts to achieve the country's water and sanitation goals expressed in the Five-Year Plan and the Sustainable Development Goals.

These binding organizations can, in the end, optimize resources and capacities available in their collaborative networks through, e.g., the development of boundary-crossing leaders and competences, as well as the use of information and communication for the implementation of water reclamation.

However, legal aspect can become restrictive. E.g. Westrate, et. al. (2019) found that for the sanitation sector the regulatory standards in Maputo were incomplete and the existing standards for sanitation were not enforced. The deficiencies in sanitation standards may affect the implementation of water reclamation as the quality of wastewater discharged is most important component in water reclamation projects, which suggests the need for developing technical norms and protocols.

6.2.3. Projects in progress

To translate the results of the tests executed in the research, as presented in chapter 5, from laboratory testing with model water to the real case in pilot scale, the softening process combined with ceramic microfiltration will be tested, using secondarily treated wastewater to the quality required for cooling systems. The research is being carried out at a pilot wastewater treatment installation as part of the partnership between the Mozambican university UEM and TU Delft, the Netherlands. The pilot research will be implemented with support of funds from the World Bank, through the MozSkills program and with support of Global Water Funds (TU Delft).

This system consists of pre-treatment with softening, coagulation and flocculation, pre-filtration using a metal filter and final treatment using a ceramic microfiltration membranes system. Depending on the optimization processes established for each stage, the system can produce an effluent with the desired quality. This combination of treatment steps allows for a compact system to be used for optimization studies to obtain treated water with different qualities and requirements for the intended applications.

Additional to the demonstration purpose, this pilot unit will also allow undergraduate and master's students from UEM, TU Delft or other partner institutions to carry out research to generate knowledge about wastewater treatment focused on water reclamation considering local implementation conditions so that they can be translated into practical water reclamation projects in industries. Benefits include:

- The identification and/or proposal of tools based on scientific evidence that contribute to increasing the availability of water for the population and reducing waste through the use of treated wastewater in non-consumptive activities such as industry;
- Reducing competition for drinking water between domestic uses and non-consumptive industrial and public uses;
- Treatment of wastewater for water reclamation prevents pollutants in wastewater from being dumped into natural water courses, causing pollution, thus improving environmental sanitation.

6.2.4. Perspectives on water reclamation for industrial use in Maputo

The Infulene WWTP was designed in 1984 and came into operation in 1987. The WWTP is located in the Infulene area and is fed by the main sewerage system, intercepting part of the water that was previously discharged into Maputo Bay. The Infulene treatment system has limited capacity as it was originally designed to serve 90,000 inhabitants with a maximum design flow of 2,000 m^3/h (555 L/s), but currently it is not operating at its full capacity, as two lifting stations are not in operation.

Recently (2025) the WWTP was rehabilitated and extended to a duplicate of the capacity. With this development, potentially, more treated wastewater becomes available for reclamation in industry (and agriculture) in Maputo.

A well-planned intervention for implementation of water reclamation for industrial use in Maputo, should include the opportunity of optimizing the use of water in different industries and institutions existent in Maputo. Some examples are given below.

The Beluluane industrial park

The Beluluane industrial park is located in the Matola-Rio, Boane District, Maputo Province and has an area of around 780 ha, including an aluminium smelting industry (180 ha), the largest industrial employer in Mozambique, and the industrial park itself (600 ha). As the water scarcity is evident in Maputo, any water savings can contribute to mitigate its impact, and in this complex there are opportunities for synergies in the optimization of the use of water.

Car wash and Small industrial recycling

In Maputo, there are many small enterprises that perform car washing, including from the public transport and railways as well small industries, such as soap and oil production and leather tanning. These small industries can optimize their use in water by e.g. recycling within their processes. For example, the car wash companies could treat their water for recycling (Zaneti et al., 2013) or could make use of de-centrally collected and treated municipal wastewater.

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Annex

Annex A

Distribution of construction industry in Maputo

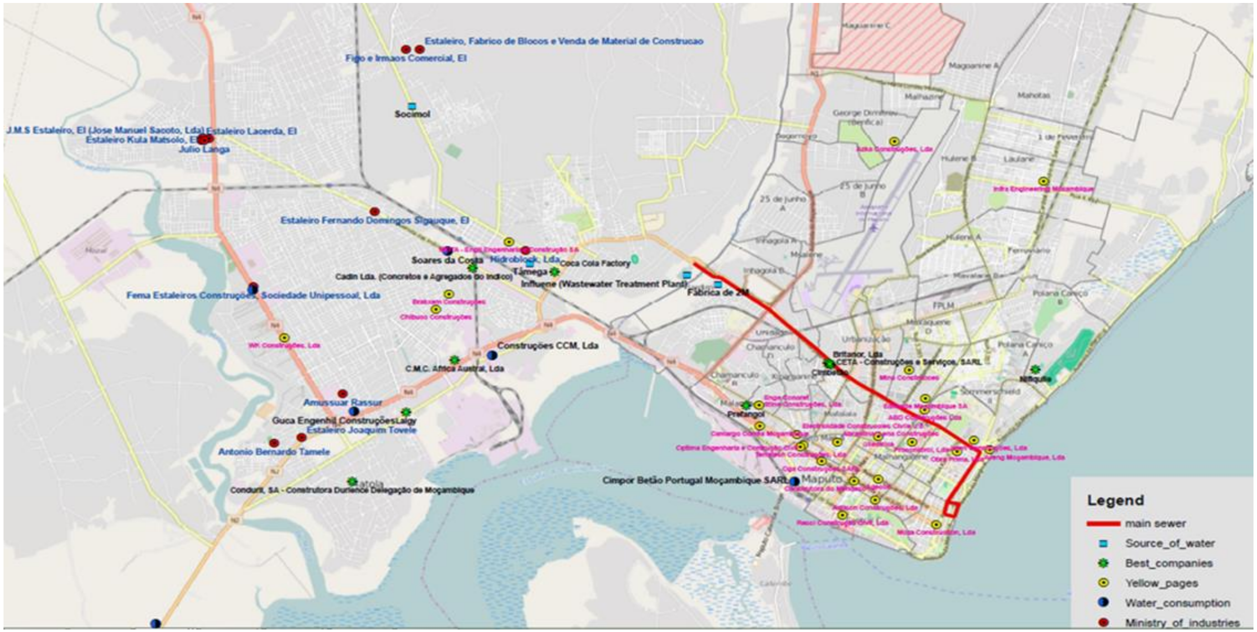

Figure 1: Distribution of construction industry in Maputo.

Annex B

Measures that act as incentive for water reclamation

1. Enforced restriction on the use of freshwater for specific applications which may limit the use of water in some industrial applications.
2. Direct subsidies, generally in the form of tax credits, grants or low-interest loans for the installation of water reclamation technologies and other capital expenditures related.
3. Reductions in payments to governments in the form of tax deductions, rate reductions, or reduced lease payments for investments in water reclamation technologies.
4. Payments or other credits for the reintroduction of recovered water into the raw water source— programs under which the water supply or wastewater treatment government compensates water users who recover and reinject treated water into its original source.
5. Pricing that imposes higher charges for the use of potable water for industrial use.
6. Competitive financing for private industrial projects.
7. Regulatory relief by eliminating certain requirements for users of reclaimed water.
8. Government procurement of water reclamation equipment, requirements that government buildings and operations maximize their reclaimed water, and structuring of water rights to reduce use of potable water.

Annex C

The fraction of total demand was calculated using the following equations:

$$f_{Cov} = {}^{Avail}/_{Dem}, \qquad [1]$$

where $Avail$ is total water available for abstraction (m^3/year) is given by **Equation 2** and Dem the total water demand is calculated using **Equation 3**.

$$Avail = Avail_{GW} + Avail_{SW}, \qquad [2]$$

where $Avail$ is the total water available for abstraction (m^3/year), $Avail_{GW}$ and $Avail_{SW}$ are respectively the groundwater (GW) and surface water (SW) available for abstraction (m^3/year).

$$Dem = Dem_{dom} + Dem_{ind}, \qquad [3]$$

where Dem is the total water demand $(m^3/year)$, Dem_{dom} is the domestic water demand $(m^3/year)$ and Dem_{ind} is the industrial water demand $(m^3/year)$.

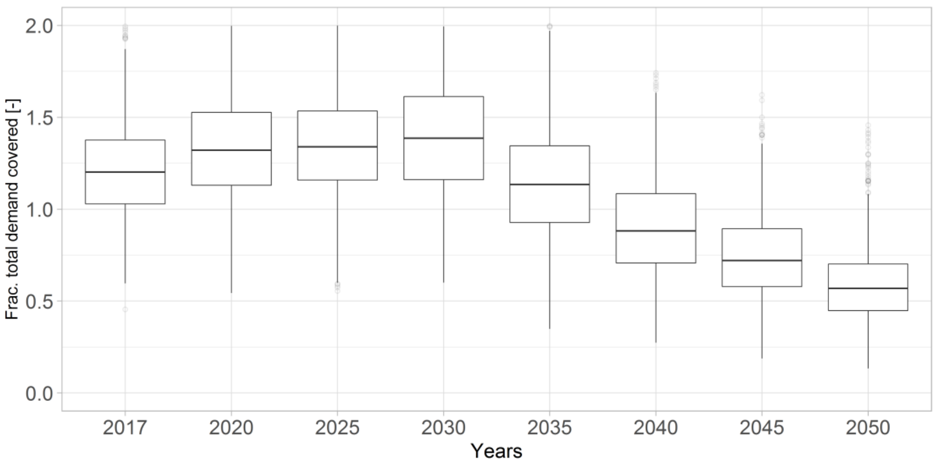

Figure 2: Fraction of total demand that can be covered using the available sources in Maputo.

Annex D

Table 1: City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
I Water quality	1. Secondary WWT	$Indicator\ 1 = \frac{x}{10}$ X: Percentage of population connected to secondary sewage treatment X = 10% $\therefore Indicator\ 1 = 1$	• Rietveld et al. Environmental Health 2016, 15(Suppl 1):31 • Masterplan Maputo
	2. Tertiary WWT	$Indicator\ 2 = \frac{x}{10}$ X: Percentage of population connected to tertiary sewage treatment X = 0% $\therefore Indicator\ 2 = 0$	• There is no tertiary WWT in Maputo
	3. Groundwater quality	$Indicator\ 3 = \frac{x}{x+y} * 10$ X = Number of samples of 'good chemical status' Y = Number of samples of 'poor chemical status' X = 25 Y = 4 $\therefore Indicator\ 3 = 8.62$	• 2015 data from point measurement. There is a monitoring of groundwater in Maputo. The data used for calculation was collected by a student that is doing PhD. This information is not yet published. Since there are several parameters considered, Electrical conductivity was used to define which samples are in good chemical status and considered only 2015 data.

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
	4. Solid waste collected	$Indicator\ 4 = \left[1 - \frac{x - 136.4}{689.2 - 136.4}\right] * 10$ X: Kg/cap/year of collected solid waste X = 191.7 kg/cap/year $\therefore Indicator\ 4 = 9$	• Challenges and opportunities in municipal solid waste management in Mozambique: a review in the light of nexus thinking. AIMS Environmental Science, 4(5): 621-639
II Solid Waste treatment	5. Solid waste recycled	$Indicator\ 5 = \frac{\%recycled\ or\ composted}{100 - \%used\ for\ incineration\ with\ energy\ rec} * 10$ % recycled waste = 1% % used for incineration with energy recovery = 0% $\therefore Indicator\ 5 = 0.12$	• Challenges and opportunities in municipal solid waste management in Mozambique: a review in the light of nexus thinking. AIMS Environmental Science, 4(5): 621-639
	6. Solid waste energy recovered	$Indicator\ 6 = \frac{\%incinerated\ with\ energy\ recovery}{100 - \%recycled/composted} * 10$ %incinerated with energy recovery = 0%; %recycled/composted = 1% $\therefore Indicator\ 6 = 0$	

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
III Basic water services	7. Access to drinking water	$Indicator\ 7 = \frac{x}{10}$ X: Percentage of total urban population with access to potable drinking water X = 82.8 $\therefore Indicator\ 7 = 8.28$	• African Green city index
	8. Access to sanitation	$Indicator\ 8 = \frac{x}{10}$ X: Percentage of total urban population with access to proper sanitation facilities. X = 48.8 $\therefore Indicator\ 8 = 4.88$	• African Green city index)
	9. Drinking water quality	$Indicator\ 9 = \frac{x}{y} * 10$ X: Total number of samples meeting standards; Y: Total number of samples X/Y = 0.756 $\therefore Indicator\ 9 = 7.56$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
IV Wastewater treatment	10. Nutrient recovery		
	11. Energy recovery		
	12. Sewage sludge recycling		
	13. WWT energy efficiency		
V Infrastructure	14. Stormwater separation	$Indicator\ 14 = \frac{B+C}{A+B+C} * 10$ A: Total length of combined sewers (km); B: Total length of stormwater sewers (km); C: Total length of sanitary sewers (km) A =200 km; B = 0km; C 0km $\therefore Indicator\ 14 = 0$	• Masterplan Maputo
	15. Average age sewer	$Indicator\ 15 = \frac{60-x}{60-10} * 10$ X: Average age sewer X = 40 $\therefore Indicator\ 15 = 4$	• Masterplan Maputo
	16. Water system leakages	$Indicator\ 16 = \frac{50-x}{50-0} * 10$ X: Water system leakages (%) X = 44% $\therefore Indicator\ 16 = 1.2$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf
	17. Operation cost recovery	$Indicator\ 17 = \frac{x-0.33}{2.34-0.33} * 10$ X: Operation cost recovery (ratio) X = 1.02 $\therefore Indicator\ 17 = 3.43$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
VI Climate robustness	18. Green space	$Indicator\ 18 = \frac{x - 16}{48 - 16} * 10$ X: Share of blue and green area (%) X = 39% $\therefore Indicator\ 18 = 7.2$	• African Green City Index
	19. Climate adaptation	• the topic is addressed in a chapter at the national and local level $\therefore Indicator\ 19 = 4$	• Estudo sobre o impacto das alterações climáticas no risco de calamidades em Moçambique Relatório Síntese – 2” Versão • Study on the Impact of Climate Change on Disaster Risk in Mozambique: Main Report
	20. Drinking water consumption	$Indicator\ 20 = \left[1 - \frac{x - 45.2}{266 - 45.2}\right] * 10$ X: m^3/person/year drinking water consumption X = 34.9m^3/person/year $\therefore Indicator\ 20 = 10$	• http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf
	21. Climate-robust buildings	• no information is available on this subject $\therefore Indicator\ 21 = 0$	

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
VII Governance	22. Management and action plans	• the topic is addressed in a chapter at the national and local level $\therefore Indicator\ 22 = 4$	• There are documents at National levels: Water loss, Master plan, Basins Management. There is no document that talks about Integrated water management
	23. Public participation	• Value for Rule of Law for Mozambique for 2016 = 16. This is very low $\therefore Indicator\ 23 = 0$	• http://info.worldbank.org/governance/wgi/pdf/EIU.xlsx
	24. Water efficiency measures	• a local policy plan is provided in a publicly available document $\therefore Indicator\ 24 = 5$	• National strategy for urban water and sanitation
	25. Attractiveness	• There is limited information on how surface water features are contributing to attractiveness of the city and wellbeing of inhabitants. $\therefore Indicator\ 25 = 2$	• http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
I Water quality	26. Secondary WWT	$Indicator\ 1 = \frac{x}{10}$ X: Percentage of population connected to secondary sewage treatment X = 10% $\therefore Indicator\ 1 = 1$	• Rietveld et al. Environmental Health 2016, 15(Suppl 1):31 • Masterplan
	27. Tertiary WWT	$Indicator\ 2 = \frac{x}{10}$ X: Percentage of population connected to tertiary sewage treatment X = 0% $\therefore Indicator\ 2 = 0$	• There is no tertiary WWT in Maputo
	28. Groundwater quality	$Indicator\ 3 = \frac{x}{x+y} * 10$ X = Number of samples of 'good chemical status' Y = Number of samples of 'poor chemical status' X = 25 Y = 4 $\therefore Indicator\ 3 = 8.62$	• 2015 data from point measurement. There is a monitoring of groundwater in Maputo. The data used for calculation was collected by a student that is doing PhD. This information is not yet published. Since there are several parameters considered, Electrical conductivity was used to define which samples are in good chemical status and considered only 2015 data.

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
II Solid Waste treatment	29. Solid waste collected	$Indicator\ 4 = \left[1 - \frac{x - 136.4}{689.2 - 136.4}\right] * 10$ X: Kg/cap/year of collected solid waste X = 191.7 kg/cap/year $\therefore Indicator\ 4 = 9$	• Challenges and opportunities in municipal solid waste management in Mozambique: a review in the light of nexus thinking. AIMS Environmental Science, 4(5): 621-639
	30. Solid waste recycled	$Indicator\ 5 = \frac{\%recycled\ or\ composted}{100 - \%used\ for\ incineration\ with\ energy\ recov} * 10$ % recycled waste = 1%; % used for incineration with energy recovery = 0% $\therefore Indicator\ 5 = 0.12$	• Challenges and opportunities in municipal solid waste management in Mozambique: a review in the light of nexus thinking. AIMS Environmental Science, 4(5): 621-639
	31. Solid waste energy recovered	$Indicator\ 6 = \frac{\%incinerated\ with\ energy\ recovery}{100 - \%recycled/composted} * 10$ %incinerated with energy recovery = 0% %recycled/composted = 1% $\therefore Indicator\ 6 = 0$	

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
III Basic water services	32. Access to drinking water	$Indicator\ 7 = \frac{x}{10}$ X: Percentage of total urban population with access to potable drinking water X = 82.8 $\therefore Indicator\ 7 = 8.28$	• African Green city index
	33. Access to sanitation	$Indicator\ 8 = \frac{x}{10}$ X: Percentage of total urban population with access to proper sanitation facilities. X = 48.8 $\therefore Indicator\ 8 = 4.88$	• African Green city index)
	34. Drinking water quality	$Indicator\ 9 = \frac{x}{y} * 10$ X: Total number of samples meeting standards Y: Total number of samples X/Y = 0.756 $\therefore Indicator\ 9 = 7.56$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
IV Wastewater treatment	35. Nutrient recovery		No data available
	36. Energy recovery		No data available
	37. Sewage sludge recycling		No data available
	38. WWT energy efficiency		No data available

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
V Infrastructure	39. Stormwater separation	$Indicator\ 14 = \frac{B + C}{A + B + C} * 10$ A: Total length of combined sewers (km) B: Total length of stormwater sewers (km) C: Total length of sanitary sewers (km) A =200 km; B = 0 km; C 0 km $\therefore Indicator\ 14 = 0$	• Masterplan Maputo
	40. Average age sewer	$Indicator\ 15 = \frac{60 - x}{60 - 10} * 10$ X: Average age sewer X = 40 $\therefore Indicator\ 15 = 4$	• Masterplan Maputo
	41. Water system leakages	$Indicator\ 16 = \frac{50 - x}{50 - 0} * 10$ X: Water system leakages (%) X = 44% $\therefore Indicator\ 16 = 1.2$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf
	42. Operation cost recovery	$Indicator\ 17 = \frac{x - 0.33}{2.34 - 0.33} * 10$ X: Operation cost recovery (ratio) X = 1.02 $\therefore Indicator\ 17 = 3.43$	• National report http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
VI Climate robustness	43. Green space	$Indicator\ 18 = \frac{x-16}{48-16} * 10$ X: Share of blue and green area (%) X = 39% $\therefore Indicator\ 18 = 7.2$	• African Green City Index
	44. Climate adaptation	• the topic is addressed in a chapter at the national and local level $\therefore Indicator\ 19 = 4$	• Estudo sobre o impacto das alterações climáticas no risco de calamidades em Moçambique Relatório Síntese – Segunda Versão • Study on the Impact of Climate Change on Disaster Risk in Mozambique: Main Report
	45. Drinking water consumption	$Indicator\ 20 = \left[1 - \frac{x-45.2}{266-45.2}\right] * 10$ X: m^3/person/year drinking water consumption X = 34.9m^3/person/year $\therefore Indicator\ 20 = 10$	• http://www.cra.org.mz/pdf/RAG_2015_n9_Int2.pdf
	46. Climate-robust buildings	• no information is available on this subject $\therefore Indicator\ 21 = 0$	

Table 1 (cont.): City Blueprint calculations and references.

Category	Indicator	Indicator score calculation	Source
VII Governance	47. Management and action plans	• the topic is addressed in a chapter at the national and local level $\therefore Indicator\ 22 = 4$	• There are documents at National levels: Water loss, Master plan, Basins Management. There is no document that talks about Integrated water management
	48. Public participation	Value for Rule of Law for Mozambique for 2016 = 16. This is very low $\therefore Indicator\ 23 = 0$	• http://info.worldbank.org/governance/wgi/pdf/EIU.xlsx
	49. Water efficiency measures	• a local policy plan is provided in a publicly available document $\therefore Indicator\ 24 = 5$	• National strategy for urban water and sanitation
	50. Attractiveness	• There is limited information on how surface water features are contributing to attractiveness of the city and wellbeing of inhabitants. $\therefore Indicator\ 25 = 2$	• http://www.cra.org.mz/pdf/RAG_2015_n9Int2.pdf

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Curriculum Vitae

Education

2015 – 2025	PhD candidate – Delft University of Technology ‘water reclamation for industrial use in Maputo'.
2012 – 2014	Master of Science in Chemistry – Rhodes University ‘Developing sample handling strategies for monitoring of pesticides distribution on same Mozambican dams with focus on solid sorbents for sample pretreatment for pesticides analysis by HPLC, CG and colorimetric methods”
1995 – 2003	Bachelor-Honours in Chemistry- Eduardo Mondlane University

Experience

2025	Support staff of Scientific Direction of Eduardo Mondlane University
2003 – present	Lecturer, at the Chemistry Department, Faculty of Science of Eduardo Mondlane University *Responsible for the several bachelor courses and bachelor and master’s supervision* *PI and collaborator of several research projects*
2008 – 2016	Head of Analytical Chemistry Section
2001 - 2003	Monitor subjects of Analytical Chemistry, where the teaching experience commenced

List of Publications

Gulamussen, N. J., Arsénio, A. M., Koop S. H. A., van Leeuwen, C. J., and Rietveld, L. C. (2025). Assessing water reclamation potential for industrial use in cities: Identifying gaps, opportunities and priorities for water reclamation in Maputo (to be submitted).

Gulamussen, N. J., (2023). Urban Planning – Searching for Solutions in Practice, WIOMSA Newsbrief, 32(1), 6-8.

Muiambo, S. L., Chauque, E. F. C, Gulamussen, N. J., Chimuca, L, Morifi, E., Nyambe, I. (2023). Modified QuEChERS method for the extraction and quantification of persistent organic compounds in vegetables from Mozambican local markets. Journal of Hazardous Materials Advances, 10, 100262 https://doi.org/10.1016/j.hazadv.2023.100262

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García, J. O. P., Gulamussen, N. J, Carvajal, Y. A., Sánchez, A. C, Mixary García, M. E, and Trujillo, A. M. (2022) Diffusivity of Some Ions in Natural Bentonite, R. Cardenas et al. (eds.), Proceedings of the 3rd International Conference on BioGeoSciences, Springer Proceedings in Earth and Environmental Sciences. https://doi.org/10.1007/978-3-030-88919-7_2

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Gulamussen, N. J., Arsénio, A. M., Matsinhe, N. P., Manjate, R. S., and Rietveld, L. C. (2021). Use of reclaimed water for unreinforced concrete block production for the self-construction of houses. Water Reuse, 11(4), 690-704. https://doi.org/10.2166/wrd.2021.031.

Rusca, M., Gulamussen, N. J., Weststrat, J., Nguluve, E., Salvador, E., Paron, P. and Ferrero, J. (2021). The Urban Metabolism of Waterborne Diseases: Variegated Citizenship, (Waste)Water Flows, and Climatic Variability in Maputo, Mozambique. Annals of the American Association of Geographers, 112(4), 1159-1178. https://doi.org/10.1080/24694452.2021.1956875.

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Munyeshuri, V., Chauque, E., Gulamussen, N. J., Mandlate, J. Richards, E. and Adelodun, A. (2021). Potential health risks of trace metals in muscle tissue of tilapia and catfish from Mozambican markets. Archives of Agriculture and Environmental Science 6(4), 508-518. https://doi.org/10.26832/24566632.2021.0604013.

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Prieto-García J. O., Suarez E. R., GULAMUSSEN N. J., Trujillo Á.M. (2018) Mozambican Adsorbents for Zinc (II) Removal in Aqueous Solutions. In: Cárdenas R., Mochalov V., Parra O., Martin O. (eds) Proceedings of the 2nd International Conference on BioGeoSciences. BG2017. Springer, Cham, 141-146. https://doi.org/10.1007/978-3-030-04233-2_12.

Conferences

Jul 2017	Speaker at 11th International conference in water reclamation and reuse, Long Beach, California.
Dec 2017	Speaker at 9th International Conference of the African Materials Research Society, Gaborone, Botswana.
Nov 2018	Speaker at Industrial Water Conference, Frankfurt, German.
Oct-Nov 2018	Speaker at the 19th WaterNet/WARFSA/GWP-SA Symposium, Livingston, Zambia.
Dec 2019	Speaker at 10th International Conference of the African Materials Research Society, Arusha, Tanzania.
Oct 2024	Speaker at The Pan Africa Chemistry Congress, Nairobi, Kenya.
Dec 2024	Speaker at 12th International Conference of the African Materials Research Society, Kigali, Rwanda.