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Water Practice & Technology Vol 15 No 2
doi: 10.2166/wpt.2020.021

The status and quantification of de facto water reuse in South Africa – a review

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Abstract

The practice of discharging insufficiently treated wastewater to surface water used for potable use (de facto reuse) is common globally. Although de facto reuse provides a sustainable supply of water, it also affects the environment and human health negatively because the inadequately treated effluents contain contaminants of emerging concern (CECs). Therefore, there is a need to determine the extent of de facto reuse in water bodies of South Africa (SA) and thus assess the potential environmental and health risks associated with the reuse of insufficiently treated wastewater in the country. This review summarizes the status of de facto reuse in SA and its negative impact on human health and the environment. Furthermore, the review provides background information on water reuse and as well as the current treatment technologies available in the country for potable water reuse. The use of a geographic information system (GIS) model in combination with caffeine (a wastewater tracer that is abundant in SA surface water systems) for the quantification of de facto reuse is also cited. Such methods, it is envisaged, will enable water management authorities to make well informed decisions regarding water quality issues in SA.

Key words: de facto reuse, geographic information system, wastewater effluents, wastewater tracers, water sustainability, South Africa

INTRODUCTION

Water is one of the most important resources that are essential for sustaining human and aquatic life. However, due to the high prevalence of droughts, global population growth, rapid industrialization and the concomitant urbanization, and the ever-growing water needs of the agricultural sector, potable water has become a limited resource (Lautze *et al.* 2014). This problem is compounded by the depreciating water quality resulting from pollution by industrial effluent discharges. In fact, water scarcity resulting from the depletion of water resources and the depreciation of the water quality is regarded as the single biggest problem facing arid and semi-arid countries (Adewumi *et al.* 2010; Chaudhry *et al.* 2017; Roccaro & Verlicchi 2018).

Key factors contributing to water scarcity in South Africa (SA)

SA is a semi-arid country plagued by large and unpredictable rainfall variations and high evaporation rates (DWA 2013a). Drought, a reoccurring component of the South African climate, is

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doi: 10.2166/wpt.2020.021

another contributing factor to water scarcity (Rouault & Richard 2003). For example, during 2015–2017, the City of Cape Town was at the sharp end of a severe drought and water levels of the six largest dams dropped from 100% to 38%. The Cape Town water crisis had far reaching consequences; the water restrictions imposed by the City led to hotel occupancy dropping by 10% in 2017 and the local economy, which is deeply rooted in the tourism industry, was drastically affected. The water crisis also posed a credit risk to the debt rating of the City of Cape Town, which at the time was at the lowest level of investment grade (i.e. Baa3). Other than the national GDP being additionally impacted, much needed investment was hampered as ratings agencies threatened further downgrades. Furthermore, the tourism and agricultural sectors, which are the two biggest consumers of water in the entire Western Cape Province (i.e. the province in which the City of Cape Town is located), were the most affected by the water crisis. Further denting the economy of the country, other provinces such as Gauteng, the economic hub of the country, were also affected by severe water restrictions. On a positive note, the City of Cape Town was very successful in curbing water usages, and anecdotal evidence suggest that the City is now regarded as a world leader in water crisis management and implementation of climate-change adaptation strategies.

The contamination of surface water by insufficiently treated effluent discharges from the wastewater treatment plants (WWTPs) also contributes to the water quality deterioration in SA (Edokpayi *et al.* 2017). Several studies conducted in various provinces of SA, whereby contaminants of emerging concern (CECs) were detected in surface water, attest to this fact (Momba *et al.* 2006; Skosana 2015; Archer *et al.* 2017b; Madikizela *et al.* 2017; Voulvoulis 2018). It appears the primary problem is that conventional treatment processes were not designed to remove the CECs, which originate mostly from households. These CECs comprise endocrine-disrupting chemicals (EDCs), pharmaceuticals and personal care products (PPCPs), nanomaterials, pathogens, and persistent organic pollutants (POPs) (OW/ORD Emerging Contaminants Workgroup 2008; Murl 2016). Notably, the presence of CECs in surface water leads to human health problems and affects aquatic organisms negatively.

It is rather concerning that most of SA's water supply comes from these polluted raw water sources, which have adverse effects on human health and aquatic life (Momba *et al.* 2006; Vidal-Dorsch *et al.* 2012; DWA 2013b; Elliott *et al.* 2017; Pennington *et al.* 2017). However, it is worth noting that numerous treatment technologies have been modified and enhanced for the specific purpose of removing pollutants such as particles, pathogens, natural organic matter, salts and CECs from wastewater (Roccaro & Verlicchi 2018; Warsinger *et al.* 2018). These technologies include adsorption, ozonation, activated carbon and membrane technology (Seow *et al.* 2016; Warsinger *et al.* 2018). Although these technologies have generally been successful in bringing an improvement to the water quality, they still have shortcomings (e.g. fouling of membranes). The fact that some of the targeted chemical and biological contaminants are not completely removed by some of these modified water treatment technologies indicates that further research into the development of more advanced technologies is required (National Research Council 2012a, 2012b).

A case for wastewater reuse in SA

The factors that contribute to water scarcity in SA coupled with competing water demands from the agricultural and industrial sectors (the biggest consumers of water in SA) and limitations associated with conventional water treatment technologies have led to a substantial number of SA communities not having an adequate supply of potable water (Adewumi *et al.* 2010; DWA 2012). For this reason, wastewater reuse has been adopted as a strategy for addressing an imbalance between water supply and societal and economic demands of potable water in SA (Okun 2002). The strategy adopted in SA is in line with the strategies of several other countries that are targeted towards wastewater reuse for agricultural and potable use (direct and indirect potable use), water conservation and for compensating for water shortfalls (Okun 2002; Roccaro & Verlicchi 2018).

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De facto reuse and mapping

The practice of discharging insufficiently treated wastewater effluent to surface water used for potable supply is termed de facto reuse (Wiener *et al.* 2016). De facto reuse is commonly practiced in many European countries and other countries such as the US and China (Rice *et al.* 2014; Wang *et al.* 2017). De facto reuse is usually used to compensate for water shortfalls resulting from climate change-induced shortages of raw water (Wiener *et al.* 2016). In SA, de facto reuse was introduced to mitigate water shortages and to address issues relating to the unavailability of storage space for the treated wastewater effluent (Skosana 2015). However, the extent of de facto reuse in the country is not known. Therefore, a need exists for the quantification and mapping of water bodies polluted by de facto reuse in SA. The mapping can be achieved using a geographic information system (GIS), which is a cost-effective tool used in different types of water resource studies (Rice *et al.* 2014; Wang *et al.* 2017; Schmid & Bogner 2018). In countries such as the USA, wastewater tracers have also been used for the evaluation of wastewater impact and as a tool for the validation of GIS-based models developed for evaluating de facto reuse (Rice *et al.* 2014).

To the best of our knowledge, no studies have been undertaken to establish the extent of de facto reuse in South Africa. To this end, this review summarizes the status of de facto reuse in SA, and its negative impact on human health and the environment. A brief comparative analysis of de facto reuse in South Africa, the continent of Africa and other developed countries is also undertaken. Furthermore, the review provides background information on water reuse and as well as the current treatment technologies available in the country for potable water reuse. Mention is also made of methods used for the quantification of de facto reuse such as GIS models. Caffeine, a wastewater tracer that is abundant in South African water systems, can also be used in combination with GIS models to investigate surface water pollution caused by wastewater effluents.

A GLOBAL PERSPECTIVE OF WASTEWATER REUSE

Wastewater reuse is a common practice worldwide and it is mainly intended for saving water and providing sustainable water supply. Jimenez & Asano (2008) conducted a global investigation of the rate of wastewater reuse and have predicted a global rate of reuse of 5.55 billion gallons per day (BGD) (Figure 1). At 45% of the total global reuse, the US has apparently the highest rate of water reuse in the world (Jimenez & Asano 2008). Although the reuse of wastewater for non-potable use is common in many countries, very few countries practice planned potable reuse. One of the factors

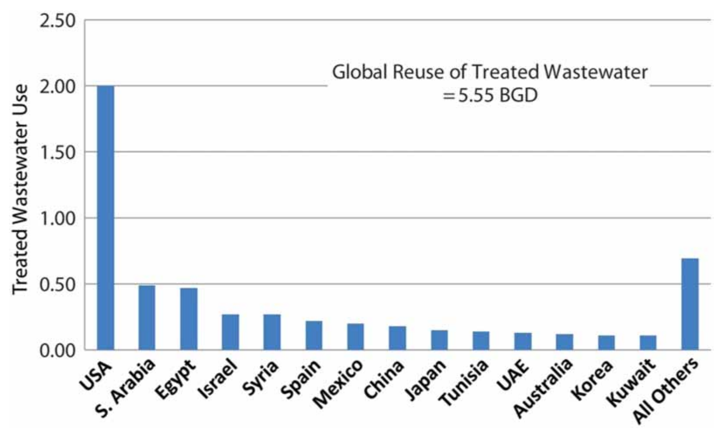

Figure 1 | Global reuse estimate of treated wastewater (Jimenez & Asano 2008).

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that influence limited implementation of planned potable reuse is public non-acceptance of this practice (Ghernaout 2019).

Numerous investigations conducted on different water suppliers around the world have revealed that the raw water sources are contaminated with de facto wastewater. In a study conducted in the Caribbean region (i.e. the West Indies), several emerging contaminants were detected using multi-residue solid phase extraction (SPE) and liquid chromatography with tandem mass spectrometry (LC-MS/MS) (Edwards *et al.* 2017). The study by Edwards *et al.* (2017) has also established the presence of artificial sweeteners, pharmaceuticals, steroid hormones and pesticides with concentration levels ranging from 3.0 ng/L to 571 ng/L. In most cases, the presence of these pollutants in surface water are indicative of pollution of surface water by insufficiently treated municipal wastewater. Similar work was carried out in the US by Elliott *et al.* (2017) on 12 surface water supplies and sediments. Whereas indole (0.0284 μg/L) and cholesterol (72.2 μg/L) were detected in the water supplies, the sediments were found to be endowed with diphenhydramine (1.75 μg/L) and fluoranthene (20,800 μg/L) (Elliott *et al.* 2017). Most of the pollutants studied by Elliott *et al.* (2017) originate from humans (e.g. indole is an organic compound found in faeces). Similar studies have been conducted in China (Wang *et al.* 2017), Malaysia (Al-Qaim *et al.* 2017), Israel (Gasser *et al.* 2010) and Germany (Rossmann *et al.* 2014) using various methods for the detection of pollutants in surface water. In these studies, wastewater tracers such as caffeine, antibiotics, chloride and various other CECs were used in combination with GIS-based models to investigate surface water pollution caused by wastewater effluents.

WATER SUSTAINABILITY OPTIONS IN SOUTH AFRICA

The Department of Water Affairs (DWA) has provided several viable options that can help to increase water supply in semi-arid countries such as SA (DWA 2011). These options include cloud seeding, rainwater harvesting (RWH), potable water reuse and importing clean water from the neighboring country of Lesotho.

Cloud seeding

The issue of the depletion of quantity and quality in water resources is critical; therefore, an urgent need exists for the exploration of alternative options for addressing the water shortfall. One of the ways to increase water supply is through cloud seeding. Cloud seeding is the stimulation of rain through the spreading of dry ice to clouds. However, in some areas, such as the Western Cape Province, the type of clouds are not favorable for rainfall stimulation.

Rainwater harvesting

Another practical option that is an old practice in rural areas is the collection of rainwater through the roofs of houses to tanks (rainwater harvesting); this water is stored and used for household uses. This option has always been viable for rural areas, and it helps especially in dry seasons when there is limited or no water in the rivers. Rainwater harvesting is one of the practical and beneficial options that provide a sustainable water supply.

Potable reuse

Potable reuse is another option that can increase the water supply and provide sustainable water resources. Moreover, there are several countries that have successfully implemented direct and indirect potable reuse using advanced treatment processes such as reverse osmosis. In SA, a mine water

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reuse plant exists that treats mine water using advanced treatment process to drinking water standards and the effluent can filter through the soil to augment an aquifer or be used for drinking purposes (DWA 2011). A second plant close to Middleburg is in operation that also treats mine water to drinking standards and is used for potable water or aquifer augmentation (DWA 2011).

Importing of raw water

One of the ways in which SA is attempting to meet its water demand is by importing water from Lesotho, a country rich in water resources that is surrounded by SA. In 1986, Lesotho initiated a Lesotho Highlands Water Project (LHWP) project for exporting water to SA through a system of large artificial dams, lakes and tunnels (DWA 2013b). About 780 million m^3 of water from these artificial lakes is transported via the tunnels to South African rivers that supply the Vaal Dam in the Gauteng Province.

RECLAMATION OF TREATED WASTEWATER IN THE AFRICAN CONTINENT

Similar to other continents, Africa is affected by water stress and scarcity. According to the World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF), the continent of Africa has the lowest number of people with access to adequate potable water supply and sanitation (i.e. total water supply coverage) (only 64% of the population). In rural areas, the total water supply coverage is lower than in urban areas (50% and 86%, respectively). This results from a combination of factors such as population growth and socio-economic conditions, which lead to increased demand for potable water supply and increased amounts of wastewater being generated.

In many parts of Africa, insufficiently treated wastewater is in some cases discharged into untreated or raw water sources that are used for potable and agricultural purposes (Bahri *et al*. 2008). In sub-Saharan Africa, is estimated that only 1% of wastewater is treated due to lack of financial and technical capacity (Bahri *et al*. 2008). In some cases, the WWTPs are dysfunctional and overloaded and thus discharge poorly treated effluents into surface water. Several other countries including Ethiopia, Ghana, and Tunisia reuse wastewater for various purposes. According to Bahri *et al*. (2008), Ethiopia generates about 35.5 million m^3 of wastewater per year in Addis Ababa originating mainly from households. This wastewater is discharged into surface waters used for agricultural and other purposes. A similar situation is also observed in Ghana, where wastewater is discharged to surface water used for the irrigation of farms and golf courses (Bahri *et al*. 2008). In Tunisia, 30 to 43% of treated wastewater is used for agricultural purposes, landscaping and golf courses. As shown in Table 1, the impact of wastewater reuse on raw water sources has not gone unnoticed.

Very few countries in Africa practice planned wastewater reuse. In Namibia, wastewater reuse began in 1968 in Windhoek due to severe water stress (Ghernaout 2019). Windhoek became the first city worldwide to reuse treated wastewater for drinking purposes. Namibia has been recycling treated wastewater for more than 50 years now. The treatment technology used in Namibia is a multi-barrier type that uses pre-ozonation, coagulation/flocculation, flotation, sand filtration, ozonation, filtration, activated carbon adsorption, ultrafiltration and chlorination. This has enabled Namibia to provide 400,000 people (21,000 m^3/day) with safe drinking water.

Since 2005, Morocco has implemented the National Program of Sanitation and Wastewater Treatment (El Moussaoui *et al*. 2019). One of the main objectives of this program is to treat wastewater, with tertiary treatment and reuse at 100% by the year 2030 (El Moussaoui *et al*. 2019). In South Africa, water scarcity challenges have given rise to the first planned direct potable (DPR) plant in

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Table 1 | A selection of raw water sources impacted by wastewater pollution across the African continent

Country	Raw water source	Reference
Kenya	Nairobi River	Ngumba *et al.* (2016)
	Mathare River	
	Ngong River	
	Athi River	
	Lake Victoria	Omosa *et al.* (2013)
	Auji River	K'oreje *et al.* (2016)
	Kisat River	
Nigeria	River Owo	Olarinmoye & Bakare (2016)
	River Ogun	
Algeria	Reghaia Lake	Elmouatezz *et al.* (2016)
Morocco	Sebou River	Perrin *et al.* (2014)
	Oued Fez	
Tunisia	Medjerda River	Abidi *et al.* (2015)
Congo	Luilu River	UNEP (2011)
	Gombe River	
Cameroon	Douala aquifer	Wirmvem *et al.* (2017)
Uganda	Lake Kyoga	Ongom *et al.* (2017)
Malawi	Lake Malawi	Chidammodzi & Muhandiki (2015)
Egypt	Nile River	Mohamed *et al.* (2013)

Beaufort West in the year 2010 (Olle & Andreas 2011). The effluent produced in this WWTP has very low water quality risks because it uses reverse osmosis, which has high treatment efficiency.

INTRODUCTION OF WATER RECLAMATION IN SOUTH AFRICA

Reclaimed water is wastewater that has been treated and reused for various purposes such as potable reuse, cooling water for industrial processes, feedwater for boilers, agricultural purposes, irrigation of golf courses, recharging of aquifers and toilet flushing for businesses (Warsinger *et al.* 2018). Reusing treated wastewater instead of using pristine water saves water and thus offers a solution to water challenges faced by arid and semi-arid countries such as SA (Andersson *et al.* 2016). Several countries are already benefiting from the reuse of treated wastewater for the purposes of augmenting surface and groundwaters to increase water supply. Although water reclamation is a potential solution for mitigating water shortages, it also increases financial, technical and institutional challenges and raises health and safety concerns (National Research Council 2012a, 2012b). In addition, very few countries reuse treated wastewater for potable use due to negative public perceptions about such a practice. The idea of converting toilet to tap water has still not found a great deal of acceptance amongst the general public (Ghernaout 2019).

The reuse of treated wastewater is albeit a long-established practice in most of the arid countries (Bischel *et al.* 2013). In addition, several countries such as Singapore, Israel, Namibia, the US, Australia and several European countries have already started implementing the reuse of treated wastewater for various applications. Despite some of the potable reuse projects not being successful due to opposition from the public, most non-potable reuse projects have been successful (Po *et al.* 2003). In the same vein, although several disadvantages of water reclamation are known, they are far outweighed by benefits such as reduction of water scarcity, less coastal pollution, conservation

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of surface water, nutrient recovery, surface and ground water augmentation, improved reliability and sustainable water resources (Po *et al.* 2003).

Water reclamation in SA was introduced in 1956, following the enactment of the South African Water Act (SAWA) of 1954, which effectively gave approval for wastewater to be treated to acceptable standards and thereafter discharged to the original raw water source (Morrison *et al.* 2001). At the time of the enactment of the Act, the CECs had either not yet been detected or were found in negligible concentrations in wastewater effluent streams. Over a period of time, rapid population growth and urbanization was accompanied by an increase in the use of PPCPs and other chemicals, which ultimately led to an increase in the concentrations of CECs in wastewater effluent. To illustrate this point, high levels of CECs were detected in the final effluent of 80% of WWTPs that were still using conventional water treatment processes in the Eastern Cape Province of SA (Mema 2010). It suffices to say that increased levels CECs posed a higher risk of illnesses from de facto reuse.

Type of water reclamation used in South Africa

There are three ways in which treated wastewater is reused, namely planned direct potable reuse (DPR), planned indirect potable reuse (IPR) and unplanned indirect potable reuse (de facto reuse) (see Figure 2) (Warsinger *et al.* 2018). DPR refers to when wastewater is treated to drinking water

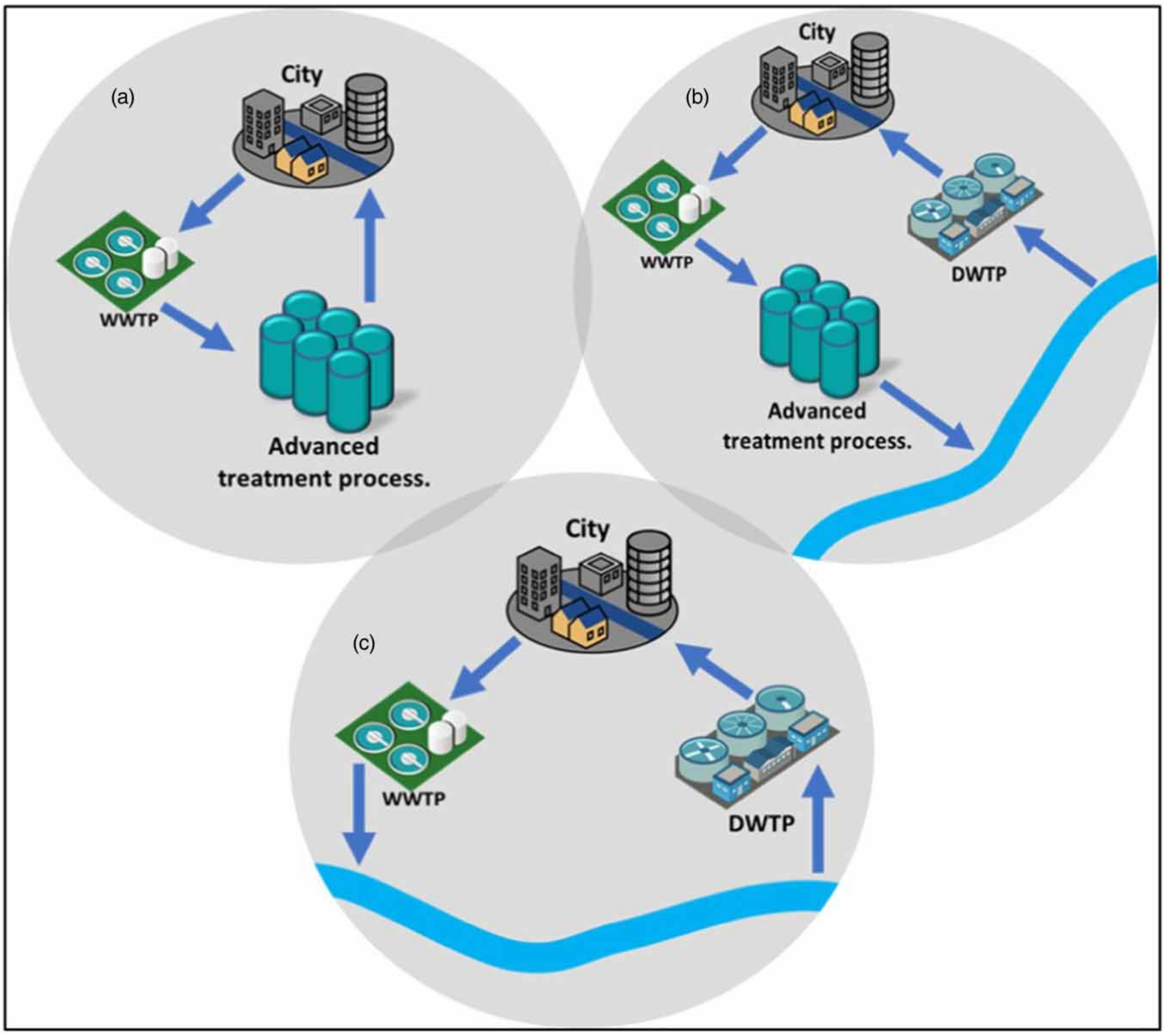

Figure 2 | Scheme for wastewater reuse: (a) DPR, (b) IPR and (c) de facto reuse.

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standards using advanced treatment processes and then directly added to the downstream water of a DWTP for distribution. IPR is the process of adding advanced-treated wastewater to a pristine water source that is used as a potable water supply following treatment from a DWTP. Unplanned indirect potable reuse (de facto reuse) is the discharging of insufficiently treated wastewater to a pristine water that is used for potable use (National Research Council 2012a, 2012b; Chaudhry *et al*. 2017). Other than referring to when a community draws its water supply from a raw water source that has been polluted with wastewater effluent (Schmid & Bogner 2018), de facto reuse is also defined as the unintentional reclamation of insufficiently treated wastewater coming from an upstream WWTP (Rice *et al*. 2014). De facto reuse has been practiced in the past 100 years and it is normally introduced when there is limited water supply (due to climate changes) to make up for the water shortfall (Rice *et al*. 2014). Unlike in several overseas countries where planned potable reuse is practiced through advanced treatment of the wastewater prior to reuse, water reclamation in SA occurs mostly as an unplanned indirect potable reuse (de facto reuse).

DE FACTO REUSE IN SOUTH AFRICA

In South Africa, there is a lack of proper treatment technologies that are capable of removing new and emerging contaminants from wastewater. Many South African rivers and dams that supply raw water for eventual potable use are seriously polluted with wastewater effluents because large amounts of wastewater are discharged on a daily basis to these surface water sources (Mema 2010). Despite many of the rivers being mainly polluted with raw sewage, SA is reliant on these polluted sources for raw water supply. A recent review conducted by Archer *et al*. (2017b) has recorded numerous emerging pollutants detected in South African water bodies by other researchers. In some of the rivers where these pollutants were detected, drinking water treatment plants (DWTPs) are situated a few kilometers away from the WWTPs, drawing raw water from the same river where the WWTPs discharge their effluents.

Based on the impact of wastewater effluent discharge on fresh water, several South African studies have concluded that most South African rivers and dams are contaminated with various contaminants such as EDCs, PPCPs and POPs (OW/ORD Emerging Contaminants Workgroup 2008; Murl 2016). The discharging of wastewater by some the WWTPs into the Nzelele and Mvundi rivers in the Vhembde district, Venda, in Limpopo Province (i.e. the northernmost province of South Africa) has been studied by Edokpayi (2016). An investigation of the compliance of these WWTPs to the South African wastewater legislation through the measurement of specific wastewater quality parameters in the wastewater effluent and the rivers was investigated (Edokpayi 2016). The results of this study revealed that some of the wastewater quality parameters did not comply with the watewater legislation for discharging wastewater effluent to surface water, thus suggesting that the WWTPs were discharging poorly treated wastewater into the rivers. Edokpayi (2016). The poor quality of the wastewater effluent apparently results from poor wastewater treatment infrastructure, scarce skills, ineffective planning and fraud (Edokpayi *et al*. 2015). In another study conducted in the Gauteng Province of South Africa, 55 CECs were detected in WWTP influent, 41 were detected in the wastewater effluent and 40 were detected downstream and upstream of a river a few miles away from a WWTP. About 28% of the 55 CECs that were investigated had a removal efficiency lower than 50%, and the removal efficiency of 18% of the same CECs was below 25% (Archer *et al*. 2017a).

In 2008, the Department of Water and Sanitation (DWS) launched a program to evaluate the performance of 831 South African WWTPs, and those that complied with the minimum DWS standards were awarded Green Drop (GD) status. This initiative was undertaken to encourage an improvement in the quality of the wastewater management with the ultimate aim of protecting

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human health and the environment (Archer *et al.* 2017b). The WWTPs were awarded an ongoing risk rating based on assessment of their design capacity, operational flow in relation to design capacity, and compliance of technical skills and final effluent quality to DWS standards. Moreover, the assessments were also intended to offer annual evaluations on operational efficiency of the plants. In 2012, it was reported that 323 of 831 WWTPs did not meet the standards set by the DWS, and 212 of the WWTPs had a high-risk rating. Moreover, the design capacity of some of the WWTPs was unknown and this made it difficult to assess the effluent quality of those treatment plants (Archer *et al.* 2017b). Although the 2013 assessments revealed some improvement with regards to compliance in the risk rating, 412 WWTPs were found to be still operating below 50% efficiency (Archer *et al.* 2017b).

Paul *et al.* (2015) conducted a study on several rivers and dams in four South African provinces, namely Gauteng, Free State, Mpumalanga and Kwa-Zulu Natal. The study was focused on quantifying different anti-retroviral (ARVs) drugs in water bodies of SA using the SPE method for the pre-concentration and ultrahigh pressure liquid chromatography (UHPLC) coupled to mass spectrometry. Since ARV drugs are not completely digested by humans, they get excreted and end up in wastewater, which makes them tracers of the presence of wastewater in surface waters. In addition, the conventional wastewater treatment processes do not completely remove these compounds, and they get released or discharged with the wastewater effluent into the surface water. Therefore, when detected in surface water, ARV drugs act as markers of wastewater effluent (de facto reuse). The average concentrations of ARV drugs quantified in the rivers and dams was found to range from 26.5 to 430 ng/L (Paul *et al.* 2015).

Pharmaceutical compounds such as non-steroid, anti-inflammatory, antibiotic, anti-retroviral, anti-epileptic, steroid hormones, and anti-malarial compounds have also been detected in South African surface water sources (Madikizela *et al.* 2017). In 2014, triclosan and ketoprofen were detected in wastewater effluent and receiving surface waters of the Mbokodweni river (Madikizela *et al.* 2017). Whereas triclosan is an antibacterial agent occurring in household products such as toothpaste and liquid soap, ketoprofen is used as an analgesic in humans and animals. The presence of triclosan in surface water is harmful to aquatic organisms because of its toxicity. Although triclosan is less toxic to humans, it precedes the synthesis of POPs, which can make their way to the food chain when wastewater is reused for agricultural purposes and thus cause harm to human health. In addition, in the aquatic environment, triclosan is known to be toxic to fish, daphnia magna and algae at levels of μg/L (Madikizela *et al.* 2014).

Reported rivers and dams affected by de facto reuse in SA

Several South African rivers and dams that have been impacted by de facto reuse are listed in Table 2.

IMPACT OF DE FACTO REUSE

The discharges of wastewater effluents are the major source of pollution of surface water. The existing methods require modification to be able to eliminate these emerging pollutants from water. The major sources of CECs are the WWTPs and their presence in wastewater effluents causes a serious threat to human health and the environment (Stackelberg *et al.* 2004; Edokpayi *et al.* 2017). Moreover, the impact of CECs on the environment depends on their concentration in the effluents as well as the volume and consistency of wastewater effluent disposal into raw water sources (Akpor & Muchie 2013). Therefore, law enforcement must be applied in order to protect the environment and human health because many societies in SA depend on these polluted raw water sources for their water supply (DWA 2013b).

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Table 2 | South African rivers and dams impacted by de facto reuse

Province	River	Reference
Kwa-Zulu Natal	Mbokodweni River	Madikizela *et al.* (2017)
	Msunduzi River	Agunbiade & Moodley (2016)
	Inanda Dam	Paul *et al.* (2015)
	Umgeni River	Agunbiade & Moodley (2014)
	Mhlathuze River	Mema (2010)
Gauteng	Roodeplaat Dam	Wanda *et al.* (2017)
	Pienaars River	Paul *et al.* (2015)
	Rietvlei Dam	
	Vaal River	DWA (2011)
North West	Crocodile River	Wanda *et al.* (2017)
	Hartbeespoort Dam	
	Megalies River	
Mpumalanga	Mkomazane River	Wanda *et al.* (2017)
	Lipoponyane River	
	Renosterkop Dam	Paul *et al.* (2015)
Western Cape	Kuils River	Swart & Pool (2007)
	Eerste River	
Free State	Orange River	Paul *et al.* (2015)
	Gariep Dam	
	Vaal Dam	
Eastern Cape	Kat River	Momba *et al.* (2006)
	Tyume River	
	Tembisa Dam	
	Keiskamma River	Morrison *et al.* (2001)

Impact of de facto reuse on the environment

It is required that specific conditions such as temperature and oxygen balance in the aquatic environment should be met for the survival of aquatic life (Edokpayi *et al.* 2017). Any changes in the survival conditions may inhibit productivity, growth and life of aquatic organisms. Any discharges of wastewater effluents impact on the oxygen demand of surface water. Therefore, when insufficiently treated wastewater is discharged into surface water it reduces the dissolved oxygen (DO) of the surface water because the wastewater effluents containing organics that are degradable to an extent that they reduce the DO levels. The acceptable standard of DO in WWTPs of SA is between 8 to 10 mg/L. However, when the DO levels are below 5 mg/L they may harmfully impact aquatic organisms. In a study conducted by Momba *et al.* (2006) on the WWTP effluents of Buffalo City and Nkokonbe Municipalities (Eastern Cape Province of SA), DO levels with a mean range of 3.26 to 4.57 mg/L were reported. An imbalance in the oxygen due to insufficiently treated wastewater in surface water negatively impacts aquatic organisms, because oxygen is vital for sustaining aquatic life and low levels of DO reduce the productivity and growth of aquatic organisms thus leading to their death (Edokpayi *et al.* 2017). In addition, several studies conducted in SA have revealed that DO levels in the wastewater effluent are below the acceptable levels (Mema 2010). This implies that the aquatic life of South Africa water bodies is endangered.

Impact of de facto reuse on human health

The reuse of wastewater effluent for various applications is accompanied by risks of contracting bacteria from surface water contaminated by poorly treated wastewater effluents. These risks have both short-term (depend on human and environmental exposure) and long-term effects (depend on consistency in water reuse) (Toze 2006). Momba *et al.* (2006) has established the presence of 21 bacterial

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species in water samples collected from raw wastewater, final effluent and receiving surface waters in the Buffalo City and Nkokonbe municipalities of the Eastern Cape. Out of the 21 bacterial species detected, 12 species, namely *Aeromonas hydrophilia, Enterobater cloacae, Escherichia coli, Klebsiella ornithinolytica, Mmorganella morganii, Pasteurella pneumoniae, Proteus mirabilis, Providencia rettgeri, Pseudomonas fluorescen, Salmonella spp., Serratia odorifera, and Vibrio parahaemolyticus*, were detected in samples collected from the receiving surface waters (Momba *et al.* 2006).

The National Research Council (NRC) has conducted a risk assessment of viruses, bacteria and parasites (norovirus, adenovirus, salmonella and cryptosporidium) associated with three water reclamation scenarios (Figure 3) (National Research Council 2012a, 2012b). The first scenario (Scenario 1) is de facto reuse and Scenario 2 is wastewater effluent that is filtered by the soil and augments an aquifer that is used for potable use. Scenario 3 is wastewater effluent that has undergone advanced water treatment processes such as reverse osmosis, microfiltration, advanced oxidation and is allowed to flow through the soil to augment an aquifer before it is used for potable use. The findings of the risk assessment revealed that in all the three scenarios, de facto reuse had the highest risk for all the four illnesses. In Scenario 2, the risks of norovirus and adenovirus were less than 0.001, but the risks for salmonella and cryptosporidium were greater than 0.001 and 0.1, respectively. Moreover, the NRC study revealed that when recycled water has undergone advanced treatment process the chances of being affected by viruses, bacteria and parasites are very finite (below 0.000001).

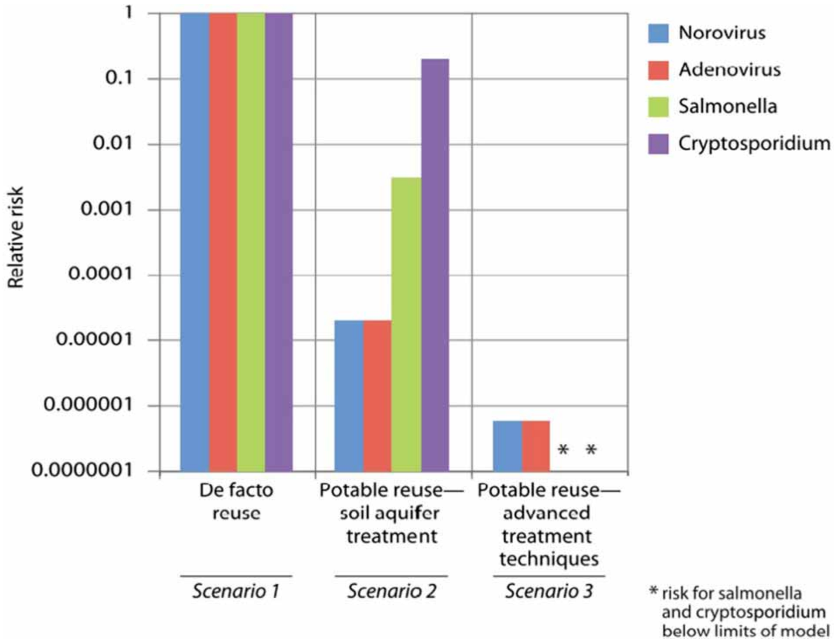

Figure 3 | Risk assessment of contracting norovirus, adenovirus, salmonella and cryptosporidium through three types of water reclamation (Scenario 1, 2 and 3) (National Research Council 2012a, 2012b).

Impact of CECs on human health and the environment

The presence of emerging contaminants in the environment affects both human health and aquatic life. According to investigations by Kellock (2013), exposure of aquatic species to these emerging pollutants result in the inhibition of their reproduction and growth as well as their growth hormones. The presence of emerging pollutants in surface water also leads to the death of fish, which negatively affects fish farming (Edokpayi *et al.* 2017). Moreover, their presence in the environment poses a threat to human health (Table 3) (Raghav *et al.* 2013).

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Table 3 | Effects of CECs on human health (Raghav *et al.* 2013)

Class of CEC	Effects on human health
Prescribed drugs	Accelerates cancer and damages organs
Antibiotics	Affects the ability to resist diseases
Steroids	Disrupts endocrine systems
Disinfectants	Genotoxic, cytotoxic, cancer-causing
Solvents	Disrupts endocrine systems, damages the liver and kidneys, respiratory impairment, cancer-causing
Fire retardants	Disrupts endocrine systems, accelerates cancer risks
Reproductive hormones	Disrupts endocrine systems
Pesticides	Disrupts endocrine systems
Plasticizers	Disrupts endocrine systems and accelerates cancer risks
Industrial additives	Toxic to humans, land and aquatic ecosystems
Personal care products	Affects the ability to resist bacteria, disrupts endocrine systems

METHODS FOR DETECTING AND QUANTIFYING DE FACTO REUSE

Notwithstanding de facto reuse being a common practice in many countries, very few countries, namely the US and China, have quantified de facto reuse. Most of the studies worldwide have instead focused on detecting and quantifying CECs in surface water. Methods for the quantification of de facto reuse such as the use of GIS and wastewater tracers have not been widely explored and implemented worldwide and in South Africa.

Geographic information system

Recent reports (Gasser *et al.* 2010; Rice *et al.* 2014; Wanda *et al.* 2017) provide evidence that wastewater tracers such as caffeine and carbamazepine are ideal indicators of the presence of wastewater effluents in surface water and can thus be used for assessing the quality of water resources. However, the method involving the use of tracers is costly and time-consuming because it requires the collection of samples in the rivers, sample preparation, performing solid phase extraction (SPE) and mass spectrometry coupled to liquid chromatography (LC) or gas chromatography (GC) to quantify the wastewater tracer concentrations. In addition, the method has limitations with regards to managing the quality of water resources because it is not practical to measure the concentrations of pollutants in all the raw water supplies (Rice *et al.* 2014). However, with the GIS method, it is possible to predict concentrations of pollutants in all raw water supplies, when it is used with site-specific concentrations of the pollutants (Rice *et al.* 2014).

A GIS is a computer-based system used for capturing, storing, manipulating, managing and analyzing spatial information (Johnson 2016). Following development of the requisite GIS model, this tool can be used for prediction of the concentrations of pollutants in surface water and the mapping of polluted waterways (Wu *et al.* 2005). GIS can also be used to present information such as river flow and spatial relationships of land features (Wu *et al.* 2005). A GIS can incorporate spatial data and give an all-inclusive view of a specific region (Martin *et al.* 2005). This coordinated view is created by incorporating sociologic, geographic, geologic, and natural variables identified with the spatial elements of the water resource issues and profiling them for use in decision making. GIS has been utilized for more than 20 years for managing spatially appropriated hydrologic modelling information. Moreover, the advantages of using GIS in hydrologic investigation include improved accuracy, less duplication, easier map storage, greater adaptability, simplicity of information sharing, more noteworthy effectiveness and higher product complexity (Ogden *et al.* 2001).

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There are four diverse applications of GIS in hydrologic applications, namely evaluation, parameter determination, model set-up and modelling. Several reported studies have used GIS for the prediction of surface runoff, point and non-point pollution, studies on water quality, modelling storm water and assessments of floods (Rice *et al.* 2014). In the US, an ArcGIS model was used to quantify de facto reuse of raw water sources and the results of this investigation revealed that some rivers were up to 100% impacted by de facto reuse (Rice *et al.* 2014). Similar works were conducted in a river in China utilizing an ArcGIS (Wang *et al.* 2017). The percentage of de facto reuse for the river was compared from 1998 to 2014 and the results revealed that the de facto reuse increased by 41% during the period under investigation (Wang *et al.* 2017). It should be pointed out that information from some measuring stations was not accessible, and de facto reuse was estimated using digital elevation mapping. This capacity of the ArcGIS model to predict various scenarios contrasts sharply with scenarios in countries such as the US that have huge databases for the development of the GIS model.

GIS model development for quantifying de facto reuse

Rice *et al.* (2014) developed a method for modelling a GIS using data collected from various sources such as the U.S. Geological Survey (USGS), National Atlas Web site and National Hydrography Data set (NHD) (Rice *et al.* 2014). The collected data included locations of all WWTPs and DWTPs, and coordinate data for the DWTPs and WWTPs. Data for stream gauges, average, minimum, maximum, and percentile stream flows were also collected. Topographic layers, city and state boundaries, and hydrography layers data were obtained as well. The collected data was incorporated into a GIS model. After programming the GIS model, it was then used to transform regional level flow lines into a network using network analysis tools from the ArcGIS software. The GIS model was employed to do the spatial analysis for DWTPs in connection with WWTPs that are upstream. The river flow upstream of the DWTP locations was traced using ArcHydro Tools. When the upstream route was discovered, all the WWTP discharges on the route were added together. Assumptions for mass balance were made which were as follows: (a) the design flow was equal to the WWTP effluent discharge; (b) there were no losses in the WWTP effluent; and (c) there was perfect mixing in all the surface water. Mass balance calculations were conducted at the intakes of DWTPs, assuming that the WWTPs were the only contributors of wastewater to the surface water. Thus, the quantity of de facto wastewater reuse was determined by dividing the sum of the upstream discharge by the average stream flow of the nearest USGS stream gauge.

Benefits of using a GIS model over manual methods

GIS-based water quality studies are more efficient than manual sample collection methods because a GIS can also map polluted waterways. A GIS is also a cost effective and time saving tool because it does not require manual sample collection. It can perform spatial analysis, which shows where objects are situated and their distance from other objects (Martin *et al.* 2005) and it also contains attribute data, which shows what things are (a GIS can provide the name of the land feature, and activities done in the land feature and close to it). Therefore, GIS can be used to investigate the sources of pollution and it is a good tool to use in case studies because it can map changes in population and developments in an area. However, when a GIS-based model is used to quantify de facto reuse it is also important to validate it with field studies (e.g. wastewater tracers).

Wastewater tracers for quantifying de facto reuse

Although wastewater tracers are time consuming and costly, they are employed to enhance and confirm the accuracy of the GIS-based method. In a US study conducted by Rice *et al.* (2014), de facto

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reuse was estimated using GIS, and sucralose was used as a wastewater tracer to confirm the precision of the GIS analysis. Sucralose is an artificial sweetener used in sweets, soft drinks, breakfast bars and others. In the US, it was suggested as a wastewater tracer by several researchers (Rice *et al.* 2014). However, the criteria for a good wastewater tracer include the tracer having a high concentration in the wastewater effluent (Gasser *et al.* 2010; Oppenheimer *et al.* 2011). In South Africa, caffeine is considered a good wastewater tracer because of its abundance in wastewater effluents. The respective caffeine and sulfamethoxazole wastewater concentrations of 2,077.5 and 1,013.2 ng/L have been reported by Archer *et al.* (2017b). Similar studies have reported the wastewater concentration levels of caffeine and lamivudine of 397 and 184 ng/L, respectively (Paul *et al.* 2015; Archer *et al.* 2017a). Therefore, caffeine is considered a good tracer in SA compared to sucralose because of its abundance in contaminated surface water. In addition, caffeine can also be used for quantifying the percentage of wastewater in surface water because of its good degradation in the environment (Hillebrand *et al.* 2011).

Gasser *et al.* (2010) have utilized alternative wastewater tracers for quantifying wastewater. When carbamazepine and chloride were used as wastewater tracers to estimate the ratio of wastewater in water sources, chloride was found to be a much superior tracer to carbamazepine for evaluating the level of wastewater in a raw water source. The mixing ratios (MR) of wastewater in the raw water were found to be 0.84 and 0.63 using the concentrations of chloride and carbamazepine, respectively (Gasser *et al.* 2010). A German study used caffeine as a tracer for the estimation of the amount of wastewater in surface water and the results showed that there was 0.4% of wastewater in the surface water (Hillebrand *et al.* 2011). Therefore, the most common method for tracking and estimating the amount of wastewater in water resources involves the use wastewater tracers. The most frequently utilized wastewater tracers are compounds found in domestic household products such as antibiotics, artificial sweeteners and carbamazepine (Hillebrand *et al.* 2011). The selection criteria for a good wastewater tracer are listed in Table 4 (Gasser *et al.* 2010; Oppenheimer *et al.* 2011).

Table 4 | Criteria for selection of a good wastewater tracer (Gasser *et al.* 2010; Oppenheimer *et al.* 2011)

Characteristic	Denotation
Specificity	The tracer must originate mainly from households
Abundance	The tracer concentration in the wastewater effluent must be high
Background level	The tracer concentration must be low in the encompassing aquifer
Persistent level in source	The tracer must have a low degradability over a more extended period
Conservative behaviour	The tracer ought not be volatile, or experience redox reactions
Mobility	The tracer ought to be highly soluble in water
Degradation	The tracer must not degrade amid transportation
Proven method	The technique for examination of the tracer must be illustrated

ADVANCED TECHNOLOGIES FOR POTABLE WASTEWATER REUSE APPLICATIONS

Current advanced treatment technologies have made it possible to reuse treated wastewater for potable use. Over the past 20 years, many countries such as Australia and Singapore have been able to expand their potable water supply using membrane technologies (Lautze *et al.* 2014). Moreover, various studies have demonstrated that the advanced membrane technologies are able to purify municipal wastewater to potable water standards.

In 1968, Windhoek (the capital city of Namibia) became the first country to practice DPR (Wilcox *et al.* 2016; Ghernaout 2019). The water reuse treatment plants add 35% to the water supply of Windhoek. The application of advanced treatment processes in Windhoek such as ultrafiltration and ozone

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in the removal of micro-organisms, protozoa, EDCs and organic matter, have so far not led to any health problems relating to wastewater reuse for potable applications (Ghernaout 2019).

In Australia, potable reuse was not considered as a practical solution until the inception of a severe drought that lasted for six years (2003–2009) (Rodriguez *et al*. 2009). The reclaimed wastewater was introduced as IPR, whereby wastewater was treated using advanced membrane technologies to augment existing surface water resources. However, potable reuse was withdrawn at the end of the drought.

The first water reuse plant to employ reverse osmosis is Water Factory 21 (a project in Orange County, California, USA), which was established in 1977. For 27 years, Water Factory 21 had a plant capacity of 19 megaliters per day (ML/day) and a new advanced groundwater augmentation system operating at 265 ML/day was only considered and introduced in 2007 (Warsinger *et al*. 2018). IPR is also practiced in many European countries, where reclaimed water adds about 70% to the water supply during periods of water shortages (Rodriguez *et al*. 2009). In Belgium, an IPR project used reverse osmosis and microfiltration to treat wastewater to drinking water standards and the water was used to augment an aquifer (Van Houtte & Verbauwhede 2012). However, some herbicide that was below the water quality standards was detected in the water treated using the microfiltration system. For this reason, the microfiltration treatment system was discontinued and from 2004 only reverse osmosis was used. England is also one of the countries that practice IPR, which it initiated in 1985 (Lazarova *et al*. 2001; Rodriguez *et al*. 2009). The advanced technologies used in England are microfiltration and ultra-violet for disinfection.

Singapore also practices IPR to mitigate water shortage problems. Currently, Singapore has four water reuse treatment plants known as the NEWater projects, which were implemented in 2003 (Ghernaout 2019). The NEWater projects use advanced treatment processes such as microfiltration, ultrafiltration, reverse osmosis and ultraviolet disinfection for the treatment of wastewater to drinking water standards. These advanced technologies have been proven to be effective in the removal of pollutants such as organic matter, pesticides, EDCs, PPCPs and herbicides from wastewater (National Research Council 2012a, 2012b). Moreover, the water quality parameters of the final water meet all the standards set by the Environmental Protection Agency (EPA) and the WHO; turbidity <0.5 nephelometric turbidity units (NTU), total dissolved solids (TDS) <50 mg/L and total organic carbon (TOC) <0.5 mg/L).

Naghizadeh *et al*. (2011) used a hollow fiber microfiltration membrane (HFMM) to purify municipal wastewater. The membrane was submerged in a bioreactor to study the elimination of chemical oxygen demand (COD), total suspended solids (TSS) and turbidity at different retention times. Results of the study revealed high removal treatment efficiency, which was ascribed to low COD, TSS and turbidity of 9 mg/L, 1 mg/l and 0.3 NTU, respectively (Naghizadeh *et al*. 2011). In another study, a hollow fiber microfiltration membrane coupled to a biocathode microbial desalination cell for wastewater purification was employed (Zuo *et al*. 2018). The conductivity, COD, total nitrogen and total phosphorus of the final effluent was found to be compliant with the respective water quality standards of 59.2 μS/cm, 35.5 mg/L, 1.65 mg/L, 0.14 mg/L. Despite its effectiveness in the removal of pollutants from surface water, membrane technology is still costly (Herman *et al*. 2017).

Other wastewater treatment technologies

The process used in WWTP involves four phases, namely preliminary treatment, primary treatment, secondary treatment, and tertiary treatment. The type of technology used in each treatment phase is dependent on the size of the population in the vicinity of that WWTP and the environmental requirements. To ensure sustainable development, the WWTPs selected must have a technology type that is appropriate for a particular developmental purpose, which may not necessarily be the best technology existing (WRC 2016). For example, non-potable vertical flow wetlands combined with ultra violet

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(UV) radiation disinfection can be used to treat greywater that can be re-used for all non-potable reuse applications because they meet all the chemical, physical and microbiological water quality standards (Arden & Ma 2018). Furthermore, using constructed wetlands over conventional treatment methods is advantageous because they reduce maintenance and operational costs and they do not demand continuous supplying and operation. The different types of technologies that can be used in different stages of the wastewater treatment process are demonstrated in Figure 4 (WRC 2016).

Van der Merwe-Botha & Quilling (2012) have surveyed different technology types in South Africa and classified them as low, medium and high based on the final effluent quality, capital and operating

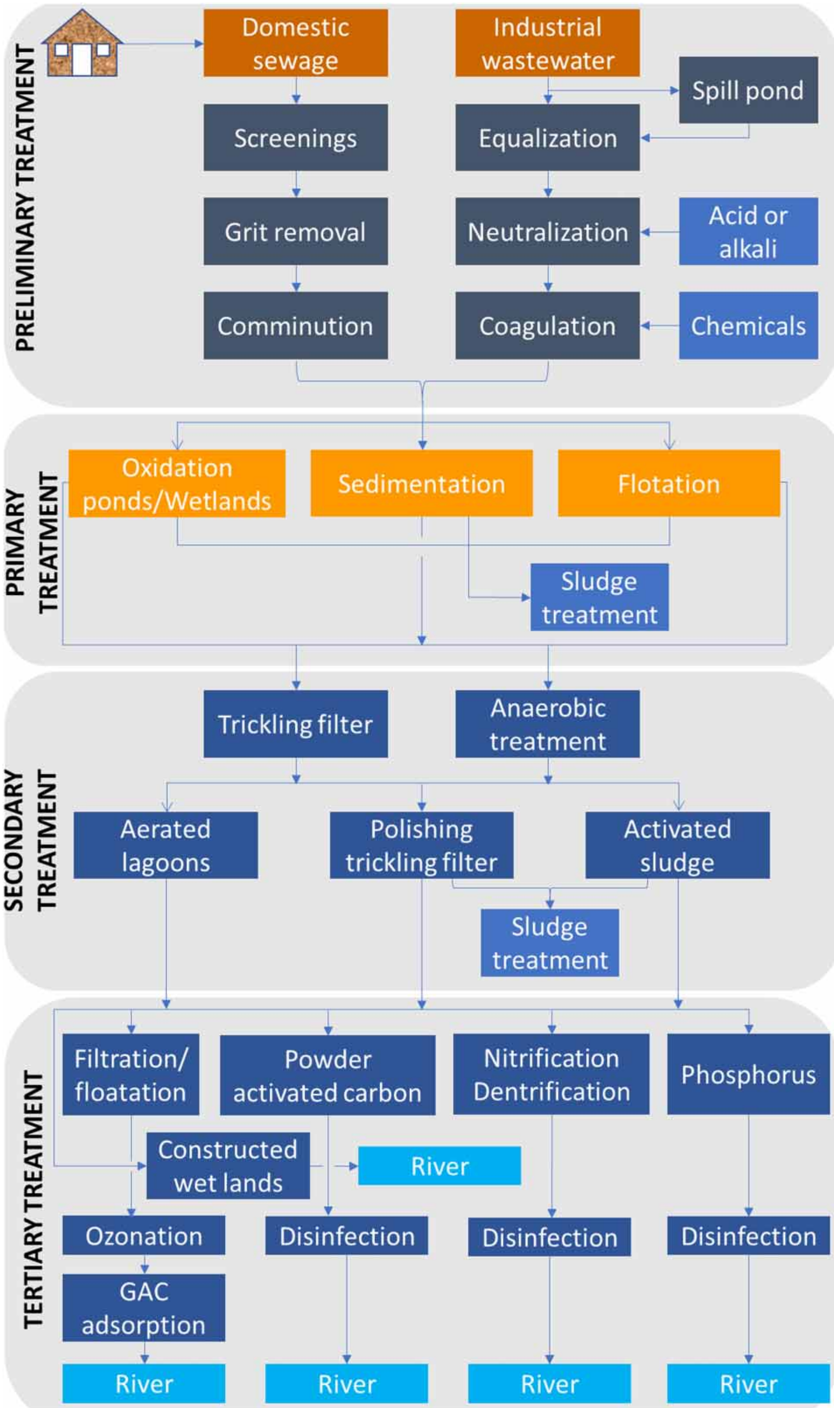

Figure 4 | Different types of technologies for wastewater treatment (modified from WRC 2016).

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costs, power usage and preservation requirements (Table 5). The types of technologies are graded according to their stage in the WWTP (preliminary, primary, secondary, tertiary and sludge treatment).

Table 5 | Technology and level of classification (Van der Merwe-Botha & Quilling 2012)

Level of treatment	Type of technology	General comment on technology
Primary	Primary settling	Low to medium
	Flow balancing	Low to medium
Secondary	Trickling filter	Low to medium
	Rotating biological filter	Medium
	Pasveer ditch	Medium
	Oxidation ponds	Low to medium
	Wetlands	Low to medium
	Extended aeration	Medium to high
	Biological nutrient removal/activated sludge	High
	Surface aeration	Medium to high
	Clarification	Low to medium
Tertiary	Chlorine gas disinfection	Medium
	Maturation pond	Low
Sludge	Gravity thickening	Medium
	Thickening by dissolved air flotation	Medium to high
	Aerobic digestion	Medium to high
	Anaerobic digestion	Medium
	Belt press dewatering	Medium
	Solar drying beds	Low
	Centrifuge dewatering	Medium to high
	Composting	Low to medium
	Palletization	High
	Disposal to land	Low

Regulations for wastewater effluent quality

It is critical that wastewater treatment plants function efficiently because they are the defining line between a healthy environment and a polluted environment. There are many serious human health-related concerns linked to water pollution by poorly treated effluents such as dilaceration of the reproductive system, which leads to ovarian cancer, breast cancer and low sperm quality (Archer 2018). Properly monitored WWTPs result in wastewater effluents that comply with standards, with up to 90% elimination of pathogens and bacteria (Okeyo *et al.* 2018). The South African National Water Act has set regulations for discharging wastewater to surface water, which WWTPs must comply with for the protection of the environment and human health (Table 6).

COST OF WATER RECLAMATION SYSTEMS

Investing in water reuse projects is a difficult and costly decision . For the most part, planned potable water reuse is more costly than de facto reuse. However, planned potable water reuse is still more affordable than desalination. The costs of water reuse fluctuate significantly in different places;

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Table 6 | Wastewater quality standards for discharging wastewater effluent to surface (DWA 2013c)

Parameter	General limit
Faecal coliforms	1,000 cfu/100 mL
Chemical Oxygen Demand	75 (mg/L)
pH	5.5–9.5
Ionized and unionized ammonia	3 (mg/L)
Nitrate	15 (mg/L)
Residual chlorine	0.25 (mg/L)
Suspended solids	25 (mg/L)
Conductivity	70–150 (mS/m)
Phosphorous	10 (mg/L)
Dissolved arsenic	0.02 (mg/L)
Dissolved cadmium	0.005 (mg/L)
Dissolved chromium (VI)	0.05 (mg/L)
Dissolved copper	0.01 (mg/L)
Dissolved cyanide	0.02 (mg/L)
Dissolved iron	0.3 (mg/IL
Dissolved lead	0.01 (mg/L)
Dissolved manganese	0.1 (mg/L)
Mercury	0.005 (mg/L)
Dissolved selenium	0.02 (mg/I)
Dissolved zinc	0.1 (mg/L)
Boron	1 (mg/IL)

they depend on location, water quality standards, treatment processes, water dispersion system needs, cost of energy, subsidies and numerous other different components (Hosseinzadeh *et al*. 2017). Generally, reusing wastewater for potable reuse is more costly than reusing for non-potable use (Ghernaout 2019). Non-potable reuse requires less treatment, contingent upon the planned utilization of the reused water. In addition, non-potable reuse can decrease the demand on water reclamation projects. Nevertheless, reusing wastewater for non-potable applications additionally involves different pipe frameworks, which can be a critical cost depending on the place and distance over which the reclaimed water must be disseminated. In order to decide on the more efficient water supply alternative for their society, the water management authorities ought to consider non-financial expenses and advantages of water reuse projects such as surface and groundwater augmentation during periods of dry seasons and high ecological impact (Herman *et al*. 2017).

CONCLUSION

The depletion of sustainable water resources in SA and other arid and semi-arid countries is a major issue. Moreover, there is an imbalance between water supply and demand because of increased population growth, urbanization, climate change impacts and advancements in the country that contribute to the increased water demand. Another problem that is indirectly contributing to the depletion of quality water resources is water pollution caused by discharges of insufficiently treated wastewater effluent (de facto reuse). Although de facto reuse is important for the augmentation of surface water when there is limited water supply, it poses serious risks to human health by exposing people to micro-organism-induced illnesses. In addition, the CECs occurring in de facto wastewater effluents inhibit the growth and reproduction of aquatic animals. Therefore, environmental and

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health laws should be enforced in order to ensure that many of the South African communities that depend on these polluted raw water sources for their water supply are adequately protected. According to the National Academy of Engineering (NAE), one of the top ten research needs for human health, social and environmental studies is the quantification of de facto reuse (Wang *et al.* 2017). The significance of quantifying de facto reuse is that it will enable the identification of potential health risks of reusing insufficiently treated wastewater. In addition, data on the extent of de facto reuse is necessary to inform water treatment facilities about the need to develop methods and water treatment trains that target the reduction of CECs from wastewater. Therefore, there is a need to develop methods such as a GIS-based models for the quantification and mapping of SA water bodies polluted by de facto wastewater reuse. Such a model can also be used by water management authorities to make well-informed decisions regarding water quality issues. In SA, the best wastewater tracer for validating the GIS model is caffeine due to its abundance in surface water and fairly good stability.

ACKNOWLEDGEMENTS

The authors would like to thank the Nanotechnology Water Sustainability (NanoWS) Research Unit, the University of South Africa (UNISA), and Water Research Commission (WRC) for financial support, and the Department of Geography UNISA for additional Intellectual support.

DECLARATION OF INTERESTS

None.

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