An Investigation into Water and Sanitation in the Eastern Cape Province and Potential for Implementation of Biotechnology Platforms

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Abstract

In contemporary South Africa, a country in transition, destruction rather than reconstruction seems commonplace. Electricity supply is at an all-time low and ‘load shedding’ is an almost daily occurrence. Similarly, more fragility of water delivery and sanitation service is being reported with the likelihood of ‘water shedding’ a soon-to-be reality. In view of the ever-increasing reported mismanagement of South Africa’s water and sanitation infrastructure, which is likely nearing the point of collapse if not already collapsed, this thesis set out to interrogate at a provincial and municipal level the status of water and sanitation in Chris Hani District Municipality (CHDM), Eastern Cape Province. One major driver behind this study was to evaluate provincial and municipal water/wastewater infrastructure as a platform to support implementation of locally developed bioprocess technologies. First, publicly available historical data was used to derive a baseline or benchmark from which to determine gains/losses in compliance, water quality and efficiency. The period 2009-2013/4 during which Blue and Green Drop reporting was routine, was used as an appropriate start point. Data thus derived indicated that, at provincial and district municipality (DM) level, potable water supply was by bulk water schemes and, sanitation was typically by waste stabilization pond (WSP) treatment of municipal sewage. The derived benchmark for the period 2009-2013/14 indicated that most plants were not compliant (~75% of the Eastern Cape Province water treatment plants (WTP) operating between average performance to critical state), operated either at- or above design capacity (Eastern Cape Province, 16%; CHDM, 19%). A large number of plants for the province (62.4%) and district (81.25%) had hydraulic design capacity or average daily flows that were unknown (information not provided in available literature or plant reports) and final effluent did not always meet the general standard (70.3% of the CHDM wastewater treatment works (WWTW)). To determine the contemporary state (2020 - 2022) of water and sanitation within CHDM, a scoping exercise of WTP and WWTW in selected local municipalities was carried out. This was done along a west-east transect by appraising WTP and WWTW in the towns of Cradock, Tarkastad, Komani, Tsomo, Cacadu, and Ngcobo. Furthermore, targeted assessment of the Queenstown WTP and the Cradock WWTW was used to derive real-time data on the status of water and sanitation infrastructure. Results showed that water and sanitation services within CHDM had, in the years between 2009-2013/14 to date, deteriorated. Freshwater demand significantly exceeded capability of water supply schemes, where demand was as much as three times greater than reported available supply. For most WWTW, operation was in excess of capacity and between 1.52 and 12 times installed hydraulic loading. The targeted scoping exercise revealed that Queenstown WTP is a moderate risk plant (Cumulative risk rating, CRR = 11 and maximum risk rating, MRR = 47.8%), whereas Cradock WWTW was in working condition but with challenges and some infrastructural dysfunction. Assessment of water/effluent quality revealed that turbidity and TOC were above SANS 241 general limit. Non-compliance in terms of nitrate/nitrite-N, ammonium-N, phosphate-P, TSS, total coliforms, *E. Coli*, and free chlorine was evident at Cradock WWTW. Unstructured interviews with plant operators corroborated these findings. The overwhelming support for bulk schemes for potable water provision and WSP for sanitation indicated a partially water secure municipal district but derelict in terms of its sanitation services. The later, it was concluded, in particular provides an ideal opportunity for implementation of platform technologies to support bioprocesses for entrepreneurship, employment, economic benefit and to secure a closed circular economy for regional water and sanitation through valorisation of co-product streams. Among the co-product streams considered in this thesis are biomass, biogas, biofertilizers, biofuels and several high value chemical products.

Acknowledgements

I would first like to thank my thesis supervisor Professor A. Keith Cowan of the EBRU at Rhodes University. Professor Cowan was always available on his email and zoom meetings whenever I ran into a trouble spot or had a question about my thesis or writing. He consistently allowed this paper to be my own work by reading my numerous revisions and helped make some sense of the confusion, but steered me in the right direction whenever he thought I needed it.

I would also like to thank the experts who were involved in the plant surveys for this research project: Director of technical services (CHDM), plant manager, plant operators and water quality technician of Queenstown WTP and Cradock WWTW. Without their passionate participation and input, the surveys could not have been successfully conducted.

To Queen’s College Boys’ High School, thank you for all the support especially the SGB chairperson Mr Allister van Schoor and the headmaster Mr Janse van der Ryst. Working at such a busy school and studying is never easy, but you allowed me to pursue this not so easy journey.

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LIST OF ABRREVIATIONS

AFP:	Advanced facultative pond
AIWPS:	Algal Integrated Wastewater Pond Systems
AO:	Advanced Oxidation
AS:	Activated sludge
ASP:	Algae settling pond
AU:	Arbitrary units
BOD:	Biological Oxygen Demand
BORDA:	Bremen Overseas Research & Development Association
BTF:	Bio/trickling filters
CAA:	Commercial activated alumina
CAC:	Commercial activated carbon
CHDM:	Chris Hani District Municipality
COD:	Chemical oxygen demand
CW:	Constructed wetlands
DEWATS:	Decentralised wastewater treatment systems
DM:	District Municipality
DO:	Dissolved oxygen
DWA:	Department of water affairs
DWS:	Department of water and sanitation
EBRU:	Environmental Biotechnology Rhodes University
EC:	Electrical conductivity
EPS:	Enhanced pond systems
EPS:	Extracellular polymeric substances
FAO:	Food and Agriculture Organization
GHG:	Greenhouse gas
GHS	General Household Survey
HRAOP:	High rate algae oxidation pond
HRAP:	High-rate algal pond
I&I:	Inflows and infiltration
IAPS:	Integrated Algal Pond Systems
IEA:	International Energy Agency
IPCC:	Intergovernmental Panel on Climate Change

IPD:	In-pond digester
LCA:	Life cycle assessment
LM:	Local Municipality
MF:	Microfiltration
MPS:	Maturation pond series
OECD:	Organisation for Economic Cooperation and Development
OP:	Oxidation ponds
PBR:	Photobioreactors
PE:	Person equivalent
PETRO:	Pond Enhanced Treatment and Operation
PFP:	Primary facultative pond
PfW:	Partners for Water,
RBC:	Rotating biological reactors
RSA:	Republic of South Africa
S:	Supplementary
SFCW:	Surface flow wetlands
SSF:	Slow sand filtration
SSFCW:	Subsurface flow wetlands
TSS:	Total suspended solids
UN:	United Nations
UV:	Ultra Violet
WAO:	Wet air oxidation
WRC:	Water Research commission
WSP:	Waste stabilisation ponds
WT:	Water treatment
WTP:	Water treatment plants
WULA:	water use license application
WWBR:	Wastewater biorefineries
WWT:	Wastewater treatment
WWTW:	Wastewater treatment works
ZAR:	South African Rand

Chapter 1: General introduction

Water supply and sanitation in the Republic of South Africa is characterised by both successes and challenges. With onset of the democratic era post-1994, the newly elected government struggled with a growing basic service delivery impasse and backlogs with respect to access to water and sanitation. A strong commitment was therefore made to ensure high service standards and substantial investment/subsidisation to achieve these goals (Herbig, 2019). Since then, the country has made progress with regard to improving access to water and provision of sanitation, but is still, for the most part, failing to meet minimum standards, especially in rural areas and informal settlements while service delivery in towns and cities is rapidly declining.

A major contributing factor to the current state of water reticulation and sewerage is the fact that South Africa's municipal systems have largely collapsed. Of the 820 WWTW, it is estimated that only 60 release clean water (Kings, 2017b). Raw or partially treated wastewater flows into rivers across the country, turning dams green, relaying waste to fragile ecosystems and harming people who use and consume the polluted water. From large metros, such as Johannesburg, to smaller rural towns, water that is flushed either frequently escapes from broken pipes or treatment plants meant to remediate the waste and produce water safe for discharge. Odendaal (2017), in fact mentions that the civil rights organisation AfriForum found that water in three municipalities in South Africa failed to meet the national standards for quality drinking water, while 59 failed to meet the set quality standards for sewage systems. The water tests conducted by AfriForum showed worrying results, especially in terms of poor sewerage management and indicated the "continuous decline in infrastructure and a lack of skilled personnel to manage water bodies." AfriForum, furthermore, revealed a drastic decline in the management of WWTW in South Africa, with an average of 67% of South African plants not functioning within the regulatory requirements. These 59 WWTW that do not meet standard pose a threat to human health, food security and the environment (Odendaal, 2017).

South Africa is comprised of 9 provinces. According to Odendaal (2017), the wastewater issues in these provinces is currently as follows: Fifteen towns across 5 municipalities in southern and northern Gauteng (the most populated province) do not comply with the national water quality standards, while 7 towns in 4 municipalities in the Western Cape failed to meet requirements. Twelve towns spread across 11 municipalities in Mpumalanga and 6 towns spread across 6 municipalities in North West also present with subpar water treatment quality. The Northern Cape (the most sparsely populated province) was home to 2 towns across 2 municipalities with poor quality sewage treatment, and in the Eastern Cape Province, towns in 5 municipalities fell short. Four municipalities from Limpopo and KwaZulu-Natal each found themselves on the list, along with 3 towns in 4 municipalities in the Free State (Odendaal, 2017).

As a case in point, Kings (2017a) affirms that in the past 6 years, 36 WWTW around the country have been visited with few working properly. Kings (2017a) relates how, at one plant in the Limpopo province, operators use a handbook with a third of its pages missing to calculate how much chlorine and lime to add to their treatment process. The ratio, meant to be informed by sampling and laboratory results, was by guesswork alone. An operator confessed that they got the job because they knew the plant's manager (Kings, 2017a).

Reprehensibly, it is not a new problem. In its 2006 State of Municipal Infrastructure report, the Council for Scientific and Industrial Research (CSIR) found that plants were "producing effluent that is almost indistinguishable from raw sewage entering the works" (Kings, 2017a). This was blamed on "gross under budgeting by the municipality" and "managers who have insufficient understanding of the technology of WWT". It concluded that it was "illogical to build more WWTW without addressing the underlying factors that lead to the failure of this infrastructure" (Kings, 2017a). Twelve years later, it appears from the dismal record of the study outlined in this article, that the situation has deteriorated even more and that the end is not yet in sight. Ironically, instead of upholding the well-known principle of "the polluter pays", sanitation authorities seem to subscribe to a new principle, namely, "pay the polluter" (themselves). According to this new principle, the responsible sanitation authorities pay the emitter/degrader/bad guy a bonus to not pollute (i.e. polluter receives a subsidy) (Haab, 2008).

Water supply and sanitation in South Africa is characterised by both successes and challenges. The country has made some progress with regard to improving access to water supply: The General Household Survey (GHS) 2018 released by Statistics South Africa (Stats SA) found that substantial progress has been made in service delivery over the years. GHS data show that households' access to drinking water (89,0%) was most common in 2018 and, improved sanitation (83,0%). South Africa also has a strong water industry with a record of accomplishment in innovation (Odendaal, 2019). Significant problems remain concerning the financial sustainability of service providers, leading to a lack of attention to maintenance. The uncertainty about the government's ability to sustain funding levels in the sector is also a concern. Two distinctive features of the South African water sector are the policy of free basic water and the existence of water boards, which are bulk water supply agencies that operate pipelines and sell water from reservoirs to municipalities.

The deteriorating state of municipal water and sanitation management in South Africa is one of the largest contributing factors to the numerous pollution problems experienced in most parts of the country and a major contributor to environmental and human health problems. The state's inability to fulfil its basic mandate on all three spheres of governance (national, regional, and local) of effectively protecting the rights and property of all persons (natural and juridical), frustrates economic growth, and is paralleled only by its neglect of limited natural resources. Herbig (2019) provides a metaphysical overview of proximate and diffuse causes of environmental and social issues impacted by this Manichean form of thinking, placing in context the increasingly opaque silhouette of the interface between wastewater mismanagement (irreverence), on the one hand, and the enviro-social impact (victimisation) thereof on the other.

Rapid urbanisation, together with accelerated economic development in South Africa, is placing enormous strain/stress on urban, peri-urban, and rural environments, especially in the underdeveloped areas of South African cities and towns (communities). This is evidenced by an estimation that during 2015, eighty percent (80%) of South Africa's fresh water resources were so badly polluted that no purification processes in the country could make it fit for consumption. Lack of investment in infrastructure to cater for the massive increase in strain has suffocated a system designed for use by a few, which is now used by so many. An exponential growth in waste volumes has accompanied this trend but appears to have been inadequately catered for by those entities responsible for its management.

Widespread corruption and endogenous malfeasance, especially in the municipal sector, has augmented the problem of effective waste abstraction and created serious contamination and health issues across the board. Although derisory wastewater mismanagement may appear to be just another local government indiscretion in a growing list of failures, it does unfortunately have undertones that are more insidious (Herbig, 2019).

Water treatment renders surface water potable while WWT is a process that repairs and coverts polluted water from an unusable state into an effluent that can be either returned to the water cycle with minimal environmental impact or reused for other purpose e.g. irrigation. This is important for fisheries, wildlife habitats, recreation and quality of life, and health concerns. If it is not properly cleaned, spread of pollutants increases and the risk of disease is exacerbated. Water treatment is crucial for health and allows humans to benefit by having a constant supply of potable water whereas WWT eliminates and/or reduces the level of contaminants to ensure an effluent of a quality for intended use. WWT is increasingly necessary to subvent drinking water shortages. Of the planet's total water reserves, only 2.5% is freshwater - and of this amount, only 0.4% is water that is fit for human consumption (Lionsgate water treatment, 2020).

By 2050, the human population is forecasted to exceed 9.6 billion. We will require 70% more food (FAO, 2011), 50% more fuel (IEA, 2019), and 50% more water (OECD, 2013). We also need to reduce CO_2 emissions by over 80% (IPCC, 2018). These targets need to be achieved to ensure economic, social, political, climate, food, fuel and water security. Photosynthetic organisms use solar energy to incorporate atmospheric CO_2 into organic molecules with a net gain in carbon. Therefore, photosynthesis mitigates climate change by counteracting increased levels of atmospheric CO_2 and, the produced biomass also provides food and livestock feed, fibre, and can even be used in technical processes to generate valuable products including biofuels and clean water. One approach to address these challenges is to recycle wastewater and CO_2 to fuel- and/or chemical-products using photosynthesis and a hypothetical bioprocess as illustrated in Figure 1.1. Hydrothermal carbonization (HTC) is an induced coalification process that converts raw biomass into a coal-like product, called hydrochar, characterized by high carbon content and high calorific value. This type of thermo-chemical conversion, also referred to as wet pyrolysis (or wet torrefaction), can be applied to a variety of non-traditional sources such as the organic fraction of municipal sewage sludge (Lucian et al., 2017)

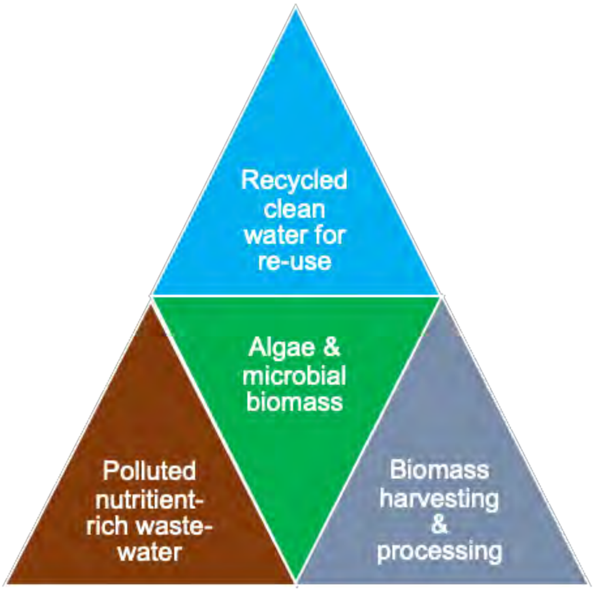


Figure 1.1 *Schematic of integrated biotechnological solution for recycle of clean water for re-use. Wastewater containing nutrients and pollutants is treated to produce an immobilized algal biomass for harvest and processing e.g. biochar generation by hydrothermal carbonization.*

Microalgae and cyanobacteria are amongst the most productive photosynthetic organisms on Earth. Microalgae have been reported to obtain higher effective photosynthetic efficiency than energy crops, their biomass can be doubled in just a few hours (i.e. as short as 3.5 h) and they have been shown to synthesize 20 times more oil per hectare than terrestrial plants (Amaro et al., 2011). Furthermore, microalgae can be cultivated on marginal land without affecting food production (Hallenbeck et al., 2014, Ho et al., 2014), are able to use industrial flue gas as a carbon source (Mata et al., 2010), and abstract nutrients from municipal or industrial wastewater. This notwithstanding, researchers have used microorganisms in an effort to explore and develop systems to mitigate CO_2 emissions and produce biofuels (Gouleke et al., 1957; Benemann et al., 1977, 1997; Chisti, 2007; Laubscher and Cowan 2020) with particular attention to the development of highly productive bioreactors using genetically manipulated algae to produce food and feed, cosmetics, healthcare products or biofuels. However, in most of these studies, large-scale cultivation of microorganisms appears unsustainable due to the high cost of fertilized media. Furthermore, separation of the biomass from the culture medium has proved prohibitively expensive and a major limitation in the scale-up of microalgal bioprocess systems.

In this thesis, a benchmark for water and sanitation in the CHDM, Eastern Cape Province will be determined. This will be followed by an assessment of the current state of water and sanitation in selected municipalities in Chris Hani District, Eastern Cape Province where a reductionist approached is employed by starting assessment at the provincial level, followed by the district level and lastly along a transect from East to West, within the district.

The data obtained will be assessed in order to address and answer the question: why biotechnology solutions, specifically integrated algal pond systems (IAPS), to water and sanitation have been largely overlooked for implementation by municipal service providers in South Africa? IAPS is a derivation of the Oswald-designed algal integrated wastewater pond systems (AIWPS) and like the New Zealand-developed, EPS, combine the use of anaerobic and aerobic bioprocesses to effect sewage treatment (Laubscher & Cowan 2020; Sutherland & Ralph 2020).

1.1 Status of water and sanitation treatment in South Africa

1.1.1 The water and sanitation framework (water and wastewater quality standards) in South Africa

After 1994, the South African government made a strong commitment to high service standards and high levels of investment were invoked to achieve those goals. Since then, the country has made some progress with regard to improving access to water supply and sanitation, but is still, for the most part, failing to meet minimum standards, especially in rural areas and informal settlements (Herbig, 2019). Contributing to this state of affairs is the fact that South Africa's municipal sewage treatment system has largely collapsed and this is most evident in smaller towns and cities. Of the estimated 824 treatment plants nationally, only 60 are considered to release clean water to river (SA facing wastewater pollution problem, 2010; Kings, 2017).

South Africa needs to reduce water demand and increase supply for its growing population and economy to ensure water security by 2030. In light of this target, the 2020/22 Annual Performance Plan presented by the Department of Water and Sanitation (DWS) reported that South Africa faces a projected water deficit of 3% by 2040 if it did not successfully implement the planned measures to reduce water demand and increase supply for its growing population.

Water service refers to water supply and sanitation services and includes regional and local water schemes, on-site sanitation and collection and treatment of wastewater. Water and wastewater services are also essential for businesses and industries and efficient provision of these services can help to promote economic development and the eradication of poverty. South Africa is generally well-endowed with infrastructure and has plans to maintain investment and improve management of this resource. While dispersed and decentralised, substantive data on condition of municipal water infrastructure assets indicates that these are not in good shape outside metropolitan and similar large urban areas.

Wastewater discharge standards are set (at least) at national level for centralized treatment systems and are appropriate for receiving environments. Key features of a water body from a discharge perspective include assimilative capacity i.e., maximum amount of pollution that can be diluted or degraded without affecting preliminary defined designated best uses (Schellenberg et al., 2020). Effluent discharge standards can be concentration-based or load-based (Schellenberg et al., 2020). Concentration-based standards are the most common, specify a permissible mass of pollutant unit volume, and usually designated as, mg/L e.g. (DWA, 2013, 2015). A limitation of concentration-based standards can be that it does not promote WWT, since dilution can be used to meet the discharge standard (Schellenberg et al., 2020). Load-based standards harmonize concepts of ambient water quality and effluent discharge through risk modelling of the water body. The total maximum daily load allocates the threshold value for a pollutant that will ensure compliance with a desired water quality standard based on stakeholder preference for the use of that water body (Schellenberg et al., 2020).

In terms of water quality standards, the limits and associated risks for domestic water as determined by the South African National Standard (SANS) 241:2015 are as follows, where:

- Health risks: parameters falling outside these limits may cause acute or chronic health problems in individuals.
- Aesthetic risks: parameters falling outside these limits indicate that water is visually, aromatically or palatably unacceptable.
- Operational risks: parameters falling outside these limits may indicate that operational procedures to ensure water quality standards are met may have failed.

The use, storage, and/or disposal of biodegradable industrial wastewater, that is wastewater which contains predominantly organic waste from industrial/commercial activities, is classified as a Section 21(e) and/or 21(g) water use activity by the National Water Act 36 of 1998 (NWA). According to Department of Water Affairs – general and special authorisation, discharge limits and conditions are set out in the National Water Act, Government Gazette No. 20526, 8 October 1999. The wastewater limit values applicable to discharge of wastewater into a water resource. The National Water Act, 1998 (Act 36 of 1998), the National Environmental Management Act, 1998 (Act 107 of 1998) as amended, and the Environmental Conservation Act, 1989 (Act 73 of 1989) all focus on pollution and water and wastewater management in South Africa. As spelt out by the South African Constitution, 1996 (Act 108 of 1996), the Municipal Structures Act, 1998 (Act 117 of 1998), Municipal Systems Act, 2000 (Act 32 of 2000) and the Water Services Act of 1997 (Act 108 of 1997), responsibility for the provision of water and sanitation services lies with water services authorities (WSA), which the Water Services Act defines as “the municipalities”.

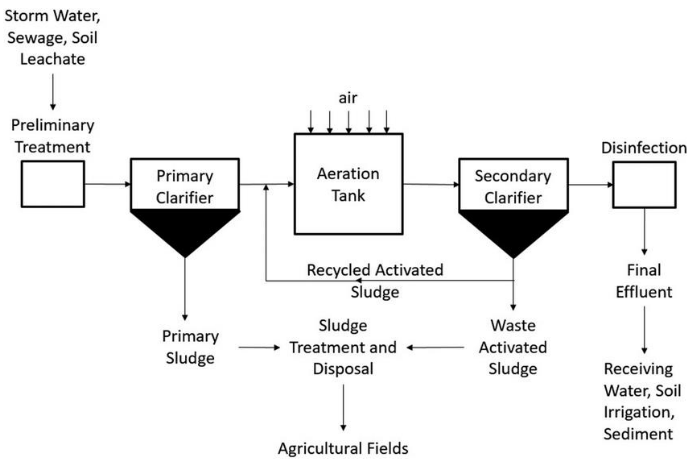
Ntombela et al. (2013) define Water Services Authorities (WSAs) as “any municipality responsible for ensuring access to water services.” As set out in the Water Services Act, WSAs are responsible for planning, implementing and operating the necessary infrastructure to provide water services to their customers. According to the Department of Water Affairs (2013) local governments (Metro, Local or District Municipalities) act as the Water Services Authorities (WSAs) and often also Water Service Providers (WSPs) for all communities in their areas of jurisdiction. The Department of Water and Sanitation (DWS) ensures that wastewater will be treated to a quality consistent with the health-based and environment targets (van der Merwe-Botha & Manus, 2011). The roles of DWS include setting limits, issuing licences, and regulating effluent releases. For example, DWS has issued legislation and guidance documentation to ensure that monitoring is being undertaken according to General and Special Standards: Government Gazette 18 May 1984 No. 9225: Regulation No. 991 18 May 1984: Requirements for the Purification of Wastewater or Effluent (van der Merwe-Botha and Manus, 2011). DWS monitors performance through a risk-based assessment called the "Green Drop" and "Blue Drop" certification processes. Mitchell et al. (2014) says, "The poor performance of wastewater treatment works (WWTW) in protecting the health of the water resource has necessitated that the DWA take action to rectify the situation. The DWA has adopted a two-tiered approach i.e. Green Drop and Blue Drop certifications."

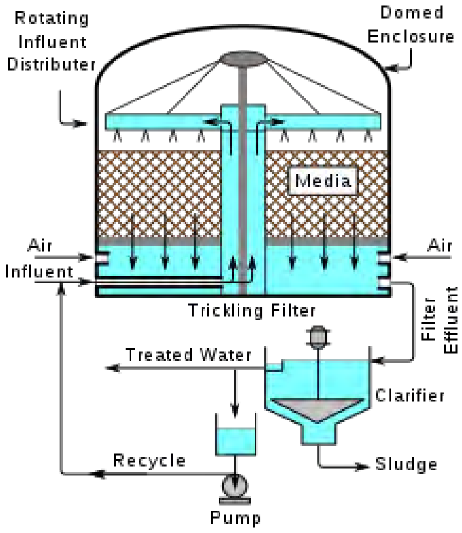
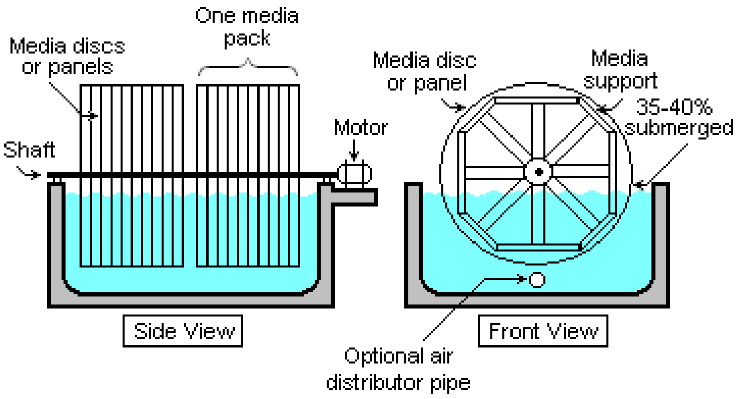
The Blue Drop and Green Drop Certification Programmes are forms of Incentive-based Regulation (IBR) pioneered by the South African Water Sector since 2008 (Manus, 2022). The Department of Water and Sanitation implemented the Blue Drop programme with the objective to encourage and acknowledge continuous improvement and performance excellence in drinking water services management in South Africa using incentive, risk and benchmarking. This programme also sought to provide the South African public with credible and transparent results on the status of their drinking water quality and the water services institutions that supply their water (WIN-SA, 2015). On the other hand, the Green Drop certification programme was designed to serve as a stimulus for change; a catalyst to establish motivation and leadership in the water sector regarding the management of wastewater services. The aim of the Green Drop programme was to create a paradigm shift by which wastewater operations, management and regulation is approached. By promoting incentive-based regulation, it thrived establish excellence as the benchmark for wastewater services (Burges, 2016). The two main outputs from the Green Drop assessment are Green Drop score for each municipal system assessed, and the Cumulative Risk Rating for each municipal wastewater treatment work calculated.

1.1.2 Types of process technologies

The most commonly used wastewater treatment technologies in South Africa include activated sludge, bio/trickling filters, rotating biological reactors, wastewater ponds, membrane bio-reactors, wetlands and aerobic granular activated sludge (e.g. Nereda, an emerging technology) (Jack, 2016). These technologies, as used by most municipalities across South Africa to treat water and wastewater are as listed in Table 1.1.

Table 1.1 *Water and WWT technologies available for use in South Africa and a brief description of general biological treatment technologies [Adapted from Mambo, 2014].*

Technology	Brief description	Reference
Activated sludge system (AS)	Involves air being introduced into primary treated wastewater combined with microorganisms that decrease the organic content of the water stream. The process itself involves disturbing and agitating sewage in an environment that is rich in naturally occurring oxygen. Requires adequate land Requires a buffer strip between human settlement and residential areas. Focused on a medium sized plant, suitable for large volumes of wastewater (>2,000 m^3/day). Requires little land area. Type of effluent is domestic and industrial. Size of contributing community is Ranges from 20 000 to 100 000 persons. Highly efficient treatment method where discharge standards are strict with respect to phosphate. High cost (Approximately R13-15 million/megalitre treated). Requires reliable electrical power.  ***Figure 1.2*** *Activated sludge wastewater treatment process flow*	(Tammaro et al. 2014). Diagram from Sanderson et al. (2016)
Bio/trickling filters	Involve living material capturing and biologically degrading pollutants. Examples include constructed wetlands (CW), slow sand filtration systems and Riparian zones/forests. It is a combination of a biofilter and a bio-scrubber and are primarily used to remove gases with acidic components. Small and medium size plant. 0.5-10Ml/day. Type of effluent is domestic. Size of contributing community is 5000-50 000 persons. Medium cost (Approximately R7-9 million/megalitre). Requires electrical power supply though the trickling filter unit does not necessarily require electricity. Requires reliable electrical power.	(Tomar & Suthar, 2011)

	 ***Figure 1.3** Biological trickling filter process flow*	Diagram from Mukhtar et al. (2020)
Rotating biological contactors	Here closely spaced parallel discs with a biofilm layer are introduced to wastewater the microorganisms in the biofilm take up the nutrients while degrading any organic compounds in the wastewater. Small and medium size plant. 500-10,000 m^3/day. Requires minimal land area. Type of effluent is domestic. Size of contributing community is 5000-50 000 persons. Medium cost (Approximately R7-9 million/megalitre treated). Requires reliable electrical power. Incorporate more instrumentation and automated process control Requires high level of reliability with respect to mechanical equipment.	(Teixeira et al., 2001; Buchanan et al., 1994)
	 ***Figure 1.4** Schematic of a rotating biological contactor*	Diagram from Ranathunga (2017)
Waste stabilisation ponds (WSP)	These are large, man-made water bodies in which blackwater, greywater or faecal sludge are treated by natural occurring processes and the influence of solar light, wind, microorganisms and algae. Typically applicable in micro to small plant size. Suitable in small/low flow volumes (500-2,000 m^3/day). Requires adequate land Requires a buffer strip between human settlement and residential areas. Type of influent is domestic, industrial, agricultural. Size of contributing community <5,000 persons. Costs (in terms of municipal affordability) Based on the current (2015/2016 industry norms) Low capital cost (Approximately R2-4 million/megalitre treated). Suitable in areas where there is minimal electricity supply.	(Jack et al., 2016)

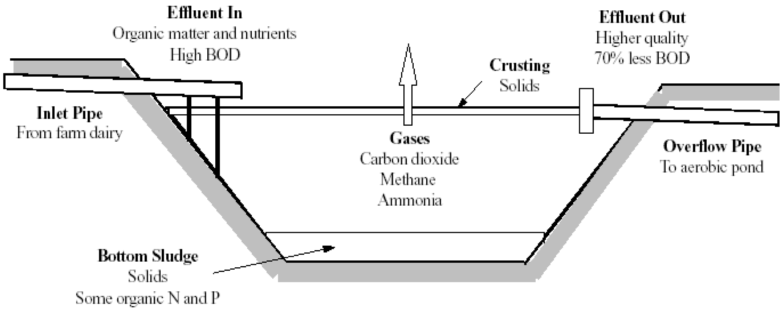


Figure 1.5 *Schematic of a waste stabilization pond*

Diagram from Shamrukh (2005)

Membrane bio-reactors	Connect membrane filtration to a biological active sludge system. Suitable for where plant capacity is needed, suitable for large volumes of wastewater. Requires little land area. Type effluent is domestic and industrial. Size of contributing community ranges from 20,000 to 100,000 persons. Highly efficient treatment method where high quality treated wastewater is required, especially for reclamation and reuse.	(Jack et al., 2016)

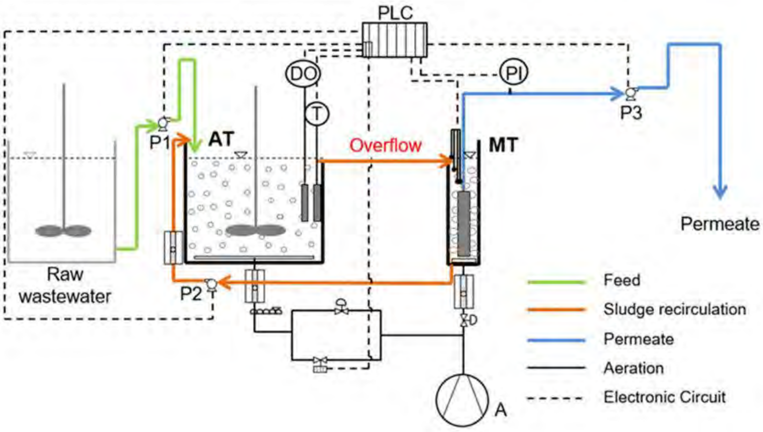


Figure 1.6 *Membrane bio-reactors process flow*

Diagram from Dimitra et al. (2020)

Constructed Wetlands (CW)	An artificial marsh built to act as a biofilter removing sediments and contaminants such as heavy metals from wastewater. Typically applicable in micro to small plant size. Suitable in small/low flow volumes (500-5,000 m^3/day. Requires adequate land. Type of effluent is treated. Low capital cost (Approximately R2-4 million/megalitre treated). Suitable in areas where there is minimal electricity supply.	(Travis et al. 2012, Kaseva 2004, Kivaisi 2001)

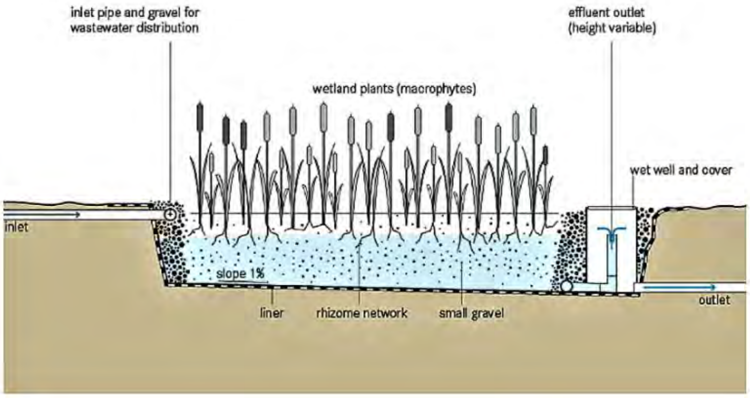


Figure 1.7 *Schematic of the Horizontal Subsurface Flow Constructed Wetland*

Diagram from Tilley et al. (2014)

Proprietary aerobic granular AS processes such as Royal HaskoningDHV's Nereda®	Nereda is a wastewater treatment technology that relies on aerobic biological action to purify wastewater before returning clean water to the environment through proprietary aerobic granular sludge technology. Size of contributing community <5,000 persons. Focused on a medium sized plant, suitable for large volumes of wastewater (10,000 m^3/day). Requires little land area especially where there are land restrictions. Type of effluent is domestic and industrial. Size of contributing community ranges from 20,000 to 100,000 persons. Highly efficient treatment method where strict Nitrogen and Phosphorus discharge standards are required. Requires reliable electrical power.	(Jack et al., 2016)

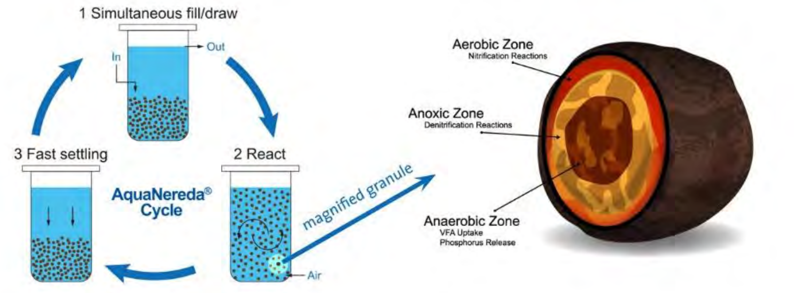


Diagram from Aqua-Aerobic Systems, Inc. (Accessed 12.09.2022)

Figure 1.8 *Process flow of the Nereda® technology*

Coagulation	Coagulation is often the first step in water treatment. During coagulation, chemicals with a positive charge are added to the water. The positive charge neutralizes the negative charge of dirt and other dissolved particles in the water. When this occurs, the particles bind with the chemicals to form slightly larger particles. Common chemicals used in this step include specific types of salts, aluminum, or iron.	(CDC, 2022)

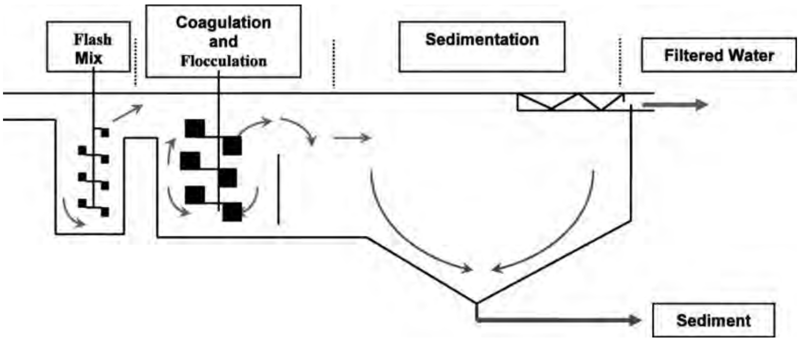


Diagram from Ebeling (2003)

Figure 1.9 *The coagulation/flocculation unit process flow*

Flocculation	Flocculation follows the coagulation step. Flocculation is the gentle mixing of the water to form larger, heavier particles called flocs. Often, water treatment plants will add additional chemicals during this step to help the flocs form.	(CDC, 2022)
Sedimentation	Sedimentation is one of the steps water treatment plants use to separate out solids from the water. During sedimentation, flocs settle to the bottom of the water because they are heavier than water.	(CDC, 2022)
Filtration	Once the flocs have settled to the bottom of the water, the clear water on top is filtered to separate additional solids from the water. During filtration, the clear water passes through filters that have different pore sizes and are made of different materials (such as sand, gravel, and charcoal). These filters remove dissolved particles and germs, such as dust, chemicals, parasites, bacteria, and viruses. Activated carbon filters also remove any bad odours. Water treatment plants can use a process called ultrafiltration in addition to or instead of traditional filtration. During ultrafiltration, the water goes	(CDC, 2022)

	through a filter membrane with very small pores. This filter only lets through water and other small molecules (such as salts and tiny, charged molecules).	
Disinfection	After the water has been filtered, water treatment plants may add one or more chemical disinfectants (such as chlorine, chloramine, or chlorine dioxide) to kill any remaining parasites, bacteria, or viruses. To help keep water safe as it travels to homes and businesses, water treatment plants will make sure the water has low levels of the chemical disinfectant when it leaves the treatment plant. This remaining disinfectant kills germs living in the pipes between the water treatment plant and your tap. In addition to or instead of adding chlorine, chloramine, or chlorine dioxide, water treatment plants can also disinfect water using ultraviolet (UV) light or ozone. UV light and ozone work well to disinfect water in the treatment plant, but these disinfection methods do not continue killing germs as water travels through the pipes between the treatment plant and your tap.	(CDC, 2022)

1.1.3 Advantages and disadvantages of common municipal wastewater treatment technologies

The most commonly used WWT technologies in South Africa include Activated Sludge (AS), bio/trickling filters (BTF), rotating biological reactors (RBC), waste stabilisation ponds (WSP), membrane bio-reactors, CW and proprietary aerobic granular AS processes such as Royal HaskoningDHV's Nereda® (Adewumi et al., 2010; Oller et al., 2011; Tomar and Suthar, 2011).

Figure 1.10 shows the range of WWT technologies presently used in South Africa (DWA, 2012). The main technology used in CHDM appears to be WSP commonly referred to as oxidation ponds (OP).

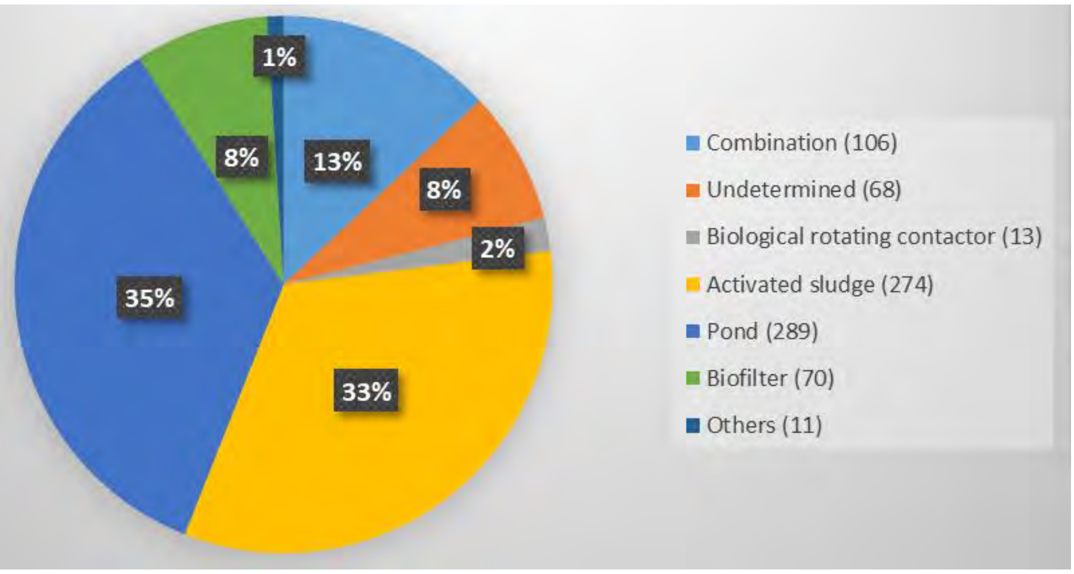


Figure 1.10 *Types of WWT technologies implemented across South Africa.*

There are various aspects to consider in selection of an appropriate WWT technology, which, in many instances is largely influenced by effluent quality standards. However, amongst other things; operations, maintenance, sludge management, financial issues and day-to-day running of the facility also need to be considered. Design, operations, maintenance and institutional resources should guide the process of selecting a preferred technology. Thus, best practice requires that factors such as availability and price of land, population size and projected growth, plant size, flow rate, influent type, treated wastewater quality, re-use opportunities (water. energy, nutrients), sludge management, sensitivity of receiving water body/land, water use license requirements, capacity and local skills base, system operations and maintenance, available funding and cost to construct the facility, and consumer ability to pay (vd Merwe-Botha & Quilling, 2012; Ambulkar, 2018).

Some advantages and disadvantages of conventional water and sanitation methodologies used for the treatment of polluted water are as listed in Table 1.2.

Table 1.2 Advantages and disadvantages of the main conventional methods used for the treatment of polluted wastewater (Crini & Litchtfouse (2019)).

Process	Advantages	Disadvantages
Activated Sludge (AS)	• Not expensive to install, offers good return on initial investment. • High quality effluent • Require less room to install and operate. • Very few odours or pests involved, which makes hygienic, safe, and convenient operation easy. • Process is relatively efficient, and there should be very little loss of pressure within the system.	• Ongoing operating costs of aerating and recycling the sludge can be high • Sludge will need to be removed and disposed of after a while, and this can cause difficulties, as well as additional costs. • The process may not be suitable for all types of industrial wastewater, which may make it inflexible for some businesses. • The activated sludge may not remain activated and aerated at all times, which will severely affect the performance of the process. • Operational requirements are demanding. Competent and highly skilled staff is required. • Requires high level of reliability with respect to mechanical equipment. Requires a formal planned and preventative maintenance programme.
Bio/trickling filters (BTF)	• Biological decomposition of components; no VOC residual products • Suitable for decomposition of acid-forming components • pH checking and correction is possible under certain conditions • Low pressure drop • Average investment and operation costs	• Fluctuations in composition and load of incoming air have serious consequences for the yield • Components with poor solubility are difficult to treat • Toxic and high concentrations of acidic components must be avoided

	• Requires moderately skilled operating staff • Requires minimal land area • No strict Nitrogen and Phosphorus standards • Low maintenance.	• Packing can become blocked by biomass • More difficult to construct than a biofilter. • More expensive than a biofilter • Waste water flow created
Rotating biological contactors (RBC)	• No specially skilled personnel required • Substantially lower energy demand • Requires moderately skilled operating staff • No strict Nitrogen and Phosphorus standards • Low maintenance.	• Slightly lower treatment efficiencies for BOD, COD, TSS, N, P • Low pathogen removal • High cost (Approximately R13-15 Million/Ml)
Waste stabilisation ponds (WSP)	• Limited technological investment, low cost, cheap/unskilled labour, and minimal maintenance costs (Mara, 2003; Jiménez et al., 2010). • They are very effective at removing disease-causing organisms (pathogens) from wastewater. • Removal of pathogens is high. Removes high concentrations of COD. • They can handle intermittent use and shock loadings better than many systems, making them a good option for campgrounds, resorts, and other seasonal properties. • Requires low skilled operating staff	• Limitation of land availability in urban areas (Jiménez, 2006) • They are less efficient in cold climates. • Odour can become a nuisance during algal blooms. • Unless they are property maintained, lagoons can provide a breeding area for mosquitoes and other insects. • They are not very effective at removing heavy metals from wastewater.
Membrane bio-reactors	• Compact • High effluent quality • High volumetric load possible • High rate of degradation • Possible to convert from existing conventional active sludge purification	• Aeration limitations • Stress on sludge in external MBR • Membrane pollution • Competent and highly skilled staff is required
Constructed Wetlands (CW)	• Low cost • Easy to operate • Low maintenance • Good nutrient removal • Operates year round • Effective removal of organic compounds and heavy metal • Requires low skilled operating staff • Removal of Phosphates and Nitrates is high	• Limited income potential • Not effective use of nutrient resources • Not as effective as tertiary treatment • Requires a big surface area of land
Proprietary aerobic granular AS processes such as Royal HaskoningDHV's Nereda®	• Requires fewer chemicals than conventional wastewater treatments • Meets strict purification standards • Significant energy savings • No plastic support media • Cost effective • Excellent effluent quality, including biological nutrient removal • Easy to operate, i.e. automated and resilient • Small footprint • Low maintenance due to removal of mixers, recirculation pumps and settling tanks.	• Odours can be an issue • Competent and highly skilled staff is required • High cost (Approximately R13-15 Million/Ml)

Coagulation /flocculation	• Process simplicity • Integrated physicochemical process • Wide range of chemicals available commercially • Inexpensive capital cost • Very efficient for SS and colloidal particles • Good sludge settling and dewatering characteristics • Significant reduction in COD and BOD • Reduces total organic carbon and absorbable organic halogens (pulp and paper industry) • Bacterial inactivation capability • Rapid and efficient for insoluble contaminants (pigments, etc.) removal	• Requires non-reusable chemicals (coagulants, flocculants, aid chemicals) • Physicochemical monitoring of effluent (pH) • Increased sludge volume generation (management, treatment, cost) • Low removal of arsenic
Flotation Froth flotation	• Integrated physicochemical process • Different types of collectors (non-ionic or ionic) • Efficient for removal of small particles and can remove low-density particles which would require long settling periods • Useful for primary clarification • Metal selective • Low retention time • Used as efficient tertiary treatment in pulp and paper industry • Mechanisms: true flotation, entrainment and aggregation	• High initial capital cost • Energy costs • Maintenance and operation costs no negligible • Chemicals required (to control the relative hydrophilicities between the particles and to maintain proper froth characteristics) • Selectivity is pH dependent

Furthermore, there are many other water and sanitation methodologies used for the treatment of polluted water e.g. chemical precipitation, which involve uptake of pollutants and separation of products formed, however, these are not relevant to this study.

1.1.4 Market share of municipal water and wastewater Treatment

The South African industrial water and wastewater treatment chemicals market is projected to grow at a Compound Annual Growth Rate (CAGR) of 2.3% during 2019-25 (Research and Markets, 2019). The growth of the water and wastewater treatment market is driven by factors, such as the rapid population growth and urbanization, stringent water treatment regulations, the rising need for new water resources, the growing emphasis on water quality and public health, and the increasing prevalence of waterborne diseases. With such a huge investment in wastewater treatment and reuse-related capital improvement projects over the next 20 years, the demand in the market studied is expected to rise in the coming years. Hence, the municipal water and wastewater treatment industry is likely to dominate the market during the forecast period as shown in Figure 1.11 (Research and Markets, 2019).

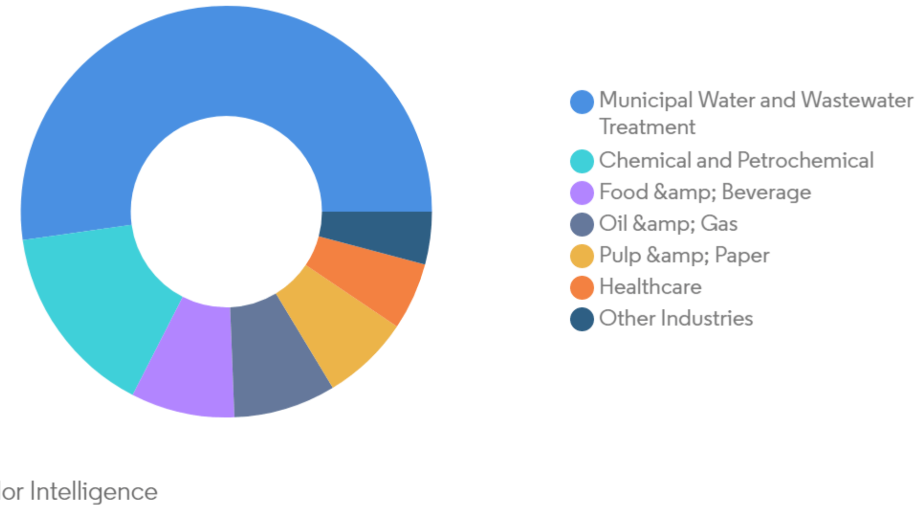


Figure 1.11 *Water and wastewater treatment technologies market, revenue (%), by end-user industry, global, 2021*

On a global scale, according to a new market research report titled, 'Water and Wastewater Treatment Technologies Market, by Type (Membrane Separation & Filtration, Sludge Management Technology, Activated Sludge), Application (Municipal, Residential, Industrial), and Geography—Global Forecast to 2029', the water and wastewater treatment technologies market is expected to reach $128.78 billion by 2029, at a CAGR of 5.4% from 2022 to 2029 (Meticulous Market Research Pvt. Ltd, 2022).

1.2 Biotechnology as a source of solutions

1.2.1 Biotechnology

Biotechnology is the use of biological organisms/systems and processes for practical or commercial purposes (Bajpai, 2018) with the aim to develop new products of industrial, agricultural, or therapeutic interest to improve the quality of human life. Here, biology is used to solve problems through the creation of breakthrough products and technologies to combat disease, protect the environment, feed the hungry, produce fuels, and make other useful products like high-value products e.g. biomass, and biogas (Shimasaki, 2014; Bajpai, 2018). Biotechnology provides processes/products where non-biological processes (like the ones stated above) are impractical, increases specificity in reactions, provides less environmentally deleterious process, saves energy, and decreases cost (Bajpai, 2018). Biotechnological methods present potential opportunities for changing the industry toward more environmentally friendly and efficient operations compared with the conventional methods. That is, biotechnological processes are environmentally friendly, energy efficient, and are more specific (Bajpai, 2018). In essence, biotechnology innovations may have the ability to simultaneously address societal challenges and produce economic benefits (National Academies of Sciences, Engineering, and Medicine, 2017).

1.2.2 Sustainability

Biotechnology, and in particular environmental biotechnology addresses environmental issues and concerns such as pollution of water and other natural resources by exploitation of biological processes, affords development and implementation of regenerative circular economic bioprocess solutions. Typically, these are passive, operate in perpetuity and for water, are largely solar and gravity driven, mostly unidirectional and balanced. Figure 1.12 is an attempt to diagrammatise this paradigm in the form of a water/ wastewater wheel and from the perspective of its operation from built environment (urban) to peri-urban space.

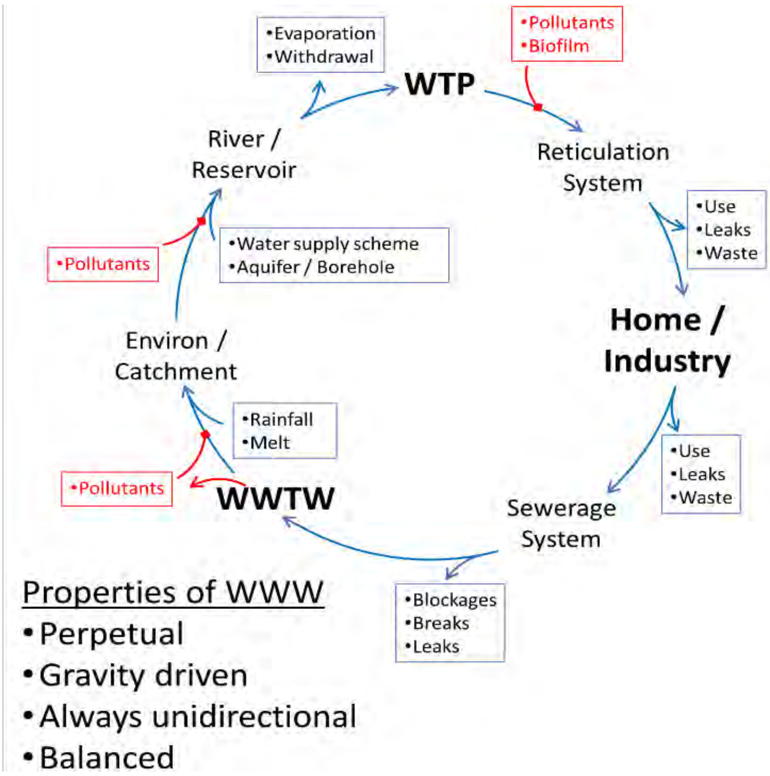


Figure 1.12 *Hypothetical anthropogenic water/ wastewater wheel as operational in the built environment and peri urban space.*

The cycle shown in Figure 1.12 differs from the hydrological cycle, which accounts for environmental condensation, precipitation and evaporation. Rather, this urban water/ wastewater cycle is an engineered system that brings clean water to, and removes used water, from each of us. The processes and people that operate this system are indeed the unsung heroes in a complex story playing out in every town, city and metro across the globe. The main pathway of water flow through this urban cycle includes loss of natural buffers (e.g. removal of natural vegetation, depressions, naked soil), reduced infiltration (e.g., rooftops, roads, parking lots, sidewalks, driveways), and engineered drainage (e.g., storm sewers, channels, detention ponds). Not surprisingly, elements of the broader hydrological cycle have been re-engineered, proportions altered, and flow (re)-directed to harness intercepted rainfall, run-off and precipitation (due to reduced infiltration, storage and evapotranspiration) and to manage frequency of peak flows to rivers which are typically much are higher in the built environment (Marsalek et al. 2006).

As a country, South Africa is already feeling the impact of resource constraints e.g. water, suggesting that sustainable resource use which is in many ways an outcome of biotechnology solutions implementation is critical for its future (Godfrey, 2021). Outdated water treatment and WWT methods like WSP are unsustainable in the long term, particularly in developing countries. To make water purification sustainable, a handful of companies are developing new technologies that aim to make water consumption part of a circular economy, which is designed to minimize and eventually eradicate waste and pollution, keep products and materials used in industry in use, and to continually regenerate natural systems (Albert, 2021).

1.2.3 Circular bio-economies

In addition to engineering an urban water/ wastewater cycle, bioengineering and particularly biotechnology potentially allow systems to mimic nature in the supply of water, remediate and repair wastewater and in the process, produce co-product streams that can be valorised. Thus, emergence of regenerative circular economic water and WWT bioprocesses.

Circular economies in water treatment and WWT are rapidly being introduced in some countries (Verstraete et al., 2007; van Loosdrecht and Brdjanovic, 2014). Consequently, biotechnology is an essential component for complete integration into energy production and resource recovery leading to the production of clean water (Nielsen, 2017). Hence, water treatment is emerging as part of the circular sustainability movement (Nielsen, 2017) while biotechnology continues to initiate, integrate and optimize bioprocess systems to reduce chemical and energy use, and increased energy production and resource recovery (Nielsen, 2017). Even though AS has stood out as a dominant reactor of choice, other types, such as biofilms, biogranules, membrane bioreactors and others, have the potential to, in some cases, be superior to the more traditional systems (Pronk et al., 2015). Microbial biotechnology is, along with other technologies, essential in this development with exciting perspectives in optimization of existing systems and development of new ones hence proposing solutions that bring us one-step closer to a true circular economy.

Even though there is still a long way to go before a truly circular system is realised, water use, purification and/or treatment, and reuse can play an important role in making circular economies a reality. The benefits of a circular economy include environmental gains, job creation, and improved competitiveness due to greater efficiencies and reduced manufacturing costs (Hodges, 2016). New opportunities exist in design for enhanced resource efficiency, re-use, and remanufacture. New businesses can be created by closing resource loops using value retention processes, and existing circular initiatives can be scaled to achieve impact. Similarly, new circular manufacturing opportunities exist in the green energy market, and adoption of renewable materials will likely yield regeneration of natural capital (Godfrey, 2021).

Our take-make-use-dispose linear economic system has enabled societies globally to prosper, albeit while simultaneously exploiting planetary resources (i.e., raw materials) and primary energy (i.e., fossil fuels) at an exponential rate (Tan & Lamers, 2021). By so doing, mismanagement of limited natural resources is inevitable. Linear- and fossil-dependent economic activities, urbanization, and population growth have increased the discharge of nutrients (nitrogen and phosphorus) to water bodies and carbon dioxide (CO_2) to atmosphere alike. This does not only pause environmental, but also economic challenges. Alternative processes circulating nutrients and carbon within the economy therefore bare a win-win potential. Waste biorefinery involves in the establishment of a sustainable circular bioeconomy based on the philosophy of recycle, reuse, remanufacture and maintaining by shifting from a linear economy according to the principle of take, make and dispose (Leong et al., 2021). Circular economy concepts - including a circular bioeconomy - aim to transition the current, essentially linear, economic system to a more sustainable one. A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015). Hence, algae-based water/wastewater systems would bring circularity to urban systems by “disassembling” and “reconstructing” the wastewater nutrients and CO_2 emissions and producing renewable energy (Calicioglu & Demirer, 2022). Circular bioeconomy approach has a lot of potential towards resolving environmental problems and food security issues. The concept of circular economy - a system in which the final disposal of waste and by-products is minimised by promoting their reuse and valorisation - can be successfully applied to bio-based production chains (Corrado & Sala, 2018). Microalgae biomass production is a cost-effective and sustainable alternative to currently used approaches to tertiary WWT because of the rapid growth rate and the ability to thrive even in extreme conditions of microalgae without secondary pollution (Lavrinovičs & Juhna, 2017; Ungureanu et al., 2019). Ultimately, biomass to energy has an advantage of that it essentially eases the municipal ratepayers in terms of water and electricity since these are the two utility accounts that every resident is expected to pay. The key goal of a circular economy is to slow, narrow, and close material resource loops, built on the foundation of renewable energy and non-toxic materials (Tan & Lamers, 2021), thus algae can be used as an efficient and economically viable biorefinery feedstock (bioeconomy).

As far as circular bio-economy is concerned, microalgal biomass production has additional advantages. These include a more efficient microalgal oil extraction ability, an increased biofuel biodegradability and non-toxicity, the possibility of co-generation of other products for use in food, cosmetics and medical industry. Moreover, it has the potential for exploitation of new by-products as crop fertilizers or food additives, (e.g. the remaining algal biomass being rich-in protein, carbohydrates and small quantities of non-extractable lipids and micronutrients) (Kokkinos et al., 2021).

Biomass can be used to produce renewable electricity, thermal energy, or transportation fuels (biofuels). Biofuel and bioenergy technologies play a critical part in renewable energy development due to the merits of bioenergy for environmental sustainability. Schlosser & Blahušiak (2011) say biorefinery is the sustainable processing of biomass into energy i.e. fuels, power, and heat in addition to a spectrum of many other marketable products namely food, feed, materials, and chemicals. A biorefinery that supplements its manufacture of low value biofuels with high value bio-based chemicals can enable efforts to reduce non-renewable fuel consumption while simultaneously providing the necessary financial incentive to stimulate expansion of the biorefining industry (Schlosser & Blahušiak, 2011).

Rapid economic development, high-energy consumption, limited supply of fossil fuels and the growing need for environmental protection, calls for ecologically friendly fuels such as biofuels to resolve conflict. Biomass may be transformed to biofuels in several ways, including physical, thermochemical, chemical, and biological processes (Sathasivam et al., 2022). A number of transportation fuels can be produced from biomass, helping to alleviate demand for petroleum products and improve the GHG emissions profile of the transportation sector. A number of companies are moving forward aggressively to develop and market a number of advanced second-generation biofuels made from non-food feedstocks, such as municipal waste and algae. Philippini et al. (2020) says biofuels are the backbone of biorefineries. Biomass can be exploited as a feedstock for anaerobic digestion (AD) toward to third-generation biofuels, including biodiesel, biogas (used as fuel to generate electricity, and is a mixture of CH_4 (60% - 70%), CO_2 (20% - 40%), and trace amounts of NH_3, H_2S, and N_2), biohydrogen, bioethanol, biomethane, and biocrude oil (Koutra, 2020). Biomethane is produced by anaerobic digestion, photosynthetic processes generate biohydrogen, bioethanol is produced by fermentation, liquid fats by thermal liquefaction, and biodiesel by transesterification or esterification of fats and oils (Jayaseelan et al., 2021). Biomass generated biofuels have the potential to run fuel cell vehicles of zero emission, power combustion engines and power plants (Jayaseelan et al., 2021). Cultivation of microalgae ensures process viability and sustainability as feedstock for clean biofuel energy production with obvious advantages of increased biomass production capability, higher yield, minimal nutrient requirements, fewer water needs and even possibility of using wastewaters containing residual nutrients and no requirements for herbicides or pesticides. In contrast to first- and second-generation biofuels produced from food crops and lignocellulosic biomass, agricultural and forestry residues, respectively, microalgal biofuels represent a sustainable alternative to fossil-based fuels, which can dominate the energy sector the following decades, provided that mass cultivation and downstream processing make substantial progress (Sakarika, 2020). Microalgae produced from WWT can also be used as feedstock for biocrude oil production through hydrothermal liquefaction, a sustainable process that can be effectively applied in wet biomass, mixed cultures, and low-lipid microalgae, resulting in a potential jet fuel. Production and application of clean biofuels is an effective way to mitigate global warming and resolve the energy crisis (Sun et al., 2022). Microalgae-based biofuels produce a high amount of lipids and minimum negative environmental consequence, reduce carbon dioxide in flue gas and WWT, and generate by-products of high value, hence a route worth taking for a sustainable future.

Bioenergy being the biggest driving force in the last 10 years, its use as a combustion fuel offsets the use of non-sustainable and fossil fuel-derived feedstock i.e. coal, wood etc. Bioenergy production is a viable option for extending the life of finite fossil fuel sources, reducing GHG emissions and mitigating global warming and climate change. The energy stored in biomass can be released to produce renewable electricity or heat. Biopower can be generated through combustion or gasification of dry biomass or biogas (methane) captured through controlled anaerobic digestion.

Microalgae could be used as an environmentally friendly and easy source of biofertilizers for crop plants. Biofertilizers for “organically” grown microalgal biomass targeting zero-waste policies and contributing to a more sustainable circular bioeconomy is also an advantage associated with algae based wastewater systems (Ungureanu et al., 2019; Morais et al., 2021). Several microalgal species, including *Chlorella* and *Arthrospira* with high nutrient removal capacity, can return valuable nutrients and micronutrients, as well as soil organic carbon, substantially improving soil quality and crop growth and coping with macro- and micronutrient deficiencies. These have an advantage of that they are beneficiated with very little input to derive a fertilizer (Sakarina et al., 2020). When used for phosphorous recovery, microalgae can be used as a successful P-enrichment bio-fertilizer for crops (Lopez et al., 2009; Antizar-Ladislao &Turrion-Gomez, 2010; Brooijmans & Siezen, 2010; Solovchenko, 2016). This is because it can utilize phosphorus mostly in the form of $H_2PO_4^-$ and HPO_4^-converting it in to an organic compound like ATP, which is a primary source of energy, by a process called phosphorylation. Mukherjee (2016) says studies revealed that microalgal fertilizers showed a higher release of phosphorus in non-sterile soil when mixed with soil phosphorus solubilizing organisms. In addition, biochar derived from algae has recently gained its importance in carbon sequestration and soil amendment properties in agriculture (Hussain et al., 2021). The biochar derived from biomass has more than 90% carbon and is rich in nitrogen and other nutrients, which can be used as a fertilizer in agriculture (Ummalyma, 2022). Algae are characterised by a relatively low carbon to nitrogen (C/N) ratio. The lower the C/N ratio, the more rapidly nitrogen will be released into the soil for immediate crop use (Watson et al., 2002). Additionally, algal biomass typically has high moisture content making algae composts both mature (extent to which biodegradable material, including phytotoxins, has decomposed) and highly stable (a measure of the biological activity of the compost) (Wu et al., 2000; Hana et al., 2014). These composted media are used in landscaping and recreational fields since the compost product is suitable as a fertiliser (Hana et al., 2014). These commodity products are crude as opposed to refined products and require not much processing, and can be used in the form of a liquid/semi-liquid/suspended liquid or solid.

Biorefining is the sustainable processing of biomass into a spectrum of marketable products namely, food, feed, materials, and chemicals (Schlosser & Blahušiak, 2011), or a process to obtain multiple products from one biomass (Sivaramakrishnan, 2022). Biorefinery can be a concept, a facility, a process, a plant, or even a cluster of facilities. Bioprocesses using waste materials, which consists of municipal solid and liquid waste to produce value-added bioproducts and metabolites regarded as waste-to-treasure, has received increasing attention as the products are renewable and display environmental benign biodegradability characteristics. These biorefineries allow the utilization of raw materials that may be widely available at low cost and sustainable for the production of high-value products. These products may be considered in terms of their energetic potential as opposed to conventional refineries where the raw materials undergo several processes after which the products are used for transportation, electricity and the further production of more complex and valuable chemicals (Roddy, 2013). The bio-based products produced in a biorefinery should be market competitive for their economic sustainability. Thus, to develop a sustainable biorefinery, it is critical to produce high value-added bioproducts along with bio-energies in an integrated biorefinery (Takkellapati, 2018). For these refined products, select entrepreneurs mine biomolecules that can be refined for the production of either pure molecular entities. These biomolecules can also be sold to primary industries like the fabrication industry e.g., others are important as bioplastics or emulsifiers, or medicine and nutraceuticals, in engineering and technology. A biorefinery can utilize all kinds of biomass such as wood (straw and bark), agricultural crops, organic waste (derived from vegetables and animals), industrial and domestic wastes and aquatic biomass (algae and microalgae from sea and freshwater) (IEA, 2009). Microalgal biomass can be used alone or mixed with other material as healthy feed and food, and it has been reported that ∼75% of annual biomass production is utilized for the manufacturing of algal powder, tablets, and capsules for animal and human food (Ummalyma, 2020; Sivaramakrishnan, 2022). Added-value compounds that microalgae present as feedstock include: lipids, proteins, carbohydrates, biopigments, and numerous secondary metabolites used for cosmetics, pharmaceuticals, natural colorants, cosmetics, food, and feed supplements (Sakarika et.al, 2020). All these valuable products, including antioxidants, can be utilized by nutritional, pharmaceutical, and cosmetic industries (Sivaramakrishnan et al., 2022).

Figure 1.13 shows valorisation options for microalgal biomass.

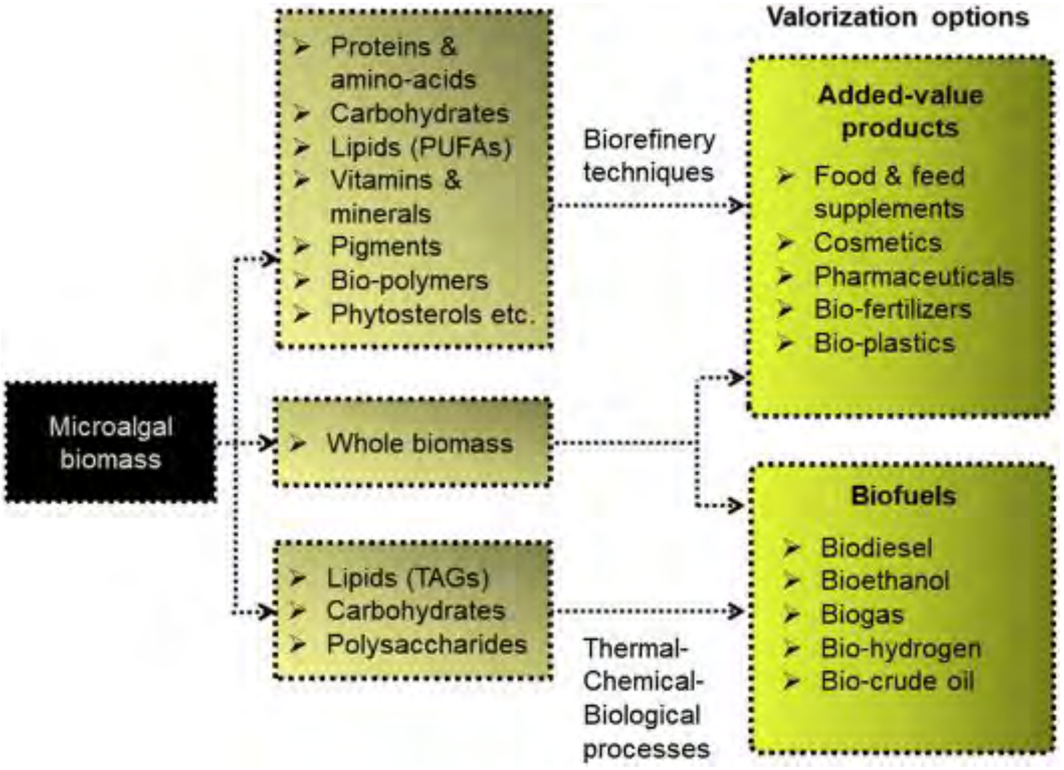


Figure 1.13 *Valorisation options for microalgal biomass.* [*Adapted from Sakarina et al. (2020)*]

Pigments, namely, chlorophylls, ß-carotene, astaxanthin, lutein, phycocyanin and carotenoids have been correlated with numerous health benefits, including prevention of cancer and cardiovascular diseases, antioxidant, anti-inflammatory, and antidiabetic activity. These also have important implication as natural colorants and nutraceuticals in food (Sahni et al., 2019; Sakarina et al., 2020). Microalgal biomass as human feed provide rich sources of carbohydrates, proteins, polyunsaturated fatty acids, essential minerals, vitamins and lipids (Becker, 2007; Chronakis & Madsen, 2011; Wells et al., 2017). As fish, animal and poultry feed, the microalgal species has found its use as feed supplements where microalgal biomass is incorporated into the feed of animals to positively influence the growth, immune response and gut function (Norambuena, 2015). In the field of cosmetics, microalgae are effectively used in the treatment of skin disorders like aging, tanning, and problems related with pigmentation. In the field of pharmaceuticals, primary and secondary metabolites produced by microalgae can be used as ingredients for the pharmaceutical industry (Bhalamurugan, 2018). Figure 1.14 shows sustainable microalgal biorefinery products coupled with food industrial wastewater.

Figure 1.14 *Sustainable microalgal biorefinery products coupled with food industrial wastewater [Adapted from Ummalyma et al. (2022)]*

Moreover, biorefineries can play an important role in the economic development of poor and developing countries, because it helps to generate employment or jobs for needy people.

1.2.4 Treatment technologies

Water treatment has been by conventional means and remains relatively unchanged. On the other hand, barring introduction of reverse osmosis, biological remediation of wastewater has for many years generally been favoured over conventional treatment, even in light of the major limitation, which is sensitivity to toxic components (Korf et al., 1996). Nevertheless, most of these biological systems (e.g., WSP) have been replaced by electro-mechanical processes that are more efficient but less energy- and user-friendly (Ho & Goethals, 2020). Consequently, many municipalities, particularly in developing countries, lack the financial resources and skills capacity to maintain and operate WTP and WWTW adequately.

Typically, treatment consists of a combination of physical, chemical, and some biological processes that operate in series to remove solids, organic matter and, sometimes, nutrients from water and wastewater. General terms used to describe different degrees of treatment, in order of increasing treatment level, are preliminary, primary, secondary, and tertiary and/or advanced treatment options (e.g., multimedia/membrane filtration, reverse osmosis, ion exchange, activated carbon, and UV). The benefits of WSP, which are common, have high removal efficiency, are simple to implement, operate and maintain, low cost, well recognized by numerous scientists and operators, and ease-of-use, and cannot be over stressed. However, stricter discharge standards, changes in wastewater compounds, high emissions of greenhouse gases, and elevated land prices have led to their demise and replacement in many places. Funding for research into the contribution of biotechnology and in particular the role that algae-based biotechnology can play in water and sanitation has increased dramatically in the past decade (Abdel-Raouf et al., 2012; Wollmann et al. 2019; Laubscher and Cowan 2020).

Microalgae are well recognized as central biocatalysts in water and WWT through uptake of organic and inorganic pollutants (Bischoff and Knauff, 1883; Frankland, 1897; Agersborg and Hatfield, 1929; Cotton, 1910; Abbott, 1948; Episona, 1948). In the mid-1950's sizable investment in understanding microalgae-wastewater interactions on a large-scale first occurred (Gotaas et.al. 1954; Oswald, 1991; Oswald, 1995; Benemann et al., 1977; Green et al., 1995; Grönlund et al., 2004; Larsdotter, 2006; Craggs et al., 2015; Ho and Goethals, 2020; Laubscher and Cowan, 2020; Sutherland and Ralph, 2020). Thus, development of efficient biotechnologies for circular economic implementation of water and WWT systems is becoming increasingly important. And, biomass production using wastewater for recycle and reuse opportunities to create new sources of raw materials for energy and material use is gaining ground (Bushman et al., 2019; Alcántara et al., 2020).

At the municipal level, some Eastern Cape Province municipalities have considered biotechnological solutions for water and WWT. Included are, AS, CW and the IAPS. Even so, very little meaningful progress has been made.

IAPS, enhanced pond systems (EPS) like the trade-marked AIWPS developed by Oswald and co-workers (Laubscher & Cowan, 2020) and other decentralised water and wastewater treatment systems (DEWATS) can also be technological platforms that render solutions to more than polluted water. The envisaged application for DEWATS is to provide WWT to areas with relatively high population density that are beyond the sewer network of the city, such as informal settlements, development and transport nodes, and schools and clinics (BORDA, 2014). Puyol et al. (2017) says, “Biotechnological processes offer an economic and versatile way to concentrate and transform resources from wastewater into valuable products, which is a prerequisite for the technological development of a cradle-to-cradle bio-based economy.” Even though DEWATS and EPS are techniques that are passive, climate friendly and sustainable development goal friendly, they are not a biotechnological process per se like IAPS since they do not have the prerequisite for the technological development of a cradle-to-cradle bio-based economy.

Such decentralised systems are ideally deployed in peri urban space, are low in energy demand and are mostly gravity driven and solar powered without additional energy requirements. Thus, power outages do not present a major challenge. Wastewater flows as low as 1 m^3 to as much as 1 000 m^3 can be handled by DEWATS. According to WRC (2015), there is little or no maintenance though performance must be monitored regularly. However, Truyens et al. (2018) says, “Although a DEWATS does not require a highly skilled operator and complex operation and maintenance tasks, proper operation and maintenance is critical for proper plant performance”. The DEWATS approach reports an 80 - 85 % reduction in Biological Oxygen Demand (BOD) and COD, 80 % reduction in phosphates and a 60 % reduction in ammonia (WRC, 2015). The reuse of treatment products may include using treated effluent for agricultural irrigation since nutrient-rich greywater is produced (BORDA, 2014) or collecting and using biogas for cooking (Truyens et al., 2018). The sludge produced is used as crop fertilizers (UN, 2015). DEWATS do not depend on an external source of energy to operate and have low maintenance costs with minimal sludge production (Odindo, 2016). These systems aim to use local materials in design but at the same time follow rigorous technical and engineering norms to realise robust but sustainable processes.

Pond Enhanced Treatment and Operation (PETRO) system is another appropriate technology applicable in the developed and developing world. The PETRO system can be an effective and low-cost treatment process when operated and maintained correctly (Albertus et al., 2018). It combines waste stabilisation pond as a low-tech primary stage and a polishing facility as a secondary stage (Shipin & Meiring, 2007). The secondary stage (PETRO facility) can be either a trickling filter or an AS process (WRC, 2015). PETRO is a relatively low-cost facility, which biologically breaks down organic matter (60% of COD removed) leading to the overall economy of PETRO, thus allowing for substantial capital and operational savings (Shipin & Meiring, 2007). This technique is also passive, climate friendly and sustainable development goal friendly, but it is not biotechnological, as it does not adhere to a cradle-to-grave bio-based economy (Puyol et al., 2017).

Artificial or constructed wetlands (CW) are another technology worth of mention. CW's remarkable treatment performance coupled with an environmentally friendly character and reduced overall costs (represent the main advantage of CW facilities, up to 90% lower compared to conventional plants offering significantly lower investment costs) and this is gradually placing CWs in the forefront of the scientific and marketing interest (Stefanakis, 2016). While conventional treatment systems have large daily volumes of sludge production, which needs handling and management on a daily basis, CW have zero production of by-products (Stefanakis, 2016). CWs consist of a bed of granular material through which effluent flows with little hydraulic resistance. The flow may be through media in the sub-surface or over the top of the bed i.e., vertical. The surface of the bed is planted with appropriate macrophytes such as *Phragmites australis*, which grows wild in many parts of South Africa. As with DEWATS, CW are constructed on-site and thus by definition are not considered typical package plants. These are however very effective at polishing partly treated or secondary treated water. Wetlands improve water quality by removing or retaining inorganic nutrients, processing organic wastes and reducing suspended sediments (U.S. EPA, 2002; Soni, 2020; Klein et al., 2018). The two types of CW configurations include surface flow constructed wetlands (SFCW) and subsurface flow constructed wetlands (SSFCW). Surface and SSFCW are wetland systems that consist of shallow basins (<1m) containing soil or other types of medium to support the roots of sedges and helophytes. Water level is controlled to maintain a shallow depth (0.2-0.4 m). In SFCW wastewater level is above the substrate (Choudhary et al., 2011), and are better suited for large community systems in milder climates. In a SSFCW, water level is maintained below a gravel substrate by a standpipe. This minimises the risk of exposure to people and greatly reduces potential for mosquito breeding. A CW can be an aesthetic feature in a peri urban space while also serving a water polishing or as tertiary treatment (WRC, 2015).

Ecosystem technologies are self-contained treatment systems designed to treat a specific waste stream using the principles of ecological engineering. They achieve this by using diverse communities of bacteria and other microorganisms, and some combination of algae, plants, trees, snails, fish and other living creatures.

Other water and WWT methods that have a biological component include AS, WSP, tricking filters, bio-filters and anaerobic treatment. While all these methods are part of the biological

WWT and use microbes to treat organic waste in sewage (Khaire, 2021) none is regarded as truly biotechnological since they do not have a prerequisite for the technological development of a bio-based economy, i.e. they do not offer an economic and versatile way to concentrate and transform resources from waste into valuable products.

1.3 IAPS as a platform technology

IAPS technology was introduced to South Africa in 1996 and a pilot plant designed and commissioned at the Belmont Valley WWTW in Grahamstown (Mambo et al., 2014a). The system has been in continual use since implementation, and affords secondarily treated water for reclamation according to its design specifications, which most closely resemble those of the AIWPS advanced secondary process (Laubscher & Cowan 2020).

Oswald and co-workers developed the concept of integrating different ponds (anaerobic, facultative, oxidation, and High rate algae oxidation pond (HRAOP)) to achieve biological WWT in the late 1950s. Today, the process is trademarked as AIWPS ® according to a U.S. Environmental Protection Agency report and in New Zealand, is termed EPS (Craggs et al., 2015). This concept technology has also been innovated and configured for southern African conditions as IAPS, an amalgamation of anaerobic and aerobic biological processes, which include: advanced facultative pond (AFP) that incorporates a fermentation pit or in-pond anaerobic digester (IPD) followed by a series of HRAOP and settlers. The real advantage of ponds is found in simplicity, economy, and reliability; but drawbacks exist and include, large surface footprint or land use, potential for odour, a tendency to become eutrophic, and accumulate sludge and rendering ponds less effective in the long-term (Oswald, 1990). Even so, when properly designed in appropriate locations, algae-based systems virtually eliminate sludge disposal, minimize power use, require less land than conventional ponds, and are much more reliable and economical than mechanical systems of equal capacity (Ho & Goethals, 2020).

IAPS are a derivation of the Oswald-designed algal integrated wastewater pond systems (AIWPS) and like the New Zealand-developed, EPS, combine the use of anaerobic and aerobic bioprocesses to effect sewage treatment (Laubscher & Cowan 2020; Sutherland & Ralph 2020). IAPS technology was introduced to South Africa in 1996 and a pilot plant designed and commissioned at the Belmont Valley WWTW in Grahamstown (Mambo et al., 2014a). The system has been in continual use since implementation, and affords secondarily treated water

for reclamation according to its design specifications, which most closely resemble those of the AIWPS advanced secondary process (Laubscher & Cowan 2020).

The legacy of IAPS is that it produces a quality effluent, is an accredited sanitation technology in South Africa through issuance of a water use license application (WULA) by DWS and as recently as 2019, is relatively easy and inexpensive to implement and maintain. IAPS has the additional benefit of generating co-product streams that can be valorised and/or beneficiated (Laubscher and Cowan 2020). Indeed and in regard to the latter, a re-evaluation of the technology at pilot scale revealed that IAPS-treated water complies with the general limit values for either irrigation or discharge into a water resource that is not a listed water resource for volumes up to 2 000 m^3 of treated wastewater on any given day. Parameters including COD, TSS, pH, DO, Electrical conductivity (EC), and N and P values were within the general limit after tertiary treatment by either a maturation pond series (MPS), slow sand filtration (SSF) or controlled rock filtration (CRF); and, there is no faecal sludge handling. Furthermore, life cycle assessment (LCA) modelling, to map both energy flows and greenhouse gas (GHG) emissions of the Belmont Valley WWTW pilot-scale IAPS treating municipal sewage, revealed that an equivalent commercial system would yield negative (–) 0.16 tonnes CO_2 per 1000 m^3 of wastewater treated indicating a technology with an ability to mitigate climate change. And, products from the 500 PE Belmont Valley WWTW pilot-scale IAPS treating municipal wastewater include water for re-cycle and re-use (~28 000 $m^3\ y^{-1}$), methane-rich biogas (~1880 $kgCH_4\ y^{-1}$ equivalent to 26 MW or, ~55 kWh $PE^{-1}y^{-1}$), and biomass (>3 tonnes DW y^{-1}).

1.3.1 Overview of the IAPS process

The integrated algal pond system (IAPS) is a passive WWT technology that can be used to remediate liquid waste from domestic, industrial, and agricultural sources and is ideally suited for implementation in the peri urban space. The system exploits the mutualistic interaction between microalgae and bacteria to generate water of a quality suitable for discharge and/or reuse (Jimoh et al., 2019).

It is therefore important to consider local conditions and client requirements prior to implementation and to design appropriately (Laxton et al., 2010). A typical IAPS or EPS comprises several interconnected modules (Fig 1.15).

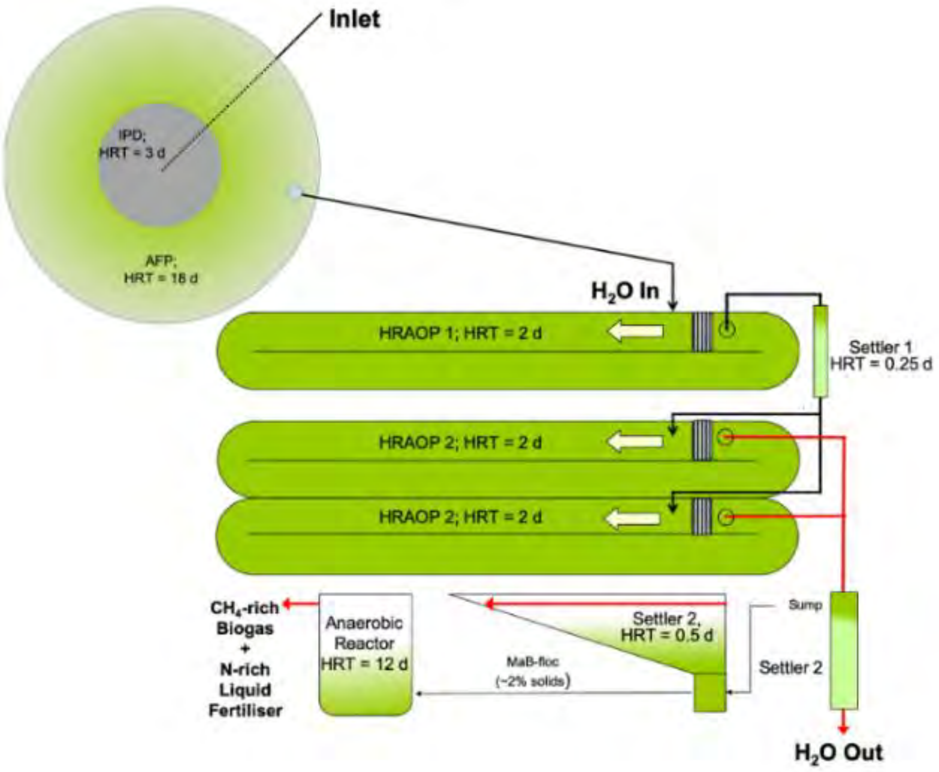


Figure 1.15 *Schematic diagram of the principal unit associated with IAPS and elaborations as constructed at Rhodes University Environmental Biotechnology Experimental Field Station, Belmont Valley WWTW, Makhanda, Eastern Cape Province (from, Laubscher and Cowan 2020).*

These include; an AFP constructed to provide an aerobic, an anoxic, and an anaerobic layer (Hosseini, 2019) and, is designed to promote growth of three distinct microbial consortia i.e. a deep anaerobic stratum supporting fermentative and methane producing bacterial consortia, an overlying facultative stratum supporting both aerobic and anaerobic growth, and finally by an aerobic surface layer heavily populated by green algae, cyanobacteria and photosynthetic bacteria (Ertas & Ponce, 2021). The hydraulic retention in this facultative reactor is typically ~3-40 days. Installation of a submerged gas collector facilitates the collection of biogas (methane) produced in the anaerobic stratum (Fig 1.16 a). With a depth of 5-6 meters, water flows via a volume of anoxic activity allowing organic matter to be converted into carbon dioxide, methane, and nitrogen gas. The CO_2 released supports algal growth in the upper layers of AFP supporting the aerobic function of this compartment from the photosynthetic oxygen (Fig 1.16 b). Development of an algal layer in the AFP effectively entraps and oxidises odour-causing compounds. Water from the AFP flows under gravity to a series of channel reactors termed HRAOP or raceways (Fig 1.16 c & d). This, the second unit of the system, is where symbiosis between microalgae and aerobic bacteria occurs by paddlewheel mixing and where algae form stable flocs which readily settle for easy removal. Here, algal photosynthesis raises the pH of treated to between 9.5 – 10 effectively killing *E. coli* and most pathogenic microorganisms. A constant linear velocity is required along the raceway for optimal nutrient abstraction, algal growth, and oxygenation. These raceway reactors have been likened to the aeration basins of AS plants with the algae-bacteria consortia suspension representing a mixed liquor (Laubscher & Cowan 2020). Indeed, HRAOP are designed to optimise algal growth and, therefore, facilitate high photosynthetic activity, with its consequent oxygen production (up to three times saturation) for heterotrophic bacteria that break down remaining dissolved organic matter, and associated elevated pH (Laubscher & Cowan, 2020). Growth of MaB-flocs and production of the associated extra-polymeric substances (EPS) which facilitate floc formation contribute to a certain amount of COD in the IAPS (Jimoh & Cowan 2017; Jimoh et al. 2019). In addition, the HRAOP environment facilitates effective removal of ammonia, phosphate and pathogens. The parameters required for greatest algal activity include sufficient sunlight and nutrients and these factors play an important role in system design (Laubscher & Cowan 2020). Figure 1.15 b below shows the he high rate algal ponds showing channel dividers used to prevent quiescent zones of flow on the leeward side of the inner pond-dividing wall.

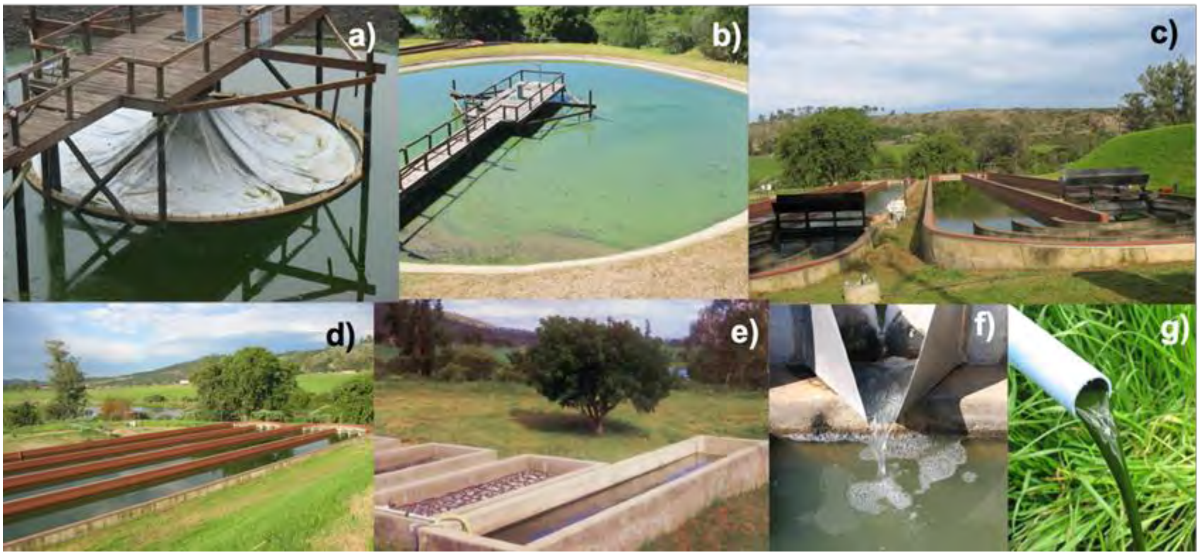


Figure 1.16 *Unit components of the demonstration IAPS WWT process located at the Belmont Valley WWTW in Makhanda, Eastern Cape Province. a) inlet and covered anaerobic reactor; b) advanced facultative pond; c & d) HRAOP or raceways; e) algal settler pond and drying beds; f) bright treated water; and g) dewatered harvested biomass.*

The algal settling pond (ASP) is where MaB-floc biomass settles and is removed from the system (Fig 1.16 e) removed before the effluent is discharged to public water bodies (Fig 1.16 f). Majority of the algae is removed through natural sedimentation of algae in the High-rate algal pond (HRAP) overflow and is either harvested and taken for further processing (Fig 1.16

g) or is treated as ‘sludge’, and sent to sludge drying beds (Fig 1.16 e). The by-product, algal biomass, is used in horticultural and agricultural plant and product production i.e. it can be successfully used as a fertilizer or soil amendment at the garden plot scale. This significantly increases crop yield of cabbage, turnip and Swiss chard compared to untreated soil (Horan et al., 2009).

The various IAPS systems rely on the combined activity of anaerobic digestion, photosynthetic oxygenation by algae, and microbial oxidation to achieve WWT (Mambo et al., 2014a, b; Cowan et al., 2016; Jimoh, 2021). Thus, the natural functionality of anaerobic, facultative and aerobic microorganisms is exploited by process design to effect WWT. Figure 1.16 shows aerial photographs of the IAPS pilot plant introduced in South Africa in 1996 at the Environmental Biotechnology Experimental Field Station, Belmont Valley, Makhanda showing the layout and positioning of the AFP (top) relative to the HRAOP, ASP, and the municipal sewage treatment works.

Figure 1.17 a – c shows the significant changes that have taken place at the Belmont Valley WWTW over a period of almost two decades. Figure 1.17 a shows the inlet pond, which is above the trickling filters, full with water, but as the years go by it is clear that it is less occupied with water and it is only full of sludge. The demise of the maturation ponds is also very significant as seen by that in 2003 and 2012, these were fairly efficient and competent maturation processes, but by 2022, there is not any water in any of those ponds and unlikely that any water was exiting the plant since the maturation pond is the tertiary treatment process prior to discharge. Filter beds are also dry, confirming the demise of the WWTW. The raceways for the IAPS are also empty indicating that there is no water coming into this plant. This is evidence of a municipal infrastructure in the EC not functioning, as it should and the WWTW serviced by the IAPS is in disrepair indicating serious issues. Even though we are advocating IAPS to be a passive process, it still requires wastewater and if there is not it dries out and nothing happens as shown in Figure 1.17 c.

Figure 1.17 *Apparent demise of process operations at the Belmont Valley WWTW from 2003 to 2022. In particular, changes to maturation dams from 2003 (a), 2012 (b) to 2022 (c). Overgrowth of the sludge drying beds; sludge accumulation in the primary settler; and dryness of biofilters, indicate a derelict and/or dysfunctional WWTW.*

Belmont Valley WWTW IAPS like others relies on naturally occurring algae to populate the raceways, for MaB-floc formation, and for generation of biomass. Figure 1.18 shows mutualism between algae and aerobic bacteria in high rate oxidation ponds. HRAP are a cost-effective technology for growing microalgae in wastewater that have many advantages, including reduced construction and maintenance costs, simple operation and lower energy consumption (Geremia et al., 2021). In addition, HRAP are typically used to treat high strength wastewater or to grow algal biomass for biofuel production.

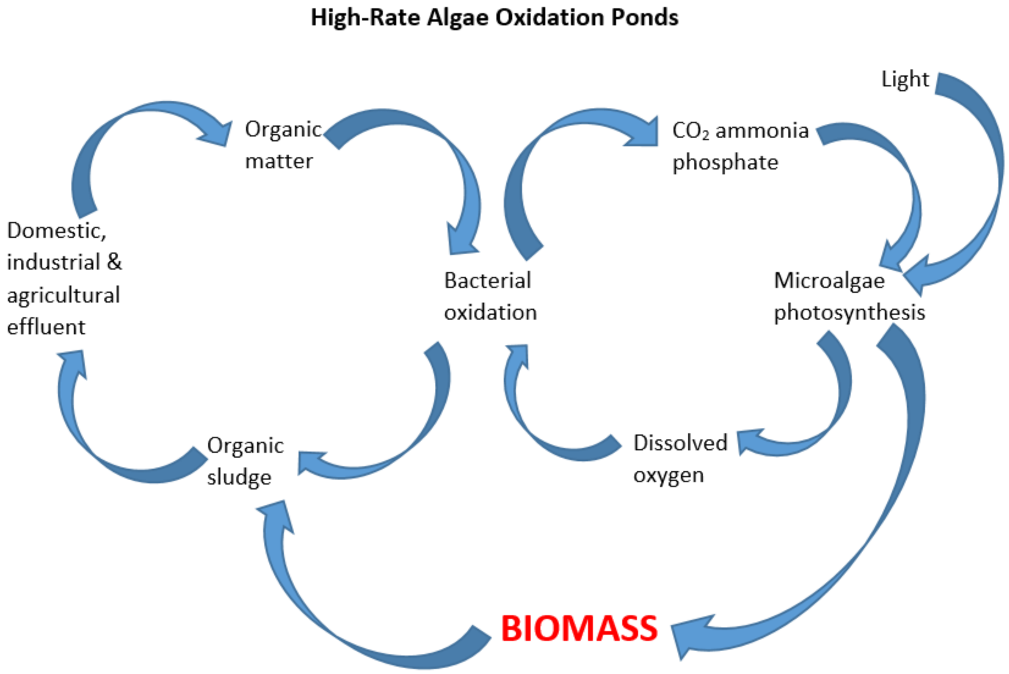


Figure 1.18*: Mutualism between algae and aerobic bacteria in high rate oxidation ponds (Oswald et al., 1955).*

Research on IAPS, AIWPS, and EPS together with advances in raceway technology and photobioreactors (PBR) have increased dramatically in recent years. A principal reason is that these systems produce three co-products: energy in the form of biogas, biomass, and effluent suitable for re-use (Amis & Lugogo, 2018). Unlike HRAP, closed systems such as PBR (generally divided into horizontal and vertical) have higher installation and operating costs but operate in controlled environments and result into better photosynthetic efficiency, which allows greater nutrient removal and more efficient biomass production (Geremia et al., 2021). Of the two types, vertical column PBR require less surface area per unit volume. Due to their compactness and low manufacturing cost, these ensure an optimal growth.

Extracellular polymeric substances (EPS) are a complex high-molecular-weight mixture of polymers excreted by microorganisms, produced from cell lysis and adsorbed organic matter from wastewater and they play a definite role in sludge flocculation (Subramanian et al., 2010). Natural EPS finds its use as a bioflocculant in water purification and in the dewatering and settling of sludge and making it an ideal natural replacement for commercially available synthetic polymers. EPS are also considered high value and can be used in many commercial applications like WWT, cosmetic, pharmaceutical, and food industry mostly as flocculant, thickener, and emulsifier (Jimoh et al., 2019; Dwiyantari & Bayu, 2020). Thus, and to ensure sustained MaB-floc production in IAPS-based WWTW, it is important that correct levels of EPS are maintained to facilitate settling and biomass recovery (Jimoh et al., 2019).

Raceway technologies are effectively easy to scale-up and cheap to build (Pruvost, 2019) while PBR have emerged in the last decades as a potential sustainable technology to combine wastewater bioremediation by nutrient removal with the production of microalgal biomass (Galinha et al., 2018). Shallow open pond raceway designs that includes basic mixing are the cheapest option for large-scale microalgal production. Compared to other photo-bioreactor (PBR) designs, they also have lower energy requirements, lower capital and operating costs, and can be built at a large scale (Brennan & Owende, 2010; Borowitzka & Vonshak, 2017).

1.4 (Bio)-Farming platform technologies

The peri-urban space experiences pressure due to a dramatic increase in human population and escalating demand for electricity, more food, more fuel, more potable water as well as to significantly reduce CO_2 emissions on global water resource, and affects the potential to produce food, livestock feed, fibre, and commodity products like biofuel (Laubscher & Cowan, 2020).

Biotechnological processes can be wastewater biorefineries (WWBR) that bridge the gap between the concepts of the biorefinery and WWT. The biorefinery concept includes different technologies able to convert biomass into added-value chemicals, products (food and livestock feed) and biofuels (biodiesel, bioethanol, biohydrogen), while concomitantly providing clean or 'fit for use' water as a product (Pott et al., 2018). This concept is derived from the petroleum refinery, which uses petroleum to produce multiple fuels and products with applications in various industries (Uggetti et al., 2013). WWBR has a great potential to contribute to the bio-based economy and augment the industrial sector by providing a link between water consumers and those responsible for its management, facilitating the recovery of resources in closed loop cycles, circular economy, where valuable nutrients and components are recovered and reused (Pott et al., 2018).

The extensive biological diversity of algae can be leveraged to produce a wealth of valuable bioproducts, either naturally or via genetic manipulation. Microalgae additionally possess a set of intrinsic advantages, such as low production costs, no requirement for arable land, and the capacity to grow rapidly in both large-scale outdoor systems and scalable, fully contained PBR.

Wollmann (2019) says, "in particular, in the context of a circular and bio-based economy and the development of biorefinery concepts, microalgae biomass produced from wastewater streams offers a great potential for sustainable bioproducts (dependent on national legislation on reusing microalgae biomass/bioproducts), such as proteins, fatty acids, pigments, biofertilizers/biochar, and animal feed." This relieves stress on much of the cost of WWT.

The algal biomass produced is co-digested anaerobically to obtain a methane-rich biogas that is further converted to electricity (Wollmann, 2019). As a rule of thumb, 1 kg algal biomass will generate methane equivalent to 1 kWh. Methane may also be used directly as a transportation fuel by local communities and for municipal tasks (Cowan & Render, 2012). Methane and biomass are most desired by primary industry (e.g., agriculture and horticulture) in the peri-urban space and position algae-based sewage treatment at the water–energy–food nexus (Laubscher & Cowan, 2020).

Biomass in the form of microalgal–bacterial flocs (MaB-flocs) is generated, and this can be harvested and beneficiated in downstream processing in biorefineries. It can be harvested as a nutrient rich fertilizer, as a foliar feed (sold as feedstock for bioplastics), as a high protein feed in aquaculture, soil-enhancing compost, and bio-fuel production. Valuable fine chemicals, oils, pigments, vitamins, nutraceuticals and pharmaceutical agents can also be extracted from biomass (Cowan & Render, 2012; Aci´en et al., 2012; del Mar Morales-Amaral et al., 2015; Jimoh et.al, 2019; Wollmann, 2019; Laubscher & Cowan, 2020;). Advantages of algal biomass than other biomasses (plant, agricultural, forest residue, etc.) are that it requires less land for cultivation, grow in wastewater and greater CO_2 sequestration ability from atmosphere serving as a carbon sink, thereby mitigating the negative effects of CO_2 as a GHG (Green et al., 1995; Arun, 2020). This may be used to justify the use of algae ponds as a sustainable technology, economical and environmentally friendly, which alleviates pressure on environmental water reserves (Oswald, 1995). Biological composition of algal biomass gets an advantage over other conventional biomass for gaseous and liquid biofuel production with less GHS emission (Arun, 2020). Secondary water produced for re-use in this process will always cost less making it a viable biotechnological process.

Most of the processes of water and WWT, while very efficient in treating water, do not allow for the beneficiation of other co-products or bio-products whereas the algal based technologies do, e.g. biological plastics where algal sludge is used to produce bio-plastics. Furthermore, IAPS is a versatile and passive bioprocess that can be used to remediate, in addition to domestic sewage, brewery effluent, food processing waste, industrial effluent and abattoir waste (Mambo et al., 2014a). Thus, IAPS could potentially be the appropriate core technology platform for developing the algal biotechnology applications such as low-cost systems appropriate for implementation in meeting environmental sustainability objectives.

1.5 Aim

To assess water and sanitation infrastructure in a provincial DM with a view to potential implementation of bio-platform technologies.

1.6 Objectives

- Assess water and sanitation infrastructure, operability, water quality compliance and status and, staff capacitation compliance in CHDM, Eastern Cape Province to derive a baseline reference;

- Scope the current (2020/22) state of water and sanitation in selected local municipalities in Chris Hani District, Eastern Cape Province;
- Evaluation of water and sanitation infrastructure for potential implementation of locally developed biotechnology platforms that could improve WT, WWT, energy generation and possibly food production in that region.

Chapter 2 - Determination of a historical benchmark for water and sanitation in CHDM, Eastern Cape Province

2.1 Introduction

Water use in the built environment spans the rural, the peri-urban, and the urban in terms of water acquisition, consumption, and repair and discharge. Typically, within this environment, this process involves a WTP decoupled from a WWTW but linked by several kilometres of water reticulation and sewage infrastructure. Biotechnological solutions offer the water and sanitation sector the potential to generate potable water and sanitation, in addition to treated water co-product streams that can be valorised for socio-economic benefit. The Rhodes university IAPS system was advocated as one such biotechnological solution (Mambo et al., 2014). Unfortunately, the South African municipal, town, and city water divisions have not favoured biotechnological technologies for deployment. This chapter sought to explore water and sanitation at the municipal level with the view to identifying the potential for use of systems such as IAPS.

To realise implementation of biotechnological solutions the status of water and sanitation technology, its operation and effectiveness, and sustainability must be assessed, which is best achieved using scoping methodology. Scoping sets boundaries and specifies parameters that will be investigated and the extent to which the area under interrogation will be explored. Furthermore, it enables the researcher to define explicitly what the study will cover and what elements will not be considered (Chetty, 2020). The study reported in this chapter either scopes or sets the boundaries for assessment for the potential of biotechnology solutions to water and sanitation in CHDM, Eastern Cape Province to establish the benchmark reference for when WTP and WWTW were more closely managed/operated and when the Green Drop and Blue Drop reporting procedures were in place.

In 2009 the Department of Water Affairs (DWA; now Department of Water and Sanitation, DWS) published an extensive survey of all municipal WWTW across South Africa. Of particular interest is the section dealing specifically with the Eastern Cape Province. Soon after publication of this report (DWA, 2009), both the Blue and Green Drop Reports and associated procedures were abandoned. A scoping of the status of water and sanitation in the CHDM, Eastern Cape Province as at 2009 was conducted in this chapter to ascertain the benchmark for WTP and WWTW in this DM.

The Republic of South Africa comprises nine provinces: Eastern Cape, Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West, Northern Cape and Western Cape. Each is governed by a unicameral legislature elected by party-listed proportional representation, and a premier elected by the legislature. While provincial legislatures are represented in the national parliament by delegations to the National Council of Provinces (NCP), primary administrative divisions of the Republic are the nine provinces. Provinces are divided into metropolitan and district municipalities with district municipalities further divided into local municipalities. The administrative divisions of the Eastern Cape Province are shown in Figure 2.1.

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***Figure 2.1** Map of the Eastern Cape Province illustrating the district and local municipal boundaries as defined by the constitution of the Republic of South Africa.*

Outside of metropolitan municipalities, there are 44 district municipalities in South Africa. These cover large regions within each province and in turn, are divided into several local municipalities. The district municipalities are responsible for "district-wide" municipal functions, including development planning, bulk supply of utilities, arterial roads, and public transport. In general, a local municipality (LM) includes one or more towns and the surrounding villages and rural areas.

For both district and local municipalities, decisions on infrastructure, technology choice and implementation, upgrade, and operation and maintenance are a function of the respective councils. As reported by DWA (2009), an analysis of water in 206 towns and sewage from 124 WWTW showed that some local and even district municipalities disregard Section 24 of the

Constitution of the Republic of South Africa (Act 108 of 1996), which ensures a healthy environment for citizens. According to the DWA (2009) report, drinking water of 4 towns and more than 60 different WWTW did not comply with national standards. Interestingly, after informing the municipalities of the prevailing situation, follow-up water analyses indicated that the water was once again safe for human consumption/ discharge to river. Municipal officials took this latter finding as clear indication of poor service delivery, in particular with regard to WWTW (Afriforum, 2020).

On 7 July 2021 it was announced by DWS that the Blue and Green Drop reporting programmes were to be resuscitated (after an absence of almost 10 years) in an effort to improve water quality and hold municipalities accountable (DWS, 2021). The last Green Drop and Blue Drop reports were published in 2013 and 2014 respectively (DWA 2013; 2014). As part of resuscitation of these programmes, DWS aims to undertake a full Green Drop audit and Blue Drop partial assessment in 2021, and a full Blue Drop audit and a Green Drop partial assessment in 2022. Thus, an ideal opportunity exists to examine the status of water and sanitation at the Provincial, DM and LM levels from a period when Blue and Green Drop reporting was routine to a time, almost 10 years hence, when such oversight was no longer being exercised.

In this chapter technology choice, operational capacity and compliance with respect to water and sanitation services were investigated within the Eastern Cape Province and more specifically within CHDM, which is also the Water Services Authority (WSA). This chapter described work carried out to establish the benchmark or reference point for use in follow-up site visits and snap-shot analyses to evaluate and analyse the potential of CHDM water and sanitation infrastructure following a hiatus in Blue and Green Drop reporting.

2.2 Materials and Methods

2.2.1 Study area

CHDM is a Category C municipality (it has municipal executive and legislative authority in an area that includes more than one municipality) situated in the north-eastern part of the Eastern Cape Province, a linking node to all regions in the province. It is bordered by Joe Gqabi District to the north, Sarah Baartman and Amathole Districts to the south, and OR Tambo District to the east. CHDM is the second-largest district in the Eastern Cape Province and covers an area of 36 407 km². The municipality comprises six local municipalities (LM), namely, Inxuba Yethemba LM, Enoch Mgijima LM, Intsika Yethu LM, Engcobo LM, Sakhisizwe LM and Emalahleni LM. Some main towns within the district are Engcobo, Cala, Cofimvaba, Cacadu (previously Lady Frere), Tsomo, Elliot, Dordrecht, Komani (Queenstown), Tarkastad, Whittlesea, Indwe, and Cradock.

This targeted scrutiny of certain plants was according to accessibility as this study commenced in early 2020 immediately before the SARS-CoV-2 outbreak and onset of the global Covid-19 pandemic and associated declaration of the national state of disaster and subsequent hard lockdowns. In addition, the local municipalities span along a transect across a vast area of the EC Province. This distribution gave a more-or-less clear representation of the province as a whole according to the reductionist theory.

2.2.2 Sources of metadata

The data accessed and analysed in this chapter were derived largely from the Blue Drop Report 2012 (DWA 2012), Blue Drop Report 2014 (DWA 2016), Green Drop Report 2011 (DWA 2011), and a report titled, '*Executive Summary Municipal Wastewater Treatment Base Information for Targeted Risk-based Regulation Eastern Cape Province status at June 2009*' (DWA, 2009). Information on all municipal water treatment and/or sanitation plants in the Eastern Cape Province was sourced from these reports and used to generate benchmark values with which to later assess the status of WTP and WWTW in the broader Eastern Cape Province in comparison with the WTP and WWTW in CHDM.

2.2.3 WTP and WWTW size distribution, technology type and capacity

To establish size distribution (micro-sized plants: <500 m^3/day, small-sized plants: 500 m^3 - 2 000 m^3/day, medium-size plants: 2 000 - 10 000 m^3/day, large-sized plants: 10 000 - 25 000 m^3/day, macro-sized plants: >25 000 m^3/day as well as undetermined from DWA/WSA), technology used, technology capacity for WWTW in both the Eastern Cape Province and CHDM, relevant data was extracted from 2011 Blue Drop Report for the Eastern Cape Province (DWS, 2011) as shown in Table 2.1.

Table 2.1 *Size distribution of the WTP in the Eastern Cape Province.*

Size distribution of WTP	**Micro-sized <500 m^3/day**	**Small-sized 500 m^3 – 2 000 m^3/day**	**Medium-sized 2 000 - 10 000 m^3/day**	**Large-sized 10 000 – 25 000 m^3/day**	**Macro-sized > 25 000 m^3/day**	**Undeter-mined**	**Total**
Number of WTP	15	29	35	10	6	68	163

The data in Table 2.1 was used to derive a pie chat as shown in Figure 2.2 for further analysis. WTP in this pie chart where given as percentages of the total 163 supply systems in the Eastern Cape Province.

To assess the operability and water quality of these supply systems, information from Blue Drop Reports for 2014 was interrogated and the outcome and percentages given as shown in the Table 2.2.

Table 2.2 *Percentage operability of the WTP in the Eastern Cape Province.*

Operability parameters of WTP in the Eastern Cape Province	**Critical state**	**Very poor performance**	**Average performance**	**Good status**	**Excellent situation**	**Total**
% operability of the WTP in the Eastern Cape Province	20	21	34	25	0	100

The data in Table 2.2 was used to construct a pie chart for further analysis of operability and water quality of these WTP (Fig. 2.3).

To establish size distribution (same as WTP sizes), technology used, technology capacity for WWTW in both the Eastern Cape Province and CHDM, relevant data was extracted from *Executive Summary Municipal Wastewater Treatment Base Information for Targeted Risk-based Regulation Eastern Cape Province* (DWA 2009). Here the reductionist approach was used where establishment of these parameters was started at provincial level to district level in this chapter and along a transect of selected municipalities in Chapter 3.

In order to establish size distribution for the Eastern Cape Province, a total of 125 WWTW around the province was considered. WWTW of comparable sizes were grouped together, total for each size was obtained and a percentage of the plants with a certain size distribution was calculated as follows:

$$\text{\% of WWTW with comparable sizes} = \frac{Total\ number\ of\ WWTW\ with\ comparable\ sizes}{125}\ x\ 100$$

Percentages for size distribution were used to draw pie charts for further analysis (Figure 2.4 a).

Size distribution in the CHDM was done in the manner as the provincial established, however, 16 WWTW found in the CHDM were considered and a percentage of the plants with a certain size distribution was calculated as follows:

$$\text{\% of WWTW with comparable sizes} = \frac{Total\ number\ of\ WWTW\ with\ comparable\ sizes}{16}\ x\ 100$$

Percentages for size distribution were used to draw pie charts for further analysis (Figure 2.4 b).

In terms of the technologies for WWT used, all provincial WWTW that use the same technology were grouped together and totals were obtained for each technology. Percentages were calculated using 125 as the total number of WWTW in the province, and a pie chat to further analyse this technology distribution was drawn as shown in Figure 2.5 a. The same procedure was followed for the CHDM were 16 WWTW found in the CHDM were considered and a pie chat was drawn for further analysis as shown in Figure 2.5 b.

Plants can either operate at– or above design capacity, below design capacity or at unknown capacity due to no available information about flow or design capacity of a plant and in some cases both. Status of level of plant operability was scoped for the 125 WWTW in the Eastern Cape Province. The status was given as a percentage of the 125 WWTW in the Eastern Cape Province and a pie chart for further analysis was drawn (Figure 2.6 a). The status was also given as a percentage of the 16 WWTW in the CHDM and a similar pie chart was drawn (Figure 2.6 b). These pie charts were compared side-by-side to come up with a clear comparison between the Province and the CHDM in terms of this parameter of the status of level of plant operability (Table 2.5).

2.2.4 Determination of system and water 'quality failure'

Most of these WWTW do not meet standards according to *E. Coli*, FC, SS, NO_3^-, NO_2^-, COD, pH, NH_4^+, and PO_4^{2-} as well as staff capacitation, and this is a cause for concern.

CHDM makes use of three indicators to determine compliance of the various WTP and WWTW. These parameters are not just peculiar to the CHDM, but they are the standard parameters used in water treatment and WWT. Parameters used to determine plant compliance include bacterial quality, physical quality and chemical quality of water. Bacteriological quality is based on *E. coli* and faecal coliform colony forming units (cfu); physical quality, in terms of pH and EC; chemical quality, in terms of suspended solids (TSS), nitrate (NO_3^--N), nitrite (NO_2^--N), chemical oxidation demand (COD), ammonia (NH_4^+-N), and orthophosphate (PO_4^{3-}). For each of these nine parameters, compliance scores were generated as shown in **Table S2.1**. Using the compliance scores, a graph of arbitrary units (AU) (computed as stated in section 2.2.5, Data analysis) was generated to analyse water quality and plant compliance and status as at 2009 for WWTW in CHDM (Fig. 2.7).

For staff capacitation, the following parameters were assessed: compliance (C) or non-compliance (NC) in terms of supervision, process controllers (operators) and operations and maintenance support. Quality failure can also be analysed by technical skills gap analysis and occupational health and safety aspects. **Table S2.2** shows information on plant staff capacity against real-time staff capacity (i.e. staff on- site) and compliance checks (i.e. technical skills status). For each of these three parameters, compliance scores were generated as shown in **Table S2.3**. Using the compliance scores, a graph of AU was generated to analyse staff capacitation compliance and status as at 2009 for WWTW in CHDM (Fig. 2.8).

2.2.5 Data analysis

In order to assess water quality and staff capacitation of CHDM water and WWTW, a score (in AU) was used to rank each treatment plant. For water quality, the following parameters were assessed: *E. coli* (limit, 0 cfu/100 ml), faecal coliform (FC) (limit, 1000 cfu/100 ml), pH (limit, 5.5-9.5), EC (limit, 150 mS/m), TSS (limit, 25 mg/L), NO_3^--N (limit, 15 mg/L), COD (limit, 75 mg/L), NH_4^+-N (limit: 6 mg/L), and PO_4^{3-} (limit, 2 mg/L).

For staff capacitation, the following parameters were assessed: compliance (C) or non-compliance (NC) in terms of supervision compliance, process controllers (Operators) and operations and maintenance support.

The information was tabulated and used to generate scores for the selected water quality parameters at each of the chosen treatment plants in CHDM and compliance (expressed as % of the maximum possible non-compliance score) calculated as follows:

$$\text{Compliance in terms of water quality} = \frac{(a+b+c+)^{\mathrm{n}}}{144} \times 100$$

where $(a+b+c+)^{n}$ is the sum of the compliance scores out of 10 per LM and, 144 represents the number of the maximum possible non-compliance score, where *a, b* and, *c* are the compliance scores out of 10 per LM.

The same was done for staff capacitation compliance (expressed as % of the maximum possible non-compliance score) and calculated as follows:

$$\text{Compliance in terms of staff capacitation} = \frac{(a+b+c+)^{\mathrm{n}}}{48} \times 100$$

where $(a+b+c+)^n$ is the sum of the compliance scores out of 3.5 per LM and, 48 represents the number of the maximum possible non-compliance score, where *a, b* and, *c* are the compliance scores out of 3.5 per LM.

2.3 Results and Discussion

2.3.1 Water treatment

Access to sufficient water is a basic right enshrined in the constitution of South Africa. However, it cannot be said that this right is realized if the quality of water poses health risks for human consumption. Seventeen (17) WSA perform water service delivery in the Eastern Cape Province through 163 WTP. The main Water Services Providers (WSP) in the Eastern Cape Province are Local Municipalities and Amatola Water which together provide potable water into municipal networks via a number of centralised bulk water schemes (DWS, 2011).

The CHDM lies on the watershed of four major river systems: The Great Fish River, the Kei River, the Mbashe River and the Orange River. The majority of towns in the CHDM are supplied from surface water sources, while some exceptions rely on groundwater supplies. Communities in the rural areas generally rely on unprotected springs, streams and boreholes for their water supply. Commercial farms are usually supplied by groundwater from boreholes (SALGA, 2011). CHDM has nine (9) WTP and a summary of these schemes and locations of WTP surveyed in this study was presented in Table 2.3.

Table 2.3 *Location of WTP in CHDM surveyed in this study.*

District Municipality	Number of WTP	Location of plant
CHDM	9	Queenstown, Cradock, Molteno, Sada, Cofimvaba, Dordrecht, Machubeni, Engcobo and All Saint's

The size distribution of the WTP in the Eastern Cape Province was shown in Figure 2.2.

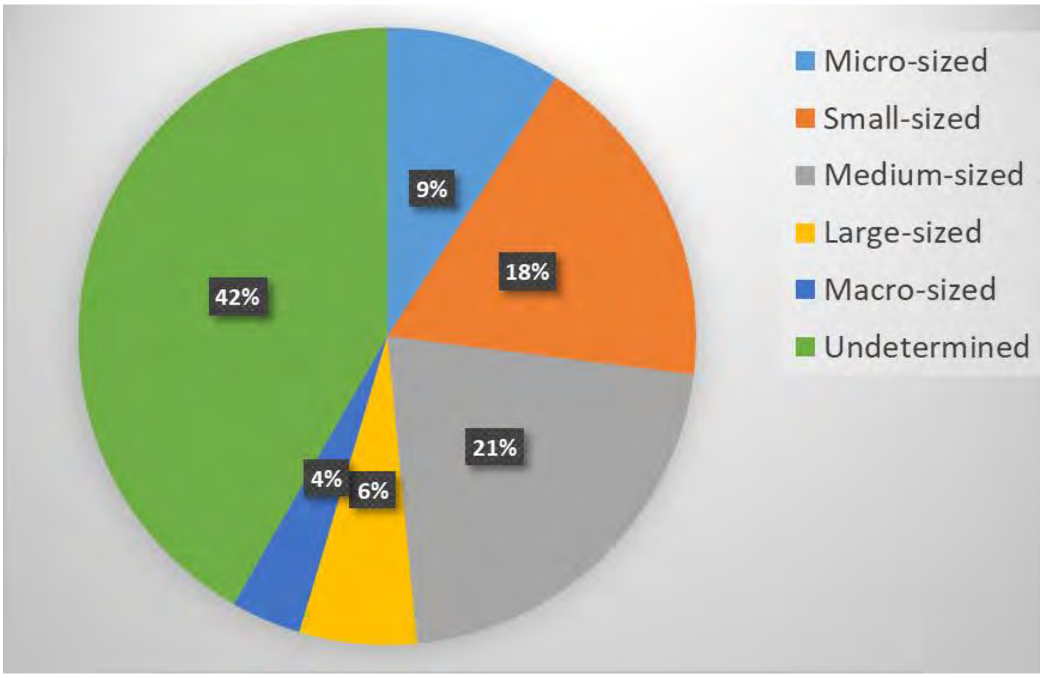

Figure 2.2 *Size distribution of WTP in the Eastern Cape Province. Data were derived from the 2011 Blue Drop Report (DWS, 2011). Size distribution is characterised as follows: micro-sized <500 m^3/day small-sized 500 m^3 – 2 000 m^3/day, medium-sized 2 000 - 10 000 m^3/day, large-sized 10 000 – 25 000 m^3/day and macro-sized >25 000 m^3/day. Undetermined means that water is obtained from other sources e.g. rivers, streams or springs that are not conventional municipal WTP.*

Of the WTP, 42% were of undetermined size/capacity and the province was evidently operating small- (18%) and medium-sized (22%) WTP. In order to fulfil the reductionist approach, the same information needed to be assessed for the WTP in the CHDM (Table 2.3); however, the information for comparison was not readily available even in the Blue Drop reports that were used in this study.

To assess the operability and water quality of these WTP, information from Blue Drop Reports for 2014 was interrogated and the outcome is shown in Figure 2.3.

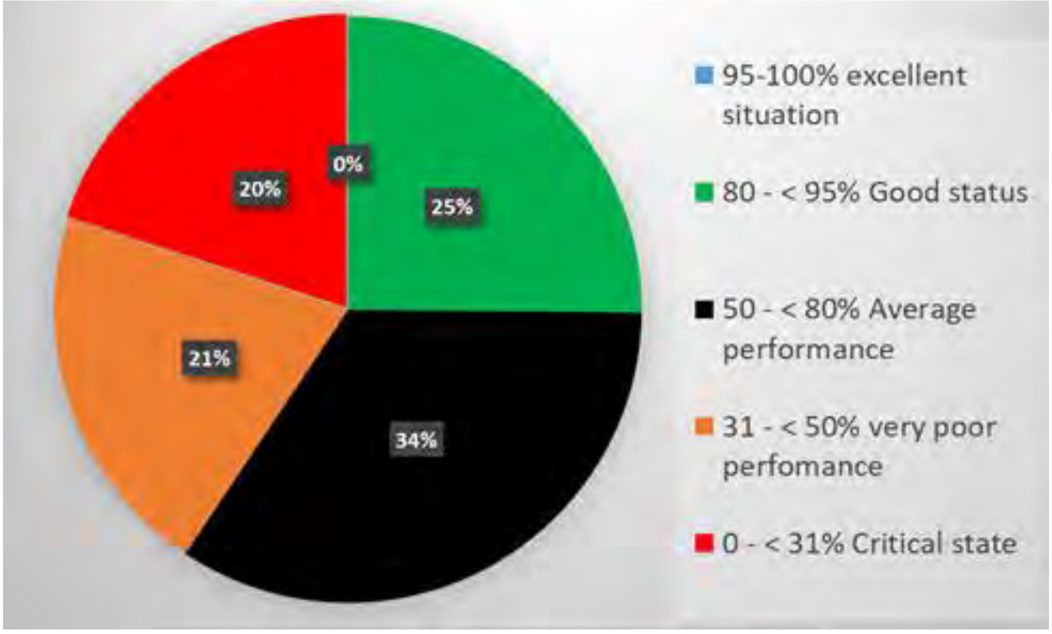

Figure 2.3 *Summary data on Blue Drop compliance for WTP in the Eastern Cape Province. Data were derived from the 2014 Blue Drop Report.*

None of the WTP in the Eastern Cape Province were operating at an excellent situation with the largest percentage (34%) on average performance. 20% of these water systems were in a critical state.

2.3.2 Wastewater treatment

To obtain information about WWT technology choice in the Eastern Cape Province and more specifically in the CHDM, relevant data was extracted from *Executive Summary Municipal Wastewater Treatment Base Information for Targeted Risk-based Regulation Eastern Cape Province* (DWA 2009) and used to scope technology choice, size distribution of WWTW and compliance status. Results in Figure 2.4 show the proportion of WWTW according to design capacity distributed in the Eastern Cape Province in comparison to those deployed in CDHM. A total flow of 345 000 m^3/day is received at the 123 treatment facilities, which has a collective hydraulic design capacity of 490 000 m^3/day (as ADWF). This means that 70% of the design capacity was taken up by the current operational flows, leaving 30% spare capacity to meet the future demand without creating additional capacity (NDHS, 2012).

From Figure 2.4, it was very clear that the situation at DM level reflects that at provincial level in terms of size distribution of WWTW and that mainly small and micro-sized plants were deployed. A comparable percentage, 18% and 19% respectively, had an undetermined design capacity. For both the province and the DM, a comparable percentage, 18% and 13% reflects medium-sized plants. A very small percentage, 4% and 6% respectively, was for large-sized plants. The major difference was that at provincial level, 2% represented macro-sized plants while at district level, no WWTW larger than 25 000 m^3/d was deployed.

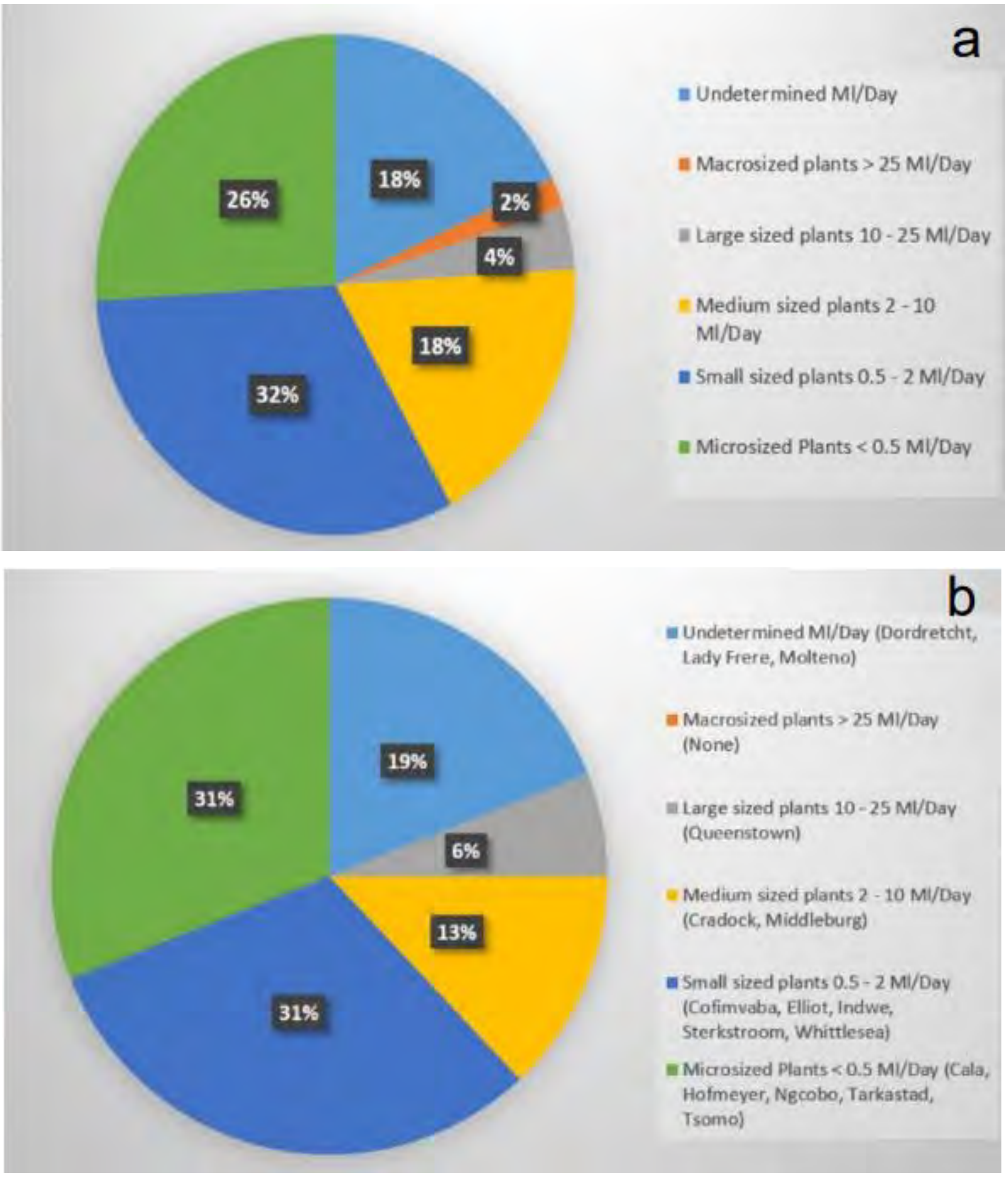

Figure 2.4 *Size distribution of WWTW deployed in the Eastern Cape Province (a) and those in CHDM (b).*

Figure 2.5 shows technology choice for WWT in the Eastern Cape Province vs the technologies that were used for WWT in CHDM.

Based on the technologies for WWT (largely waste stabilisation pond, WSP) in CHDM and the Eastern Cape Province at large, the province was well-positioned for implementation of biotechnological solutions like IAPS. Since Eastern Cape is an agricultural province, the many oxidation pond or WSP systems that were either overloaded, dysfunctional or in a state of disrepair would with minimal cost input be upgraded and converted to algae-based WWTW processes such as IAPS to provide water for recycle and irrigation, biogas for energy, and bio-fertilizers etcetera.

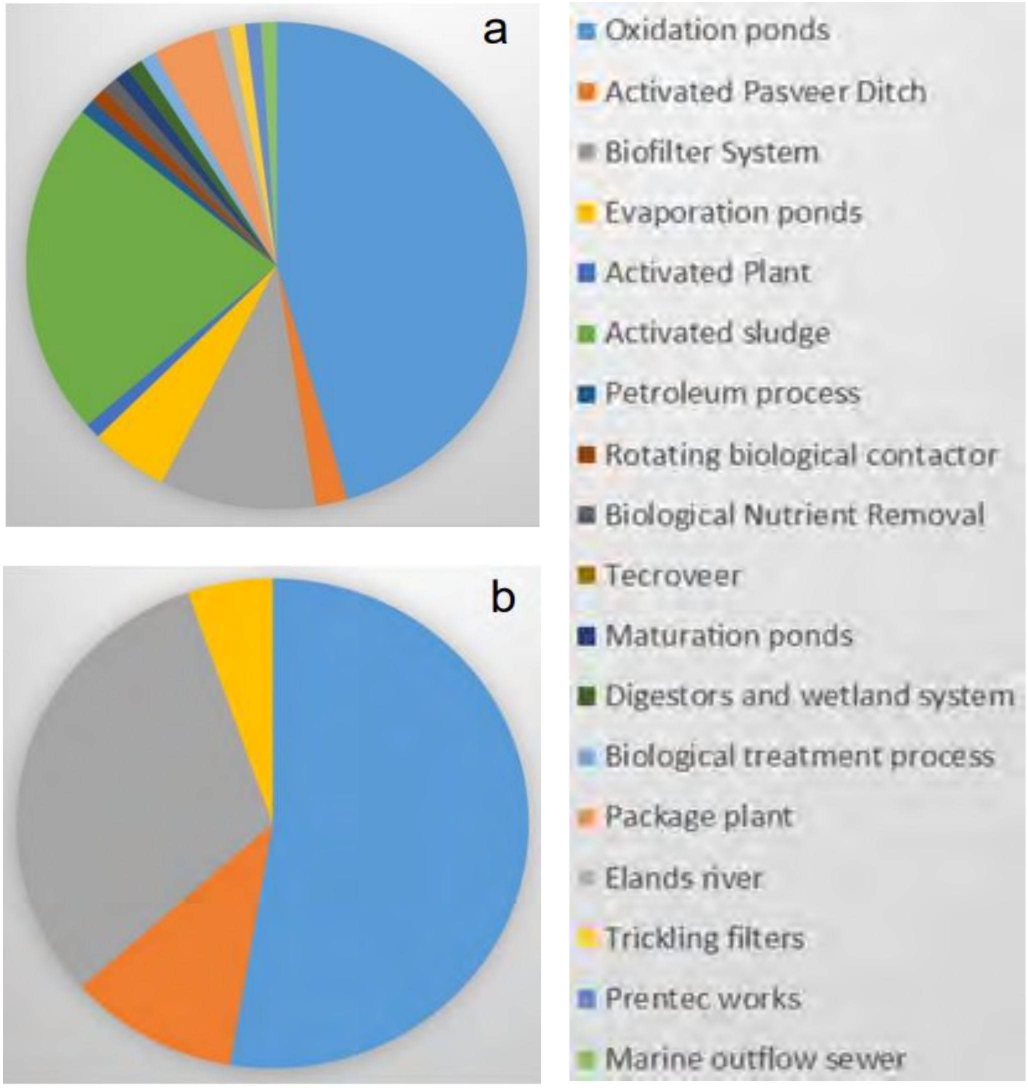

Figure 2.5 *Technologies used for WWT in the Eastern Cape Province (a) vs the technologies used by local municipalities in CHDM (b).*

CHDM is the WSA for all local municipalities in the district. Included are; Inxuba Yethemba, Tsolwana, Inkwanca, Lukhanji, Intsika Yethu, Emalahleni, Engcobo and Sakhisizwe. Table 2.4 shows type of authorisation and license status of WWTW in CHDM. General authorisation (GA) was at a threshold below which a licence (i.e. authorisation) is not required. Thresholds vary according to situation in different water management areas (WMA) and between catchments within WMA. It is obviously important to check the GA requirements because they may eliminate the need for a licence. It was however recommended that the regional DWA office be contacted to obtain guidance on interpretation of GA for the area in question.

Table 2.4 *Type of authorisation and license status of WWTW in the CHDM.*

WWTW	Type of authorization	License status	River receiving treated effluent	Catchment Management Area
Cala	Exemption	Yes	Tsomo River	Mzimvubu to Keiskamma
Cofimvaba	GA*	Unknown	Cofimvaba River	Mzimvubu to Keiskamma
Cradock	Exemption	Yes	Great Fish River	Fish to Tsitsikamma
Dordrecht	Undetermined	Unknown	Irrigation and golf course	Upper Orange
Elliot	Exemption	Yes	Ikhowa River	Mzimvubu to Keiskamma
Hofmeyer	Exemption	Yes	Teebus	Mzimvubu to Keiskamma
Indwe	Exemption	Yes	No discharge	Mzimvubu to Keiskamma
Cacadu	GA	No	Undetermined	Mzimvubu to Keiskamma
Middleburg	Permit	Yes	Farm Dam & irrigation/Klein Brak	Fish to Tsitsikamma
Molteno	Undetermined	Unknown	Stormberg River	Upper Orange
Ngcobo	Exemption	Unknown	Cefana River	Mzimvubu to Keiskamma
Queenstown	Exemption	Yes	Komani River	Mzimvubu to Keiskamma
Sterkstroom	Exemption	Yes	Unknown tributary of Hex River	Mzimvubu to Keiskamma
Tarkastad	Exemption	Yes	Tarka River	Fish to Tsitsikamma
Tsomo	GA	Unknown	French drain	Mzimvubu to Keiskamma
Whittlesea	GA	Unknown	Klipplaat river	Mzimvubu to Keiskamma

* = General Authorisation

In addition to possession of a valid license, level of operability (defined as the ability to keep a plant safe and reliable and in functioning condition according to predefined operational requirements) as a percentage of the 125 WWTW in the Eastern Cape Province vs the 16 WWTW in the CHDM was also determined and is shown in Figure 2.6.

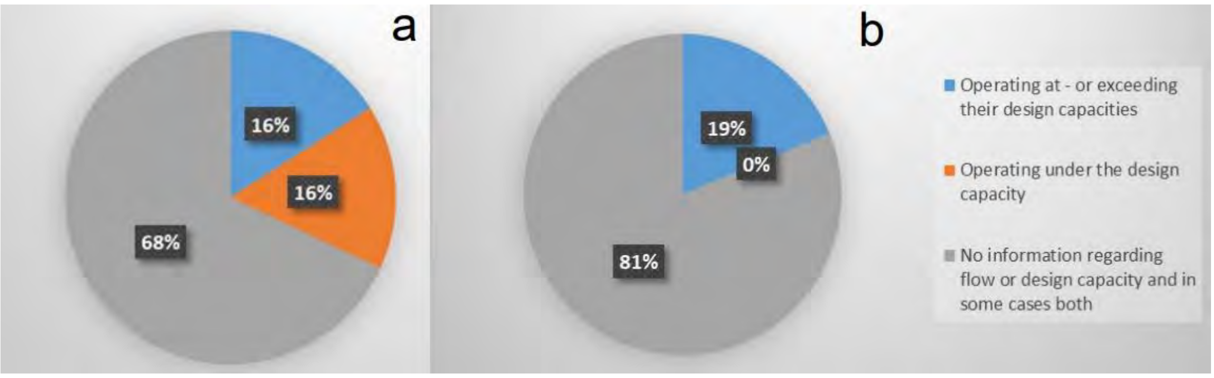

Figure 2.6 *Status of level of operability as a percentage of the 125 WWTW in the Eastern Cape Province (a) vs the 16 WWTW in the CHDM (b).*

Results clearly indicated a problem within the province as no information regarding flow or design and in some cases both, was available for 68% of WWTW. Of the WWTW for which information was available 16% were reported as operating at, or in excess of, design capacity. Even so, daily flows were not measured at some WWTW mainly for the following reasons:

- No Instrumentation Technician appointed as part of the Operation and Maintenance Team to repair existing flow meters,
- No flow meters were in place (mostly as result of budgetary constraints) or meters were to be installed or were in the process of being installed,
- Poor or no daily record keeping of the inflows on the designated proformas (where this in place) by the Process Controllers.

Table 2.5 gives an overview of WWTW in CHDM in comparison to those of the entire Eastern Cape Province in terms of operability at, or in excess, of design capacity. As part of the operability criteria, there is obligation that all WWTW in South Africa make provision for effluent quality to secure the integrity of surrounding watersheds and environments. Over the years, regulatory parameters have been documented to serve as a guideline for quality monitoring/management purposes (Water Act, 1998; DWA, 2013). Unfortunately, many WWTW in all district municipalities of the Eastern Cape Province did not appear able to meet legislated standards in terms of the water quality parameters for discharge to river including *E. Coli*, FC, EC, TSS, NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, and COD as shown in Table 2.5.

Table 2.5 *An overview of CHDM WWTW operating at or in excess of design capacity compared to those of the Eastern Cape Province.*

Parameter	**Percentage (%)**	
	Eastern Cape Province	**CHDM**
Below design capacity	18.4	0
Above design capacity	19.2	18.75
Unknown/no available information	62.4	81.25
Average design capacity (m^3/d)	56 020	6 020
Average inflow (m^3/d)	56 290	6 530
Average flow in excess of capacity (m^3/d).	13 690	-2 350
Average flow as % of design capacity	151	151
Standards not met	E. Coli; FC; EC; SS; NO_3^-; NO_2^-; NH_4^+;PO_4^{2-}	E. Coli; FC; pH; EC; SS; NO_3^-; NO_2^-; COD; NH_4^+, PO_4^{2-}

All WWTW in CHDM operated either near or in excess of design capacity. Even though the proportion of WWTW operating near or in excess of design capacity was comparable for district and province a significant number of works (18.4%) operated below design capacity. A large number for the province WWTW (62.4%) and district WWTW (81.25%) had hydraulic design capacity and or average daily flows that were either undetermined or not known which was a cause for concern. Table 2.5 clearly shows that there were major discrepancies between provincial and DM in terms of the following parameters: plants operating below design capacity, plants with unknown/ no available information, average design capacity, average inflow, and average flow in excess of capacity. However, there was a close resemblance between the two in terms of plants operating above design capacity, average flow as percentage of design capacity and standards not met in terms of *E. Coli*, FC, EC, SS, NO_3^-, NO_2^-, NH_4^+ and PO_4^{2-}. It might be expected that CHDM would mirror the province in all respects since it is a DM, however, this was not the case as Eastern Cape Province seemed to operate at high design capacity plants, high average inflow in excess of capacity while CHDM operates at substantially lower averages.

In terms of meeting the general standard and hence compliance of operations, detailed scrutiny of accumulated information revealed that 64.58% was derived for WWTW in CHDM. That is, only three WWTW (Whittlesea, Sterkstroom and Queenstown) out of the sixteen met the general standard and compliance criteria (Fig. 2.7). Note: an arbitrary score of ≤ 3 shows compliance and that of > 3 shows non-compliance of the WWTW.

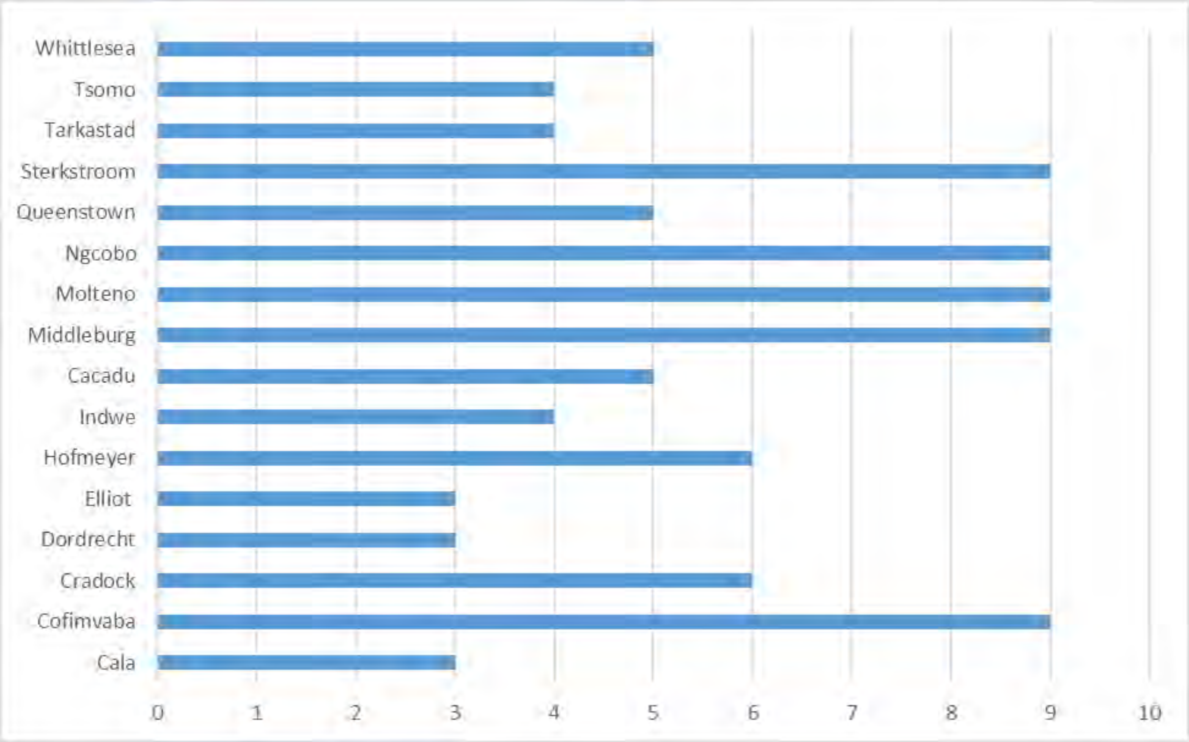

Figure 2.7 *Water quality compliance and status as at 2009 for WWTW in CHDM. Values were computed from data published by DWS (DWA, 2009) and analysed as described in Materials and Methods.*

This clearly indicated that the technology that was presently in use was not able to address the sanitation requirements satisfactorily and, that the final effluent for discharge to river did not meet the general standard (DWA, 2013). Consequently, downstream pollution, contamination of water sources, spread of disease and a general decline in environmental health was likely to happen. Admittedly, factors contributing to the obtained result were in some instances due to, no available information, and no or poor monitoring, along with many other extenuating circumstances that seemed to have combined to create a trend that was unsustainable. Even so, the Queenstown WWTW in Komani, Sterkstroom WWTW and the Whittlesea WWTW showed highest compliance whereas other WWTW in CHDM were non-compliant.

According to the 2009 Executive Summary, it is imperative to note that WWTW that exceed hydraulic capacity were not necessarily those that were non-compliant. Due to a lack of comprehensive water quality information for a number of WWTW, compliance and non-compliance trends could not be determined and for this reason, all "no information" parameters were simply scored as NC (Non-Compliant). Based on available information, capacity and resources of the WSA/WSP, in terms of staff skill and capacity, funds and ease of procurement of materials and equipment, play a greater role in the ability to maintain standards that were compliant.

In terms of meeting the general standard and hence compliance of operations, detailed scrutiny of accumulated information revealed that 70.83% was derived for WWTW in CHDM. Tarkastad and Hofmeyer did not meet all three general standard and compliance criteria for staff capacitation. All the other fourteen WWTW complied in only one out of the three general standard and compliance criteria for staff capacitation (Fig. 2.8). Note: an arbitrary score of <2 shows compliance and that of ≥2 shows non-compliance of the WWTW.

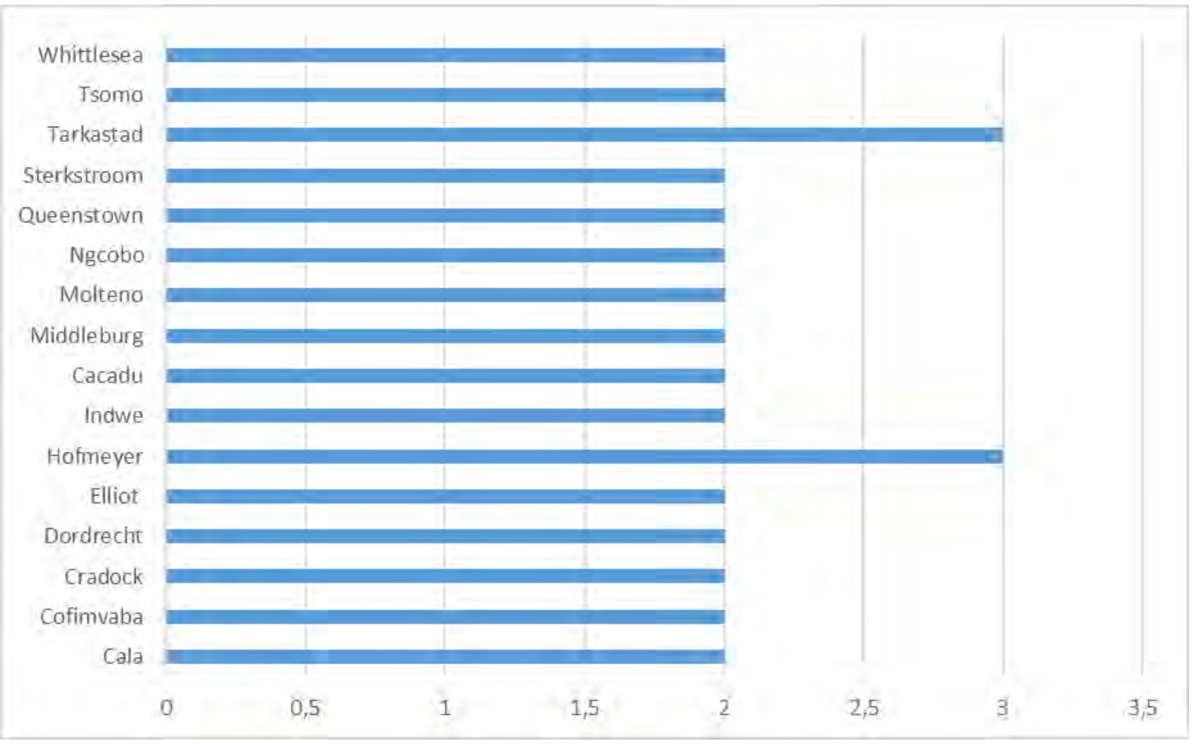

Figure 2.8 *Staff capacitation compliance and status as at 2009 for WWTW in CHDM. Values were computed from data published by DWS (DWA, 2009) and analysed as described in Materials and Methods*

A disturbing factor is that in the Eastern Cape Province in general, high percentages of personnel employed in "skilled' positions, did not comply with the requirements for supervisor (≈14%) and process controller (≈16%) roles. A significant number of positions were not filled by any form of skill or by inadequate/inappropriate skill. Most WSA did not indicate if vacancies exist.

It was clear that the majority of WWTW had skills shortages in terms of Supervisor and Process Control positions. Technical staff required per the legislated requirements was either unknown, not applied or understood or a combination thereof as one had to operate within the O&M budget specified and the availability of required skills in the market. Not until all existing staff per WWTW were properly assessed (qualifications and experience), registered and categorised according to Class of Works was it be possible to quantify actual vacancies and specify needs with a greater degree of accuracy.

Related to occupational health and safety aspects in WWT for WWTW in the CHDM, no confirmed information was provided from the municipality hence "no info" is interpreted as non-compliance.

2.4 Summary and conclusion

In this chapter, studies were carried out to assess water and sanitation in the Eastern Cape Province using publicly available data in an effort to determine the volume of water treated, the size of WTP and WWTW, and type of technology used to treat water or wastewater. Also of paramount importance, this chapter sought to assess whether these treatment plants were compliant with regulations concerning water and effluent quality at provincial, district, and LM level.

Results revealed that at provincial level water treatment technologies comprised primarily access to large bulk water schemes for provision of potable water and for sanitation, the use of WSP for treatment of municipal sewage. Of the examined plants, most were not within regulatory compliance. Specifically, non-compliance was evident with regard to operability where most of the plants were either at- or above design capacity, staff capacitation at supervisory level, and final effluent for discharge to river not meeting the general standard. Similarly, at the district municipal level, water and sanitation access to potable water was mainly through bulk water schemes and for sanitation, the technology of choice seemingly being WSP for treatment of municipal sewage. Again, most were non-compliant and likewise because of poor water and effluent quality, over capacity, operability and below optimum water staff capacitation. It was concluded, based on the parameters that were used, that water and sanitation technology provision within the Eastern Cape Province and an associated DM, CHDM was lacking and at fault in the following areas: poor water and effluent quality, over capacity of plants, operability and water staff capacitation coupled with poor maintenance of water and sanitation infrastructure.

Given that Blue and Green Drop reporting had for whatever reasons been suspended, provided the ideal opportunity to determine whether status of water and sanitation both at provincial and district municipal level had changed in the period, i.e. between 2014 to 2020/22.

Chapter 3 - Current state of water and sanitation in selected municipalities in Chris Hani District, Eastern Cape Province

3.1 Introduction

The Eastern Cape Province has two Metropoles, East London and Gqeberha, and neither are major players in the supply and processing of product from provincial primary industries. Thus, decentralisation of infrastructure is essential to ensure sustained production and supply of produce in terms of cultural practice, which includes beef cattle, dairy, goats, sheep, corn, sugar beet, sorghum, citrus, pineapple, and vegetables. All are important outputs of agriculture, the major primary industry of the province, which is widespread indicating potential for several centres of activity including Komani, Mthatha, Kirkwood, and Cradock and for many, and these activities occur in the peri-urban space. Water and sanitation bioprocess technologies, which provide, in addition to clean water, much-needed co-products such as biofertilizers and biogas are typically also located in the peri-urban space. Thus, such systems might be ideal low-cost vectors for sustained economic growth, particularly if implemented to support agriculture, the major primary industry (Rose et al., 2007; Cervantes-Godoy & Dewbre, 2010; Mambo et al., 2014 b; FAO, 2017).

Both district municipalities and local municipalities across South Africa suspended use of the Blue Drop and Green Drop reporting protocols in 2013/14 respectively. The reason for that suspension was that the department, as the regulator, was unable to ensure compliance standards were being met, so rather than report this non-compliance to the public, they decided to suspend the reporting programme (Turton in Bega, 2021). Other challenges that faced the Green Drop Programme and the municipalities implementing the programme included: lack of human resource capacity to prepare effective corrective action plans and/or wastewater risk abatement plans; lack of finances for mainstreaming of wastewater treatment in municipal decision-making; lack of forward planning; problematic bureaucratic processes; complex relationship between some municipalities and DWS; theft, vandalism and misuse of wastewater treatment infrastructure and not enough transparency (Ntombela et al., 2016). Since these were designed to ensure oversight of operations and maintenance it was of interest to determine, after an hiatus of nearly eight years, the current state (2020/22) of water and sanitation at municipal level within the Eastern Cape Province. This was achieved through survey of WTP and WWTW along an East-West transect across CHDM, site visits and operator interviews at targeted treatment plants, and by assessment of snap-shot data on water quality.

3.2 Materials and Methods

3.2.1 Study Area

The study area was CHDM and the local municipalities of Inxuba Yethemba, Enoch Mgijima, Intsika Yethu, Engcobo, Sakhisizwe and Emalahleni. A transect from west to east (Fig. 3.1) was used to focus the study on towns across CHDM including Cradock, Tarkastad, Komani, Tsomo and Engcobo. This targeted scrutiny of certain plants was according to accessibility as this study commenced in early 2020 immediately before the SARS-CoV-2 outbreak and onset of the global Covid-19 pandemic and associated declaration of the national state of disaster and subsequent hard lockdowns. In addition, the local municipalities span along a transect across a vast area of the EC Province. This distribution gives a more-or-less clear representation of the province as a whole according to the reductionist theory.

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Figure 3.1 *Transect across CHDM showing towns targeted in the study area.*

3.2.2 Surveys, Site Visits, & Operator Interviews

Survey included accessing metadata and related information from CHDM, the respective local municipalities, Google Earth (Google Earth Pro, version 9.156.0.0), and from informal and formal scientific literature (DWA, 2009; 2011; Kulati, 2014; 2016; CHDM, 2015; DWS, 2020; 2020). Selected data was extracted, tabulated, and mean values calculated for the different parameters as indicated in Results.

Site visits were to Queenstown WTP and Cradock WWTW[1]. All visits were by appointment through the Director, Technical Services, Enoch Mgijima LM and were supervised by either

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[1] To avoid physical contact due to COVID-19 and, also to not disrupt work during hours, hard copies of the questionnaires were issued to operators to complete in their own free time. This would also not compel respondents to answer questions under duress in the presence of the researcher.

the plant manager or process controller who provided a guided tour of the works. For WTP, the following information was sought: source of water to be treated; technology used for water treatment; volume of water treated per day; design and operating capacity of plant; and what happens to waste produced; typical impurities in water; who are end users of treated water; cost of plant operations, hydraulic retention time (HRT); future of plant; prospects for using biotechnological solutions and knowledge of these; general level of experience of staff in water/WWT. For WWTW, the following information was sought: source of wastewater to be treated; technology used; volume of wastewater treated per day, design and operating capacity of plant, waste disposal; typical impurities in wastewater; where does the treated wastewater end up; how safe is it to discharge the treated water into the environment; cost of operation, HRT; future of the plant; prospects for using biotechnological solutions knowledge personnel; whether personnel has experience of WWTP from somewhere else. During each site visit the host presented an overview of the plant and its design capacity, the treatment process, water quality, and staffing.

A combination of unstructured interview along with a questionnaire (**Figure S3.1**) were used to acquire information on manager/operator perceptions, and day-to-day plant operation and maintenance. Questions were designed to be open ended to avoid simple "yes" or "no" answers. This has an advantage that it allows exploration of a range of possible topics related to the research question and supports understanding of hypotheses. Questionnaires were collected, information from each respondent categorised per question and analysed. Despite questionnaires being inexpensive, practical, quick to get results from, award scalability, comparability, offer easy analysis and visualization, offer respondent anonymity, little time constraints, as well as cover every aspect of a topic, they also have their downsides as experienced by the researcher. The use of questionnaires opened up to dishonest answers because of fear of being victimised. Some of the questions were left unanswered maybe because there were differences in understanding and interpretation of the questions.

Hyman and Sierra (2016) say there are three basic guidelines for writing good questions that relate to surveys:

1. Specific questions should be created only after thorough consideration of research questions, which have been formalized in writing.
2. When working on a questionnaire, constant reference to research questions should be done.

3. For each question written, understanding of how responses to that question will help to answer the research questions.

The questionnaires in the questionnaire were based on the above guidelines.

Ethical clearance or approval was not necessary for this thesis because the information sought for was freely available in the public domain (e.g. published biographies, newspaper accounts), and the analysis of datasets, was either open source or obtained from other researchers. In addition, the data obtained was properly anonymised and informed consent was obtained at the time of original data collection.

3.2.3 Water Quality

To ascertain quality of treated water within CHDM, snap-shot data was obtained for the Queenstown WTP which included pH, turbidity, EC, free Cl_2, total organic carbon (TOC) and *E. coli* and are expressed as mean ± standard deviation (SD).

For the Cradock WTP and WWTW, data for the following parameters was obtained: pH, dissolved oxygen (DO, mg/L), EC (mS/m), COD (mg/L), nitrate/nitrite-N (mg/L), ammonium-N (mg/L), phosphate-P (mg/L), total suspended solids (TSS, mg/L), total coliform count (cfu/100ml), *E. Coli* (<1 taken as 0) (cfu/100ml), and free chlorine (mg/L).

Grab water samples were from appropriate discharge points according to process flow following plant standard operating procedures (SOP) and the above listed parameters analysed by a commercial laboratory (Talbot Laboratories) operating as Water Technology (Cape) (Pty) Ltd, Deal Party, Port Elizabeth.

3.2.4 Data Analysis

Most WWT systems are designed using BOD of 0.08 kg/PE/d organic load, equivalent to 200 L PPPD hydraulic load (Henze et al. 2008; Cowan et al. 2016). For the purposes of this study, design capacity of WWTW is assumed to be; BOD = 0.08 kg/PE/d (where 1 PE = 80 g BOD/d equivalent to 200 L/PE/d). BOD was therefore calculated as follows:

$$\text{Total BOD per day (BOD/d)} = \text{PE} \times 0.08\text{kg}$$

And, where design capacity is expressed as volume per day, a value of 200 L per PE was used to calculate population the plant was designed for:

$$\text{PE} = \frac{Design\ capacity\ (L)}{200L}$$

Operational capacity is then calculated as:

$$\text{Operational Capacity} = \frac{Census\ population\ PE}{Population\ the\ plant\ was\ designed\ for\ PE}$$

For survey, final effluent water quality from WTP was metered against the South African National Standard (SANS 241, 2015) and the 2014 Blue Drop report; and for WWTW, water quality was assessed using the General Standard (DWA, 2013) and the 2014 Green Drop report.

For targeted sites, thirteen parameters including pH, EC, DO, total dissolved solids (TDS), TSS, turbidity, nitrates, nitrites, phosphates, ammonium-N, COD, and residual chlorine were assessed. On site measurements at the Queenstown WTP for pH, EC, TOC, residual/free chlorine and turbidity were done. Water quality analysis was also as per the national standards (SANS 241, 2015) and the 2014 Blue Drop report for WTP and was as per General Standard (DWA, 2013) and the 2014 Green Drop report for the WWTW.

A CRR for any WTP presents an overall risk profile of a plant i.e., it measures performance of the WTP against a set of criteria, including design capacity (A), capacity exceedance rating (B), effluent failure rating (C) and technical skills rating (D). The cumulative risk rating (E) as defined by DWA as:

$$E = A * B + C + D$$

Where

A = design capacity (which also represents hydraulic loading);

B = average daily flow in excess or below capacity;

C = number of non-compliant parameters of final effluent discharged into the receiving water source;

D = non-compliance in terms of the Technical skills.

3.3 Results and Discussion

3.3.1 Surveyed Treatment Plants – Systems and processes

Identified and surveyed plants along the west-east transect across CHDM are listed in Tables 3.1, 3.2 and 3.3.

Analysis of WTP and WWTW revealed that most were operating in excess of capacity and in the range 1.52 to 12 times installed hydraulic loading. Plant treatment efficiency may thus be severely compromised in terms of BOD removal as organic loading has increased substantially due to increased PE (Table 3.1). For example, Cradock WWTW, designed to service a PE of approximately 24,150, but as at 2011, PE had increased to 36,671 with concomitant change in capacity ratio to 1.52 (152% of design capacity). The worst-case scenario along this west-east transect appeared to be Cala where calculated operational capacity ratio was 12 (1,200% of design capacity). These findings emphasise the increased pressure being exerted on all aspects of a very fragile sanitation system, which likely is collapsing if not already collapsed. All data in Table 3.1 cement the fact that demand on WTP and especially WWTW is far higher than the specified design capacity. Furthermore, results are based on census 2011 and for each; PE is substantially different from present day PE (i.e., 2021/2022).

From the above results (Table 3.1) and in particular based on the quantity of wastewater produced, it is evident that freshwater demand significantly exceeds capability of water supply schemes e.g. in Komani, where demand (30,920 m^3/d) is more than double reported available supply (12,000 m^3/d). This appears true for all surveyed systems as shown in Tables 3.1 and 3.2. Furthermore, reticulation is associated with leaks, wastage, and inevitable evaporation in poorly managed and maintained systems leading to water loss along the value chain. Thus, in theory, estimated water demand is likely much higher than that estimated in this survey.

3.3.2 Targeted Treatment Plants – Systems and processes

Due to emergence of the SARS-CoV-2 virus, Covid-19 disease and ensuing national state of disaster and subsequent hard lockdown across South Africa, aspects relating to site visitation were adversely affected. Under the circumstances, every effort to contact local authorities responsible for water and sanitation in the towns of Cala (Sakhisizwe LM) and Ngcobo (Engcobo LM) failed. In short, a decision was taken to target only two towns along the transect in an effort to obtain the required information i.e., the western town of Cradock and the more central city of Komani.

***Table 3.1** WTP and WWTW surveyed along the west-east transect across CHDM as shown in Fig. 3.1.*

Town	Treatment Plant	Process Technology	Design Capacity (m^3/d)[A]	Population[B]	Population equivalent (PE)
Cradock	Cradock WTP	Gariep Water Scheme/Conventional [C]	-	36,671	
	Cradock WWTW	AS & Biofilters	4,830		Estimated wastewater produced = 7,330 m^3/d Total BOD/d = 2,933.68 kg Current operational capacity = 36,671 PE/24,150 PE = **1.52**
Tarkastad	Tarkastad WTP	Tarkastad Water Scheme/Conventional	-	6,000	
	Tarkastad WWTW	WSP	170		Estimated wastewater produced = 1,200 m^3/d Total BOD/d = 480 kg Current operational capacity = 6,000 PE/ 850 PE = **7.5**
Komani	Queenstown WTP	Catchment/Conventional	-	154,617	
	Rathwick WWTW	AS & Biofilters	12,000		Estimated wastewater produced = 30,920 m^3/d Total BOD/d = 12,369.36 kg Current operational capacity = 154,617 PE/60,000 PE = **2.57**
Cacadu	WTP	Cacadu Rural Water Supply Scheme/Conventional	-	26,371	
	WWTW	Evaporation ponds	0		Wastewater produced = 5,270 m^3/d Total BOD/d = 2,109.68 kg Current operational l capacity = n.d.[D]
Tsomo	WTP	Tsomo River Abstraction/Conventional	-	2,100	
	WWTW	WSP	200		Wastewater produced = 420 m^3/d Total BOD/d = 168 kg Current operational capacity = 2,100PE/1,000 PE = **2.1**
Cala	WTP	Ncora Bulk Water Project/Conventional	-	15,000	
	WWTW	WSP	250		Wastewater produced = 3,000 m^3/day. Total BOD/day = 1200 kg Current operational capacity = 15,000 PE/1,250 PE = **12.0**
Ngcobo	WTP	Xuka, Chefane, & Ngcotyana rivers & boreholes	-	9,835	
	WWTW	WSP	500		Wastewater produced = 1,970 m^3/day. Total BOD/day = 786.80 kg Current operational l capacity = 9,835 PE/2,500 PE = **3.93**

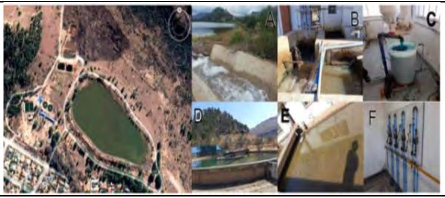
[A] Design capacity assumed as per PE; BOD = 0.08 kg PPPD (where 1 PE = 80 g BOD/d equivalent to 200 L/PE/d (Henze et al. 2008; Cowan et al. 2016)

[B] Population figures as per RSA census (2011)

[C] Conventional water treatment as per DWA (2013) and according to SANS 2015

[D] n.d. = Not determined

Table 3.2 *Survey of WTP along the west-east transect across CHDM*

WTP	Google image/Actual image	Technology	Demand (m^3/d)	Water quality	Comment
Cradock	A 	Gariep Water Scheme/ Conventional	7,330	SANS 241 (2015)	One responsible person for WTP and WWTW. +ve BD Status (2014)
Tarkastad	Under construction	Tsolwana/ Tarkastad Water Scheme/ Conventional	1,200	SANS 241 (2015)	Quanti-Tray/51 and Quanti-Tray/2000 are used when quantifying coliforms, *T. coli* and *E. coli* to provide easy, rapid, and accurate bacterial counts (CHDM, 2022).
Queenstown		Catchment/Conventional	30,920	SANS 241 (2015)	GPS coordinates: 531"53'38.2"; E26"53'30.0". 5 process controllers are available at the plant on a rotational basis.
Cacadu	Under construction	Cacadu Rural Water Supply Scheme through Macubeni Dam. /Conventional	5,270	SANS 241 (2015)	Macubeni damn is having challenge of silting. Less formal access to water supply. Service reservoirs supplied by boreholes or from natural water resources (rivers and springs) service the town. Some of these resources are not working or are inadequate (Emalahleni Municipality, 2003:20)
Tsomo River Abstraction and Water Treatment works		Tsomo River Abstraction/Conventional	420	SANS 241 (2015)	More than 40,000 households are set to benefit from this project. 25,000 m^3/d reservoir is also constructed.
Cala (Ncora Bulk Water Project)		Ncora Bulk Water Project, Tsomo River, Boreholes /Conventional	3,000	SANS 241 (2015)	Plant to deliver 5,000 m^3/d
Ngcobo		Ngcobo Bulk Water Supply through Xuka, Chefane, & Ngcotyana rivers & boreholes	1,970	SANS 241 (2015)	Engcobo LM residents drink dirty water from a stream with animals as shown in the photograph.

[A] The Fish-Sundays River Canal Scheme comprises a canal and tunnel system, which supplies Orange River water from the Great Fish River valley to the Sundays River valley to supplement existing water supply in the Eastern Cape Province. Since 1992, water from the Sundays River valley has been supplied to Port Elizabeth. It is estimated that up to 200 million m3 of Orange River water could eventually be transferred to the Port Elizabeth metropolitan area annually (See inserted image)

***Table 3.3** Surveyed WWTW along the west-east transect across CHDM*

WWTW	Google image/Actual image	Technology used	Capacity (m^3/day)	Water quality	Comment
Cradock		AS & Biofilters	4,830	General Standard (DWA, 2013)	One responsible person for WTP and WWTW; 4 process controllers; Critical Risk Green Drop Status (DWS, 2014)
Tarkastad		WSP	170	General Standard (DWA, 2013)	Overloaded OP and pollution of Tarka River; High Risk Green Drop Status (DWS, 2014); Quanti -Tray/51 and Quanti-Tray/2000 used when quantify coliforms and *E. coli*.
Rathwick - Queenstown		AS & Biofilters	12,000	General Standard (DWA, 2013)	Access to plant denied. Referred to Cradock WWTW; Critical Risk Green Drop Status (DWS, 2014)
Cacadu	Under construction	Evaporation ponds	0	General Standard (DWA, 2013)	Pump station failure; Cacadu River impacted; Rural agriculture and community; Critical Risk Green Drop Status (DWS, 2014)
Tsomo		WSP	200	General Standard (DWA, 2013)	Critical Risk Green Drop Status (DWS, 2014)
Cala	Under construction	WSP	250	General Standard (DWA, 2013)	Upgrading of the Cala WWTW to a 3,000 m^3/d AS nutrient removal plant, two pump stations and associated rising mains; Critical Risk Green Drop Status (DWS, 2014)
Ngcobo	 	WSP	500	General Standard (DWA, 2013); OP over-loaded and neglected, giving rise to offensive odours. This leads to pollution of the Cefane river.	Existing WWTW is overloaded and incapable of treating the incoming sewage to a satisfactory standard. Proposed new works facility with a daily throughput capacity of more than 2000m^3 but not less than 15000m^3 and to treat approximately 3,000 m^3 of wastewater per day. Critical Risk Green Drop Status (DWS, 2014)

3.3.2.1 Queenstown WTP

To gain insight into and information about water provision in CHDM one of the largest regional WTP, viz. Queenstown WTP, was surveyed via site visit and unstructured operator interview. Findings presented in Figure 3.2 illustrate the treatment process. Berry reservoir acts as the storage dam and is immediately upstream of the plant (Queenstown WTW Operator 2020, personal communication) which serves the city of Komani and surrounds. Constructed in 1950, this treatment plant has capacity to produce 17 500 m^3/d and serves 18 463 households with PE = 68 872. Queenstown WTP has a cumulative risk rating (CRR) of 11 (CHDM, 2018).

A low risk i.e., with CRR < 10 indicates a plant that is functioning fairly well, but may need attention to reduce the risk profile. Moderate risk (CRR≥10 & ≤ 15) plants, require serious attention to ensure reduced risk whereas high-risk plants (CRR >15 & ≤ 18) the treatment plant requires urgent attention to reduce risk profile and if at critical risk (CRR >18 & ≤ 21), critical attention will be required to reduce risk profile. Thus, Queenstown WTP is a moderate risk facility but has maximum risk rating (MRR) of 47.8% (CHDM, 2018). In terms of MRR, 0% is lowest risk to public health and the environment, even though this is not possible in practice and 100% is critical risk for the plant to public health and the environment (Green Drop report, 2012).

Water gravitates into the WTP and treatment commences with initial disinfection by chlorination (Fig. 3.2 b) followed by addition of aluminium sulphate/alum (Fig. 3.2 c), clarification using Dortmund tanks (Fig. 3.2 d), mechanical filtration of particulate matter, (Fig. 3.2 e), and final disinfection by chlorination (Fig. 3.2 f). Prior to release to municipal reticulation, treated water must meet the South African National Standard (SANS 241, 2015),

See Appendix S5.

Figure 3.2 *Google Earth image of Queenstown WTP adjacent to Berry Reservoir (top panel) and a collage illustrating the steps in the water treatment process (bottom panel). a) Water detained in Berry Reservoir; b) inlet and chlorination of water from Berry Reservoir; c) aluminium sulphate/alum coagulant/flocculent treatment; d) clarification in Dortmund settlers; and, e) final chlorination of the top-flow prior to release to municipal reticulation.*

3.3.2.2 Rathwick Queenstown WWTW

Unfortunately, efforts to arrange a site visit to Rathwick Queenstown WWTW were deflected by CHDM. Excuses ranged from the plant is in state of disrepair; and/or, it was simply not possible due to plant failure. An image of the topographical layout of this WWTW is shown in Figure 3.3. Clearly visible is the proposed expansion of the plant as proposed in a 2012 waste management licence application (DEA, Ref 12/9/11L378/1) granted to CHDM by Deputy Director-General: Environmental Quality & Protection to allow for expansion or changes to existing facilities for process or activity governing release of pollution, effluent or waste; and, to allow for treatment of effluent, wastewater or sewage.

Figure 3.3 *Google Earth image illustrating the Rathwick Queenstown WWTW and adjacent (municipal) waste management activity as per waste management licence application (DEA, Ref 12/9/11L378/1) granted to CHDM.*

The Rathwick-Queenstown WWTW treats wastewater from Queenstown and surrounding areas. The works is a combined bio-filter/AS plant with an estimated treatment capacity of 12 000 m^3/d. The final effluent from Queenstown WWTW discharges into Komani River (DWA, 2009; Blue Drop Report, 2010).

3.3.2.3 Cradock WTP

Unlike Queenstown WTP, that receives raw water directly from dams into Berry reservoir before treatment; Cradock WTP obtains its water from raw water dams that store water from Gariep Fish-Sundays River Canal Scheme (Fig. 3.4).

Survey showed that canal water from the Fish River is stored in raw water dams, which then feed the WTP before water is reticulated into Cradock town.

Just like Queenstown WTP, Cradock WTP uses conventional treatment systems to produce portable water for human use. Availability of storage dams might insinuate that Cradock has a fairly secure water services infrastructure since it has access to a larger water scheme.

Figure 3.4 *Raw water dams that store water from Gariep Fish-Sundays River Canal Scheme before it is channelled to Cradock WTP for treatment and reticulation to Cradock town.*

3.3.2.4 Cradock WWTW

Contrary to the situation concerning Queenstown-Rathwick WWTW, the technical director very easily and readily redirected interests towards the Cradock WWTW for scrutiny through survey to gain first-hand information about process flow, current day operation and staff establishment. The Cradock WWTW was another of the targeted sites that was accessible during Covid-19 pandemic.

To gain insight into operational status at the Cradock WWTW a site visit and accompanying survey was conducted and the results are summarised in Figure 3.5. Evaluation of the process flow indicated a plant that was in working condition but with some major challenges. For example, one of the two aeration tank mixers was non-functional (Fig. 3.5 D), two lateral aerators were dysfunctional (Fig. 3.5 E), and one Dortmund clarifier was dysfunctional (Fig. 3.5 G). This, again, evidences the poor operation and maintenance of wastewater and sewage treatment infrastructure in the Eastern Cape Province. This and associated neglect contributes to pollution of water resources and has a direct impact on human health and the environment.

Figure 3.5 *Cradock WWTW (top panel) and components of the process flow (bottom panel). a) wastewater flow into the WWTW; b) screening of the wastewater; c & d) grit chamber; e) aeration tanks lateral aerators; f) removal of excess bacteria in a sedimentation tank; g) clarification in Dortmund clarifiers; h) Landfill; i) Storage tanks for chlorinated wastewater before final treatment and discharge.*

3.3.3 Water quality

To obtain information about the efficiency of the treatment process at time of site visit several key physicochemical parameters of the treated water were assessed and the results are shown in Table 3.4. While snap-shot data is of limited value in terms of overall water quality, it nevertheless informs on methodology used, operator diligence, and actual diel water quality. Thus, the final effluent from both the Queenstown and Cradock WTP, assessed in accordance with SANS 241, displayed water quality that was within the general authorization limits for either irrigation or discharge of up to 2 000 m^3 on any given day are also given (DWA, 2013).

Water from Queenstown and Cradock WTP was within the pH range. Free chlorine is also within the chlorine range for both plants. Turbidity is above range for both plants since it is greater than 1 Nephelometric Turbidity Units (NTU). EC is within range for both plants (≤ 170 mS/m). TOC is out of range at the Queenstown WTP since it is above 10 mg/L. TDS is within range for Cradock WTP as well as total coliform count and *E. Coli*.

In terms of water quality, the above notwithstanding, even though it seems to fit the general authorisation for discharge, it is clear that turbidity and TOC are parameters that are in excess of the SANS 241, 2015 general limit.

Although turbidity was reduced by 99.89% from 38.81 to 1.56 NTU at the Queenstown WTP, turbidity is above the SANS 241 standards by 0.56. This implies that the water system under study is not suitable for domestic uses with reference to turbidity. Even though Queenstown WTP is a moderate risk facility with a maximum risk rating (MRR) of 47.8%, turbidity still exceeds limits indicating poor operation and maintenance of water treatment infrastructure.

Total Organic Carbon (as C) for the raw water at the plant is 13.92 mg/l. At the treatment plant, TOC in the treated water was not measured. Compared to SANS 241 general limits, the TOC in raw water was out of range, implying non-compliance with the SANS 241 general limits due to similar reasons stated for non-compliance in terms of turbidity.

Table 3.4 *Snap-shot water quality data of the final effluent from the Queenstown and Cradock WTP. Mean values for the different parameters tested at the Queenstown and Cradock WTP were calculated, recorded and compared against the general standards for drinking water to ascertain treatment efficiency at the two treatment plants. Also shown are standards for drinking water (DWA, 2015).*

Parameter (units)	**SANS 241, 2015**	**Komani (Queenstown WTP)**	**Cradock (Cradock WTP)**
pH	≥ 5.0 to ≤ 9.7	8.5	8.35
Free Chlorine (mg/L)	≤5	1.42	0.54
Turbidity (NTU)	Operational ≤1	1.56	1.15
EC (mS/m)	≤ 170 mS/m above intake	15.9	42.2
Total Organic Carbon (TOC, mg/L)	≤ 10	13.92	-
Nitrate-N (mg/L)	≤ 11	-	-
nitrite-N (mg/L)	≤ 0.9	-	-
Ammonia-N (mg/L)	≤ 1.5	-	-
Total dissolved solids (TDS, mg/L)	≤ 1200	-	272
Total coliform count (cfu/100ml)	≤ 10	-	0
E. Coli (<1 taken as 0) (cfu/100ml)	0	-	0

Since access to Rathwick-Queenstown WWTW was not granted, only results for Cradock WWTW are available. Results show compliance with the general limit for irrigation and discharge for only pH, DO, EC, and COD.

Parameters that were above general standard for either irrigation or discharge included: nitrate/nitrite-N (21.7 mg/L; limit, 15 mg/L), ammonium-N (7.5 mg/L; limit, 6 mg/L for irrigation and 3 mg/L for discharge), phosphate-P (23.55 mg/L; limit, 10 mg/L for both irrigation and discharge), TSS (74.5 mg/L; limit, 25 mg/L), total coliform count (222 259 cfu/100ml; limit for irrigation and discharge is ≤1000 cfu/100ml), *E. Coli* (18 498 cfu/100ml; limit, 5000 cfu/100ml, <1 taken as 0), and free chlorine (0.48 mg/L; limit, 0.25 mg/L). These results show a system appears to be overloaded in terms of nitrate/nitrite-N, ammonium-N, phosphate-P, TSS, total coliform count, E. Coli, and free chlorine confirming preliminary survey data which indicated an operational capacity of 152% of design (Table 3.1).

Non-compliance in terms of nitrate/nitrite-N, ammonium-N, phopshate-P, TSS, total coliform count, *E.* Coli, and free chlorine may be as a result of an aberrent process flow due to lack of appropriate mixing, lateral aeration, and settling as determined during the site visit (section 3.3.2.4).

***Table 3.5** Snap-shot water quality data for the final effluent from the Queenstown and Cradock WWTW. Results were compared against the general authorization limits for either irrigation or discharge of up to 2 000 m^3 on any given day (DWA, 2013).*

Parameter (units)	**General limit: Irrigation** [A]	**General limit: Discharge** [A]	**Komani (Rathwick - Queenstown WWTW)**[B]	**Cradock (Cradock WWTW)**
pH	5.5-9.5	5.5-9.5	-	7.3
DO (mg/L)	>2	>2	-	17
EC (mS/m)	70 $mS\cdot m^{-1}$ above intake to a maximum of 150 $mS\cdot m^{-1}$	70 $mS\cdot m^{-1}$ above intake to a maximum of 150 $mS\cdot m^{-1}$	-	55.2
COD, mg/L [C]	75	75	-	65
Nitrate/nitrite-N (mg/L)	15	15	-	21.7
Ammonium-N (mg/L) [C]	6	3	-	7.5
Phosphate-P (mg/L)	10	10	-	23.55
TSS (mg/L)	25	25	-	74.5
Total coliform count (cfu/100ml)	1000	1000	-	222 259
E. Coli (<1 taken as 0) (cfu/100ml)	Below 5000	Below 5000	-	18 498
Free Chlorine (mg/L)	0.25	0.25	-	0.48

[A] General Authorisations in terms of section 39 of the national water act (Republic of South Africa, *Water Act 1998*)

[B] Not available – access to plant denied by the technical director due to plant not in its good state.

[C] Values attained onsite

3.3.4 Unstructured interview outcomes

In order to obtain first-hand information about the day-to-day operations, management and state of WTP and WWTW in the study area, unstructured interviews supplemented with a questionnaire, were carried out at the Queenstown WTP and Cradock WWTW. The interviews were with a senior process controller who was also tasked with answering the questionnaire and a summary of the outcome is shown in Table 3.6.

Table 3.6 *Summary findings from unstructured interviews with plant operators at Queenstown WTP and Cradock WWTW*

Questions relate to:	**Process controller responses**	
	Queenstown WTP	Cradock WWTW
Design & capacity	• Demand of 7.330 m^3/day	• Capacity of 4.830 m^3/day • WWTW is currently operating at exactly its design capacity
Process control & staff	• Five process controllers • Water quality technician has plant audit and Blue Drop assessment experience from other WTPs and visits other WTPs on monthly basis • Conventional method for water treatment is used	• Water quality technician has experience as a process controller -Vhembe DM (Limpopo) and Industrial Effluent Plant Operator at Ekurhuleni Water Care Company (ERWAT) • Technician is responsible for Cradock WTP and WWTW and visits them together with Middleburg WWTW thrice per week.
Operation & maintenance	• Very costly process due to electricity, chemicals, and maintenance expenses; • Standard operating procedures typical of a WTP are being followed and water meets the general standards set by DWS	• Plant is operating under standard operating procedures; • Plant has approximately 80% compliance of the final effluent at any given period when measured against the general standards set by DWS. • No comment about the cost of running the plant • Appointment of a consultant in order to deal with the issues relating to bulk infrastructural challenges
Challenges & prospects	• Operators understand the importance of co-product beneficiation e.g. fertilizer and biogas • Refurbishment and upgrading of the plant is the future of this plant, if population grows or new industries are built, or the town gets bigger and there are more people in Komani	• Operators understand the importance of co-product beneficiation e.g. fertilizer and biogas • Never considered biotechnological solutions in the treatment of wastewater; believes the existing technology is appropriate and is able to achieve compliance. However, embraces biotechnological solutions to WWT

In summary, the outcome of unstructured interviews revealed that the Queenstown WTP and Cradock WWTW are following standard operating procedures despite the challenges faced in terms of water quality as portrayed in Tables 3.4 & 3.5. These plants also experience severe overload as shown in Tables 3.1, 3.2 & 3.3, even though from unstructured interviews supplemented with a questionnaire, they appear to be operating optimally.

The respondents left some questions in the questionnaire blank; reasons were not provided. This could be due to fear of being victimised or due to the fact that there were differences in understanding and interpretation of the questions.

3.4 Comparison of historical and current statuses of WT and WWT plants in the EC Province

Water treatment and WWT have deteriorated when comparing previous (Chapter 2 results) and results in this chapter, Chapter 3, which reflect the status currently. All plants surveyed were operating in excess of capacity and, thus showed increased pressure being exerted on all aspects of a very fragile sanitation system. This observation may explain in part the likely collapse, if not already collapsed system processes. Due to an increased population, demand for water is relatively higher than supply. This comes as a result of damaged reticulation associated with leaks, wastage, and inevitable evaporation in poorly managed and maintained systems ultimately leading to water loss along the value chain.

3.5 Summary and conclusion

In this chapter, a scoping exercise on the current state of water and sanitation in selected and targeted local municipalities in CHDM, Eastern Cape Province was conducted. This was done by first constructing a west-east transect, followed by survey of water and WWTW along said transect, targeted scrutiny of certain plants according to accessibility as this study commenced in early 2020 immediately before the SARS-CoV-2 outbreak and onset of the global Covid-19 pandemic and associated declaration of the national state of disaster and subsequent hard lockdowns. Unstructured plant operator interviews were also conducted in conjunction with questionnaires and lastly evaluation of water quality.

A survey of water and sanitation plants along the west-east transect in CHDM revealed that potable water is provided to towns within the study area from water schemes. WSP is the most common sanitation technology for treatment of wastewater. The exception being the cities of Cradock and Komani where biofiltration coupled with AS is used. Freshwater demand significantly exceeded capability of water supply schemes e.g. in Komani, where demand (30,920 m3/d) is more than double reported available supply (12,000 m3/d). Result also showed that most systems were operated in excess of capacity and in the range 1.52 to 12 times installed hydraulic loading.

A targeted scoping exercise, which included site visits and unstructured operator interviews with questionnaires, revealed the following: Komani has its own dedicated WTP (Queenstown WTP). The plant is a moderate risk (CRR =11; MRR = 47.8%) plant, meaning that it requires serious attention to ensure reduced risk. Upon site visit, Cradock WWTW was in working condition but with some major challenges of infrastructural dysfunction within the plant. The Cradock WTP and Rathwick-Queenstown WWTW were among the targeted sites but permission to visit was unfortunately and presumably due to the Covid-19 pandemic, never granted. Unstructured interviews revealed that the Queenstown WTP and Cradock WWTW were following standard operating procedures despite challenges faced in terms of water quality and system overload. Assessment of water/effluent quality revealed that turbidity and TOC were parameters that were above the SANS 241 general limit. Non-compliance in terms of nitrate/nitrite-N, ammonium-N, phosphate-P, TSS, total coliforms, *E. Coli,* and free chlorine was evident at the Cradock WWTW. It is concluded, based on the parameters that were used, that even though WTP seemed compliant for most of the parameters, WWTW were generally non-compliant in terms of most of the parameters examined.

CHAPTER 4: General Discussion & Conclusion

4.1 Dynamics of the water treatment and WWT in CHDM, EC

This thesis set out to cross-examine water and sanitation infrastructure in a provincial DM with a view to potential implementation of bio-platform technologies, and the study commenced in early 2020 immediately before the SARS-CoV-2 outbreak and onset of the global Covid-19 pandemic and associated declaration of the national state of disaster (Department of Co-operative Governance and Traditional Affairs, 2020) and subsequent hard lockdowns. Consequently, the research topic, direction, and manner in which the investigation was to be carried out was adjusted from an infield-based study to a more interrogative desktop-type study. Indeed, so severe was lockdown and mandatory social distancing that research students were not permitted on campus or in laboratories for a period that in most cases exceeded 7 months. Further, most places were not easily accessible, including municipal WTP and WWTW that had been earmarked for study.

Even so, in light of prevailing circumstances where most people were working from home and not permitted to interact, it was still possible to obtain much of the publicly available data and to construct from that data useful scenarios that related to the status of water and sanitation in the Eastern Cape Province, CHDM and its associated local municipalities. A decision was taken to focus the study on water and sanitation in the Eastern Cape Province in order to derive a baseline reference for the period between 2009 and 2014, and thereafter, to scope the current state i.e. between 2020 and 2022, and to use the information to determine the potential for implementation of platform biotechnologies such as IAPS for municipal water and sanitation in the Eastern Cape Province.

To achieve this, both a provincial and municipal district reference point were established by analysis of data from the period between 2009 and 2014 when Blue and Green Drop reporting was carried out regularly. Parameters that were used included plant size distribution, technology of choice, and compliance in terms of water and effluent quality. These reference data revealed that most WTP rely on large bulk water schemes for provision of potable water and are of undetermined size/capacity and, that the province is evidently operating mainly small- and medium-sized WTP. Furthermore, all WWTW in the Eastern Cape Province and CHDM operate either at- or in excess of design capacity with the technology of choice being WSP/OP. For most of these treatment systems, operational processes were non-compliant in terms of water quality, capacity, and water staff capacitation. This trend was mirrored from provincial to district and LM level.

Findings from the period between 2009 and 2014 formed a reference point or baseline measure which was then used to gage the contemporary (i.e. between 2020 and 2022) status of water and sanitation at treatment plants along a west-east transect across CHDM. Detailed survey of these treatment plants, targeted site visits and unstructured interview and questioning, followed by evaluation of water quality at the targeted facilities confirmed the non-compliant state of water and sanitation treatment at the DM level.

An evaluation of these reference points or baseline parameters in the contemporary, i.e. between 2020 and 2022, revealed that most WTP and WWTW were still operating in excess of capacity and in the range 1.52 to 12 times installed hydraulic loading, showing a significant increase from 2014, and hence severely compromised plant treatment efficiencies in terms of BOD removal as organic loading has increased substantially due to increased PE. The major sanitation technology remained, WSP/OP and potable water was still accessed through bulk water schemes - many still under construction. Targeted scoping provided further evidence of the situation at hand for water and sanitation in the Eastern Cape Province e.g. that targeted plants were moderate risk plants that needed serious attention to reduce risk. This risk has however been exacerbated in the period between 2014 and 2020 as a result of larger water treatment volumes, more water treatment as well as increased water demand and low operational capacity with no size adjustment for these plants. Furthermore, assessment deteriorated in terms of quality and service since Green and Blue Drop reporting was either suspended, or allowed to lapse. Thus, during the period between 2009 and 2014 to between 2020 and 2022 there had been no apparent change in status of either water treatment and supply while sanitation remained largely by WSP and both treatment process and quality of the final effluent had deteriorated due largely to continued low operational capacity and an insufficiency of adequately trained staff.

An overview regarding the legislated standards not being met by the various works whose responsible Municipality/Organisation and responsible authority is CHDM, as captured at the DWA Regional Office and/or the data collected from the respective municipalities as per the prescribed format, showed that plants are either mostly non-complaint or there is no information regarding the parameters measured. These works might not necessarily be in urgent need of expansion, rehabilitation, refurbishment or upgrading, augmentation, and redressing management of the inflows, but rather a biotechnological solution that is passive, cost effective and generate other by-products like bio-fertilizers in the process is needed.

4.2 Biotechnology options available for the CHDM and EC Province

As far as the Eastern Cape Province and CHDM are concerned, an increased demand for water that appears to exceed supply implies need to employ a more viable method for treating water and wastewater, which can be fulfilled by water recycle from a platform technology that delivers this co-product for primary industry including agriculture. Further, the study area revealed an abundance of WSP systems (mostly derelict or in need of repair/upgrade) easily converted to algae-based WWTW for cultivation for biomass, biogas generation, and other commodity and co-products of high-value. Ho & Goethals (2020) state that pond technology of the future will involve upgrades by addition of rock filters, CW, advanced integrated wastewater process systems, wastewater-fed ponds, and aerated ponds, many of which will include microalgae for cultivation and water treatment. Pond systems are also the most widely applied type of large-scale reactor for microalgae cultivation, because of simple construction and low investment costs (DOE, 2016). Given this scenario, it appears that at a provincial level and at a district municipal level, microalgae-based WT and WWT would be an ideal fit in a province that is largely rural and driven by agriculture.

The future outlook for municipal WWT with pond technology already in place is very important for Africa, many developing parts of the world and certainly for sub-Saharan Africa. Optimization of pond performance has been evolving since the 1960s and has developed to a point where high removal efficiency, simplicity, and low cost have been achieved which is well-recognized by numerous scientists and operators (Ho and Goethals, 2020). Production of microalgal biomass using wastewaters offers the possibility of recycling industrial residues to create new sources of raw materials for energy and material use. Thus, microalgae WWT from a biological and technological approach together cement a move towards biorefinery platform technologies for water and wastewater with co-product beneficiation to derive water for recycle, biomass and/or biogas, and feedstock for extraction of either commodity or high-value products. In the context of a circular and bio-based economy and the development of biorefinery concepts, microalgal biomass produced from wastewater streams offers great potential for sustainable production of bioproducts (Wollmann et al., 2019; Lehtoranta et al., 2022). Lehtoranta et al. (2022) emphasise decentralisation of WWT systems and the need to separate black water from grey water upstream to ensure water for recycle, biomass, biogas, and feedstock for extraction of a quality without the stigma attached; that it is derived from municipal sewage. Algae-based water treatment technologies provide an opportunity for recovery of water for recycle, sequestration of greenhouse gases, and generation of biomass. Indeed, it has been estimated that treatment plants in South Africa receive >5,258,000 m^3 wastewater per day at an estimated cost of ZAR 3.5 billion per annum (DWS, 2009).

To date, there remains little or no return on investment or cost recovery by the sector. Moreover, most of the ‘treated’ water is unaccounted for and certainly not available for re-use. By way of example, IAPS-based algae-to-energy sewage treatment has been shown to provide meaningful energy and co-product recovery (water, biofertilizers, biomass and biogas) within the peri-urban space in order to alleviate pressure on an already strained water–energy–food nexus (Laubscher & Cowan, 2020). Perhaps adoption of this and/or similar microalgae-based WWT technologies (Wollmann et al., 2019) will ensure a circular economic approach to water/wastewater management. Ho & Goethals (2020) accentuate this by saying that prevalence of ponds cements national-international recognition and emphasises the role of this important technology in WWT serving both populated urban areas as well as small rural communities.

In launching the International Decade for Action ‘Water for Life’ 2005-2015, UN Secretary General Ban Ki-moon reiterated this fact that, “Clean water has become scarce and will become even scarcer with the onset of climate change. And the poor continue to suffer first and most from pollution, water shortages and the lack of adequate sanitation" (Winter & Carden, 2022). Reference point data revealing poor plant operability and poor quality final effluent for discharge led to a suggestion that, this is reason enough for regulatory authorities and decision-makers to re-evaluate the position and choice of water and sanitation technologies implemented. Such re-evaluation can perhaps probe embarking on a direction that is commensurate with primary industry at local and regional level where platform technologies replace the seemingly ill-fated and high-cost electro-mechanical processes. Such biotechnology options may include algae-based water treatment systems, e.g. IAPS, which can be utilised to build fledgling industries in local environments to support primary industry upon which local and regional economies depend. Precisely this ideology is being vigorously explored by water scientists and process engineers across the planet. Indeed, interest in novel and innovative water and WWT technologies has grown exponentially in the last ten years. By 2020, one hundred novel technologies for the treatment of organic and inorganic wastewater streams had been documented (Armah et al., 2020). In addition, in the period 1990-1999, whereas just 6180 studies on algae-based water and WWT were published, 16 700 were published in the period 2010-2020, and more than 48 100 from 2010 to 2022 (Google Scholar; accessed 14 May 2022). This escalation in research output emphasizes the growing significance of algae-based water/wastewater research, development and innovation globally and the importance of this branch of biotechnological endeavour.

This present study confirmed that water quality of most of the Eastern Cape Province and CHDM treatment plants and compliance status are questionable due likely to increased stress placed on already developed but aging infrastructure because of an increase in either water demand or volumes treated since 2009 -2014 to the present. This might call for plant upgrades or for novel technology processes. As the world embraces the sustainable development goals (SDG), which emphasize the need to protect the environment and utilize the bio-circular economy, it becomes attractive for municipalities to embrace biotechnology as a way forward. Resources recovered from wastewater fall into many categories such as water for re-use, energy, biofuels, fertilisers and biopolymers. Thus, resource recovery is intrinsically linked to sustainable and circular practices such as process intensification, resource circularity and waste valorisation, which can reduce plant footprint, improve operating costs, increase energy efficiency, reduce negative externalities and offset the carbon footprint of treatment facilities (Renfrew et al., 2022).

By utilising algae-based water/wastewater systems, several advantages become immediately evident in addition to microbial processes having the potential to address the future food-fuel-energy-water nexus. These advantages include efficient carbon capture, recovery of nutrients from wastewater, the potential to satisfy many global demands e.g. energy, higher energy yields, use of non-arable land, and rich source of interesting and useful metabolites for adaptation to a wide range of environmental conditions (Benedetti et al., 2018). Power that reaches the surface of our planet from sunlight is massive (~100,000 terawatts-year (TW-y)). The current human global energy demand is ~15 TW-y and it is predicted to be ~24 TW-y for anthropic activities by 2030 (Hambourger et al., 2009; Cho, 2010). The fact that sunlight energy significantly exceeds demand even 8 years from now is evidence that sunlight might fully provide for future world energy demand (Chu & Majumdar, 2012). Microalgae, through oxygenic photosynthesis convert CO_2 into reduced carbon compounds using light and water. This use of sunlight and CO_2 to produce a variety of organic molecules and biomass, by the extensive cultivation of photosynthetic organisms, has the potential to cover a significant portion of global energy demand (Stephenson et al., 2011). Biological processes are generally cost effective in terms of energy consumption and chemical usage. A good example is that biological nutrient removal (BNR) has emerged as the preferred approach for nutrient removal. Here modifications of biological treatment systems so that the microorganisms in these systems can more effectively convert nitrate nitrogen into inert nitrogen gas and trap phosphorus in solids that are removed from the effluent (US EPA, 2013). Thus, microalgae biomass has effective removal abilities of wastewater pollutants such as nutrient compounds (microalgae need CO_2, nitrogen, and phosphorus to grow), suspended solids, coliform bacteria, heavy metals and other harmful chemicals, and decreases the value of both COD and BOD (Morais et al., 2021). Wollman et al. (2019) say that numerous organic and inorganic impurities in municipal, industrial, and agricultural waters, ranging from microplastics to high nutrient loads and heavy metals, endanger our nutrition and health, thus their removal becomes an essential part of our day-to-day life. These components act as essential nutrients that support microalgal biomass production (Li et al. 2020) and microalgae can be able to remove inorganic nutrients up to 100% (Ummalyma et al., 2022).

The use and hence removal of CO_2 from the atmosphere (a GHG that plays a huge role in climate change), and sequestering of nutrients that can cause pollution is a significant environmental advantage. Microalgal biomass is a renewable energy source in addition to its carbon content being totally derived from CO_2, with the potential to fix and recycle CO_2 exhausts from fossil fuel burning; hence algal biomass production is hinged towards CO_2 bio-mitigation and global carbon emission reductions. This is also evidenced by life cycle analysis (LCA) modelling, to map both energy flows and GHG emissions of the Belmont Valley WWTW pilot-scale IAPS treating municipal sewage. This scale revealed that an equivalent commercial system would yield negative (–) 0.16 tonnes $CO_2 \cdot 1000\ m^{-3}$ of wastewater treated indicating a technology with an ability to mitigate climate change (Cowan et al., 2016). Studies also show that microalgae can tolerate extreme conditions and grow in diverse environments and they can be cultivated using water and atmospheric carbon dioxide, which can help reduce the production cost compared to other organisms. Microalgal biomass comes with expected environmental and economic gains: less land demand, thus avoiding competition with other land-based crops also taking into account the potential for cultivation in non-arable areas; and, resistance of several species to salinity or even growth in marine environments with obvious benefits for cultivation in coastal areas. Cultivation of microalgae also ensures efficient carbon capture and faster development of new domesticated strains, effortlessly transforming inorganic carbon into complex organics in aquatic environments (Chisti 2007; Li et al., 2008; Singh and Gu 2010; Carmichael et al., 2017; Benedetti et al., 2018; Yadav et al., 2020; Sun et al., 2022). Moreover, microalgae can be grown on degraded land (Baicha, 2016). Remediation of wastewater or polluted water to improve final effluent quality for recycle to produce clean water for re-use is another significant advantage that microalgal biomass provides. This is achieved through natural disinfection, thus able to replace energetically expensive treatment steps in conventional WWT. According to Sivaramakrishnan et al. (2022), the energy consumption of a microalgae WWT system (0.2 kW/h/m^3) is 10 times less when compared to the conventional WWT system (to 2 kW/h/m^3).

Based on the already available pond infrastructure and technology at provincial and district municipal levels of the EC Province, there is every reason to argue for the conversion and/or upgrade of these ponds to manifest microalgae-based WT and WWT processes. The most successful process to date, which has been demonstrated in the EC Province, is the Belmont Valley WWTW pilot-scale IAPS system. Systems such as IAPS have numerous advantages, which render them a priority option for implementation of biotechnology solutions that could be suitable for a largely rural province like the Eastern Cape which has agriculture as its foremost primary industry. IAPS, as mentioned elsewhere in this thesis, is a passive water/wastewater treatment technology derived from the Oswald designed AIWPS® and executes treatment based on biological activity of microorganisms, solar energy and gravity (Oswald 1991; Oswald *et al*., 1994; Mambo *et al*., 2014; Laubscher & Cowan, 2020). Life cycle analysis has shown that nature-based solutions such as IAPS and HRAOP present some of the most environmentally friendly alternatives when compared to undistinguishably sized activated sludge systems (Garfi *et al*., 2017). Arashiro *et al*. (2018) says, "Comparable conclusions were derived after LCA of HRAOP for treatment of wastewater and resource recovery by small communities." In addition, and as mentioned above, LCA of energy flows and greenhouse gas (GHG) emissions from a 500-person equivalent IAPS treating municipal sewage yielded net energy of 153.0 MJ per day (Laubscher & Cowan, 2020) and -0.16 tonnes CO_2 per megalitre of wastewater treated (Cowan *et al*., 2016).

4.3 Conclusion

In a bid to address an ever-increasing world population, growing in both number and affluence, together with exacerbation of the environmental burden associated with waste assimilation, new thinking is required to address both water and WWT and resource productivity. In this study, an in-depth examination of water and sanitation in the Eastern Cape Province and prospective for implementation of biotechnology platforms was embarked on. Here, water and sanitation infrastructure at a provincial and DM level was interrogated with a view to implementation of bio-platform technologies - specifically algae-based water treatment technologies. Data on water and sanitation in CHDM and the Eastern Cape Province helped to derive a baseline reference, which was then contrasted with the current (2020/22) state of water and sanitation in selected local municipalities across the same district.

It is concluded, based on the parameters that were used, that water and sanitation technology provision within the Eastern Cape Province and CHDM is lacking. In particular and at fault were the following: poor water and effluent quality, over capacity of plants, operability and water staff capacitation, and poor maintenance of infrastructure. While WTP seemed compliant for most of the parameters utilised in this study, WWTW were generally non-compliant in terms of most of these parameters. During the period 2009/14 to 2020/22 there had been no apparent change in status of either water treatment and supply while sanitation remained largely by WSP and both treatment process and quality of the final effluent had deteriorated due largely to continued low operational capacity and an insufficiency of adequately trained staff.

Demand for water along with a prevalence of WSP, while derelict and dysfunctional, is seen as an opportunity - to begin integrating bio-platform technologies. By doing so, municipalities can provide sustainable feedstock for the local and regional primary industry which is agriculture, particularly if algae-based water and sanitation is implemented. Potential outcomes include; water for irrigation, (bio)fertilizers, biogas, biomass and the commodity and high-value products that algal biomass provides. Thus, to alleviate regional and national water and sanitation infrastructure issues, which is likely nearing the point of collapse if not already collapsed, introduction of biological- and more specifically, algae-based WWTW should be considered.

Microalgal WWT reduces wastewater pollutants and at the same time produces biomass of value. Mitigation of global warming through bio-fixation of anthropogenic CO_2 and other greenhouse gases, stands out as another advantage of microalgal WWT, maximizing CO_2 and O_2 mass transfer with high remediation potentials. This brings the advantage of easily generating biomass, biogas, and many other co-products of high-value that can circulate nutrients and carbon with the aim to keep products, components, and materials at their highest utility and value at all times. This can lead to a more circular economic approach of water and

WWT, which has a lot of potential towards resolving environmental problems, and food security issues that are so prevalent globally.

Biotechnology platforms such as IAPS will aggrandize thereby creating a great chance of developing more novel biotechnology products in addition to the speed at which they can be developed. These technologies, offer the ability to achieve the highest degree of purification at lowest possible cost and, with minimal maintenance. When appropriately configured, these passive systems shoulder fluctuating shock loads with consistent generation of desired effluent quality. These novel technologies will cost less over an extended period to run due to minimal skill levels required for operation and maintenance of a technology like an IAPS. Therefore, a gap analysis should be considered to better assess biotechnology platform implementation to determine the full benefit to the South African water sector. If municipalities are to have the above-mentioned value chains in place, it affords opportunity, not only for the entrepreneur who starts a business, but also for secondary entrepreneurs, sales agents, and extension workers who carry information and products to farmers in the peri-urban space. This helps in generating health and wealth, rather than by importation hence easing the pressure currently on the food and energy demand.

Future work must consider interrogation of water and sanitation infrastructure at a national and even regional scale particularly if the view is to implement bio-platform technologies such that the benefits can be adequately derived and audited. Such an analysis should be underpinned by proper laboratory-based or infield-based study rather than an interrogative desktop-type study. Lock down regulations have been relaxed a bit due to an apparent significant subsiding of Covid-19 cases in SA, allowing for research students to again enjoy campus and laboratory amenities. And, most places are again easily accessible, including municipal WTP and WWTW and can be earmarked for a more in depth study of a similar nature.

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SUPPLEMENTARY INFORMATION

Chapter 1

No supplementary information

Chapter 2

Table S2.1 *Assigned compliance scores for final effluent quality at selected WWTW in CHDM*

Name of WWTW	**Scale**									
	0	1	2	3	4	5	6	7	8	9
Cala					√					
Cofimvaba						√				
Cradock						√				
Dordrecht	√									
Elliot					√					
Hofmeyer	√									
Indwe	√									
Cacadu	√									
Middleburg					√					
Molteno						√				
Ngcobo				√						
Queenstown							√			
Sterkstroom							√			
Tarkastad				√						
Tsomo	√									
Whittlesea							√			

Table S2.2 *Regulatory requirement for staff capacity against actual staff capacity employed at works and compliance with technical skills status*

Compliant	**C**
Non-compliant	**NC**
Undetermined	**NI**

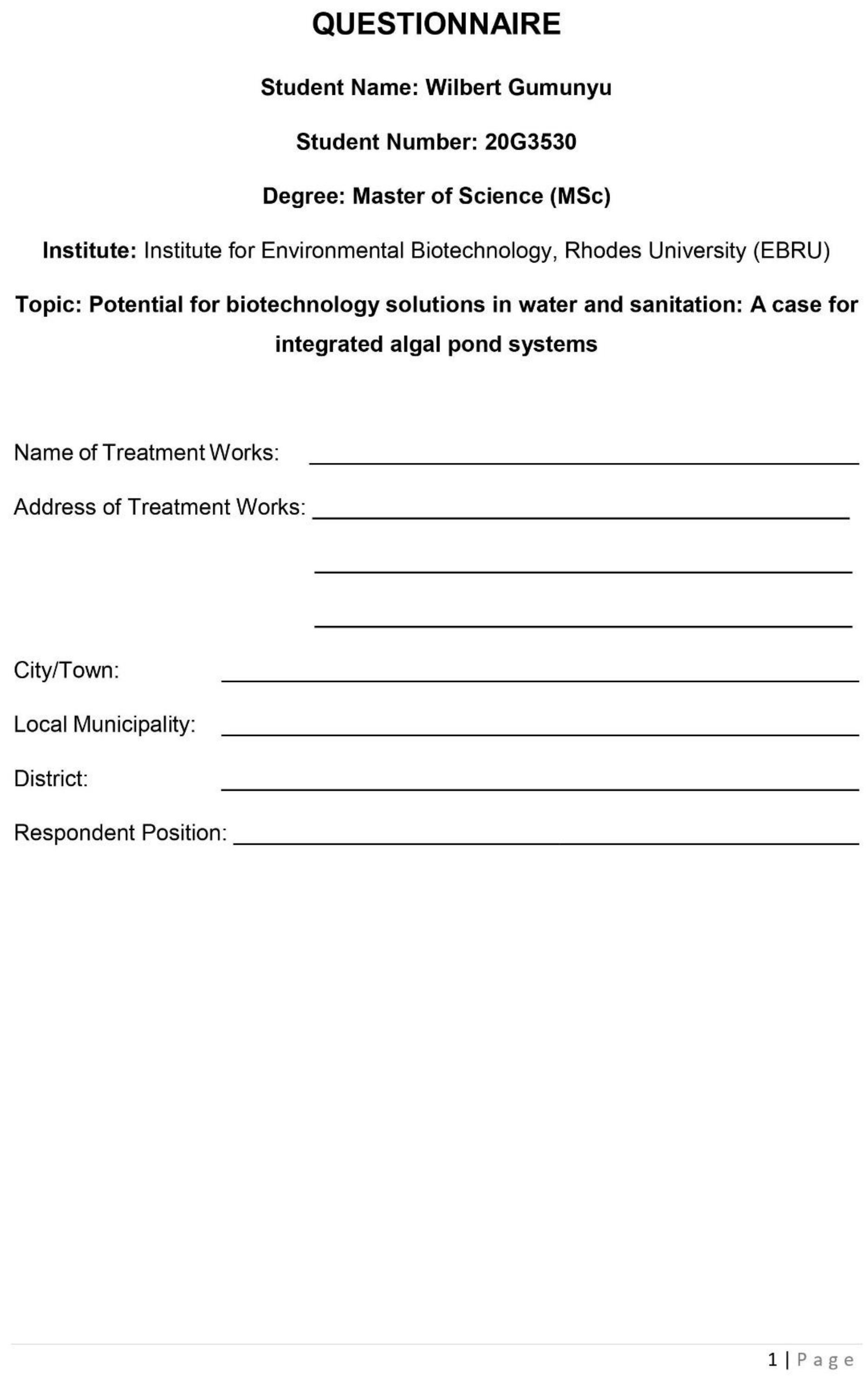
WWTW		**Staff Capacity Regulatory Requirement**		**Staff Capacity Existing: Staff Employed on Works (Supervisor / Process Controller, etc. & Qualifications e.g.: class V operator etc.)**				**Compliance (C) / Non-Compliance (NC) in terms of Supervision**	**Compliance / Non-compliance in terms of Process Controllers (Operators)**	**Compliance in terms of Operations and Maintenance support**
	Class	**Supervisor** (* - denotes part time availability)	**Process Controllers**	**Supervisor:** Current Situation (Class)	**Supervisor:** Current Situation (Employed)	**Process Controllers:** Current Situation (Class)	**Process Controllers:** Current Situation (Employed)			
Cala	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Cofimvaba	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Cradock	D	Class V	Class II	Class V	0	Trainees	4	NC	NC	C
Dordrecht	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Elliot	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Hofmeyer	D	Class V	Class II	Class V	NI	Class II	NI	NI	NI	NI
Indwe	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Cacadu	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Middleburg	E	Class V	Class I	Class V	0	Not Classed	4	NC	NC	C
Molteno	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Ngcobo	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Queenstown	B	Class V	Class IV	Class IV	1	Not Classed	4	C	NC	C
Sterkstroom	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Tarkastad	D	Class V	Class II	Class V	NI	Class II	NI	NI	NI	NI
Tsomo	D	Class V	Class II	Class V	0	Class II	0	NC	NC	C
Whittlesea	D	Class V	Class II	Not Classed	2	Not Classed	2	NC	NC	C

Table S2.3 *Assigned compliance scores in terms of staff capacitation for selected WWTW in the CHDM*

WWTW	**Scale**			
	0	1	2	3
Cala			√	
Cofimvaba			√	
Cradock			√	
Dordrecht			√	
Elliot			√	
Hofmeyer				√
Indwe			√	
Cacadu			√	
Middleburg			√	
Molteno			√	
Ngcobo			√	
Queenstown			√	
Sterkstroom			√	
Tarkastad				√
Tsomo			√	
Whittlesea			√	

CHAPTER 3

Figure S3.1 *A questionnaire as set out below has the following properties to assist in attaining as much detail as possible from the respondent: basic information about the researcher and his institution is set out clearly, the thesis topic is outlined, as well as details of the WTP or WWTP and basic details of the respondent. Responses were gathered and analysed.*



QUESTIONNAIRE

Student Name: Wilbert Gumunyu

Student Number: 20G3530

Degree: Master of Science (MSc)

Institute: Institute for Environmental Biotechnology, Rhodes University (EBRU)

Topic: Potential for biotechnology solutions in water and sanitation: A case for integrated algal pond systems

Name of Treatment Works: ____

Address of Treatment Works: ____

____

____

City/Town: ____

Local Municipality: ____

District: ____

Respondent Position: ____

1. What is the Wastewater Treatment (WWT) process that is being used in this plant?

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____

2. How much wastewater/water do you treat per day? What is the Design capacity of plant and operating capacity?

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3. What is the source of water that is purified here? Is it dam water, sewage or it also includes industrial/agricultural?

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4. What is the COD and BOD?

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5. How much ammonium is in the water?

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6. Are there any heavy metals or other pollutants in the water? If so, which ones?

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7. How many operators do you currently have at this plant? What are the duties?

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8. How costly is it to run this plant especially in terms of electricity and any other inputs?

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9. What do you do with the sludge and does it cost money, is it safe?

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10. How long does it take to get the water out from entering the plant (i.e. Hydraulic retention time) until it is safe again to discharge to the environment?

11. Where does the water go after treatment, does it go directly to consumers, or into a maturation pond or directly to river or irrigation etc.?

12. Does the water meet the general standards set by DWS to go to consumers or into a river?

13. What is the future of this plant, let us say the population grows or new industries are built, or the town gets bigger and there are more people here?

14. What do you think of an idea where your plant can also make you some fertilizer and biogas to be sold into the community for small farmers/ subsistence agriculture etc?

15. Have you ever considered biotechnological solutions in the treatment of wastewater? Yes or No. Whichever answer you give, please explain why?

16. Are there any challenges associated with the water and sanitation department in adopting biotechnological solutions in the treatment of wastewater?

17. Do you have any knowledge on any biotechnological solutions used in the wastewater treatment? Yes or No.
    If yes, how do you think this will benefit this plant:

If no, would you be interested in learning and knowing more about these solutions:

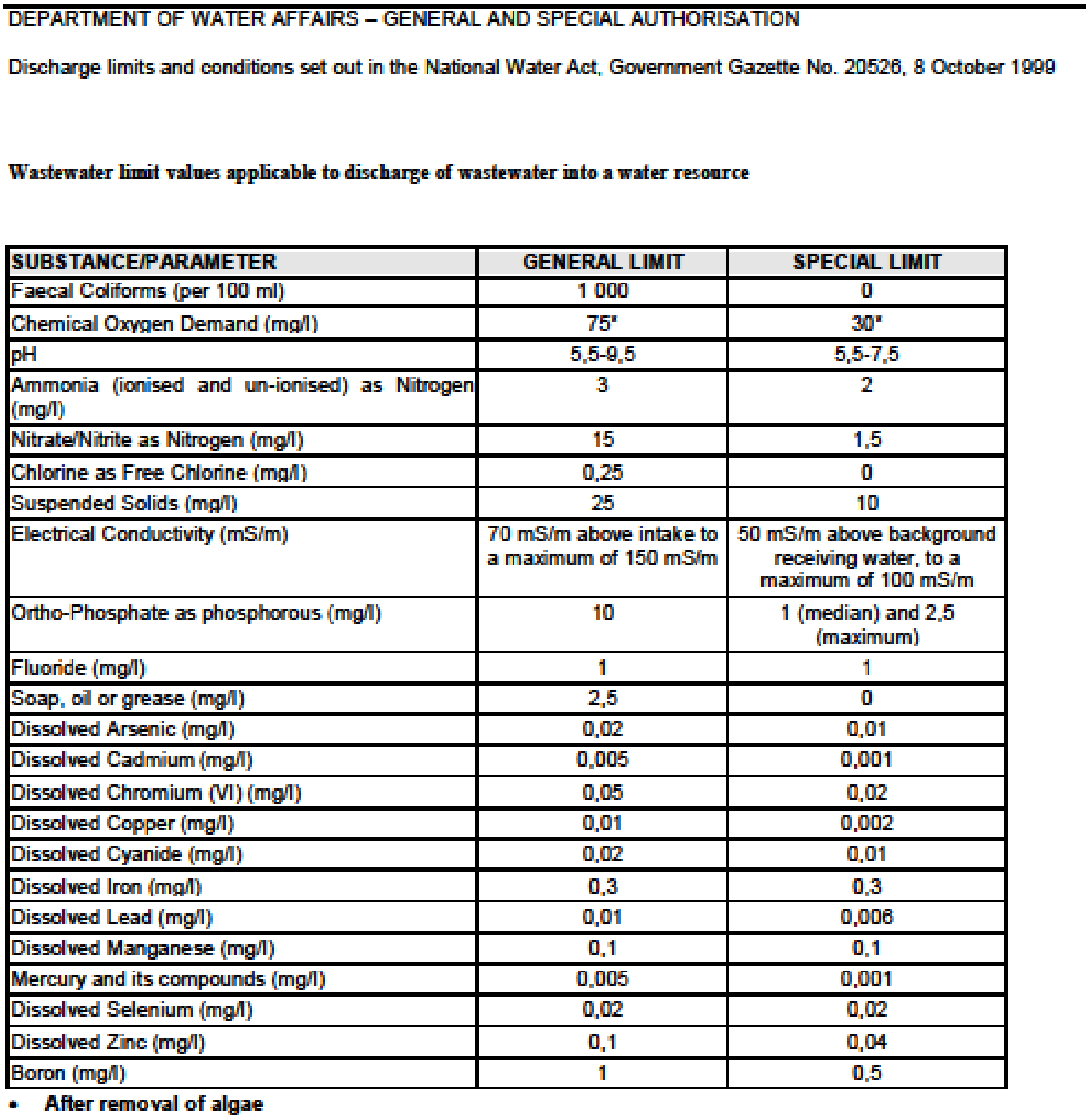
18. What other experience do you have from a WTP or WWTP where you have worked?

19. Do you perhaps know of any other WTP or WWTP and how often do you visit them?

20. Apart from Chlorine, what other chemicals do you use to treat the water from the inlet until it is distributed to the consumers.

Thank you

***Table S3.1** Indicators for wastewater quality management, highlighting the limit values relevant to discharge of wastewater into a receiving water body as set out by the South African wastewater regulatory legislation. Discharge limits and conditions are set out in the National Water Act, Government Gazette No. 20526, 08 October 1999. These have not been updated for a while, hence some of the water quality problems.*



DEPARTMENT OF WATER AFFAIRS – GENERAL AND SPECIAL AUTHORISATION

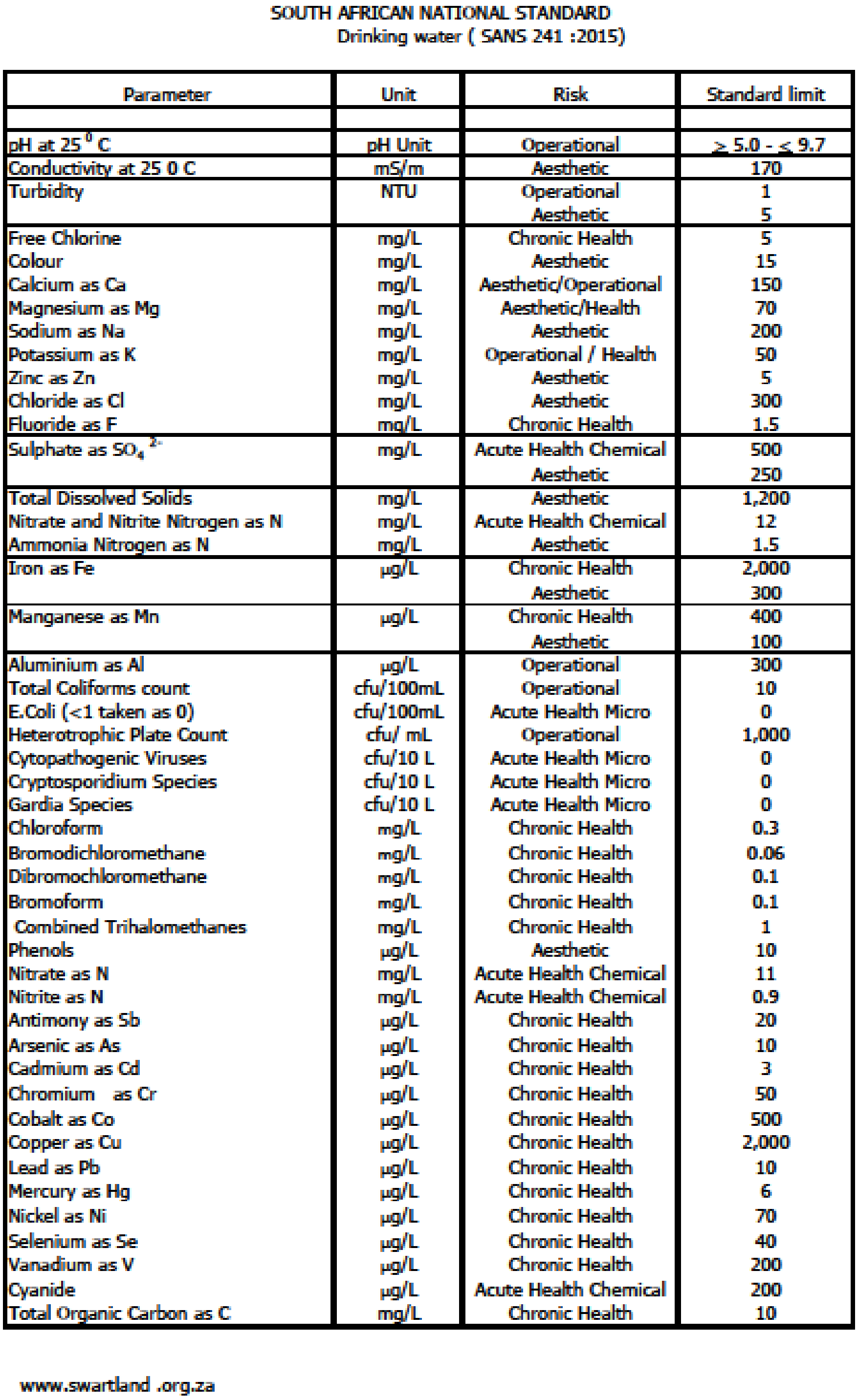
Discharge limits and conditions set out in the National Water Act, Government Gazette No. 20526, 8 October 1999

Wastewater limit values applicable to discharge of wastewater into a water resource

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECIAL LIMIT
Faecal Coliforms (per 100 ml)	1 000	0
Chemical Oxygen Demand (mg/l)	75*	30*
pH	5,5-9,5	5,5-7,5
Ammonia (ionised and un-ionised) as Nitrogen (mg/l)	3	2
Nitrate/Nitrite as Nitrogen (mg/l)	15	1,5
Chlorine as Free Chlorine (mg/l)	0,25	0
Suspended Solids (mg/l)	25	10
Electrical Conductivity (mS/m)	70 mS/m above intake to a maximum of 150 mS/m	50 mS/m above background receiving water, to a maximum of 100 mS/m
Ortho-Phosphate as phosphorous (mg/l)	10	1 (median) and 2,5 (maximum)
Fluoride (mg/l)	1	1
Soap, oil or grease (mg/l)	2,5	0
Dissolved Arsenic (mg/l)	0,02	0,01
Dissolved Cadmium (mg/l)	0,005	0,001
Dissolved Chromium (VI) (mg/l)	0,05	0,02
Dissolved Copper (mg/l)	0,01	0,002
Dissolved Cyanide (mg/l)	0,02	0,01
Dissolved Iron (mg/l)	0,3	0,3
Dissolved Lead (mg/l)	0,01	0,006
Dissolved Manganese (mg/l)	0,1	0,1
Mercury and its compounds (mg/l)	0,005	0,001
Dissolved Selenium (mg/l)	0,02	0,02
Dissolved Zinc (mg/l)	0,1	0,04
Boron (mg/l)	1	0,5

- **After removal of algae**

Table S3.2 *South African National Standard, Drinking water (SANS 241:2015). These guidelines were used against the results from the study in order to ascertain drinking water quality. The results were analysed by taking means of the data obtained and compare it to the South African National Standard, drinking water to have an overview of the drinking water quality in the CHDM selected municipalities along a transect from East to West.*



SOUTH AFRICAN NATIONAL STANDARD
Drinking water (SANS 241 :2015)

Parameter	Unit	Risk	Standard limit
pH at 25 ^{0} C	pH Unit	Operational	≥ 5.0 - ≤ 9.7
Conductivity at 25 0 C	mS/m	Aesthetic	170
Turbidity	NTU	Operational	1
		Aesthetic	5
Free Chlorine	mg/L	Chronic Health	5
Colour	mg/L	Aesthetic	15
Calcium as Ca	mg/L	Aesthetic/Operational	150
Magnesium as Mg	mg/L	Aesthetic/Health	70
Sodium as Na	mg/L	Aesthetic	200
Potassium as K	mg/L	Operational / Health	50
Zinc as Zn	mg/L	Aesthetic	5
Chloride as Cl	mg/L	Aesthetic	300
Fluoride as F	mg/L	Chronic Health	1.5
Sulphate as SO_4^{2-}	mg/L	Acute Health Chemical	500
		Aesthetic	250
Total Dissolved Solids	mg/L	Aesthetic	1,200
Nitrate and Nitrite Nitrogen as N	mg/L	Acute Health Chemical	12
Ammonia Nitrogen as N	mg/L	Aesthetic	1.5
Iron as Fe	µg/L	Chronic Health	2,000
		Aesthetic	300
Manganese as Mn	µg/L	Chronic Health	400
		Aesthetic	100
Aluminium as Al	µg/L	Operational	300
Total Coliforms count	cfu/100mL	Operational	10
E.Coli (<1 taken as 0)	cfu/100mL	Acute Health Micro	0
Heterotrophic Plate Count	cfu/ mL	Operational	1,000
Cytopathogenic Viruses	cfu/10 L	Acute Health Micro	0
Cryptosporidium Species	cfu/10 L	Acute Health Micro	0
Gardia Species	cfu/10 L	Acute Health Micro	0
Chloroform	mg/L	Chronic Health	0.3
Bromodichloromethane	mg/L	Chronic Health	0.06
Dibromochloromethane	mg/L	Chronic Health	0.1
Bromoform	mg/L	Chronic Health	0.1
Combined Trihalomethanes	mg/L	Chronic Health	1
Phenols	µg/L	Aesthetic	10
Nitrate as N	mg/L	Acute Health Chemical	11
Nitrite as N	mg/L	Acute Health Chemical	0.9
Antimony as Sb	µg/L	Chronic Health	20
Arsenic as As	µg/L	Chronic Health	10
Cadmium as Cd	µg/L	Chronic Health	3
Chromium as Cr	µg/L	Chronic Health	50
Cobalt as Co	µg/L	Chronic Health	500
Copper as Cu	µg/L	Chronic Health	2,000
Lead as Pb	µg/L	Chronic Health	10
Mercury as Hg	µg/L	Chronic Health	6
Nickel as Ni	µg/L	Chronic Health	70
Selenium as Se	µg/L	Chronic Health	40
Vanadium as V	µg/L	Chronic Health	200
Cyanide	µg/L	Acute Health Chemical	200
Total Organic Carbon as C	mg/L	Chronic Health	10

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Chapter 4

No supplementary information