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Research paper

Comparative life cycle assessment (LCA) of pre-treatment technologies for desalination in South Africa

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In the context of South Africa's water scarcity, desalination has emerged as a possible solution for coastal areas. However, the quality of the intake water for desalination is often problematic, prompting the need for pre-treatment. The aim of this study was to conduct a comparative environmental life cycle assessment (LCA) on 4 seawater filtration systems intended for the pre-treatment of a reverse osmosis desalination project. These systems were implemented in a pilot trial and are based on modern water treatment technologies, namely, granular filtration (pressure driven and gravity driven), dissolved air flotation (DAF), and ultrafiltration (UF). For all 4 systems, data were collected for both the construction and operation phases, and LCAs were performed, resulting in environmental scores that allow for comparison based on the pre-treatment of 1 kL of seawater of the same quality. The SimaPro LCA tool and the ReCiPe midpoint method were used and environmental scores were calculated for 18 impact categories, including climate change, acidification, toxicity, eutrophication, resource depletion, etc. This methodology also allowed the identification of the highest environmental burdens/scores within each system. The most significant finding is that local electricity consumption is responsible for the greatest proportion of environmental impacts. Thus, the systems consuming more energy for operating equipment such as blowers, pumps, and mixers were found to have the highest environmental burdens. Hence, the DAF system has the highest environmental scores for most impacts, followed by the single-phase gravity filtration system, then the two-phase partial pressure filtration system and finally the UF system. Therefore, focus should shift towards energy optimisation of process units, especially the rotary ones, as well as energy mitigation and recovery strategies. The use of renewable energy for pre-treatment should also be considered locally.

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INTRODUCTION

South Africa's freshwater resources are limited and unequally distributed. By 2030 a deficit of 17% between the supply and demand for water is predicted for the country (DWS, 2018). The past decade also saw unprecedented droughts that challenged municipalities in providing water, with water restrictions implemented in 6 of the 8 metropolitan municipalities in the country (DWS, 2018 and DPWI, 2022). A series of factors contribute to and exacerbate this situation, including climate variability, diminishing freshwater sources, deteriorating infrastructure, rapid urbanization, a growing economy, and an expanding population (DWS, 2108). In this context, the careful management and reconciliation of freshwater supplies is of utmost importance in ensuring sustainability of water provision, with several interventions being included in the current and revised draft National Water Resource Strategy. One of these reconciliation strategies is the desalination of seawater, with the potential to increase the supply of freshwater for coastal areas (DWA, 2013; DWS, 2022). However, compared to conventional potable water, abstraction and treatment is energy intensive and expensive (World Bank, 2019).

Desalination refers to a range of water treatment technologies that separate salts from water, resulting in a useful water product (DWA, 2013). The use of desalination to augment the water supplies of many water-stressed regions is becoming far more prevalent than in the past, due to several advancements which have made the relatively expensive technology more accessible, particularly for developing countries (Ghaffour et al., 2013). There are different types of desalination technologies and these can be categorised as thermal-based, membrane-based, and hybrid (Darre and Toor, 2018). The reviews in the literature (Darre and Toor, 2018; World Bank, 2019; Aende et al., 2020; Curto et al., 2021; Zhao and Van der Bruggen, 2021, to name a recent few) on these technologies highlight important trends, i.e., the rapid increase of capacity for desalination, as well as decreasing energy consumption and costs. In particular, membrane technologies like reverse osmosis (RO) show a marked development due to their relatively lower energy consumption, lower costs, and a lower environmental footprint (World Bank, 2019). RO dominates the desalination market and comprises about 65% of the total installed capacity (Nassrullah et al., 2020). A seawater reverse osmosis (SWRO) plant usually contains 4 units: pre-treatment, pumping, membrane reverse osmosis, and post-treatment (Zhao and Van der Bruggen, 2021).

Pre-treatment of the feed water is important to preserve the long-term functionality of a RO membrane by preventing fouling. Fouling is "the build-up of undesired deposits on the membrane surface or in the membrane structure" (Anis et al., 2019, p. 6), negatively affecting the operation of RO plants by requiring cleaning, higher feed pressure (and associated higher energy consumption) and premature membrane replacement (Nguyen et al., 2012). These problems can be prevented by the correct pre-treatment of the feed seawater to reduce particulate/colloidal, inorganic and organic foulants (including microorganisms) prior to reaching the membranes. These pre-treatment systems are highly specific, requiring careful analysis in determining the most appropriate strategy in which one or more pre-treatment processes are employed. These methods are influenced by characteristics of the feed seawater (salinity, pollutants, microorganisms, etc.), as well as the required water product quality and other notable site-specific factors such as cost of labour, available area, energy cost, and local demand for electricity (Valavala et al., 2011).

Pre-treatment methods can be classified as conventional, membrane, or hybrid, and extensive reviews of each are provided by Anis et al. (2019), Kavitha et al. (2019) and Badruzzaman et al. (2019). The conventional methods are based on physical and chemical technologies employed in other water treatment processes and these include coagulation-flocculation, media filtration, dissolved air floatation and disinfection (chlorination, ozonation and ultrasound). The membrane methods include micro-, ultra- and nanofiltration, and a variety of membrane types and materials have been used and are the subject of continuous research (Anis et al., 2019 and Kavitha et al., 2019). Each of these methods has advantages and limitations, with the hybrid systems attempting to maximise the advantages while achieving process efficiency and the desired quality of output. This is also the aim of new emerging methods (e.g. forward osmosis) as well as new membrane materials (ceramic, polymeric and nanomaterials) being developed (Anis et al., 2019 and Ahmed et al., 2021).

One common thread in the use and development of existing and new pre-treatment methods is the need to lower energy consumption and associated environmental impacts while achieving efficient pre-treatment, in the context of increasing and varying pollution in the incoming seawater (Anis et al., 2019). Therefore, the measurement of the environmental performance of pre-treatment methods employed is important, with the literature demonstrating the use of environmental life cycle assessments (LCAs) in the development of quantitative assessments facilitating comparison (see Aziz and Hanafiah (2021) and Lee and Jepson (2021) for comprehensive reviews). However, most of these LCA studies target the entire SWRO desalination plant and very few focus specifically on pre-treatment methods, even though pre-treatment is considered to contribute significantly to the energy requirements and environmental impacts of RO desalination (Anis et al., 2019). This study aims to fill this research gap in the local context, as the few LCAs that have been undertaken with emphasis on pre-treatment were conducted within Germany (Beery and Repke, 2010 and Luo 2017) and the Arabian Gulf (Al-Sarkal and Arafat, 2013 and Al-Kaabi et al., 2021).

Desalination has been investigated as a possible alternative to increase the supply of municipal water for the South Coast Water Supply Scheme in the south of the eThekwini Municipality, KwaZulu-Natal Province, South Africa. Umgeni Water, the regional water board in charge of supplying treated water to the local municipality, has planned a 150 ML/day SWRO desalination plant near the mouth of the Lovu River, close to the Indian Ocean shore. The plant has been designed and associated feasibility and environmental impact assessments have been initiated and some undertaken. A decision regarding the most appropriate pre-treatment method was needed and 4 different systems were further investigated in a pre-treatment pilot plant. A simplified LCA (cradle to gate) was conducted for each system, based on the operational data from this pilot plant. The aim was to quantitatively evaluate the environmental performance of each system and, together with the technical performance and other factors, to contribute to the decision-making process in determining the best pre-treatment for the planned SWRO plant. Comparative LCAs have been cited previously in the literature for conventional water systems (e.g. Bonton et al., 2012 and Amores et al., 2013) as well as for desalination and pre-treatment systems using different technologies, including nano-filtration (e.g. Al-Kaabi and Mackey, 2019; Tarpani et al., 2021 and Bordbar et al., 2022;). They also informed the methods used in this study.

PRE-TREATMENT SYSTEMS INVESTIGATED

Seawater intake from the Indian Ocean on the south coast of the eThekwini Municipality is characterised by high concentrations of algae (see Table 1). The majority of these cells have been identified as pico-plankton (<2 µm in size), and are expected to cause biofouling of a potential RO membrane and should hence be removed upstream of these membranes (Umgeni Water, 2016). Therefore, pre-treatment needs to be designed to accommodate overall high background algae concentrations as well as occasional algal blooms/red tide effects. These events are likely to occur in summer, resulting in turbidity and total organic carbon spikes. Table 1 illustrates the key pre-treatment water parameters at the proposed SWRO project site including the average, minimum, and maximum source water quality expectations and target pre-treatment objectives.

Table 1. Key pre-treatment water design parameters – Lovu site (Umgeni Water, 2016)

Parameter	Source water quality			Target water quality
	Minimum	Average	Maximum	
Total dissolved solids (TDS)	34 880	35 111	36 160	-
Temperature	17.2	21.8	25.5	-
Turbidity (NTU)	0.3	1.5	17.0	<0.5
Silt density index (SDI_{15})	3.1	5	>6	<3 (at least 95% of the time) <5 (at all times)
Chlorophyll *a* (µg/L)	0.22	0.88	4.55	0
Total organic carbon (TOC) (mg/L)	0.6	1.3	3.1	<1
UV_{254} (cm^{-1})	0.0003	0.007	0.19	<0.5
Total algal count (cell/L)	<1 000	<10 000	130 000	-
Total hydrocarbons (µg/L)	Non-detectible	Non-detectible	Non-detectible	<0.04
pH	8.0	8.1	8.3	4 – 9

In order to achieve the targeted water quality, 4 systems have been designed and implemented in the pre-treatment pilot plant. The 4 systems are:

- Rapid gravity tri-media filtration system (System 1)
- Two-stage dual-media partial pressure filtration system (System 2)
- Two-stage DAF/dual-media filtration system (System 3)
- Ultrafiltration (UF) system (System 4)

The first 2 systems analysed in this study comprise of granular filtration technology, while the third system makes use of dissolved air flotation (DAF) which involves the removal of contaminants by aeration. The fourth system utilises advanced ultrafiltration achieved through a membrane. In the pilot plant all 4 systems use the same intake pipe, settling and storage tanks, and strainer. Figure 1 illustrates the systems investigated as well as the functional relationships between them.

As seen from Fig. 1, the abstraction and storage are shared, as are the filtered water storage and wastewater disposal units. Certain system components that make up the backwash stage are shared between Systems 1 to 3 only, such as air blowers and the filtered water tanks from which the water product is drawn for backwash. This has been taken into consideration when accounting inputs for each individual system, with a process of allocation followed (based on proportions).

System 1 involves granular, gravity-driven filtration of seawater and makes use of 3 varied media (anthracite, silica and garnet). A backwash mode is triggered when the rising water level above the media reaches the overflow pipe of the filter column. This backwash requires about 1 m^3 of water. This water is withdrawn from the pre-treated water product and is fully allocated to waste after backwashing.

System 2 also relies on a granular filtration and 2 separate filters are used in this system. The first filter (Phase 1) involves the granular, gravity-driven filtration of raw water through a dual-media composite of silica and anthracite. A backwash is triggered when the rising water level above the media reaches the overflow pipe of the filter column. Backwash comprises of a combined air/water rinse, with 0.8 m^3 of water required for backwashing. The second filter (Phase 2) relies on granular filtration under an applied pressure through a dual-media composite of silica and anthracite. A backwash is triggered when there is a pressure difference of ~15 kPa between the inlet and outlet. This can also be activated manually by the use of a manual trigger. Backwash comprises of a combined air/water rinse followed by a water rinse employing 0.4 m^3 of wash water.

System 3 relies on a combination of dissolved air flotation (DAF) and granular filtration technologies. Two separate filtration processes (Phase 1 and 2) were used in this system. The dissolved air flotation (DAF) unit is followed by a rapid gravity dual-media filtration system. The DAF unit removes suspended particulate matter (mainly picoplankton <2 µm in this particular source) from the seawater feed. This removal is achieved by dissolving air into the feed water under pressure, then releasing the air at atmospheric pressure causing the formation of tiny bubbles which adhere to the suspended contaminants, floating them to the surface where they are skimmed (Palaniandy et al., 2017). This particular DAF unit is designed with an integrated bubble production system using an in-line saturator which bubbles the gas through the DAF chamber, and independent coagulation and flocculation systems, which make use of in-line coagulation and flocculation tanks. Mechanical mixers are used in these processes. The second filter (Phase 2) relies on granular, gravity-driven filtration through a dual media composite of silica and anthracite. A backwash is triggered when the rising water level above the media reaches the overflow pipe of the filter column. This can also be activated manually by the use of a manual trigger. Backwash comprises a combined air/water rinse followed by a water rinse with 0.8 m^3 of wash water required.

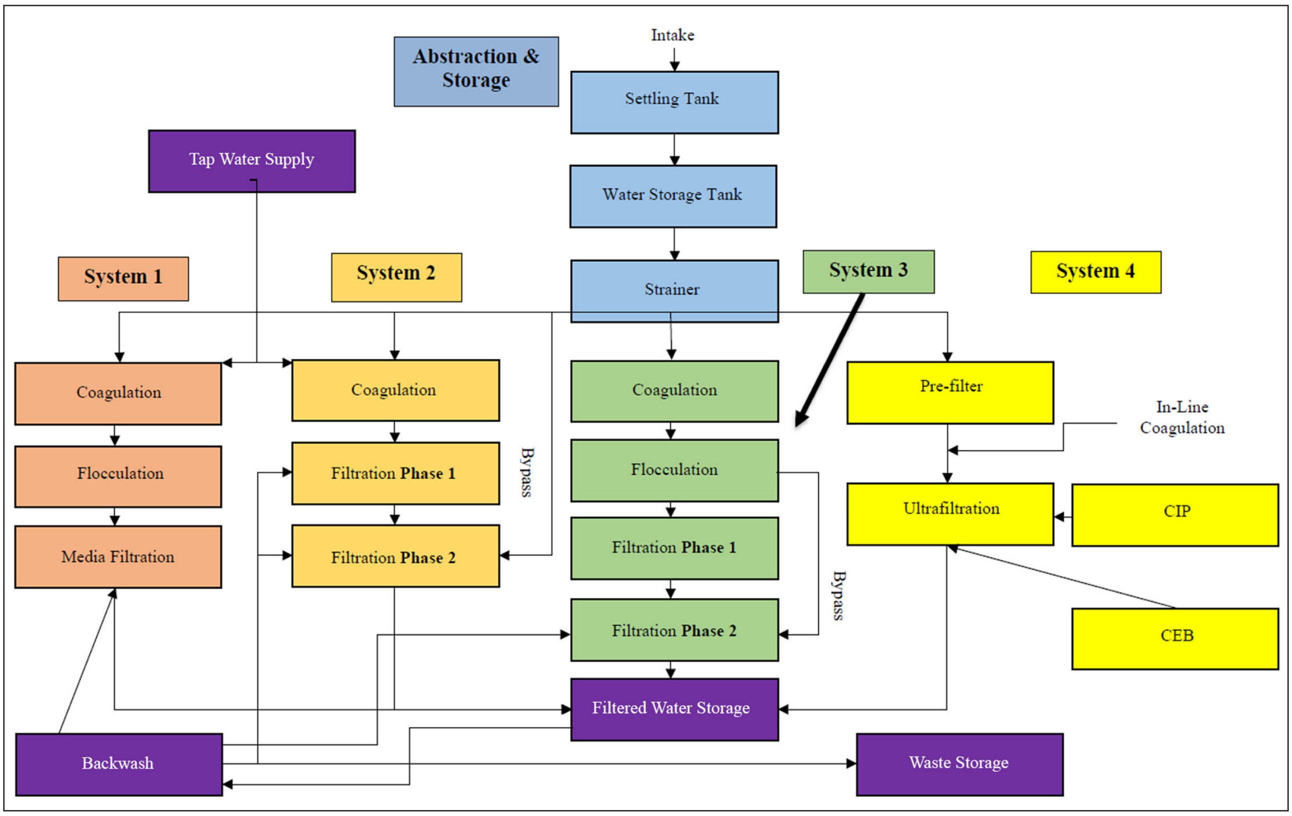

Figure 1. Simplified pre-treatment pilot plant process diagram

System 4 uses UF membranes to separate contaminants from the feed seawater. An automatic, self-cleaning pre-filter ensures that the long-term functionality of the UF membrane is preserved and removes large particles prior to membrane exposure. The feed flow rate ranges from 2–6 m^3/h, which partly determines the filtration rate through the filters. The membrane itself has a pore size not exceeding 0.08 µm and is housed in 1 of 4 membrane modules through which the flow may be independently directed on the basis of operating conditions. The membrane modules operate at a trans-membrane pressure (TMP) range of 0.1–2 bar (1 bar being the equivalent of 100 kPa in SI units). A TMP of 1.5 bar is required for backwashing and the membrane design life is 5 years. A chemically-enhanced backwash (CEB) is occurring automatically. This involves the use of UF filtrate and either an acid or base combined with an oxidant to effectively clean contaminants from the membrane surface. The addition of these chemicals ($FeCl_3$, NaOH, HCl and NaClO) is facilitated by the use of in-line dosing tanks complete with agitators and level switches. In addition, a cleaning-in-place (CIP) system is designed to circulate a chlorinated caustic (or other basic chemical) solution and a suitable acid solution. When clogging of the membrane is related to organics, the caustic–chlorinated cleaning takes place before the acid cleaning. The opposite takes place when the clogging is caused by iron, manganese or salts.

The inputs and the outputs for each of the 4 systems investigated were established by using the amounts of material for the respective components making up each system (construction stage), together with the energy and chemicals required for operation of each system (operational stage). This inventory is an important stage in the LCAs conducted and was the basis for calculating the environmental burdens/scores of each system.

METHODOLOGY

A life cycle assessment is a tool that is used to determine the potential environmental impact of a product or process by identifying and quantifying the inputs and outputs of a specific system. According to the ISO 14040 (ISO, 2006), the LCA process is a systematic method consisting of 4 main stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. A brief explanation of each of these phases will follow with the inclusion of relevant details pertaining to this study.

Goal and scope definition

As the opening stage of an LCA study, goal and scope definition describes the systems under analysis, the objectives and reasons for performing the research, as well as the overall scope of the project. The aim of this research was to estimate environmental impacts for various pre-treatment processes prior to the RO desalination stage. Therefore, the target audience comprises of scientists and engineers involved in the development and design of water treatment systems and pre-treatment technologies, together with the relevant authorities in municipal and national water departments.

Defining the scope of the research should be completed in combination with the goal statement and should include aspects such as selecting the function and functional unit, demarcating the system by establishing the system boundaries and listing data requirements, assumptions and restrictions encountered during the study (Khosravi et al., 2022). The function for all 4 systems investigated is to produce pre-treated water of a certain quality. To ensure a relevant basis for comparison, the functional unit for this study was defined as 1 kL (1 m^3) of pre-treated seawater to the quality specified in the Umgeni Water guidelines as a target for pre-treatment (see Table 1). This functional unit will be used to relate all data collected in the inventory stage and acts as a reference unit for the modelled impact assessment scores. The period of study was 1 year, covering 1 cycle of seasonal variability in the local environment.

For each system considered, the construction and operation phases were investigated, while the decommissioning phase was considered negligible, based on the findings of numerous studies summarised by Loubet et al. (2014) for conventional processes and Lee and Jepson (2021) as well as Fayyaz et al. (2023) for membrane processes. The scope of the LCA is shown in Fig. 2, where the black box demarcates the system boundary.

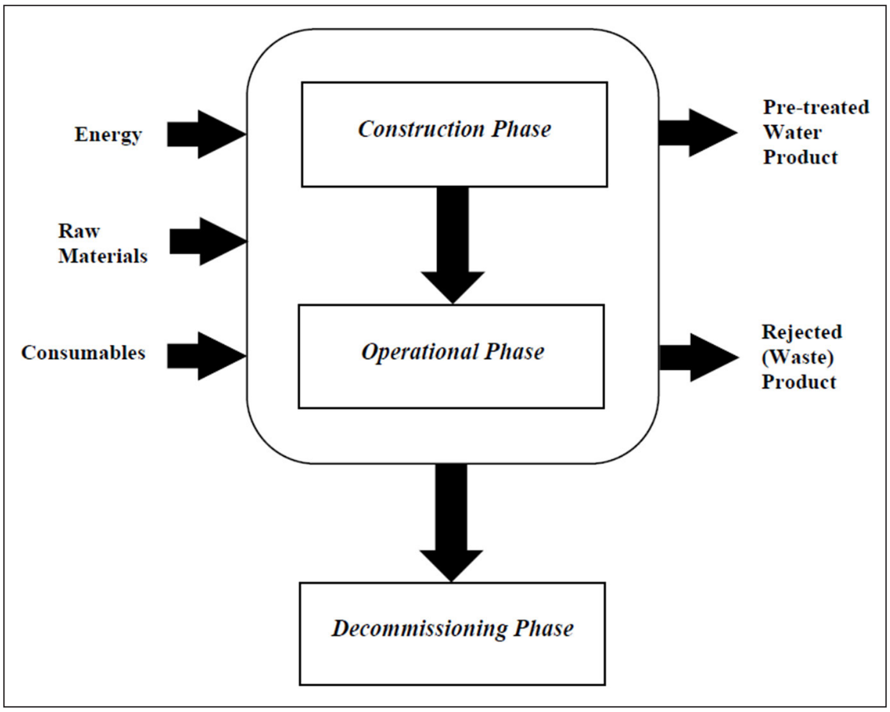

Figure 2. System boundary

Direct measurements that were obtained from the pilot plant (e.g. energy or chemicals directly measured) and sources such as design specifications and process flow diagrams were preferred. Secondary sources were used to search for component data where there was difficulty contacting manufacturers. These included trading catalogues and company databases of the products under consideration. Periodical water quality assessments were available for use via Umgeni Water services.

A series of assumptions were made during the data collection phase. The major assumption concerned the operational times of the plant: that the plant would be operational for 24 hours a day for an entire year, with 2 of the 4 systems operational at any time. Operational data were collected for the first few months only and it was assumed that the same pattern continued during the entire year. Monitoring equipment that was omitted from the analysis included flowmeters, pressure gauges, and turbidity analysers, due to their relatively low energy consumption and mass. Additionally, the masses of PVC valves were considered negligible, although this was compensated for by performing a conservative calculation when quantifying the mass of PVC piping. Other assumptions included estimating a longer lifespan of filter media for Systems 1 to 3 so that replacement was not required for the duration of the pilot trial, as advised by the design engineers and technicians at Umgeni Water. For System 3, a single recirculation was assumed for the DAF component before proceeding to the second phase of filtration.

Limitations were experienced due to the unavailability of some data and the difficulty of transforming a process into a suitable model. For example, detailed piping schedules were unavailable which resulted in physical measurements being used and pipe thickness obtained from a local source (DPI Plastics, 2017). With respect to the modelling stage, a number of challenges arose. Due to software limitations, there was difficulty in quantifying the waste product. The waste phase was thus excluded and a sensitivity analysis performed to validate this decision, which illustrated a minor contribution of less than 1.5% per system. The SimaPro LCA software did not contain certain specialist inputs/materials that were utilised in the case study. Examples were the 3 media filtration constituents (silica, anthracite, garnet) which were thus modelled as 'sand'. Similarly, construction materials such as stainless steel and carbon steel were modelled as 'steel, chromium steel 18/8' and 'steel, low-alloyed', on the basis of prior research (Goga et al., 2019) and resemblance to the listed material. Finally, all rotary components in the pilot plant, including pumps and agitators, were modelled to run continuously for the purposes of conducting the study.

Inventory analysis

The inventory analysis stage consisted of collecting relevant data and thereafter quantifying input and output flows for the various systems under study. Data collection commenced with the compilation of a typical process flow diagram (PFD) for each of the systems. This was followed by a diagram delineating the LCA scope illustrating the processes to be included in the analysis. An illustration of such a diagram for System 1 is presented in Fig. 3 and similar diagrams were also produced for Systems 2 to 4. Based on these diagrams, spreadsheet-based modelling was undertaken

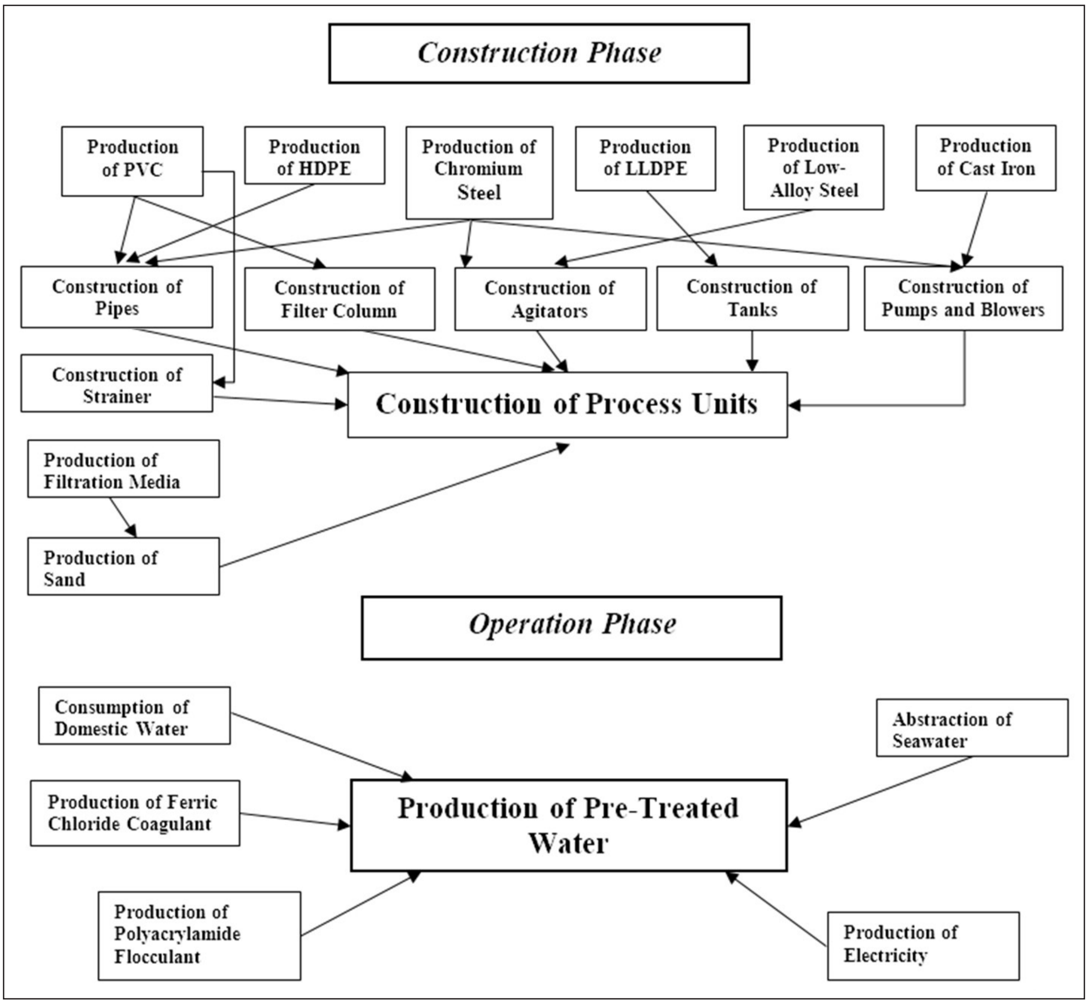

Figure 3. Processes included for System 1 (scope of the LCA inventory for System 1)

to collate material and energy flows for each unit operation. This included the volumetric calculations for process vessels and pipes. Following the material input required for the construction of the various unit operations, the electricity requirement for each system was calculated and/or measured. Backwashing data were calculated separately based on provided temporal data. Once all the data were consolidated, they were scaled according to the functional unit and used as input into the SimaPro model. The database used within the SimaPro software was ecoinvent v3 (ecoinvent, 2022). Datasets were customized by using South African energy. The methods used for data collection for the various components in System 1 are detailed, followed by a brief explanation of additional features present in Systems 2 to 4.

Construction phase – general components in System 1

General components used in each of the systems include tanks, pipes, pumps, mixers, air blowers, filter columns, and strainers. The weight for each of these items was calculated based on available dimensions provided in the design specifications or in company databases.

All of the tanks, with the exception of those used for coagulant dosing, were constructed of linear low-density polyethylene (LLDPE). The masses of the tanks were calculated by obtaining the vessel's volume based on each tank's height, diameter, and wall thickness. Thereafter, a typical density of LLDPE was used to obtain the mass. Most of the pipes used in the systems were constructed of polyvinylchloride (PVC) due to its durability, lightweight structure, and non-corrosive nature. Additionally, the temporary nature of this pilot trial called for lower construction and maintenance costs which favours PVC as opposed to other commonly used piping materials.

As a fundamental component of any water treatment plant, pumps were located strategically to control the flow from one process unit to another, or from a collection of process units to another one. The masses of pumps were provided in design specifications and were simplified to a single entity inclusive of additional parts such as motors, gears, bearings etc. The masses of mechanical mixers, which were used throughout the coagulant dosing and flocculation phases, were also mentioned in design specifications which were provided by the design consultants at Umgeni Water.

The mass of the PVC filter columns was obtained in a similar manner to the tanks and pipes. In addition to the filter column casing, other materials used in its construction included mild steel for the framing and support triangulation. Based on the relatively minor masses of these components, they were excluded from the inventory analysis of this system. Additionally, a y-type strainer was utilised in the preliminary intake system prior to reaching the filter column. It was constructed predominantly of PVC with the mass being obtained through specifications supplied by Umgeni Water. The system also makes use of air blowers in its backwash phase, constructed predominantly out of cast iron. Masses of these components were sourced from a supplier catalogue.

Construction phase – additional components in Systems 2 to 4

Table 2 lists differences between Systems 1 and Systems 2–4. The determination of masses for the general components present in each system were all accomplished in a similar manner to System 1.

Operational phase – Systems 1 to 4

For the production of pre-treated water in System 1, the main inputs considered were the energy consumed by the rotary equipment (pumps, mixers and air blowers), as well as the chemicals utilised in the dosing and flocculation phases. An iron(III) chloride ($FeCl_3$) coagulant was dosed to the seawater at a rate of 10 mg/L at optimal operating capacity. Table 3 illustrates some of the differences between the operational phase of System 1 and the other systems. These revolve mainly around energy input and chemical dosing.

Table 2. Components and differences between Systems 1 to 4 in the construction phase

System 1	System 2	System 3	System 4
Coagulation tank Flocculation tank	No flocculation tank	DAF unit comprising of a prefilter, flotation tank, coagulation and flocculation tanks and mixers, dosing containers, buffer tank, scum rake mechanism, saturator and compressor	Prefiltration unit followed by a series of ultrafiltration (UF) modules constructed from polyvinylidene fluoride (PVDF)
Tri-media filter (gravity)	Pressure vessel in addition to a similar filter column for gravity filtration	Dual media rapid gravity filters	
See detailed explanations in the previous sections	Additional buffer tank in between the 2 filtration phases	The carbon steel saturator (DAF unit) has a compressed air capacity of 0.23 m^3	UF modules produced filtered water at a much faster rate (6 m^3/h as opposed to 2.5 m^3/h)
See detailed explanations in the previous sections	Additional feed pump controlling flow into pressure filter and backwash pump for both filters	Additional pumps to control raw water flow through each sub-unit in the DAF	Only 2 feed pumps required in addition to a CIP pump and a CEB pump for the cleaning in place and backwash phases

Table 3. Systems 1 to 4 operational parameters – energy and chemicals used

System 1	System 2	System 3	System 4
2.16 kWh/kL	2.02 kWh/kL	3.52 kWh/kL	0.56 kWh/kL
Ferric chloride (coagulant) and polyacrylamide (flocculant)	Ferric chloride (coagulant)	Ferric chloride (coagulant) and polyacrylamide (flocculant)	Cleaning chemicals needed – hydrochloric acid (HCl), sodium hydroxide (NaOH), hydrochloric acid (HCl) and sodium hypochlorite (NaOCl)

Building the SimaPro model

All material and energy data collected in the inventory stage were scaled down and expressed in terms of the functional unit, i.e., per kL water. Thus, the corresponding units for material inputs were kg/kL water, energy inputs as kWh/kL and chemicals required as mg/kL water. Within the SimaPro software new categories were created and each system was constructed, with individual inputs. Each phase of treatment per system was created as an individual unit process which resulted in an intermediate product, linking to the next phase.

Impact assessment

As the third phase of an LCA study, the impact assessment stage relates inputs and outputs of the systems to potential environmental impacts and effects. Quantification of these impacts thus allows comparison between systems from an environmental life cycle perspective. According to the ISO series (ISO 14040: ISO, 2006), there are 3 necessary steps that form part of this phase: selection of impact categories, classification, and characterization.

The life cycle impact assessment method employed for this study was the ReCiPe midpoint hierarchist version v1.12, with European characterisation factors (see National Institute for Public Health and the Environment (2016) for details). It calculates environmental impact scores by using characterisation factors for the inputs (e.g. raw materials and energy) and the outputs (e.g. pollution and waste) that contribute to an environmental impact (Huijbregts et al., 2006). For this study, the environmental impact categories considered are climate change, terrestrial acidification, toxicity, depletion of abiotic resources, eutrophication, photochemical oxidation, land use, ionising radiation, and particulate matter formation.

The second step of the impact assessment involves assigning inventory data to the categories selected in the preceding stage and is commonly referred to as classification. This step is computed by the SimaPro software. The final mandatory stage, i.e. characterisation, involves assigning the relative contribution of system inputs and outputs to the selected impact categories. This entails the multiplication of the quantity of substances that constitute these flows by their respective characterisation factors to quantify their relative contributions to the category considered (Huijbregts et al., 2006; ISO, 2006). This process is also computed automatically by the SimaPro software, which displays each contribution in terms of the respective category's reference unit (e.g. kg CO_2 equivalents for climate change).

Interpretation

The final stage of an LCA study involves the identification and evaluation of information obtained from the results and their presentation to the intended audience. For this study 1 kL (1 m^3) of pre-treated water product was analysed for the 4 systems. Data were described based on material inputs, and thereafter aggregated into main material inputs (e.g. infrastructure, chemicals, electricity, filter media, etc.). Following this, the impact assessment was aggregated per unit process to quantify the relative environmental burden of each phase of pre-treatment for each system. This was made possible through the use of the 'analyse groups' function available in the modelling software. This process of identification, analysis, and evaluation of the results from the impact assessment stage is summarized in the 'Results and discussion' section.

RESULTS AND DISCUSSION

Comparative analysis of systems

Figure 4 and Table 4 show the results of the impact assessment of all 4 systems, expressed in the same functional unit (1 kL of pre-treated water) as percentages (Fig. 4) and as actual scores (Table 4). It is evident that System 3 has the highest overall contribution to most categories. This can be attributed to its high

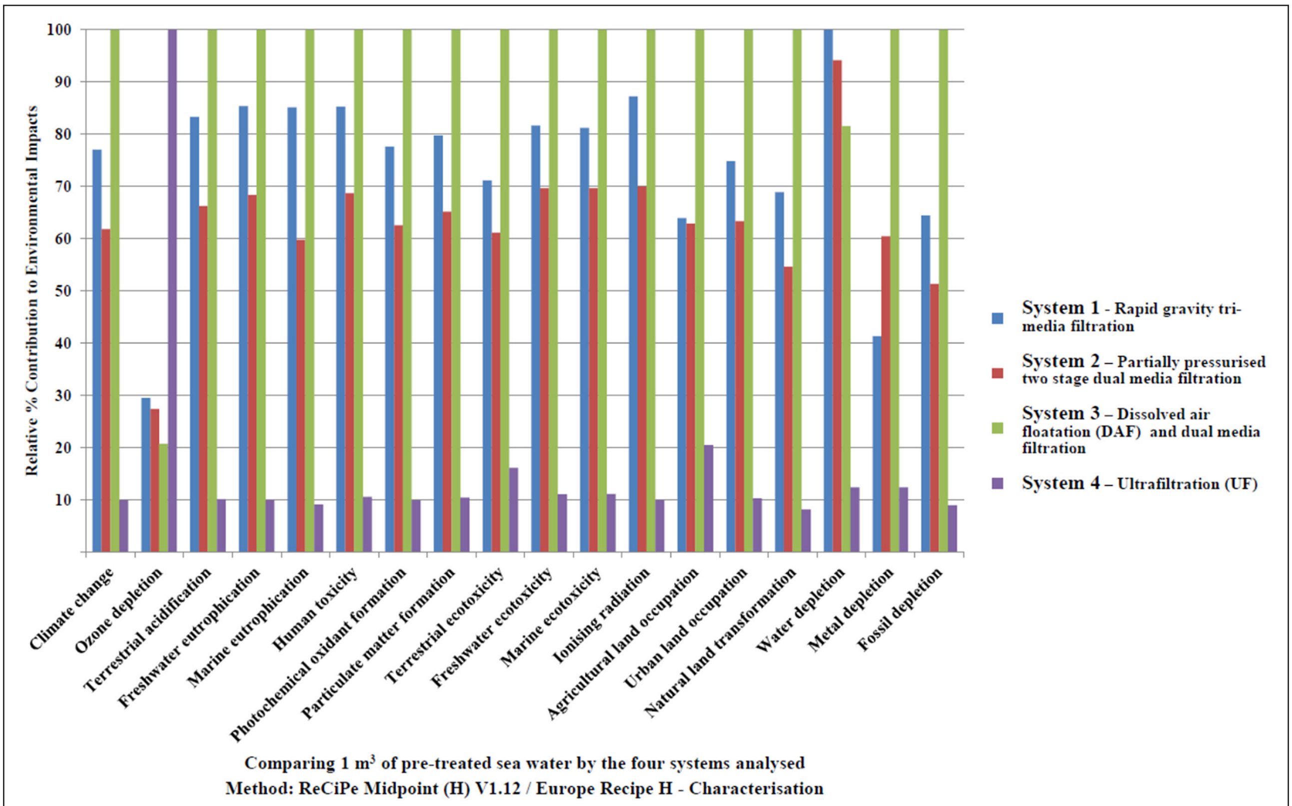

Figure 4. Comparative results for Systems 1 to 4

Table 4. Environmental scores for System 1 to 4 per kL of pre-treated seawater; the highest contributions are highlighted in red, while the second, third and fourth (least) contributing scores are highlighted in brown, blue and green, respectively

Impact category	Unit	System 1	System 2	System 3	System 4
Climate change	kg CO_2 eq.	2.54	2.04	3.30	0.33
Ozone depletion	kg CFC-11 eq.	6.75×10^{-8}	6.27×10^{-8}	4.74×10^{-8}	2.29×10^{-7}
Terrestrial acidification	kg SO_2 eq.	2.29×10^{-2}	1.83×10^{-2}	2.76×10^{-2}	2.80×10^{-3}
Water depletion	m^3	1.61×10^{-2}	1.51×10^{-2}	1.31×10^{-2}	2.00×10^{-3}
Metal depletion	kg Fe eq.	1.25×10^{-1}	1.83×10^{-1}	3.02×10^{-1}	3.76×10^{-2}
Fossil depletion	kg oil eq.	6.49×10^{-1}	5.17×10^{-1}	1.01	9.07×10^{-2}
Human toxicity	kg 1.4-DB eq.	1.14	9.15×10^{-1}	1.33	1.41×10^{-1}
Terrestrial ecotoxicity	kg 1.4-DB eq.	4.16×10^{-5}	3.58×10^{-5}	5.85×10^{-5}	9.44×10^{-6}
Freshwater ecotoxicity	kg 1.4-DB eq.	3.5×10^{-2}	2.99×10^{-2}	4.28×10^{-2}	4.76×10^{-3}
Marine ecotoxicity	kg 1.4-DB eq.	3.33×10^{-2}	2.85×10^{-2}	4.09×10^{-2}	4.58×10^{-3}
Freshwater eutrophication	kg P eq.	1.7×10^{-3}	1.36×10^{-3}	2.00×10^{-3}	2.00×10^{-4}
Marine eutrophication	kg N eq.	8.77×10^{-4}	6.16×10^{-4}	1.03×10^{-3}	9.45×10^{-5}
Agricultural land occupation	m^2a	4.35×10^{-2}	4.28×10^{-2}	6.81×10^{-2}	1.40×10^{-2}
Urban land occupation	m^2a	1.07×10^{-2}	9.1×10^{-3}	1.44×10^{-2}	1.49×10^{-3}
Natural land transformation	m^2	6.66×10^{-5}	5.28×10^{-5}	9.66×10^{-5}	7.98×10^{-6}
Photochemical oxidant formation	kg NMVOC	1.19×10^{-2}	9.58×10^{-3}	1.53×10^{-2}	1.52×10^{-3}
Ionising radiation	kBq U235 eq.	1.39×10^{-1}	1.11×10^{-1}	1.59×10^{-1}	1.58×10^{-2}
Particulate matter formation	kg PM10 eq.	6.13×10^{-3}	5.01×10^{-3}	7.69×10^{-3}	8.07×10^{-4}

energy consumption due to the various mechanical equipments in operation. The system with the lowest environmental burden is System 4, although it has the highest score for ozone depletion only. This is due to the construction of infrastructure, specifically the use of PVDC for the manufacture of the UF membranes.

Table 4 and Fig. 5 summarise the environmental scores of each system for each impact category. For most of these categories the highest contributor is electricity consumption and this is in agreement with literature (Beery and Repke, 2010; Al-Sakar and Arafat, 2013; Luo, 2017; Al-Kaabi et al., 2021). In particular, these environmental burdens are emphasized and can be traced back to the coal-intensive South African electricity mix and its associated pollution to air, water and soils. These emissions are expected to be even higher with the energy crisis experienced (Pretorius et al., 2015).

Figures 5 to 8 show that electricity consumption is the main contributor to environmental impacts in all categories, except for ozone depletion, water depletion, and metal depletion. For the first 2 systems, the use of domestic water in the coagulation phase contributed significantly to the categories of ozone and water depletion, respectively. Systems 3 and 4 did not use domestic water in the coagulant dosing phases, but instead relied on a method that dosed the feed water directly. For all the systems, metal depletion was due to the construction of infrastructure, which mainly consisted of pipes, tanks, mixers, and pumps. Overall, the contribution from the construction of infrastructure is relatively low compared to that from electricity consumption.

Energy and associated impacts – contributions and comparisons

Although a comparison between the pre-treatment processes under investigation can be made, there are differences associated with each process and these should be noted. Table 5 highlights the main process-related differences between the systems which account for differences in electricity use and subsequent impacts.

Although Systems 2 and 3 both consist of 2 treatment phases (see Table 5), electricity consumption is mitigated in System 2 by the omission of an independent flocculation phase. This emphasizes the potential for electricity mitigation for water filtration systems using 'in-line' processes, as opposed to independent dosing systems. This observation is further justified by System 4 which comprises of a totally automated in-line coagulation and flocculation system. This configuration results in fewer rotary units in the form of mechanical pumps and mixers and consequently far lower electricity requirements than the other 3 systems. Figures 9 to 12 detail electricity usage for each of the systems and show the main process units' contributions to overall electricity consumption.

The electricity consumption figures for this study ranged from 0.56 to 3.52 kWh per kL (m^3) of treated water (see Table 5). Al-Sarkal and Arafat (2013) showed energy consumption of 0.2 to 1.0 kWh/kL for conventional pre-treatment (as in Systems 1 to 3) based on their study and similar studies of entire SWRO desalination plants in the Arabian Gulf. Elimelech and Philip (2011) present an energy consumption of around 1 kWh/kL for pre-treatment and Zarzo and Prats (2018) cite a range of 0.543 to 0.680 kWh/kL for similar processes for an Australian large-scale plant. Voutchkov (2018) presented an energy consumption of 0.39 kWh/kL (~11% of an entire plant) for Pacific Ocean water desalination. However, Luo (2017), in a pilot plant setting, reported higher electricity consumption for pre-treatment prior to RO, namely 1.42 kWh/kL for DAF combined with UF and 1.82 kWh/kL for a novel pre-treatment technology involving submerged ceramic membranes. Loubet et al. (2014) showed in their review that conventional water technology systems (similar to those employed in Systems 1 to 3) typically require from 0.58 to 2.11 kWh/kL treated water, although they analysed entire systems used for freshwater and wastewater treatment and not desalination. UF pre-treatment in SWRO plants has an energy consumption of 0.08 to 0.1 kWh/kL (Al-Sarkal and Arafat, 2013), increasing up to 0.3 kWh/kL (Fane, 2018) and 0.46 kWh/kL (Zarzo and Prats, 2018); however, this is lower than the 0.56 kWh/kL figure for System 4 using similar technology. Hence, the range of electricity consumption for Systems 1 to 4 was higher in comparison to that reported in the literature. This is mainly because of the pilot scale of the pre-treatment operations but is also due to the different quality of the seawater to be treated. Larger scale operations would benefit from economies of scale and are more energy efficient. However, the high algal load at the Lovu location increases the energy required, due to increased coagulation/flocculation and mixer requirements. Al-Kaabi et al. (2021) showed that electricity consumption for pre-treatment of seawater prior to RO in the Arabian Gulf is dependent on the quality of seawater (mainly the parameter of salinity, but also the concentrations of pollutants including microorganisms) and that a 25% reduction can be achieved in most environmental burdens by selecting locations for SWRO plants with lower salinity and pollution levels, thus reducing intensity of pre-treatment required. Other initiatives to lower energy consumption of pre-treatment have been summarized by Elimelech and Philip (2011), Fane (2018) and Anis et al. (2019), and include bio pre-treatment, gravity-driven membranes and novel membranes (e.g. graphene oxide) among the multitude of interventions directed at the processes themselves.

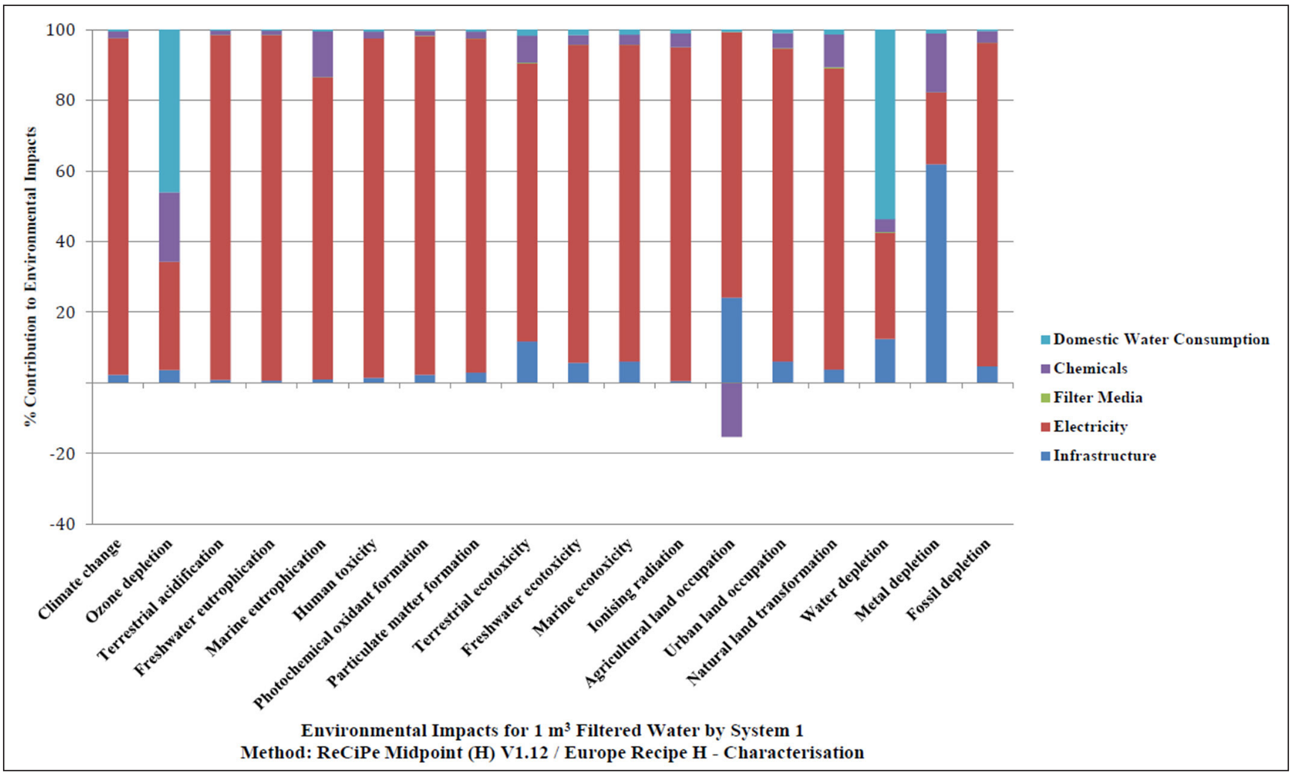

Figure 5. Contributions to environmental scores for System 1

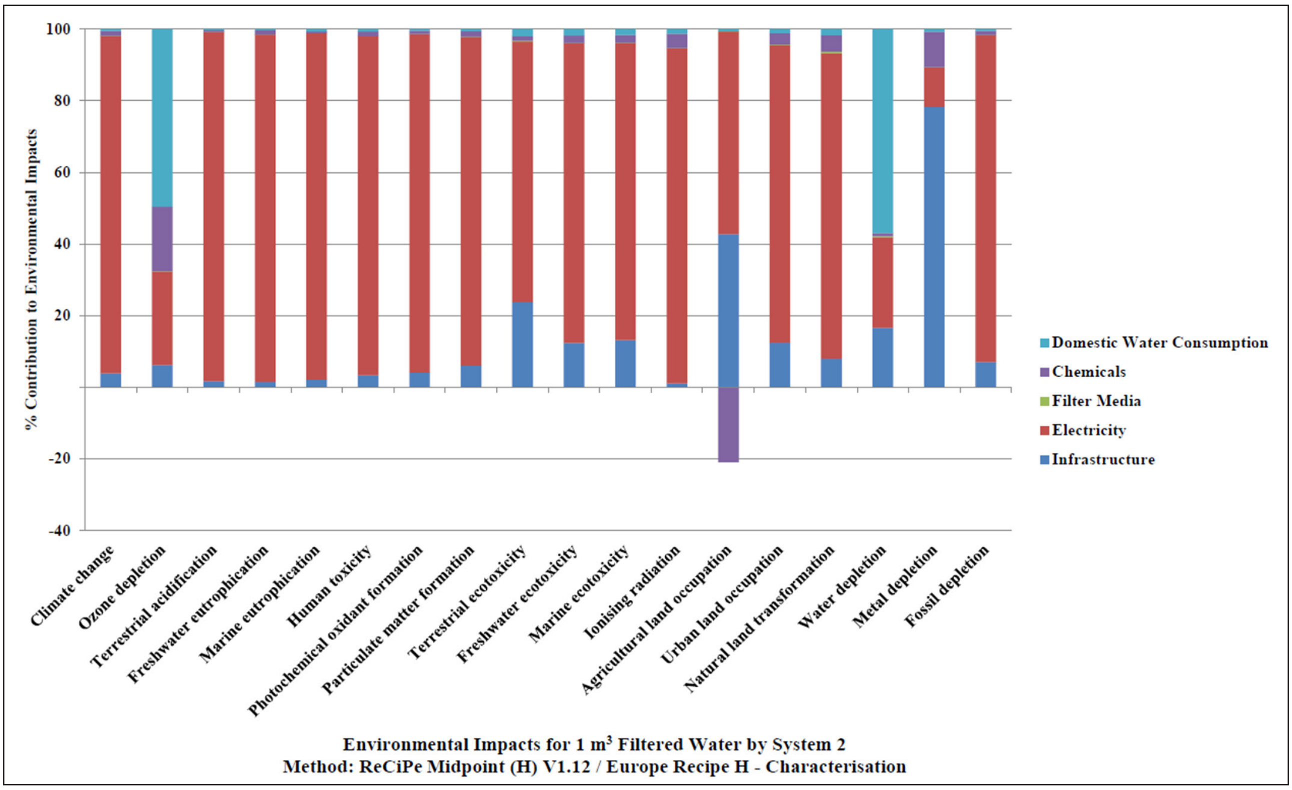

Figure 6. Contributions to environmental scores for System 2

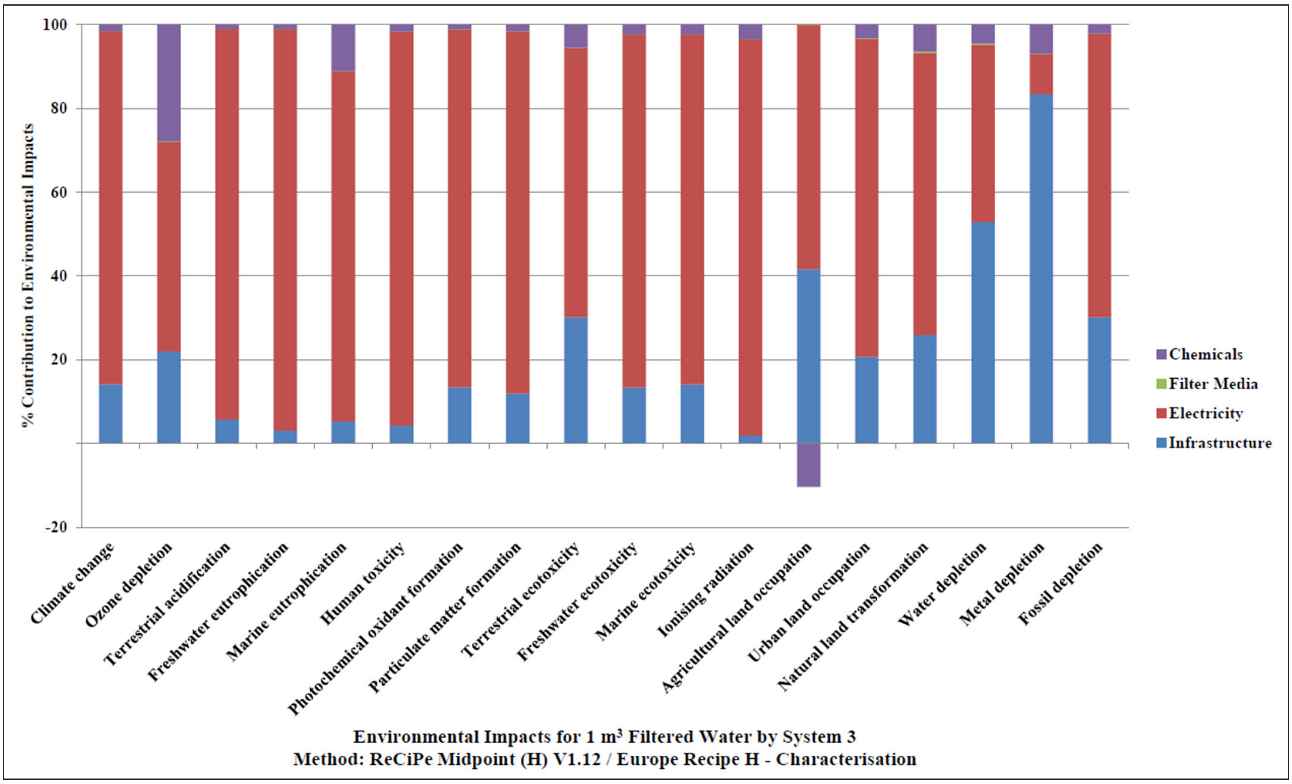

Figure 7. Contributions to environmental scores for System 3

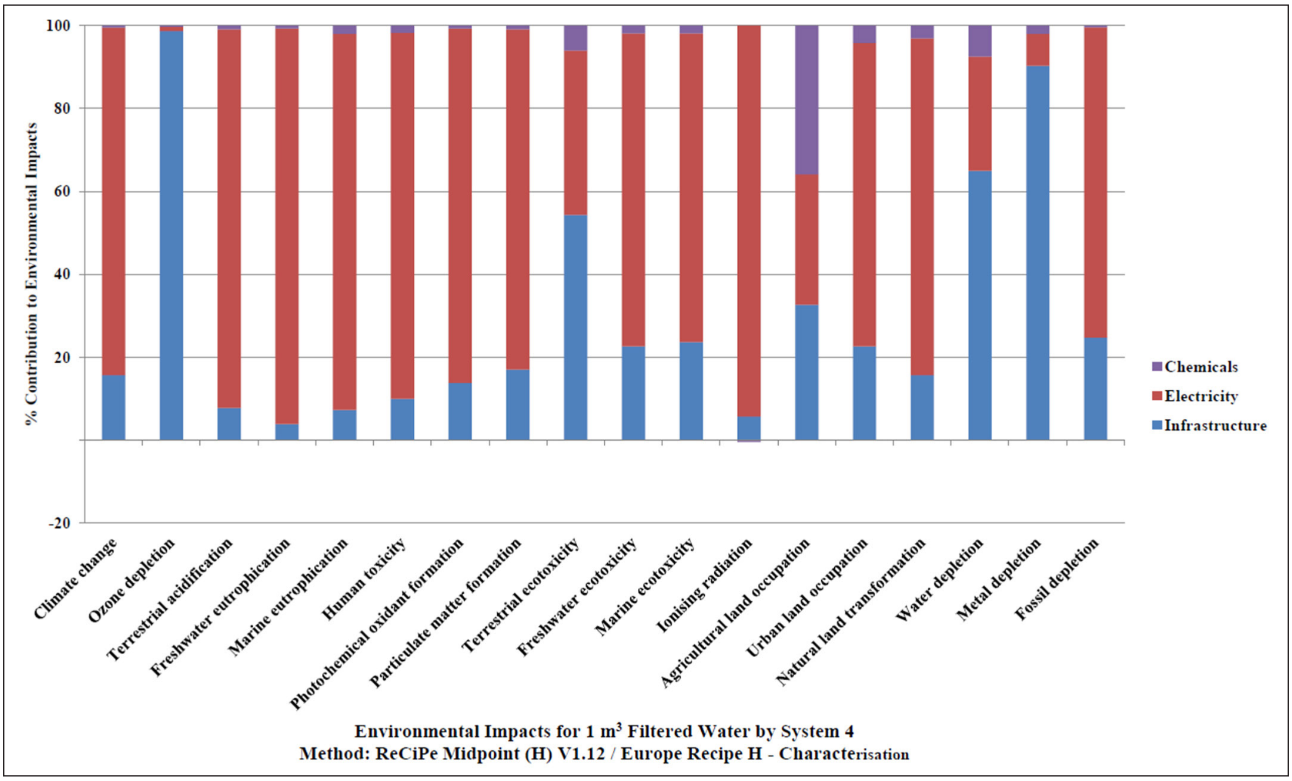

Figure 8. Contributions to environmental scores for System 4

Table 5. Differences between the pre-treatment systems investigated

Parameters	System 1	System 2	System 3	System 4
Stages of pre-treatment	Single stage	Two stage	Two stage	Single stage
Independent coagulant dosing phase	Yes	Yes	Yes	No
Independent flocculation phase	Yes	No	Yes	No
Electricity (kWh/kL pre-treated seawater)	2.16	2.02	3.52	0.56

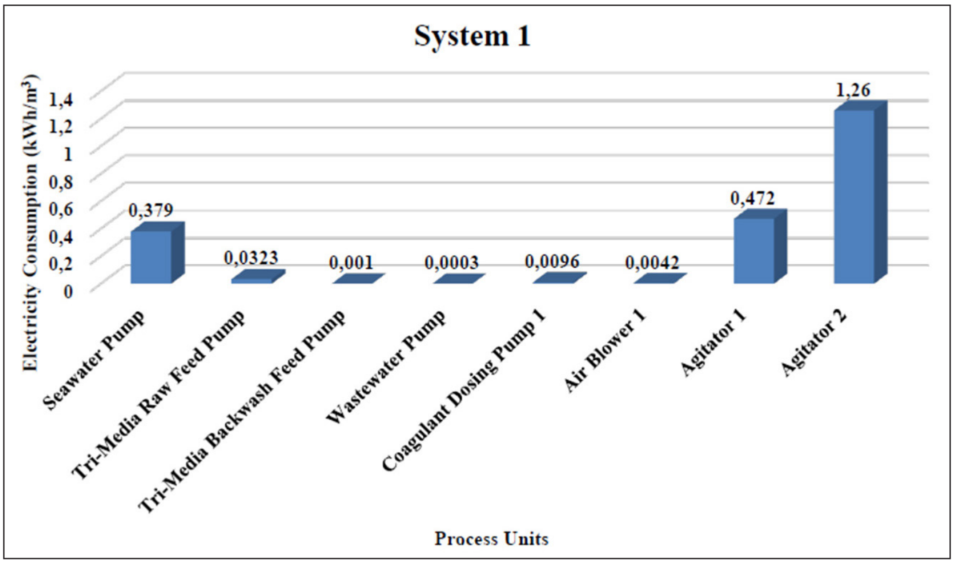

Figure 9. Electricity used by process units in System 1

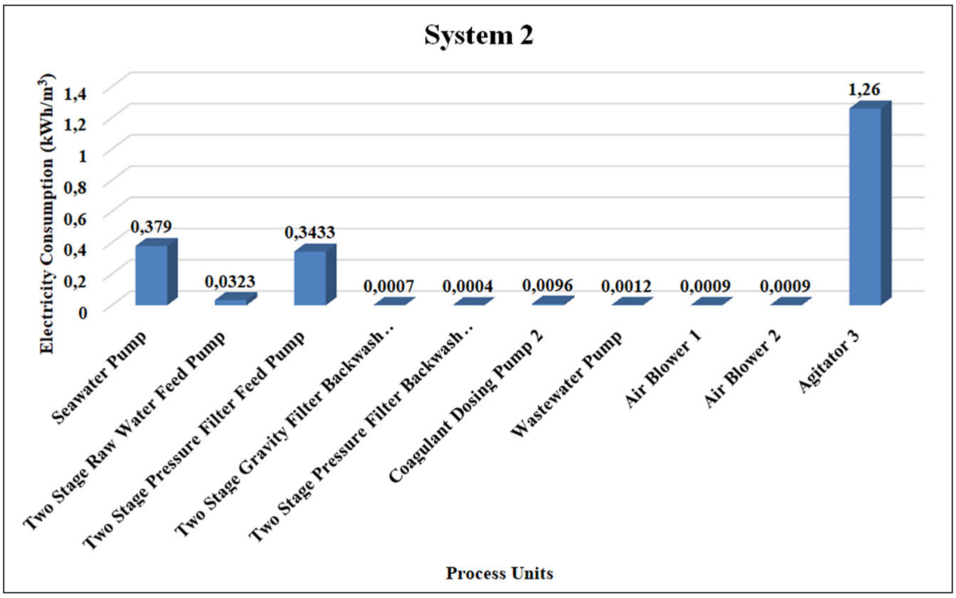

Figure 10. Electricity used by process units in System 2

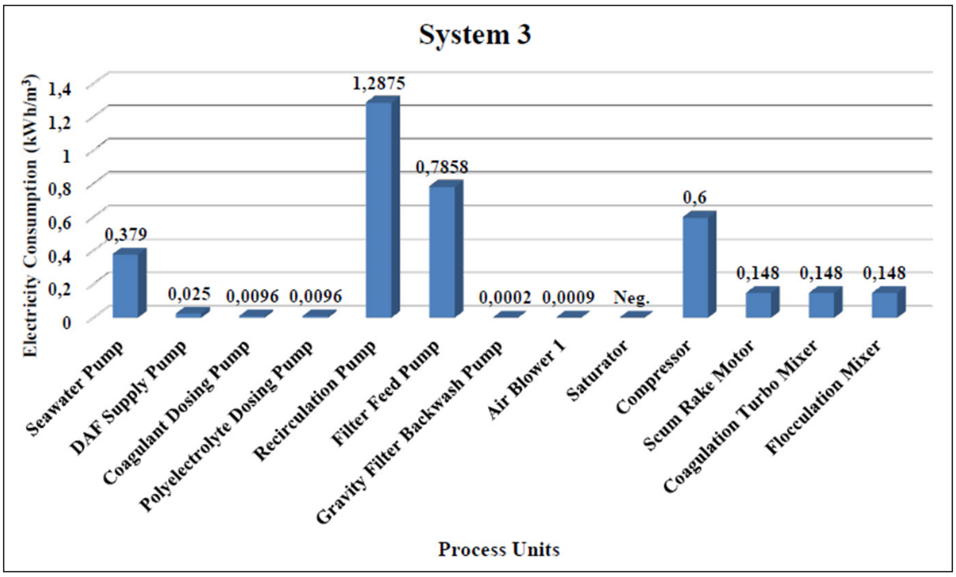

Figure 11. Electricity used by process units in System 3

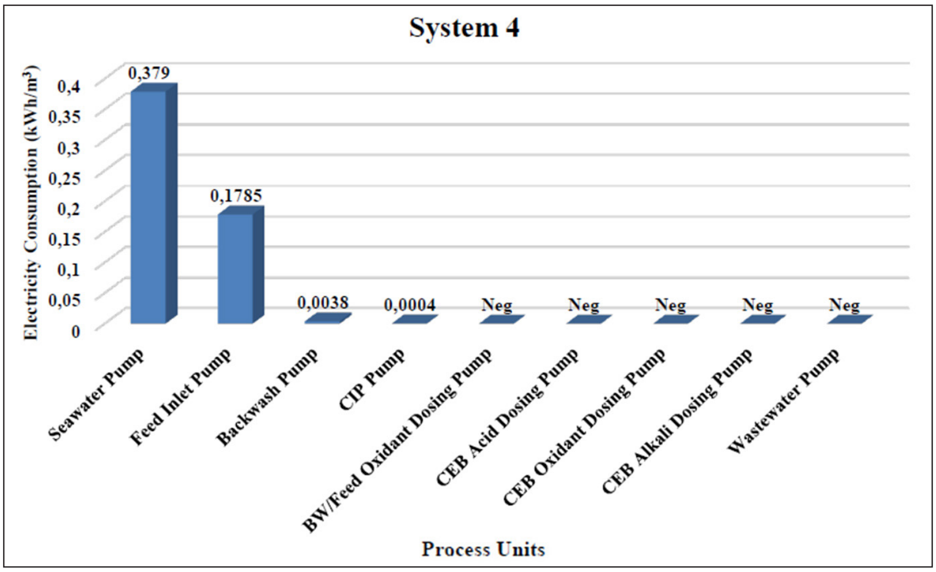

Figure 12. Electricity used by process units in System 4

Another strategy to reduce the environmental burden of pre-treatment due to energy is switching to less polluting forms of energy and in particular using renewable energy. Gude and Fthenakis (2020) and Nassrullah et al. (2020) showed by detailed reviews the ways in which various renewable energy sources can be used for desalination, such as solar (photovoltaic and thermal), wind and hybrid technologies. Renewable energy can decrease carbon emissions as well as lower many of the environmental scores presented in Table 4, and should be further investigated. Goga et al. (2019) showed that theoretically replacing conventional coal-based South African electricity with photovoltaic solar power has the potential to substantially reduce greenhouse gas emissions from desalination for the entire RO plant from 4.17 to 0.28 kg CO_2eq/kL potable water.

Beery and Repke (2010) calculated comparable GHG emissions from UF to conventional media filtration for pre-treatment prior to RO desalination. For conventional water treatment processes the figures for global warming potential ranged from 0.51 to 1.57 kg CO_2eq/kL for potable water systems and were found to depend greatly on the electricity consumption of the system as well as the electricity mix per country (Loubet et al., 2014). In comparison, the impact of climate change for this study varied between 0.33 and 3.33 kg CO_2eq/kL and extended past the range cited in the literature for conventional processes. This again can be attributed to the lower production efficiencies of the pilot plant operations and the coal-based South African energy mix.

Chemicals and associated impacts

The use of chemicals and energy are closely linked in a SWRO plant (Al-Kaabi et al., 2021), and although the burdens of chemicals are relatively minor, they are still considered significant. Figure 5 shows that this percentage contribution is higher for Systems 1 and 3 as opposed to Systems 2 and 4. System 4 is interesting because it uses 4 different chemicals, as opposed to the other systems which use fewer (1 or 2 – see Table 3). Generally, chemicals have the lowest percentage contribution due to their small dosage. In addition to contributing directly to environmental scores for the different impacts, chemicals had an additional effect on freshwater depletion (due to the dilutions required). There is a proportional relationship between dosage and freshwater required for Systems 1 to 3. Certain chemical inputs, i.e. the addition of ferric chloride for Systems 1 to 3 and hydrochloric acid and sodium hypochlorite for System 4, had a positive impact on agricultural land occupation. The production and use of ferric chloride and hydrochloric acid are dependent on the manufacture of chlorine in which wood chips are used (according to the process data in SimaPro). Their use in the production and manufacturing of chemicals benefits agricultural land occupation.

To reduce the overall impacts from chemicals in pre-treatment, dosing rates and the selection of chemicals can be optimized. For example, Al-Kaabi et al. (2021) showed that, as a coagulant, ferric chloride has lower environmental burdens compared to aluminium salt alternatives and that burdens can be greatly mitigated by choosing different, yet functionally similar, chemicals. All systems investigated in this research project use the better performing ferric chloride as a coagulant. Coagulant use can be reduced altogether by changing the process design, as shown by Al-Mashharawi et al. (2012) who conclude that the installation of low-pressure membranes in desalination pre-treatment can reduce the quantity of chemical coagulants required. This is clearly observed when analysing System 4. Goga et al. (2019) also recommended the substitution of traditional chemical and mechanical separation treatment with newer pressure-driven membrane technologies such as MF, UF, and NF. This requires careful consideration as literature shows that UF operations for pre-treatment in the long term (longer than investigated in this study) can be prone to bio-fouling due to algal break down and are generally more costly due to membrane replacement (Badruzzaman et al., 2019).

CONCLUSIONS

The aim of this study was to investigate and compare the environmental performance of 4 systems for the pre-treatment of seawater prior to RO desalination on the south coast of the eThekwini Municipality, South Africa. These systems were investigated in a pilot plant setting. The results show that the UF-based system (System 4) had the best environmental performance followed by the single-phase gravity-driven granular filtration (System 1), then the two-phase pressurized filtration (System 2) and finally by the DAF-based system (System 3). Electricity consumption was observed to have the highest overall burden for most environmental impacts considered, for all systems, which is in line with previous findings in the literature. However, the energy consumption figures and the associated environmental impacts were higher than those in the literature, mainly because of the pilot plant scale and the coal-based electricity mix in

South Africa. The infrastructure required (i.e. the construction of process units) and the chemicals employed for operations had much lower contributions to the environmental scores. The UF system incorporated automated in-line dosing systems, as well as fewer pumping units, leading to greater efficiency with regard to electricity consumption. The other systems were shown to be less efficient in terms of electrical input requirements. The UF system also needed the highest number of chemicals; however, their percentage contribution to environmental scores was the lowest due to optimized dosage. For the 3 systems using conventional dosing, there was a proportional relationship between the use of chemicals and potable water requirements for dilution and dosing purposes. On the other hand, the use of certain chemicals, particularly ferric chloride, was shown to positively impact the category of agricultural land occupation. Possible improvements that would yield the best outcome would include increasing the energy efficiency of pre-treatment processes and supplementing energy requirements through solar energy. It is considered worth investigating the benefits of using slightly higher chemical dosage as this would benefit the system if it leads to less energy required. These interventions are particularly important when upscaling the pre-treatment processes from the pilot plant to a large-scale SWRO plant.

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AUTHOR CONTRIBUTIONS

Mr Wade Draper was the main researcher and had inputs into the overall conceptualisation of the study and the methodology. He undertook all the data collection, field work, SimaPro modelling and the main interpretation of the results, as well as the writing of a part of the initial draft of the paper. He also revised some figures after the review. Dr Elena Friedrich contributed with the detailed conceptualisation of the study, some field work, data curation, validation of results and part of the interpretation. She did most of the draft writing and the revision after the review. She also undertook the supervision, project administration and funding acquisition for this study. Dr Taahira Goga played a part by writing sections of the initial draft paper and updating the literature review, performing data validation, improving interpretation and contributing to the revision after the review.

DATASETS

Detailed modelling data are available on request from the corresponding author.

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