

# The potential of decentralised wastewater treatment in urban and rural sanitation in South Africa: lessons learnt from a demonstration-scale DEWATS within the eThekweni Municipality

Preyan Arumugam<sup>1</sup>, Lungiswa Zuma<sup>2</sup>, Susan Mercer<sup>1</sup>, Lloyd Govender<sup>3</sup>, Jonathan Pocock<sup>1</sup>, Christopher J Brouckaert<sup>1</sup> and Teddy Gounden<sup>1</sup>

<sup>1</sup>Water, Sanitation & Hygiene Research & Development Centre, School of Engineering, University of KwaZulu-Natal, Durban 4041, South Africa

<sup>2</sup>eThekweni Water and Sanitation, Durban 4000, South Africa

<sup>3</sup>Bremen Overseas Research and Development Association, Durban 4001, South Africa

The design principles of decentralised wastewater treatment systems (DEWATS) make them a practical sanitation option for municipalities to adopt in fast-growing cities in South Africa. Since 2014, a demonstration-scale DEWATS with a modular design consisting of a settler, anaerobic baffled reactor (ABR), anaerobic filter (AF), vertical down-flow constructed wetland (VFCW) and horizontal flow constructed wetland (HFCW) has been in operation in eThekweni. A performance evaluation after the long-term operation was undertaken in 2019 by comparing the final effluent with national regulatory requirements. Despite limitations in characterising the raw wastewater, a comparison of the settler and final effluent quality indicated high ( $\geq 85\%$ ) removal efficiencies of total chemical oxygen demand (COD<sub>T</sub>), ammonium-N (NH<sub>4</sub>-N) and orthophosphate-P (PO<sub>4</sub>-P), 75% removal of total suspended solids (TSS) and 83.3% log<sub>10</sub> removal of *Escherichia coli*. Lack of exogenous and endogenous carbon and high dissolved oxygen (DO) concentrations ( $> 0.5 \text{ mg}\cdot\text{L}^{-1}$ ) inhibited denitrification in the HFCW, resulting in 12.5% of the effluent samples achieving compliance for nitrate-N (NO<sub>3</sub>-N). Moreover, mixed aggregate media and low residence times in the HFCW may have also contributed to poor NO<sub>3</sub>-N removal. During the COVID-19 lockdown, an unexpected shutdown and subsequent resumption of flow to the DEWATS indicated a 16-week recovery time based on achieving full nitrification in the HFCW. Although design modifications are necessary for the HFCW, the installation of urine diversion flushing toilets at the household level will reduce the nutrient loading to the DEWATS and potentially achieve fully compliant effluent. Alternatively, the application of two-stage vertical flow constructed wetlands to improve denitrification should also be explored in the South African context. With an improved design, DEWATS has the potential to fill the gap in both urban and rural sanitation in South Africa, where waterborne sanitation is still desired but connections to conventional wastewater treatment works (WWTWs) are not possible.

## CORRESPONDENCE

Preyan Arumugam

## EMAIL

[ArumugamNanolalP@ukzn.ac.za](mailto:ArumugamNanolalP@ukzn.ac.za)

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## INTRODUCTION

Service delivery inequality remains evident in South Africa, spawned by the legacies of apartheid (Sutherland et al., 2014). Compounded by rapid, uncontrolled urbanisation, population growth and circular migratory patterns in fast-growing metropolitan cities like eThekweni (Durban), the increasing prevalence of informal settlements within the urban periphery has left municipalities with limited resources to meet the demand of servicing these communities (eThekweni Municipality, 2021). This leads to backlogs in basic service delivery such as water and sanitation.

Sanitation statistics in South Africa indicate that 84.1% of the population have access to improved sanitation, defined as either a flush toilet connected to either a sewer, septic tank, or conservancy tank or a ventilated improved pit latrine (Stats SA, 2022). Reaching the remaining 16% appears to be the most problematic, largely due to informal settlements becoming more numerous and increasingly dense within urban and peri-urban edges (eThekweni Municipality, 2021). There is a strong aspiration for waterborne sanitation and, although not sustainable in a water-challenged country like South Africa, municipalities are pressurised to provide flushing toilets which are historically associated with wealth and dignity (Gounden et al., 2006). This is exacerbated by the fact that dry sanitation is not always acceptable to the user, with complaints of clogging and odour issues (Roma et al., 2013). As a provisional measure, approximately half of the informal settlements within the eThekweni Municipality are provided with flushing toilets, showers and washing basins in the form of community ablution blocks that are connected to the central sewer network or an alternative system (eThekweni Municipality, 2021).

Mirroring sanitation delays are housing backlogs. A new directive within the eThekweni Municipality favours in-situ formal housing upgrades of informal settlements over identifying new plots and relocating communities (eThekweni Municipality, 2021). However, even if these developments are serviced with water-efficient toilets, ageing infrastructure at conventional centralised wastewater treatment works (WWTWs) means that they cannot cope with the increased hydraulic loading. Even if WWTWs are upgraded, challenges such as cable theft render these systems inoperable for unexpected periods (DWS, 2022). Moreover, according to the latest Green Drop Report, only 23 out of 995 WWTWs evaluated achieved Green Drop certification (cumulative score of  $\geq 90\%$ , for

which effluent quality forms 30% of the evaluation score) (DWS, 2022). Even the Joint Monitoring Programme, which provides the indicators for achieving the United Nation's Sustainable Development Goals (SDGs), has no data regarding the proportion of the South African population who have access to safely managed sanitation services, i.e. full treatment and safe disposal or reuse of generated domestic wastewater (WHO and UNICEF, 2021). Thus, there is an urgent need to look at alternative, affordable, practical, and sustainable sanitation solutions.

The benefits of decentralised wastewater treatment systems (DEWATS) are well known (Singh et al., 2009; Kerstens et al., 2012; Reynaud, 2014). To date, DEWATS have been designed and implemented in many developing countries by non-governmental organisations such as the Bremen Overseas Research and Development Association (BORDA) (Sasse, 1998; Gutterer et al., 2009). Unlike central WWTWs that require high energy for operation and chemicals for treatment, DEWATS use biological and physical processes via simple technologies in a modular design. The gravitational flow to these systems allows them to operate without pump stations, making them a lower-cost option where waterborne sanitation is needed (Singh et al., 2009; Singh et al., 2019). Moreover, after the primary (settler) and secondary treatment (anaerobic baffled reactor and anaerobic filter), the nutrient-rich anaerobically treated effluent can be suitable for agriculture provided that there is significant removal of pathogens (Gutterer et al., 2009). This is appropriate for social housing developments where the treated effluent can be reused for irrigating gardens (for aesthetic purposes/ornamental crops) or rerouted back to households for reuse in flushing. It can also be incorporated into school sanitation planning where waterborne sanitation is provided but connections to the centralised sewer network are not practical.

The National Sanitation Policy encourages the use of decentralised sanitation systems in South Africa (DWS, 2016) but, as of 2022, implementation of DEWATS on a community scale is limited to only a single demonstration-scale system. The purpose of this system was to test the feasibility of decentralised sanitation for communities within the eThekweni Municipality. Commissioned in 2010 and fully operational in 2014, the demonstration-scale DEWATS, based on BORDA design principles (Sasse, 1998; Gutterer et al., 2009), treats raw wastewater generated from 84 households.

Originally, the eThekweni Municipality purposed this DEWATS for integration with agricultural reuse of the effluent from the anaerobic filter (herein referred to as the AF effluent). The results of several field trials have been documented for a variety of crops (Musazura et al., 2015; Odindo et al., 2016). However, a recent study by Musazura and Odindo (2021) highlighted that the high nutrient loading in the AF effluent can result in delayed flowering and uneven ripening for maize crops, while pathogen (*Escherichia coli*) contamination was possible with overhead irrigation of leafy vegetables such as cabbage and lettuce. The authors recommended dilution of the AF effluent or further treatment to deactivate the pathogens which may be present (Musazura and Odindo, 2021).

Tertiary treatment in constructed wetlands can provide effluent that is safe for discharge to a water source. Constructed wetlands (CWs) are a common treatment option in DEWATS due to their buffering capacity to filter suspended solids and biologically reduce the nutrient content (especially nitrogen) through microbial degradation (nitrification/denitrification) and plant assimilation (Kadlec and Wallace, 2009; Vymazal, 2010; Stefanakis et al., 2014). Nitrification requires aerobic conditions since it is an oxidative process, while denitrification occurs in anoxic conditions (i.e., in the presence of nitrate but in the absence of oxygen) (Lee et al., 2009; Saeed and Sun, 2012). The application

of DEWATS with CWs is beneficial for informal settlement upgrades where space limitation precludes the reuse of the treated effluent for agriculture. Although using similar technologies with a modular design, it must be noted that DEWATS, in the South African context, are not classified as package plants, which require electrical energy and chemicals to augment biological treatment (Van Niekerk et al., 2009).

Performance evaluations of the primary and secondary treatment modules of the demonstration-scale DEWATS have been conducted (Pillay et al., 2018) and, more recently, an investigation into the treatment efficiency of the CWs after design upgrades to improve performance (Arumugam and Buckley, 2020). However, an assessment of the DEWATS in its entirety after the long-term operation is necessary if this design is to be integrated into scenarios where compliance with the Department of Water Affairs' (now the Department of Water and Sanitation) Revised General Authorisation (GA) limits (DWA, 2013) is needed for safe discharge of the final effluent into a water source. Therefore, this study aimed to evaluate the demonstration-scale system after continuous operation without any long-term disturbances in flow, by comparing the final effluent quality to the GA limits. In addition, during the 2020 national COVID-19 lockdown Levels 4 and 5, access to the site was restricted halting all maintenance activities. Consequently, the DEWATS received no flow for 162 days due to a blockage upstream. This unplanned shutdown of the system provided an opportunity to assess the recovery time of the DEWATS (referred to as operability following long-term shutdown).

## METHODS

### Description of the eThekweni demonstration-scale DEWATS

The DEWATS is located in a community in Newlands East, north of central Durban (KwaZulu-Natal, South Africa). The design daily flow is  $41.6 \text{ m}^3 \cdot \text{d}^{-1}$  based on an estimated 5 persons per household (HH) and 10% reserve (Pillay et al., 2018). As the DEWATS uses a modular design, raw domestic wastewater initially flows into a two-chamber settler with a volume of  $31.5 \text{ m}^3$  for primary treatment via sedimentation and flotation. The organic material from the settler effluent is then degraded through three parallel anaerobic baffled reactor (ABR) trains (Figs 1 and A1, Appendix), with each train having a volume of  $22.05 \text{ m}^3$ . Considering that this DEWATS was constructed for research purposes, the only reason for three parallel trains was to test the performance of the ABR under different hydraulic loading rates. Trains 1 and 2 are identical, consisting of 7 equal-sized chambers. Train 3 was constructed with 4 chambers; the first three being twice the size of a single chamber in Trains 1 and 2 (Foxon et al., 2006). The baffles within the ABR chambers force the wastewater to travel up and down, further settling the biomass and allowing the suspended and soluble solids to be degraded. A two-chamber anaerobic filter (AF) with gravel media allows for the attachment of microbial biomass responsible for the further anaerobic treatment of the ABR effluent. The AF of each train has a total volume of  $26.66 \text{ m}^3$  (Fig. A2, Appendix). Successive treatment in the ABR and AF forms the secondary treatment modules which can remove up to 90% of the biodegradable chemical oxygen demand (bCOD) resulting in nutrient-rich AF effluent (high in ammonium-N concentration and low in total COD (COD<sub>t</sub>) compared to the influent) (BORDA, 2017; Truyens et al., 2018).

The AF effluent from Train 1 is further treated in a hybrid subsurface flow constructed wetland (CW) system consisting of a single vertical down-flow CW (VFCW) and a single horizontal flow CW (HFCW) (Fig. 1). The purpose of the serial CW design was to promote the conditions necessary for nitrification in the VFCW and subsequent denitrification in the HFCW.

The remaining AF effluent from Trains 2 and 3 are used for irrigation trials conducted on-site or directed back to the main sewer line. The CW system was designed for a flow of  $13.9 \text{ m}^3 \cdot \text{d}^{-1}$  on the assumption that each train would receive a third of the daily flow.

A low-capacity siphon doses the VFCW to allow for intermittent feeding as per the design of this type of CWs with an average volume of  $1.87 \text{ m}^3 \cdot \text{dose}^{-1}$ . The area of the VFCW is  $96 \text{ m}^2$  ( $9.8 \text{ m} \times 9.8 \text{ m}$ ;  $l \times b$ ) and  $0.75 \text{ m}$  in depth with a design hydraulic loading rate (HLR) of  $0.14 \text{ m} \cdot \text{d}^{-1}$ . The original design depth of the VFCW was  $1.5 \text{ m}$ ; however, this was limited to  $0.75 \text{ m}$  to maintain the hydraulic gradient for gravitational flow to the next treatment module. The  $0.55 \text{ m}$  filter layer includes well-graded ( $C_u = 4.64$ ) unwashed river sand ( $D_{10} = 0.4 \text{ mm}$ ) over a  $0.15 \text{ m}$  drainage layer consisting of  $4\text{--}25 \text{ mm}$  coarse gravel ( $D_{10} = 4.4 \text{ mm}$ ). A thin layer ( $\approx 0.05 \text{ m}$ ) of coarse sand to fine gravel ( $0.5\text{--}2 \text{ mm}$ ) was added to the surface of the VFCW and compacted to cause temporal surface water accumulation (flooding), thus improving the hydraulic retention time within the CW. The distribution system consists of

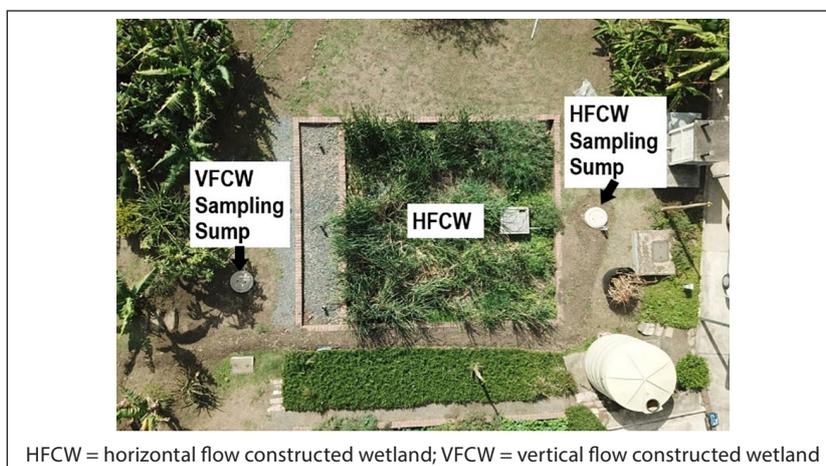
eight  $75 \text{ mm}$  (dia.) pipes with alternate perforations on the sides of the pipe (i.e., not in pairs). The VFCW is planted with *Cyperus sexangularis* and *Typha capensis* ( $5\text{--}6 \text{ plants} \cdot \text{m}^{-2}$ ) (Arumugam and Buckley, 2020). A double layer of impermeable lining acts as a liner at the bottom of the bed to prevent groundwater contamination.

The treated VFCW effluent flows continuously to the HFCW which has a surface area of  $66 \text{ m}^2$  ( $8.1 \text{ m} \times 8.15 \text{ m}$ ;  $l \times b$ ) and a depth of  $0.9 \text{ m}$ . The media consists of  $50\text{--}80 \text{ mm}$  gravel stones at the inlet. The filter media in the middle of the HFCW consists of irregular-shaped mixed gravel of  $8\text{--}20 \text{ mm}$  and  $25\text{--}80 \text{ mm}$  aggregates/broken stones in a ratio of  $5:1$ . The HFCW is permanently impounded to maintain the saturation level at  $0.15 \text{ m}$  below the surface of the bed (Arumugam and Buckley, 2020). The discharge from the HFCW is piped by gravitated flow to the trunk sewer so that none of the treated effluent is released into the immediate environment (field or river). The HFCW is also planted with *C. sexangularis* and *T. capensis* ( $5\text{--}6 \text{ plants} \cdot \text{m}^{-2}$ ).

Both CWs have sampling sumps with a working volume of  $440 \text{ L}$  at the outflow line for composite sampling as represented in Fig. 2.



**Figure 1.** Aerial view of the Newlands Mashu demonstration-scale decentralised wastewater treatment system (DEWATS) within the eThekweni Municipality (taken September 2019)



**Figure 2.** Aerial view of the sampling sumps (September 2019)

## Other installations

For raw wastewater (influent) characterisation, a whole effluent sampler (WES) was installed upstream of the DEWATS in early 2019 (Fig. A3, Appendix). The function of the WES is to collect flow-proportional composite samples from a known volume of well-mixed influent, and then discharge this sampled volume back into the DEWATS. The volume of wastewater sampled is from households only, with no additional streams (like stormwater or industrial wastewater) that could potentially have different characteristics to the volume sampled, and is thus representative of the incoming raw wastewater at a specific time. Raw wastewater characterisation aids in the design and planning activities of wastewater treatment plants, particularly DEWATS.

## Operation and maintenance – descumming

Scum removal is an operational requirement for DEWATS to prevent accumulation that may lead to blockages in the primary and secondary treatment modules. For this study, descumming was increased from once to twice a week to reduce the time for scum accumulation in the settling chambers, thus making removal easier and requiring only one trained personnel. The liquid and solid fractions of the scum were removed manually using a bucket and spade during continuous operation (i.e., with no long-term disturbances in flow) from the settler and the first ABR chamber of each train and quantified at the WASH R&D Centre laboratory at the University of KwaZulu-Natal (UKZN).

## Sampling

### Flow measurements

An electromagnetic flow meter (SAFMAG) installed in the sump following the AF of each train records the flow rate to produce the cumulative daily flow. This data is logged in 10-min intervals using an Omniflex Teleterm M3e Data logger. A pressure transducer (dipperLog Nano b, Heron Instruments Inc.) was installed inside the siphon chamber to record the discharge rate per dose.

### Scum characterisation

Since the scum characterisation was not a focus of this study, the scum from a single descumming event was collected during normal operation, physically sorted and evaluated to determine the chemical and physical constituents for information purposes with no influence on the performance evaluation of the DEWATS.

### Wastewater and effluent

Sampling under continuous operation was carried out over 16 weeks starting in February 2019. Based on the cumulative daily flow averaging  $14.9 \text{ m}^3 \cdot \text{d}^{-1}$  and the volume of each component of the DEWATS, a sampling interval timeline was generated based on the calculated residence time in each module. Three 1 L grab samples (30 s intervals between each) were taken from the settler at the start of each week. Three grab samples of the ABR and AF effluent were taken from the 7<sup>th</sup> chamber of the ABR and the siphon chamber at 1.5 and 3.5 days after the settler samples, respectively, also in 30 s intervals. As individual samples were taken, these are not referred to as replicates.

On the 5<sup>th</sup> day of each week, composite samples were taken from the CW sampling sumps. Based on the average dose volume of the siphon at  $1.87 \text{ m}^3$ , and the working volume of the sump at 398 L, it was predicted that the entire drainage volume from a single dose will fill up the CW sampling sump 4.7 times. For each fill of the sump, three 1 L samples were taken (with 30 s intervals between each sample). Each of these samples was referred to as a 'sub-composite sample'. The first sub-composite sample from Fill 1 was

mixed with the first sub-composite sample from Fill 2, and so on. Likewise, the second and third composite samples from Fill 1 were mixed with the second and third sub-composite samples from Fill 2, respectively, and this continued until all fills were sampled. Thus, there were three final composite samples for analysis. Considering the diurnal flow rate of the DEWATS, these final composite samples were not regarded as true replicates and were analysed as individual samples. Both CWs could not be sampled consecutively (i.e., on the same day), due to the fill and drain mechanism of the sump that caused a pulsing feed to the HFCW which differed from its operational design for continuous flow (Kadlec and Wallace, 2009). As a result, there were 8 sampling events per CW over the 16 weeks with all other grab samples taken weekly.

The recovery performance evaluation was carried out in September and December 2020 when maintenance activities resumed after the COVID-19 lockdown, and the upstream blockage could be cleared. The recovery time was based on the time taken for the DEWATS to achieve full nitrification (i.e. nearly all of the  $\text{NH}_4\text{-N}$  concentration oxidised to  $\text{NO}_3\text{-N}$ ). Only the final effluent quality (HFCW effluent) was analysed with a single composite sample taken per sampling event (i.e., not in 30 s intervals as per the sampling during continuous operation). Sampling began in Week 3, following the resumption of flow. However, heavier lockdown restrictions disrupted sampling and samples were taken only on Weeks 3, 6, 7, 8, 10 and 16, totalling 6 sampling events.

## Chemical and microbial analyses

A Jenway 3540 pH & conductivity meter was used to measure pH and electrical conductivity (EC). Dissolved oxygen (DO) was measured using a BOECO - DO-580 handheld meter. Total COD (COD<sub>t</sub>) ammonium-N ( $\text{NH}_4\text{-N}$ ), nitrate-N ( $\text{NO}_3\text{-N}$ ) and total nitrogen (TN) and orthophosphate-P ( $\text{PO}_4\text{-P}$ ) were measured with a Merck NOVA 60 Spectroquant. To estimate the biodegradable COD (bCOD) concentration (both soluble and particulate fractions), the oxygen uptake rate (OUR) was measured using a BM-Evo Respirometer.

All determinants measured with the Spectroquant were prepared and analysed according to the standard operating procedure (SOP) supplied with the test kit supplied by Merck. Total suspended solids (TSS) were measured according to Standard Methods (2540 D) (APHA, 2017). All samples, except for COD<sub>t</sub> and TN, were filtered (using a Whatman 1.2  $\mu\text{m}$  pore size filter paper) and the filtrate was prepared for analysis to avoid interference by the TSS concentration in the measurement by the spectrophotometer. Indicator bacteria, *E. coli* colony counts only, were measured using the Merck Petrifilm 3M plate and recorded as colony-forming units (CFU)· $\text{mL}^{-1}$  converted to CFU·100  $\text{mL}^{-1}$ . All analyses, except for the bCOD, were carried out in the on-site laboratory where the DEWATS is situated. The bCOD fraction was measured at the WASH R&D Centre laboratory, University of KwaZulu-Natal.

## Data analysis

### Loading rate

The organic, nutrient and pathogen loading to each module was calculated using Eq. 1:

$$\text{Loading rate (g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}) = q \times C_i \quad (1)$$

where  $q$  is the hydraulic loading rate ( $\text{m}\cdot\text{d}^{-1}$ );  $C_i$  is the concentration of the settler effluent ( $\text{mg}\cdot\text{L}^{-1}$ ).

### Performance of each module

The performance of each module of the DEWATS was measured by the removal efficiency and mass removal rate of the suspended solids, organic and nutrient content in the settler effluent.

## Removal efficiency

The percentage removal (removal efficiency) of each pollutant was measured by Eq. 2.

$$\text{Removal efficiency (\%)} = \left( \frac{C_i - C_o}{C_i} \right) \times 100\% \quad (2)$$

where  $C_i$  is the concentration of the settler effluent ( $\text{mg}\cdot\text{L}^{-1}$ ) and  $C_o$  is the concentration of the effluent from each respective module ( $\text{mg}\cdot\text{L}^{-1}$ ).

## Mass removal rate

The mass removal rate of organic and nutrient content was calculated by Eq. 3:

$$\text{Mass removal rate (\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1})} = q (C_i - C_o) \quad (3)$$

where  $q$  is the hydraulic loading rate ( $\text{m}\cdot\text{d}^{-1}$ );  $C_i$  is the concentration of the settler ( $\text{mg}\cdot\text{L}^{-1}$ ) and  $C_o$  is the concentration of the effluent from each respective module ( $\text{mg}\cdot\text{L}^{-1}$ ).

## Comparison of the final effluent quality in relation to the General Authorisations

The % of samples achieving compliance was measured using Eq. 4.

$$\% \text{ of samples achieving compliance} = \frac{n}{n(\text{tot})} \times 100 \quad (4)$$

where  $n$  is the number of CW effluent samples that were equal to or below the General Authorisations (discharge) limit for that parameter and  $n(\text{tot})$  is the total number of samples analysed.

## RESULTS AND DISCUSSION

### Performance under continuous operation

#### Influent characterisation

Unfortunately, accumulated grit seized the macerating pump inside the WES, thus delaying its commissioning and field use at the beginning of the 2019 (continuous operation) sampling campaign. Thus, influent characterisation was not possible.

#### Hydraulic loading

The flow through Train 1, feeding the CW system, ranged from 1.7–104.4  $\text{m}^3\cdot\text{d}^{-1}$  with an average flow of 17.7  $\text{m}^3\cdot\text{d}^{-1}$  during January–May 2019. Low flows were experienced during blockages upstream of the DEWATS, while high flows occurred during holidays and heavy rainfall periods (Fig. A4, Appendix).

Based on the data from the pressure transducer inside the siphon chamber, the average siphon dose was discharged over 208 s. The dosing rate to the VFCW per dose was 0.53  $\text{m}^3\cdot\text{min}^{-1}$ , while the cumulative daily flow to the VFCW was 15.6  $\text{m}^3\cdot\text{d}^{-1}$ . This equated to an HLR of 0.16  $\text{m}\cdot\text{d}^{-1}$ , higher than the design HLR of 0.14  $\text{m}\cdot\text{d}^{-1}$ . The slight difference in the cumulative daily flow in Train 1 and flow entering the hybrid CW system was due to the pressure transducer measurements being read between 00:00 and 23:59 and based only on the volume discharged during each dose over 24 h whereas the SAFMAG flow meter installed after the AF records the flow rate every 10 min.

#### Scum

The density of scum removed ranged from 1 305–1 616.8  $\text{kg}\cdot\text{m}^{-3}$  across the three ABR trains with the highest density removed from Train 1 (Table A1). The higher scum density in Train 1 is assumed to be because Train 1 received the majority of the flow over the monitoring period in relation to the total flow into the

DEWATS (Fig. A4, Appendix). The depth of the scum layer was approximately 0.05 m, covering most of the outlet pipes of the settling chambers.

The solid material was composed of menstrual material, nappies, plastics, and occasionally asphalt. Despite increasing the descumming frequency to twice a week during the sampling campaigns, it is recommended that descumming occurs once a week to limit the effect of scum accumulation on operation and the risk of downtime. However, for future DEWATS applications, grit chambers or screens need to be installed upstream of DEWATS as a preventative measure.

#### Settler effluent characterisation

The effluent quality of each module over the monitoring period is given in Table 1. For the calculation of loading and mass removal rates, the HLR of 0.16  $\text{m}\cdot\text{d}^{-1}$  was used. The average CODt concentration in the settler was  $927 \pm 345.2 \text{ mg}\cdot\text{L}^{-1}$ , equating to a loading rate of 148.3  $\text{gCODt}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ . The bCOD (soluble and particulate fractions) was estimated to be 760  $\text{mg}\cdot\text{L}^{-1}$  from the OUR analysis (Table A2). Nutrient loading, measured only by total nitrogen, was 11.8  $\text{gN}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ . The average *E. coli* colony count was  $1.1 \times 10^6 (\pm 8.9 \times 10^5) \text{ CFU}\cdot 100 \text{ mL}^{-1}$ . Since it is expected that primary treatment via sedimentation and flotation would have already occurred in the settler before sampling, this is not a true representation of the raw wastewater characterisation.

#### Organic removal

The cumulative removal efficiencies of CODt from the settler effluent were 22.1%, 61.4%, 94.2% and 95.9% after the ABR, AF, VFCW and HFCW, respectively (Table 1). Removal of the bCOD fraction was 15.3% after the ABR and 63.9% after the combination of the primary and secondary treatment modules. The overall mass removal rate of CODt was 142.2  $\text{gCODt}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  based on the final effluent quality. The absence of bCOD from the VFCW effluent and HFCW effluent implies that all of the available bCOD in the AF effluent was oxidised in the VFCW. Moreover, it would imply no bCOD as a carbon source for denitrification in the HFCW (Table A2).

#### Nutrient removal

The major nitrogen fraction after primary and secondary treatment is ammonium-N (85.2% of the total nitrogen concentration) with an average concentration of 52 ( $\pm 12$ )  $\text{mg}\cdot\text{L}^{-1}$  in the AF effluent. The cumulative removal efficiencies of  $\text{NH}_4\text{-N}$  were 91.7% and 98.1% after the VFCW and HFCW, respectively. Like CODt degradation, the majority of  $\text{NH}_4\text{-N}$  transformation occurs in the VFCW, which was expected since both processes are oxygen dependent. However, the impact of the absence of bCOD in the VFCW effluent on denitrification is evident by the poor nitrate-N ( $\text{NO}_3\text{-N}$ ) removal in the HFCW, where only 9.5% of  $\text{NO}_3\text{-N}$  concentration was reduced. Moreover, the DO concentration in the VFCW effluent ranged from 1.7–2.9  $\text{mg}\cdot\text{L}^{-1}$  and 1.3–2.5  $\text{mg}\cdot\text{L}^{-1}$  in the HFCW effluent. Bertino (2010) found that denitrification occurs in low DO concentrations, but not above 0.3–0.5  $\text{mg}\cdot\text{L}^{-1}$ . Above this DO concentration, denitrifying bacteria utilise oxygen instead of  $\text{NO}_3\text{-N}$  as the terminal electron acceptor in their respiration (Bertino, 2010). The cumulative total nitrogen removal efficiency from the settler was 6.5%, 17.1%, 33.4% and 48.5% after the ABR, AF, VFCW and HFCW, respectively. Overall, the mass removal rate of total nitrogen was 5.7  $\text{gN}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ .

The average orthophosphate ( $\text{PO}_4\text{-P}$ ) concentration was 8.3 ( $\pm 3.4$ )  $\text{mg}\cdot\text{L}^{-1}$  in the AF effluent and 3.1 ( $\pm 1.3$ )  $\text{mg}\cdot\text{L}^{-1}$  after the HFCW, equating to an overall removal efficiency of 62.7% (Table 1).

**Table 1.** Effluent quality after each subsequent module during long-term operation with no disturbances in flow (February–May 2019)

| Parameter   | Settler effluent |  |  | ABR effluent |  |  | AF effluent |  |  | VFCW effluent |                         |  | HFCW effluent |                         |                  |
|---|------------------|--|--|--------------|--|--|-------------|--|--|---------------|-------------------------|--|---------------|-------------------------|------------------|
|   | <i>N</i>         | Range (min–max)                            | Mean (± std dev)                                 | <i>n</i>     | Range (min–max)                            | Mean (± std dev)                                 | <i>n</i>    | Range (min–max)                            | Mean (± std dev)                                 | <i>n</i>      | Range (min–max)         | Mean (± std dev)                                 | <i>n</i>      | Range (min–max)         | Mean (± std dev) |
| CODt (mg·L <sup>-1</sup> )                            | 39               | 320–1 696                                  | 927 ± 345.2                                      | 36           | 112–1 456                                  | 722 (± 326.1)                                    | 40          | 140–860                                    | 357.8 (± 198.7)                                  | 21            | 24–115                  | 53.5 (± 28.3)                                    | 23            | 4–86                    | 38.1 (± 26.2)    |
| NH <sub>4</sub> -N (mg·L <sup>-1</sup> )              |                  |  |  |              |  |  | 48          | 22–68                                      | 52 (± 12)  | 24            | 0–16                    | 4.3 (± 4.7)                                      | 24            | 0–5                     | 1 (± 1.6)        |
| NO <sub>3</sub> -N (mg·L <sup>-1</sup> )              |                  |  |  |              |  |  |             |  |  | 24            | 3.8–53.8                | 29.6 (± 13.8)                                    | 24            | 10.5–41.7               | 26.8 (± 10.2)    |
| TN (mg·L <sup>-1</sup> )                              | 48               | 39–97                                      | 73.6 ± 13.7                                      | 45           | 22–80                                      | 63.8 (± 13.7)                                    | 48          | 26–74                                      | 61 (± 12.9)                                      | 24            | 27–69                   | 49 (± 11.5)                                      | 24            | 26–52                   | 37.9 (± 9.2)     |
| PO <sub>4</sub> -P (mg·L <sup>-1</sup> )              |                  |  |  |              |  |  | 48          | 2.6–17                                     | 8.3 (± 3.4)                                      | 24            | 3.5–7.1                 | 5.1 (± 1)  | 22            | 1.3–6.4                 | 3.1 (± 1.3)      |
| TSS (mg·L <sup>-1</sup> )                             | 48               | 32–1 002                                   | 242.9 ± 169.6                                    | 45           | 24–114                                     | 70 (± 18.5)                                      | 48          | 18–130                                     | 49.3 (± 23.1)                                    | 24            | 4–72                    | 36.3 (± 18.1)                                    | 24            | 1–68                    | 20.5 (± 19.8)    |
| pH  | 48               | 6.7–8                                      |  | 45           | 6.9–8.5                                    |  | 48          | 7.2–8.3                                    |  | 24            | 5.6–7.9                 |  | 24            | 6.4–7.9                 |                  |
| EC (mS·m <sup>-1</sup> )                              | 48               | 54.5–106.1                                 | 91.4 ± 12.5                                      | 45           | 62.4–97                                    | 83.4 (± 9.9)                                     | 48          | 75.9–105.3                                 | 95 (± 7.9)                                       | 24            | 53.7–81.7               | 70.8 (± 7.3)                                     | 24            | 49.3–76.2               | 65.2 (± 7.1)     |
| DO  |                  |  |  |              |  |  |             |  |  | 24            | 1.7–2.9                 | 2.1 (± 0.2)                                      | 24            | 1.3–2.5                 | 2 (± 0.3)        |
| <i>E. coli</i> (CFU·100 mL <sup>-1</sup> )            | 48               | 5 × 10 <sup>4</sup> –2.9 × 10 <sup>6</sup> | 1.1 × 10 <sup>6</sup> (± 8.9 × 10 <sup>5</sup> ) | 46           | 5 × 10 <sup>4</sup> –9.1 × 10 <sup>5</sup> | 4.8 × 10 <sup>5</sup> (± 2.6 × 10 <sup>5</sup> ) | 48          | 3 × 10 <sup>4</sup> –8.2 × 10 <sup>5</sup> | 3.2 × 10 <sup>5</sup> (± 1.8 × 10 <sup>5</sup> ) | 24            | 0–3.7 × 10 <sup>5</sup> | 5.5 × 10 <sup>4</sup> (± 9.9 × 10 <sup>4</sup> ) | 24            | 0–2.8 × 10 <sup>3</sup> | 508 (± 854)      |
| <i>E. coli</i> log <sub>10</sub> removal from settler |                  |  |  |              | 0.36                                       |  |             | 0.54                                       |  |               | 1.3                     |  |               | 3.34                    |                  |

Shaded areas indicate 'did not measure'

**Table 2.** Final (HFCW) effluent quality under continuous operation (2019) and after long-term shutdown (2020) with the percentage of samples achieving compliance with the General Authorisation limits for safe discharge into receiving water

| Parameter                                  | HFCW effluent (under continuous operation) 2019 |                         |                      |                                   | HFCW effluent (during recovery) 2020 |  |  | GA limit (DWS, 2013) |
|--|---|-------------------------|----------------------|-----------------------------------|--------------------------------------|--|--|----------------------|
|  | <i>n</i>  | Range (min–max)         | Mean (± std dev)     | % of samples achieving compliance | <i>N</i>                             | Range (min–max)                            | Mean (± std dev)                                       |                      |
| CODt (mg·L <sup>-1</sup> )                 | 23  | 4–86                    | 38.1 (± 26.2)        | 87                                | 6                                    | 44–87.3                                    | 62.7 (± 14.3)  | 75                   |
| NH <sub>4</sub> -N (mg·L <sup>-1</sup> )   | 24  | 0–5                     | 1 (± 1.6)            | 100                               | 6                                    | 2–24                                       | <b>11.3</b> (± 7.3)                                    | 6                    |
| NO <sub>3</sub> -N (mg·L <sup>-1</sup> )   | 24  | 10.5–41.7               | <b>26.8</b> (± 10.2) | 12.5                              | 6                                    | 6.8–45.9                                   | <b>27</b> (± 15.7)                                     | 15                   |
| TN (mg·L <sup>-1</sup> )                   | 24  | 26–52                   | 37.9 (± 9.2)         |                                   | 5                                    | 30–54.7                                    | 42.9 (± 10.7)  |                      |
| PO <sub>4</sub> -P (mg·L <sup>-1</sup> )   | 22  | 1.3–6.4                 | 3.1 (± 1.3)          | 100                               | 5                                    | 2.8–5.5                                    | 4.4 (± 1.1)  | 10                   |
| TSS (mg·L <sup>-1</sup> )                  | 24  | 1–68                    | 20.5 (± 19.8)        | 75                                | 5                                    | 10–25                                      | 19 (± 5.5)   | 25                   |
| pH   | 24  | 6.4–7.9                 |                      | 100                               | 5                                    | 6.8–7.4                                    |  | 5.5–9.5              |
| EC (mS·m <sup>-1</sup> )                   | 24  | 49.3–76.2               | 65.2 (± 7.1)         | 100                               | 5                                    | 54.4–85.9                                  | 71.7 (± 13.4)  | 150                  |
| <i>E. coli</i> (CFU·100 mL <sup>-1</sup> ) | 24  | 0–2.8 × 10 <sup>3</sup> | 508 (± 854)          | 83.3                              | 5                                    | 5 × 10 <sup>2</sup> –8.8 × 10 <sup>4</sup> | <b>1.9 × 10<sup>4</sup></b> (± 3.9 × 10 <sup>4</sup> ) | 1 000                |

Bold text denotes that the mean concentration does not meet the General Authorisations for safe discharge

### Pathogen removal

The level of indicator faecal coliforms, *E. coli*, in the settler effluent was 1.1 × 10<sup>6</sup> (± 8.9 × 10<sup>5</sup>) CFU·100 mL<sup>-1</sup>, with an overall log<sub>10</sub> removal of 3.34 after final treatment in the HFCW. Despite the VFCW being responsible for the majority of the organic and nutrient removal, pathogen removal was greater after the HFCW with die-off suspected to be the main removal process. The final effluent contained 508 (± 854) CFU·100 mL<sup>-1</sup> of *E. coli* (Table 1).

### Compliance with the General Authorisations

For the duration of the 16-week sampling campaign, ≥ 85% of the final effluent samples (*n* = 8) were compliant with the GA limits for discharge for organics (CODt), ammonium-N (NH<sub>4</sub>-N), orthophosphate-P (PO<sub>4</sub>-P), pH and electrical conductivity (EC). The number of samples compliant with faecal coliforms (*E. coli*) and TSS was 83.3 and 75%, respectively. Only 12.5% of samples were compliant with nitrate-N (NO<sub>3</sub>-N) (Table 2). The action of the pump in the sampling sumps resulted in suspended matter from the walls of the sump interfering with actual TSS concentration in the drainage from each CW. Therefore, the actual TSS in the CW effluent is suspected to be much lower than

indicated and perhaps ranging below the GA limit of 25 mg·L<sup>-1</sup> in both CW effluents (Table 2).

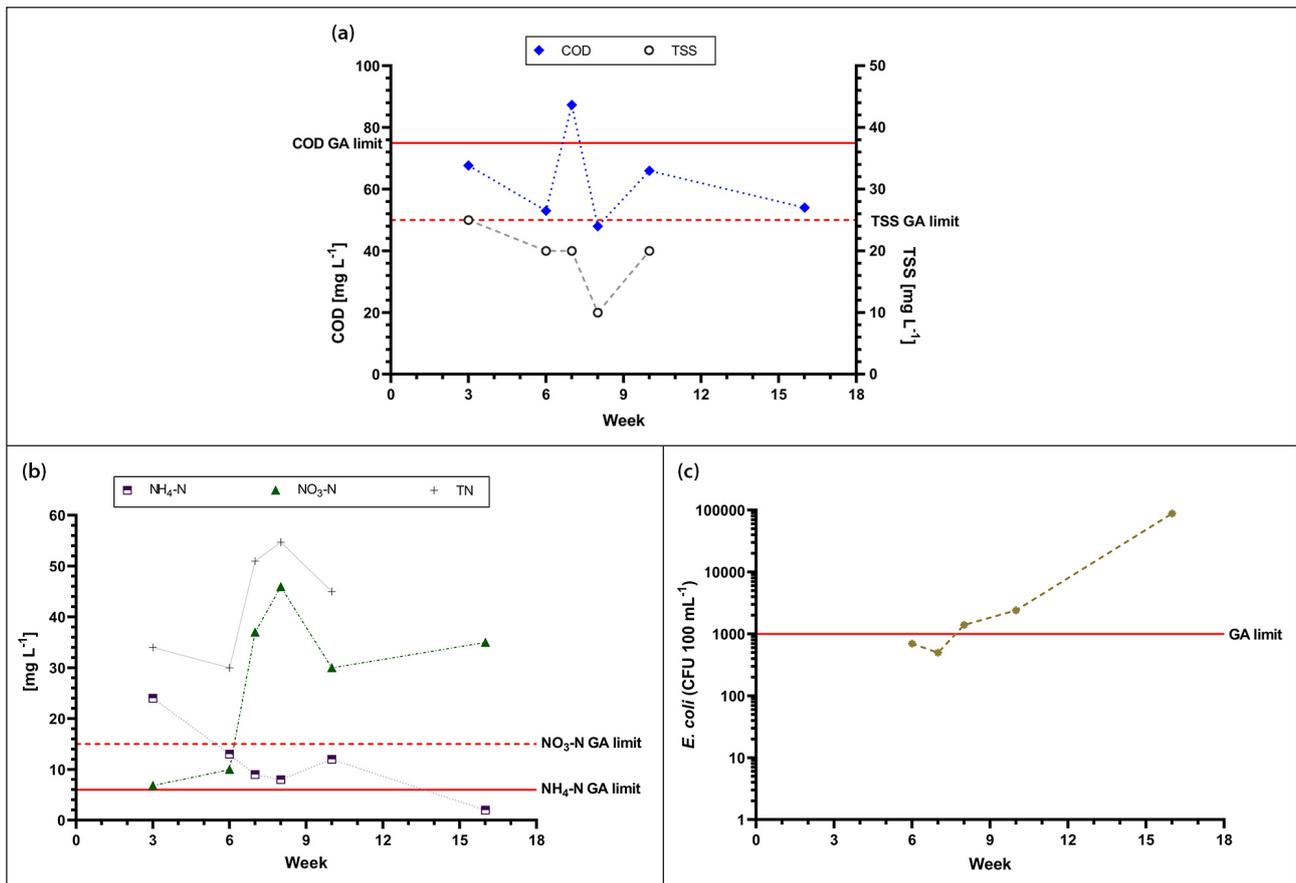
### Performance after the resumption of operation

#### Flow monitoring

After the removal of the blockage (when site access returned), flow to the DEWATS resumed in September 2020, after a period of 162 days. Flow through Train 1 ranged from 0–67.92 m<sup>3</sup>·d<sup>-1</sup> with an average flow of 14.4 m<sup>3</sup>·d<sup>-1</sup> from September to December 2020. As with continuous operating conditions, low flows were attributed to blockages upstream of the DEWATS while high flows correlated with high rainfall events. Overall, the CWs operated above the design HLR for 60% of the recovery period (Fig. A5, Appendix).

#### Recovery

After the resumption of flow to the DEWATS, CODt concentration was predominantly below the GA limit of 75 mg·L<sup>-1</sup> ranging from 44–87.3 mg·L<sup>-1</sup> (Fig. 3a). The time taken for the NH<sub>4</sub>-N concentration to reach below the GA limit of 6 mg·L<sup>-1</sup> was 16 weeks. The average NH<sub>4</sub>-N concentration was 11.3 (± 7.3) mg·L<sup>-1</sup> (Table 2).



**Figure 3.** Final effluent quality during recovery monitoring: (a) total chemical oxygen demand (CODt) and total suspended solids (TSS); (b) ammonium-N (NH<sub>4</sub>-N), nitrate-N (NO<sub>3</sub>-N) and total nitrogen (TN) concentration; and (c) *E. coli* colony counts in the final effluent (September–December 2020)

Figure 3b shows a steady decrease in NH<sub>4</sub>-N concentration from Weeks 1 to 9, fluctuating above the limit in Week 10, but below the GA limit by Week 16. This is due to the start-up of the VFCW, indicating a gradual increase in nitrification over time. Nitrifying bacteria are generally slow-growing bacteria with long generation times (Wang et al., 2012). Nitrate-N concentration ranged from 6.8–45.9 mg·L<sup>-1</sup>. As with continuous operation, a grab sample of the VFCW effluent indicated no bCOD. Therefore, it was assumed that denitrification was again limited by the lack of available exogenous carbon.

Figure 3c demonstrates colony counts of *E. coli* which ranged from 5 × 10<sup>2</sup> to 8.8 × 10<sup>4</sup> CFU·100 mL<sup>-1</sup>, the peak seen during the last sampling event (Week 16). All other samples were near the GA limit. It is possible that during the shutdown the bacterial cells were able to accumulate within the CWs and were washed out during the heavier rainfall events toward the latter part of the sampling period.

Based on the comparison of the final effluent quality during continuous operation and operation following the long-term shutdown (162 days), it can be assumed that the recovery time for the system to reach continuous operating conditions is of the order of 16 weeks.

### Overall assessment

Under continuous operation, the current design of the eThekweni decentralised wastewater treatment system (DEWATS) does not produce safe discharge quality effluent based on its NO<sub>3</sub>-N removal capacity (Tables 1 and 2). Denitrification rates are highly dependent on available carbon which provides the electrons

required to convert NO<sub>3</sub>-N to N<sub>2</sub> (Saeed and Sun, 2012; Robertson and Groffman, 2015). The lack of bCOD in the VFCW and HFCW effluents implies that complete bCOD oxidation occurred in the VFCW and there was no endogenous carbon in the HFCW. Moreover, it is suspected that the loosely packed, irregular-shaped, mixed gravel in the HFCW contributed to low residence times even after permanently impounding the outlet. Maintaining the saturated level of the wastewater at 0.15 m below the surface of the gravel media resulted in surface water accumulation during peak flows which may have resulted in passive aeration by diffusion of atmospheric oxygen. In this case, since denitrifying bacteria are facultative heterotrophs, oxygen, instead of nitrate, will be used as the preferred electron acceptor when DO concentration is high (Kadlec and Wallace, 2009) contributing to poor NO<sub>3</sub>-N removal overall (Saeed and Sun, 2012).

Moreover, the reuse of the final effluent will be more suitable for agriculture due to the lower nutrient concentrations and *E. coli* counts. In fact, with reference to the GA limits, the final effluent quality meets the South African regulatory requirements for reuse agriculture with volumes up to 500 m<sup>3</sup>·d<sup>-1</sup> (DWS, 2013).

Although the estimated recovery time is 16 weeks, it could be potentially shorter as sampling during this time was inhibited by further COVID-19 lockdown restrictions.

### RECOMMENDATIONS

To maintain the simple and practical design of DEWATS with its low operating and maintenance principles, it is recommended that the media of the hybrid CW system be amended to improve effluent quality. Two-stage VFCWs have been successfully

implemented in Austria for improved total nitrogen removal (Langergraber et al., 2008; Langergraber et al., 2009; Langergraber et al., 2014). In the first stage, a 0.5 m filter layer with 2–3.2 mm sand was used which was found to restrict full nitrification of the influent (approximately 80% nitrification was observed) and the complete mineralization of the organic matter (OM). Based on this observation, the filter media of the VFCW in the hybrid CW system can be amended to 2–3 mm to limit the full oxidation of the bCOD from the AF effluent. Moreover, the inclusion of an organic layer (such as dried plant matter or biochar) may provide available endogenous carbon for denitrification towards the bottom of the VFCW and exogenous carbon in the HFCW. Concerning the filter media of the HFCW, Sasse (1998) recommends round gravel of uniform size, preferably between 6–12 mm or 8–16 mm medium gravel, the latter supported by the design recommendations of Langergraber et al. (2019). Lastly, the outlet pipe should be permanently impounded to maintain the saturation level at 0.2 m below the surface of the gravel to prevent diffusion of oxygen into the HFCW and contribute to improved residence times for NO<sub>3</sub>-N and *E. coli* removal. However, despite these media amendments, the two-stage VFCW must also be investigated in the South African context.

### Other potential technology integrations to improve overall effluent quality

In addition to design modifications to the DEWATS, removing nitrogen at the source provides an opportunity to reduce the nutrient loading, particularly nitrogen, to the DEWATS. European household wastewater characterisation indicates that approximately 75% of the total N load in wastewater streams is derived from urine (Henze, 1997). If urine could be separated from the blackwater and solid fraction, then this will potentially reduce the nitrogen loading to the DEWATS and essentially improve the total nitrogen removal capacity of the CWs in whatever configuration is chosen (hybrid CW system or two-stage VFCW). For example, urine diversion flushing toilets can separate the urine from the faecal matter and flushing water while also allowing for nutrient recovery from the separated urine similar to the Valorisation of Urine Nutrients in Africa (VUNA) project, although the latter was in combination with dry sanitation (urine-diverting dry toilets), within the eThekweni Municipality (Udert et al., 2015).

### CONCLUSION

This study evaluated the performance and sustainability of a decentralised approach for community sanitation in South Africa using BORDA design principles. While a comparison of the final effluent quality from the demonstration-scale DEWATS in eThekweni indicates that continuous discharge is not possible, simple design modifications are recommended for the tertiary treatment modules (in this case, a hybrid CW system) to achieve fully compliant effluent for safe discharge. Moreover, the application of the two-stage vertical flow constructed wetland (VFCW) design for improved total nitrogen removal also needs to be explored in the South African context.

However, in line with the reduction of potable water for flushing and the potential of resource recovery from urine on larger scales, a combination of low-flush technologies such as urine diversion flushing toilets can be combined with DEWATS to fast-track sanitation delivery at the community level. The knock-on effect is the reduction in the nutrient loading to the DEWATS so that fully compliant effluent for safe discharge is possible. The combination of these two technological approaches will unblock the service delivery pipeline, attain user aspirations, reduce environmental pollution by recharging receiving waters with compliant effluent, as well as decrease water consumption for

flushing and irrigation (if agriculture is desired by the community served). This will contribute to better management of this scarce resource in a drought-prone country like South Africa. Lastly, to ensure the operational reliability and sustainability of the system, social assessments need to be conducted to determine migratory patterns of the community (such as when persons return to their rural homesteads in the case of urban dwellers) and other activities that impact the influent to and hence the operation of the DEWATS.

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### AUTHOR CONTRIBUTIONS

PA conceptualised the work, interpreted the data and wrote the first draft of the manuscript. All other authors reviewed and edited the manuscript before submission.

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## APPENDIX

During the commissioning phase of the DEWATS, Train 1 was noted to receive the bulk of the flow (50%) due to the outlet pipe of Train 1 of the ABR in the collection chamber being 0.05 m and 0.06 m lower than that of the outlet pipes of Trains 2 and 3, respectively (Fig. A2). An end cap drilled with a hole of 0.05 m was placed on the baffle pipe in the 6<sup>th</sup> chamber of the ABR to effectively act as a choke to reduce the flow through Train 1

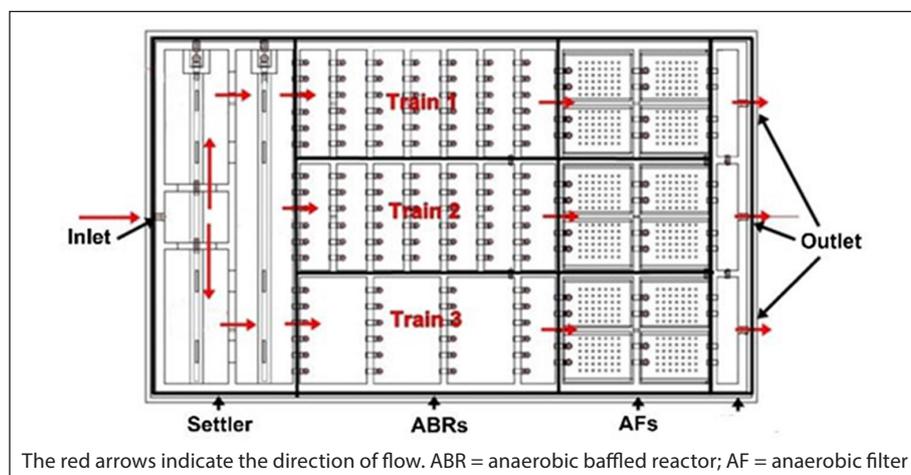
thereby regulating the flow across all three trains. However, Train 1 still received the majority of the daily cumulative flow, and in April 2018 a second end cap with a drilled hole of 0.02 m (dia.) was installed in the outlet pipe of Train 1 leading to the siphon chamber. Subsequent flow measurements through Train 1 indicated a reduction in flow by almost 40% to 15.5 m<sup>3</sup>·d<sup>-1</sup> compared to the pre-insertion of the second end cap.

**Table A1.** Density of scum removed from the settler and first ABR chamber of the DEWATS after 4 days of accumulation (February 2019)

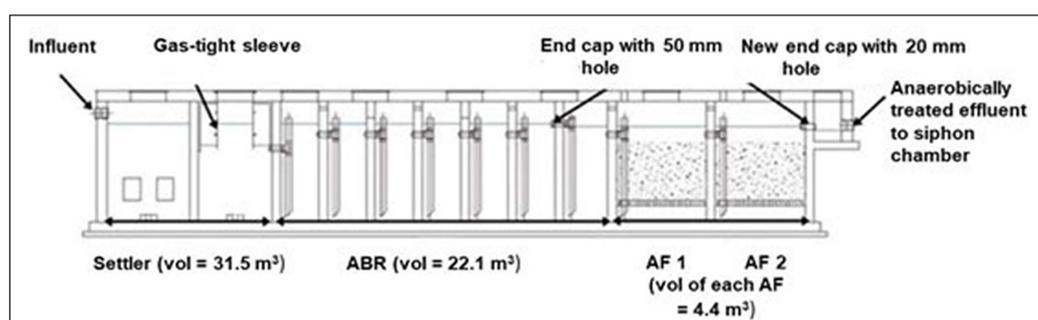
|                               | Train 1 | Train 2 | Train 3 |
|-------------------------------|---------|---------|---------|
| Density (kg·m <sup>-3</sup> ) | 1 616.8 | 1 305   | 1 453   |
| <i>n</i> = 1                  |         |         |         |

**Table A2.** Total biodegradable (soluble and particulate) COD (bCOD) concentration data from Train 1 of the DEWATS and cumulative % removal from the settler effluent across the treatment modules (January–May 2019).

|                      | bCOD (mg·L <sup>-1</sup> ) | % Removal from settler effluent |
|----------------------|----------------------------|---------------------------------|
| Settler              | 760                        | -                               |
| ABR 7                | 644                        | 15.3                            |
| AF 1                 | 307                        | 59.6                            |
| AF2 / siphon chamber | 274                        | 63.9                            |
| VFCW effluent        | Not detected               | 100                             |
| HFCW effluent        | Not detected               | -                               |



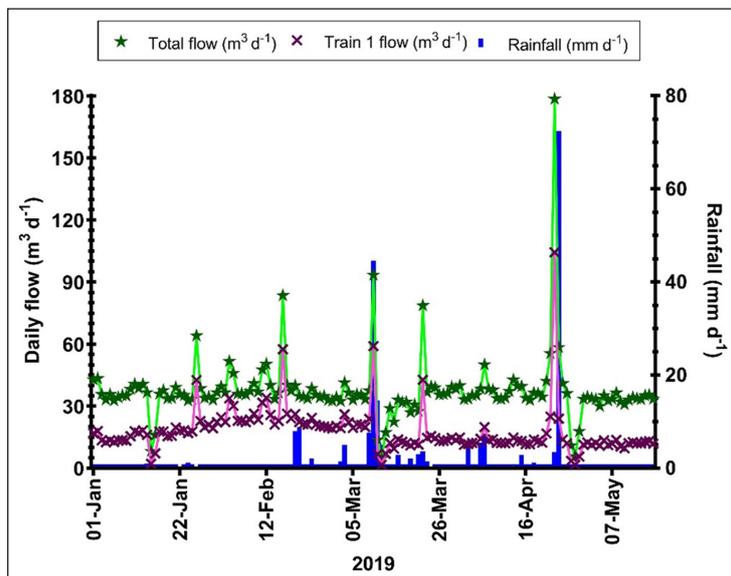
**Figure A1.** Illustrative plan view of the primary (settler) and secondary (ABR and AF) treatment modules of the DEWATS (inserted from Schoebitz, 2013)



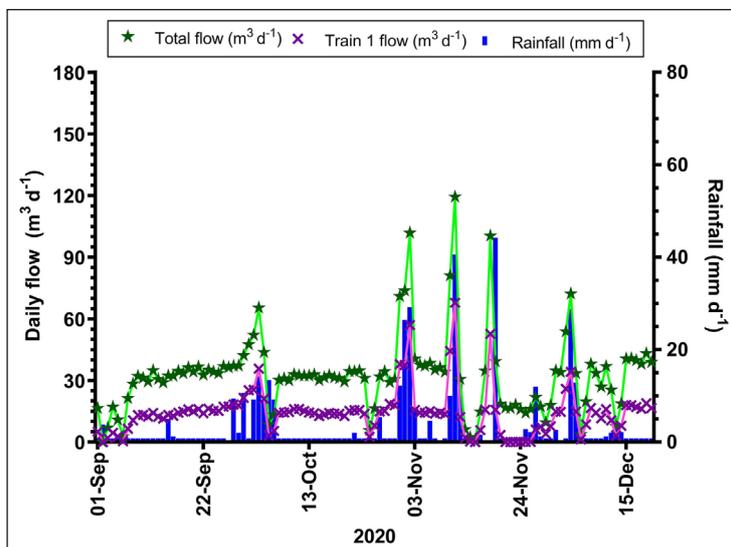
**Figure A2.** Cross section of Train 1 of the ABR (April 2018)



**Figure A3.** Annotated front view of the Whole Effluent Samper (WES) (courtesy of Tapuwa Mary Carolyn Sahondo)



**Figure A4.** Daily cumulative flow through the entire DEWATS in comparison to Train 1 and daily rainfall (January–May 2019)



**Figure A5.** Daily cumulative flow through the entire DEWATS in comparison to Train 1 and daily rainfall (September–December 2020)