NITROGEN AND PHOSPHORUS DYNAMICS IN PLANTS AND SOIL FERTIGATED WITH DECENTRALISED WASTEWATER TREATMENT EFFLUENT.

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Highlights

• Fertigation with treated wastewater can supplement N and P fertilisers in peri-urban agriculture.

• Fertigation with treated wastewater increases soil inorganic N and P which may be taken up by plants or leached.

• Irrigation scheduling reduces the risks of N and P leaching down the soil profile to groundwater resources.

• Sustainable fertigation using DEWATS effluent needs monitoring for pathogens and trace elements accumulation.

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Abstract

Municipalities in South Africa face problems in providing sanitation to unserved informal settlements in peri-urban areas and rural nodes. The Decentralised Wastewater Treatment System (DEWATS) connected to community ablution blocks can be an option, with the treated effluent then applied to agricultural land. However, the management of treated wastewater through irrigation of crops must be environmentally sustainable. This study therefore investigated nitrogen (N) and phosphorus (P) dynamics in soil irrigated with DEWATS effluent. A field study with banana and taro in a randomised complete block design with three blocks and two irrigation treatments (DEWATS effluent without fertiliser vs tap water + fertiliser) was carried out over a period of 992 days at the Newlands-Mashu Research Site, Durban, South Africa. Data were collected on crop N and P uptake, soil chemical properties, and nutrient leaching together with groundwater monitoring. Nitrogen and P uptake was not significantly different ($p > 0.05$) between the two irrigation treatments. Irrigation with DEWATS effluent increased soil N and P concentrations within the upper 0.3 m implying its importance as a fertiliser source. Leaching of N and P from DEWATS effluent treated plots was comparable to that from the tap water + fertiliser treatments. However, to manage excess water in the soil, practices such as irrigation to meet crop water requirements with room for rainfall and installation of subsurface drainage when possible can be employed.

Keywords: groundwater monitoring, nitrate leaching, orthophosphate, treated wastewater.

1. Introduction

Due to rapid urbanization, South African municipalities face challenges to provide water and sanitation to residents in informal settlements on city peripheries (Ashipala and Armitage, 2011). The Decentralised Wastewater Treatment System (DEWATS) connected to community ablution blocks can potentially provide onsite sanitation to these residents (Crous et al., 2013). The DEWATS is a water-borne modular system that comprises of a Settler Tank, an Anaerobic Baffled Reactor (ABR) and an Anaerobic Filter (AF), sometimes with a Vertical Flow Constructed Wetland and a Horizontal Flow Constructed Wetland (HFCW) that further purify the effluent (Sasse, 1998). The DEWATS is a robust system that transforms organic nitrogen (N) and phosphorus (P) into their inorganic forms, produces low quantities of sludge, operates without electricity requirements and has a long biomass retention time (Reynaud and Buckley, 2016). The produced effluent contains mineral nutrients such as nitrogen (N) and phosphorus (P), which, from studies reported by Foxon et al. (2005), do not meet the South African Department of Water and Sanitation (formerly Department of Water Affairs) standards for disposal into water bodies. The current standards (DWA, 2013) have less stringent restrictions on the amounts of N and P allowed for irrigating crops with wastewater. Water quality issues of consideration for irrigation using treated wastewater include specific ion toxicity, nitrate content, salinity, heavy metals and pathogens (Raschid-Sally and Jayakody, 2009; Scott et al., 2010; WHO, 2006; WWAP, 2017). Guidelines on managing these issues have been developed by the Food and Agriculture Organisation (FAO) and the World Health Organisation (Pescod, 1992; USEPA, 2012; WHO, 2006). Therefore, reuse of treated wastewater in agriculture is the most commonly recommended way for managing wastewater if done in an environmentally sustainable way (Levy et al., 2011; WWAP, 2017).

The use of treated wastewater in agriculture has been driven by different factors including water scarcity, food demand and increased pollution of surface water resources (WWAP, 2017). Some of the limitations

in using treated wastewater for irrigation are the effects of excessive nutrients on crop yield and soil nutrient imbalances which might be environmentally detrimental (Pedrero et al., 2010). Nutrients from treated wastewater added to the soil undergo different transformation processes driven by various biotic and abiotic factors including, but not limited to, soil properties such as texture, mineralogy, structure, pH, temperature, and water content (Levy et al., 2011; Ogbazghi et al., 2016; Sahrawat, 2008).

Several studies have been done on the potential of DEWATS effluent in agriculture (Bame et al., 2013; Bame et al., 2014; Musazura et al., 2015). Column studies on nutrient retention and leaching in three contrasting soils irrigated with ABR effluent were conducted by Bame et al. (2013). Pot trials were also conducted to investigate the potential of ABR effluent as a source of nutrients and its effects on soil chemical properties under maize (*Zea mays*) cropping (Bame et al., 2014). Musazura et al. (2015) investigated nutrient uptake and leaching in soil under ABR effluent irrigation using Swiss chard (*Beta vulgaris var* Circla.

However, to promote the use of DEWATS effluent in agriculture as part of urban sanitation management, factors such as land area requirements, crop types, effluent management and impact on the environment (Pescod, 1992) must be considered. This is particularly important considering that the effluent will be produced throughout the year. Questions that arise include (a) can agricultural systems with high water and nutrient (N and P) demanding crops such as banana and taro (intercropped) be used to utilise water and nutrients from effluent fertigation; and (b) if the crops can remove nutrients, what are the impacts on nutrient retention in the soil and deep percolation towards the groundwater?

By understanding N and P dynamics in a soil planted to banana and taro this investigation aimed to provide information that can be used to produce future practical guidelines for the use of DEWATS effluent for fertigation. The specific objectives were to investigate the effects of DEWATS effluent on (i)

N and P uptake by the two crops, (ii) soil chemical properties, (iii) N and P dynamics in the soil and (iv) the potential for groundwater pollution, following irrigation with DEWATS effluent at a field scale.

2. Materials and Methods

2.1. Experimental site

The study was done at Newlands-Mashu research site, Durban, KwaZulu-Natal (KZN), South Africa (30°57'E, 29°58'S) (Figure 1). Durban experiences a sub-tropical climate with an annual rainfall of approximately 800 - 1 000 mm and temperature range of 16 - 33°C (Schulze, 1997). The soil at the experimental site is a clay loam classified as a Sepane (Se) form, Katdoorn family (Se 1210) (Soil Classification Working Group, 1991); an Aquic Haplustalf (Soil Survey Staff, 2014). The soil is underlain by an unconsolidated material with signs of wetness, which is not permanent wetness as that would be a G horizon. The pedocutanic B shows signs of gleying as does the A horizon. The soil has very low hydraulic conductivity (K_{sat}) values (< 4.68 mm $hour^{-1}$), especially in layers between 0.3 and 1 m depths some negligible K_{sat} values have been reported (Musazura et al., 2015). The site is also characterised by an elevation of between 39.13 and 43.51 m above sea level, gently sloping slope of 3.29 % and a groundwater gradient of 0.035 m m^{-1}.

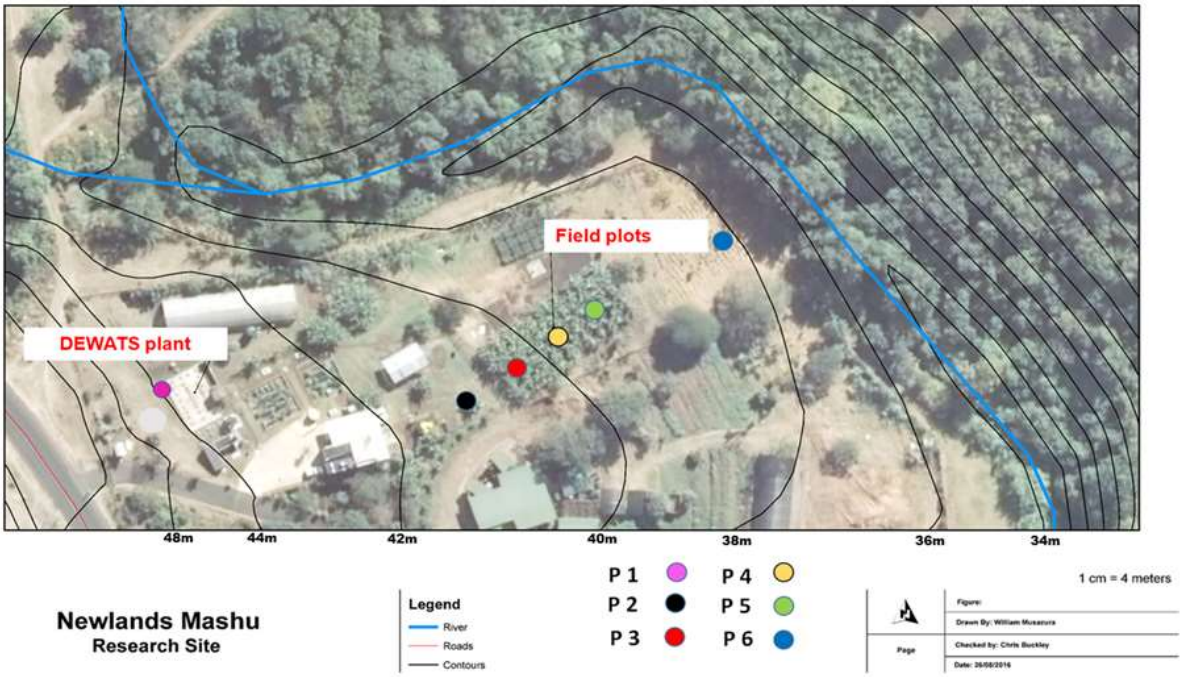

Figure 1: The Newlands-Mashu experimental site map showing contours, positions of the piezometers (P1, P2 and P6 outside, and P3, P4 and P5 inside the field plots) used in the study and the location of a river nearby.

2.2. Experimental design and trial management

A field experiment was laid out in a randomised complete block design with three blocks (replicates) and two irrigation treatments i.e. DEWATS effluent with no fertiliser applied vs tap water plus fertiliser application as recommended by the Soil Fertility Section, Cedara, Department of Agriculture and Rural Development, KZN. The fertilisers were applied at a rate of 250 kg N ha^{-1} $annum^{-1}$ as urea (46 % N) and 269 kg K ha^{-1} $annum^{-1}$ as KCl (52 % K). Urea was applied in eight split applications per each year while KCl was applied in three split applications. The soil P test was greater than the target soil test, and so no P fertiliser was applied. The test crops used in the study were banana (*Musa paradisiaca*) with taro (*Colacasia esculentum*) grown as an intercrop. The experiment was conducted over two growing seasons, which totalled 992 days for both crops. The crops were planted on 13 November 2013 and during the first 201 days, effluent could not be used for irrigation due to technical

problems and so all treatments during that period were watered with tap water. Two types of DEWATS effluent were used during the study i.e. HFCW effluent (DEWATS effluent after the second of the constructed wetlands at the study site) was used from 201 to 504 days after planting (first harvest). During the second cropping cycle irrigation was switched to AF effluent (DEWATS effluent after the AF but before the wetlands). Irrigation with AF effluent was done from 504 to 992 days. An ESP-Me ® drip irrigation controller was used for irrigation scheduling. The effluent was pumped from the DEWATS to a 10 L capacity JoJo ™ tank where it passed through a Rainbird ™ irrigation system comprised of automatic self-cleaning screen filters which prevented clogging of drippers and pipes. The effluent was further pumped to the field. Netafim ™ drippers were calibrated to deliver 2 L of effluent per cycle. A fixed amount of 5.5 mm irrigation depth was applied over four cycles day^{-1}. Fullstop ™ wetting front detectors (WFDs) installed at two soil depths (0.3 and 0.5 m) monitored irrigation percolation. Weather information (rainfall, relative humidity, wind speed and reference evapotranspiration) was collected by a CR1000 datalogger (Campbell Scientific Inc., Utah, USA) located 10 m from the field. The Penman-Monteith grass reference evapotranspiration (Et_o) was automatically calculated by the algorithms of the datalogger using the weather information collected, following FAO methods (Allen (1998). The crop evapotranspiration (Et_{crop}) was determined as a product of crop factors (K_c) and reference evapotranspiration (Et_o). All the soil and plant samples were collected within central 42 m^2 quadrants of each of the 90 m^2 plots. Sampling was done on six banana and eight taro plants within each quadrant.

2.3. Effluent characterisation

About 50 mL aliquots of treated effluent used during the study were collected from the HFCW and the AF. The effluent was taken to the site laboratory and immediately analysed for NH_4^+- N, NO_3^-- N and PO_4^{3-}-P using a NOVA 60 Merck Spectroquant ® (Merck Millipore, Germany) following standard methods for water and wastewater analysis (APHA, 2005).

2.4. Soil properties

Soil samples were collected before planting and after each harvest (504 and 992 days after planting) to monitor changes in soil chemical properties over time. Sampling was done using a Dutch auger (50 mm diameter) at two different soil depths (0.3 and 0.6 m). Soil samples were collected randomly from five different places (within a 0.4 m radius from the plant stem) in the inner 42 m^2 quadrant of each plot. The five subsamples were bulked to make a composite sample for each plot. Soil particle size analysis was done following the hydrometer method described by Rowell (2014). Soil P was extracted using Ambic-2 solution (0.25M NH_4CO_3 + 0.01M Na_2EDTA + 0.01M NH_4F + 0.05 g L^{-1} Superfloc (N100), adjusted to pH 8 with a concentrated ammonia solution). Phosphorus was determined colorimetrically using a modification of the Murphy and Riley (1962) molybdenum blue procedure (Hunter, 1974). Soil inorganic N (NH_4^+- N and NO_3^-- N) were extracted from freshly collected soils using 2M KCl followed by filtering using Whatman ® No. 2 paper according to Mynard and Kalra (2008). The filtrates were then analysed using a Merck Nova 60 Spectroquant ® (Merck Millipore, Germany) according to standard methods (APHA, 2005). Except for inorganic N, all soil analyses reported in Table 1 and during the study were conducted at the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara, KwaZulu-Natal) according to standard methods (The Non-Affiliated Soil Analysis Work Committee and Soil Science Society of South Africa (1990).

Table 1: Initial soil chemical properties and particle size distribution of the Sepane soil at Newlands-Mashu.

Soil parameter	Depth (m)	
	0-0.3	0.3-0.6
Clay (%)	35	43
Silt (%)	42	31
Sand (%)	23	26
Textural class	Clay loam	Clay
Organic C (%)	2.9	2.6
Total N (%)	0.29	0.27
Inorganic N (mg kg^{-1})	24.2	23
Extractable P (mg kg^{-1})	39.3	11.9
Exchangeable K ($cmol_c$ kg^{-1})	0.30	0.18
Exchangeable Ca ($cmol_c$ kg^{-1})	12.2	8.1
Exchangeable Mg ($cmol_c$ kg^{-1})	7.8	7.4
Exchangeable acidity ($cmol_c$ kg^{-1})	0.05	0.07
Total cations ($cmol_c$ kg^{-1})	20.4	15.7
Acid saturation (%)	0	0
pH (KCl)	5.2	5.1
Extractable Zn (mg kg^{-1})	22.8	6.9
Extractable Mn (mg kg^{-1})	3.7	11.1
Extractable Cu (mg kg^{-1})	9.5	5.8

2.5. Nitrogen and phosphorus leaching

Nutrient leaching during the study period was monitored using the WFDs. Leachates were collected from the WFDs from 295 days after planting after heavy rainfall events and when the WFDs were full as signalled by their visual indicator. Samples from the WFDs were collected by extracting water through a 2 mm diameter pipe connected to the below-ground water collector using a 60 mL syringe. Leachates were analysed for inorganic N and P (PO_4^{3-}-P) using a NOVA 60 Merck Spectroquant ® (Merck Millipore, German) following standard methods (APHA, 2005).

2.6. Groundwater monitoring

Six piezometers (1 m deep) were installed in different locations (Figure 1). Installation of piezometers was done according to methods described by Rasiah et al. (2005). Polyvinyl chloride pipes (50 mm diameter and 1.2 m long) were perforated and the bottom of the pipe covered with 250 µm polyester cloth to filter the water entering**.** They were then inserted into holes bored with a bucket auger (50 mm diameter). The

water levels were monitored during heavy rainfall periods using a homemade electric sounding device (water level meter). The device responded to water by emitting light and sound. The depth from the ground surface to the end of the device sensor was measured using a measuring tape and recorded as water level below the ground surface. Water samples collected from the piezometers at random intervals during the experimental period were analysed for inorganic N and P as described for the WFD samples (APHA, 2005).

2.7. Crop nutrient uptake

Banana plant tissue analysis was done after each harvest (504 and 992 days after planting). Banana leaf tissues were collected from the third upper fully developed leaves on the centre of the lamina blade at flowering stage. Taro tissue samples were collected from the corms after the first crop harvest. Taro tissue samples were not collected during the second season since they failed to establish well. The collected samples were bulked to form a composite sample for each plot and oven dried at 70ºC for 72 hours. All the plant tissue samples were analysed following standard methods for plant analysis (Riekert and Bainbridge, 1998). Dried samples were ground and sieved using a 1 mm mesh and analysed for N and P. Ground plant samples were acid digested using HCl and P analysis was done using inductively coupled plasma optical emission spectroscopy (ICP-OES) Vista MPX (SpectroFlame Modula; Spectro, Kleve, Germany). Plant tissue N was determined by the Automated Dumas dry combustion method using a LECO CNS 2000 (Leco Corporation, Michigan, USA).

Total fresh mass of banana plants was determined by measuring the whole above-ground mass soon after harvesting. Banana plants were then subsampled from different plant parts (leaf and stem) and used to determine gravimetric water content after drying at 70ºC for 72 hours (Kalra, 1997). The dry mass was calculated as a product of dry matter proportion and total fresh mass. Nutrient uptake was then calculated

as a product of total dry mass and plant tissue nutrient concentration (Equation 1). Taro dry mass was determined by harvesting the whole plant and drying at 70^{o}C for 72 hours.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \text{Total dry mass (kg ha}^{-1}\text{)} * \text{Plant tissue nutrient concentration (kg kg}^{-1}\text{)} \quad (1)$$

2.8. Data analysis

All the data collected were analysed using GenStat 18th Edition (VSN International, 2015). Analysis of variance (ANOVA) was conducted to show differences between the main factors and their interactions (where applicable) at the 5 % significance level. Where a significant difference was observed ($p < 0.05$), means were separated using standard error of mean differences. Significantly different data are presented through boxplots and bar graphs showing standard error of mean differences.

3. Results

3.1. Rainfall and crop water requirements

The rainfall and crop water requirements (evapotranspiration) information at Newlands-Mashu over the 992 days experimental period is presented in Figure 2. Evapotranspiration was higher than rainfall throughout the whole experimental period, except for July 2015 and 2016 when it was very low. Very high rainfall was reported in May and July 2016 compared to other months.

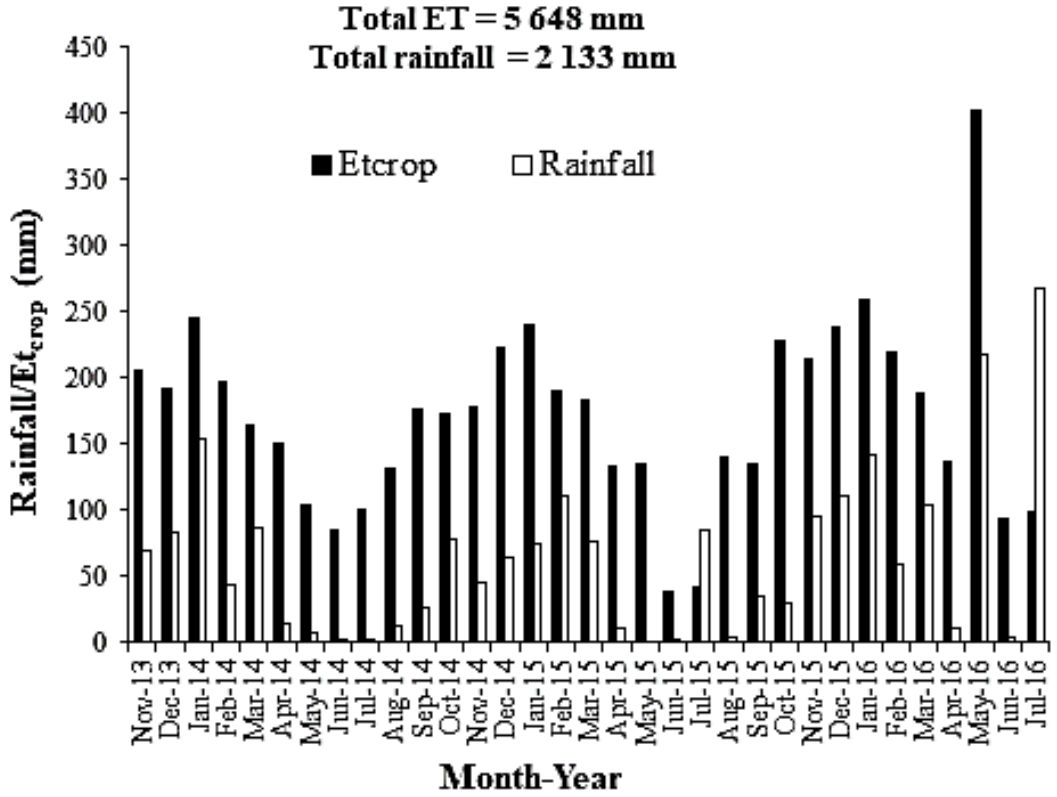

Figure 2: The rainfall and crop water requirements (Etcrop) data for Newlands-Mashu over the 33 months (992 days) period of the study.

3.2. Effluent characterisation

The AF effluent was much higher in NH_4^+-N and P compared to the HFCW effluent but lower in NO_3^--N (Table 2). In common with other domestic wastewaters, the effluents used contain very low quantities of heavy metals (Bame et al., 2013; Bame et al., 2014; Musazura et al., 2015) and thus these were not considered further within the scope of this investigation.

Table 2: Nitrogen (N) and phosphorus (P) concentrations, chemical oxygen demand (COD), pH, electrical conductivity (EC), sodium adsorption ratio (SAR) and microbial counts (mean ± standard error of mean differences) for the anaerobic filter and horizontal flow constructed wetland (HFCW) effluents used during the study.

Effluent source		NO_3^--N (mg L^{-1})	NH_4^+-N (mg L^{-1})	PO_4^{3-} (mg L^{-1})	Tot. N (mg L^{-1})	COD (mg O_2 L^{-1})	pH	EC (mS m^{-1})	SAR	*E. coli* (cfu**)	*Salmonella* (cfu)
Anaerobic filter	Mean ± Se*	2.1 ± 0.5	54.8 ± 1.6	10.5 ± 1.5	60.6 ± 2.7	524.5 ± 391.1	7.65 ± 0.06	1.2 ± 0.1	3.1 ± 0.01	40 000 ± 257	33 000 ± 845
	Median	1.8	55.6	8.7	59.8	133.6	7.68	1.2	3.1		
	Range	0.2 - 4.1	48.1 - 60.1	5.9 - 19.5	51.2 - 68.4	81.2 - 2470	7.33 - 7.98	0.9 -1.4	3.06 - 3.1		
	n	10	10	10	10	19	19	19	3		
HFCW	Mean ± Se	12.7 ± 6.4	6.7 ± 7.	4.1 ± 0.5	19.4 ± 7	67.9 ± 7.5	6.73 ±0.09	74.1 ± 2.8	3.4 ± 0.03	1 300 ± 532	1 650 ± 650
	Median	10.2	7.2	3.9	18.1	66	6.57	70	3.4		
	Range	3.1 - 24.9	5 - 7.9	5.9 - 19.5	8.1 - 32.1	31 - 159	6.24 - 7.71	54 - 99	3.3 - 3.4		
	n	3	3	3	3	19	19	19	19		

* Standard error of mean differences

**cfu is the coliform units per 100 mL

3.3. Soil chemical properties

Mean squares for soil chemical properties at two different depths (0.3 and 0.6 m) over three sampling periods showed significant differences at different soil depths for organic C ($p < 0.01$) and extractable P ($p < 0.001$). Soil pH significantly differed between irrigation treatments ($p < 0.01$). There was a significant difference in total N ($p < 0.01$) and NO_3^--N ($p < 0.001$) over the three sampling periods. Significant interactions between soil depth and time were observed with regards to total inorganic N ($p < 0.05$) and NH_4^+-N ($p < 0.01$). All other comparisons were non-significant.

The concentrations of extractable P and organic C at different depths (combined for all irrigation treatments and different sampling times) are given in Table 3. Higher concentrations of extractable P and organic C were observed in the 0.3 m depth compared to 0.6 m depth.

Table 3: Concentrations (n = 18; mean ± standard error of mean differences combined for all irrigation treatments and different sampling times) of organic carbon (C) and extractable phosphorus (P) at two different soil depths.

Soil depth (m)	Organic C (%)	Extractable P (mg kg^{-1})
0.3	3.0 ± 0.1^{a}	54.4 ± 6^{a}
0.6	2.6 ± 0.1^{b}	7.7 ± 2^{b}

Superscripts a, b in the same column represents means that are significantly different at 5 % level.

The soil pH values for the two irrigation treatments (combined for all soil depths and sampling intervals) are shown in Figure 3. The soil pH was higher in the DEWATS treatments than in tap water + fertiliser treatments.

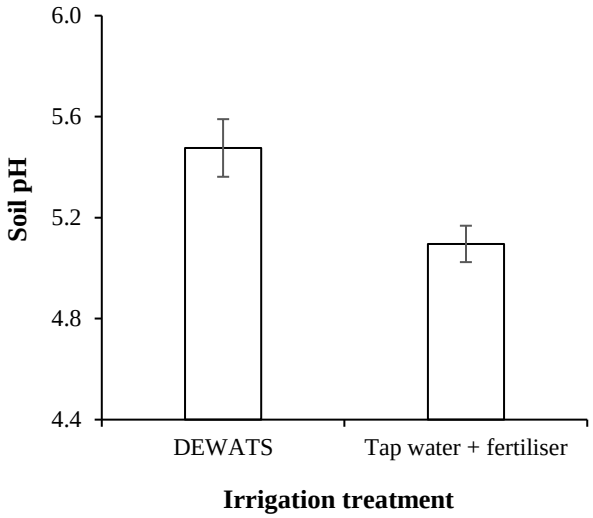

Figure 3: Soil pH (KCl) under the two irrigation treatments (n = 18; mean ± standard error of mean differences combined for all soil depths and sampling intervals).

Concentrations of total N and NO_3^--N over three sampling times (combined for all irrigation treatments and soil depths) are reported in Table 4. High concentrations of total N were found 504 days after planting and the values were not significantly different before planting and at 992 days after planting. The concentrations of NO_3^--N significantly decreased from planting to 504 days after planting. Later NO_3^-N significantly increased and attained a very high value at 992 days after planting.

Table 4: Soil concentrations (n = 12; mean ± standard error of mean differences, combined for all irrigation treatments and two soil depths) of total nitrogen (inorganic + organic N) and NO_3^--N over three sampling periods.

Time	**Total-N (mg kg^{-1})**	**NO_3^- -N (mg kg^{-1})**
Before planting	2750 ± 337 **b**	9.0 ± 0.5 **b**
504 Days after planting	3192 ± 300 **a**	4.1 ± 0.8 **c**
992 Days after planting	2792 ± 466 **b**	21.3 ± 4.0 **a**

Superscripts a, b and c in the same column represents means that are significantly different at 5 % level.

Figure 4 describes the soil total inorganic N and NH_4^+-N contents between the two soil depths over different sampling periods. The soil NH_4^+-N content increased with time. The highest increase was attained in the 0.3 m soil depth at 992 days after planting.

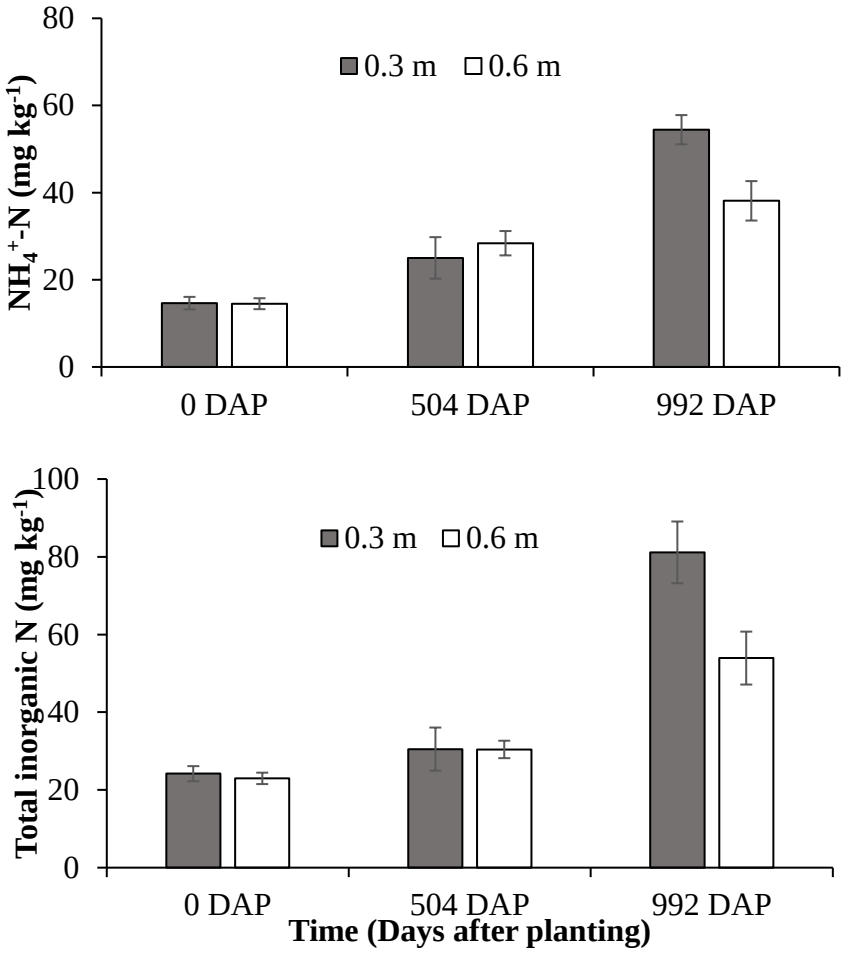

Figure 4: Concentrations of soil total inorganic N (NH_4^+-N + NO_3^- -N) and NH_4^+-N (n = 12; mean ± standard error of mean differences) at the two soil depths at 0, 504 and 992 days after planting (DAP).

3.4. Nitrogen and phosphorus leaching

There was a significant interaction between irrigation treatment, depth and time ($p < 0.05$) on the concentrations of N leached. From 295 to 331 days after planting there were generally high N concentrations in leachates from all treatments and depths (Figure 5). As the growing period progressed, concentrations stabilised in all treatments until 853 days after planting. The N concentrations in the DEWATS treatment at 0.3 m began to rise at 899 days after planting reaching a significantly high value of 244 mg L^{-1} at 992 days after planting (Figure 5).

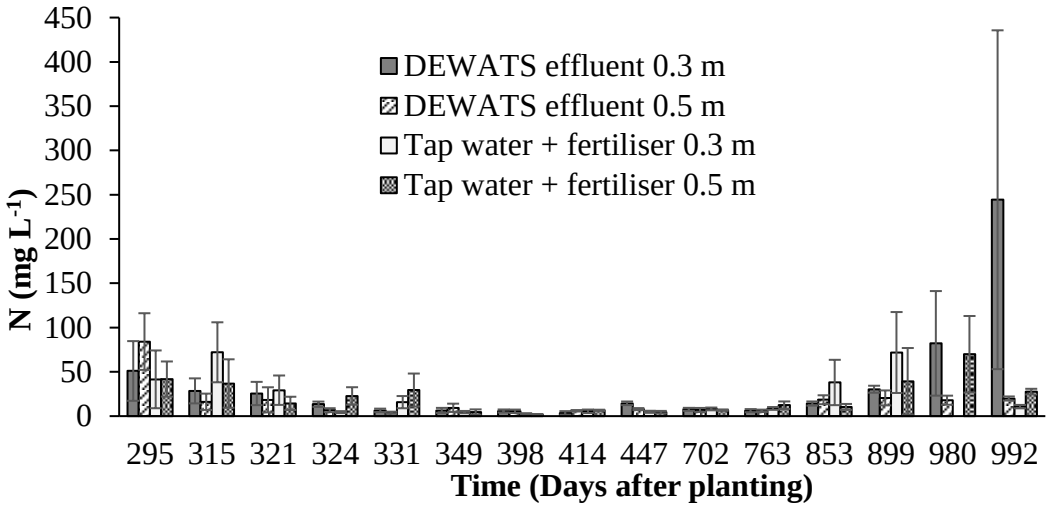

Figure 5: Concentration (n = 3; mean ± standard error of mean differences) of inorganic nitrogen (N) in leachates collected from the wetting front detectors in the two irrigation treatments at two depths from 295 to 992 days after planting

Significant differences ($p < 0.001$) over time were found with respect to P leaching. The average concentrations of inorganic P in soil leachates monitored between 295 and 992 days after planting are shown in Figure 6. Phosphorus increased from 0.1 mg L^{-1} (295 days after planting) to reach a maximum

concentration of 9.97 mg L^{-1} (702 days after planting), which later declined to a concentration of < 2.5 mg L^{-1}.

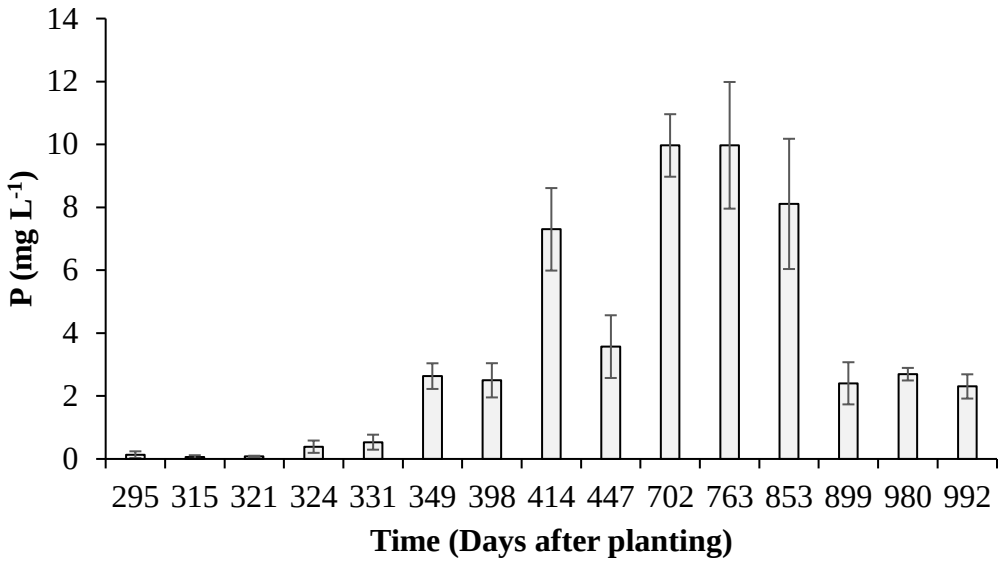

Figure 6: Concentration of inorganic phosphorus (P), in leachates collected from the wetting front detectors between 295 and 992 days after planting. Means combined for all soil depths and irrigation treatments (n = 12; mean ± standard error).

3.5. Groundwater monitoring

The average water levels were generally lower in piezometers P1 and P2 (0.7 m and 0.59 m below ground level, respectively) compared to the field plots piezometers (P3, 0.35 m; P4, 0.37 m; P5, 0.36 m) (Table 5). The water levels monitored between December 2015 and August 2016 varied in the different piezometers i.e. P1 (0.4 – 0.81 m below ground level), P2 (0.44 - 0.70 m below ground level), P3 (0.1 – 0.49 m below ground level), P4 (0.12 – 0.53 m below ground level) and P5 (0.13 – 0.46 m below ground level). No water was detected in the piezometer (P6) outside and below the field plots throughout the period studied.

Table 5
The depth of water levels below ground surface (Mean ± standard error of mean, median, minimum, maximum, range, 25% and 75% quartiles) in piezometers installed down to 1 m at different locations in the experimental site. P1 and P2 upslope from the field plots, P3, P4 and P5 within the field plots and P6 after the field.

Piezometer	Elevation (m.a.s.l)	n	Number of observations	Mean ± standard error of mean	Median	Minimum	Maximum	Range	25 % quartile	75 % quartile
				m						
P1	43.59	4	4	0.70 ± 0.10^{a}	0.80	0.40	0.81	0.41	0.60	0.81
P2	41.13	4	4	0.59 ± 0.07^{ab}	0.60	0.44	0.70	0.26	0.47	0.70
P3	40.44	4	4	0.35 ± 0.17^{b}	0.40	0.10	0.49	0.39	0.25	0.45
P4	39.93	4	4	0.37 ± 0.09^{b}	0.42	0.12	0.53	0.41	0.27	0.48
P5	39.45	4	4	0.36 ± 0.08^{b}	0.43	0.13	0.46	0.33	0.28	0.45
P6	39.13	4	0	–	–	–	–	–	–	–

The superscripts a and b denote means which are significantly different within each column of the table.
m.a.s.l refers to meters above sea level.

The means for N concentrations from the different treatments are shown in Figure 7. The NO_3^--N concentrations in samples from the WFDs were very high in the DEWATS treatment at 0.3 m (36.3 mg L^{-1}) compared to the DEWATS treatment at 0.5 m (13.3 mg L^{-1}) and tap water + fertiliser at 0.5 m (12.2 mg L^{-1}). The water table had the lowest concentration of NO_3^--N (3.4 mg L^{-1}).

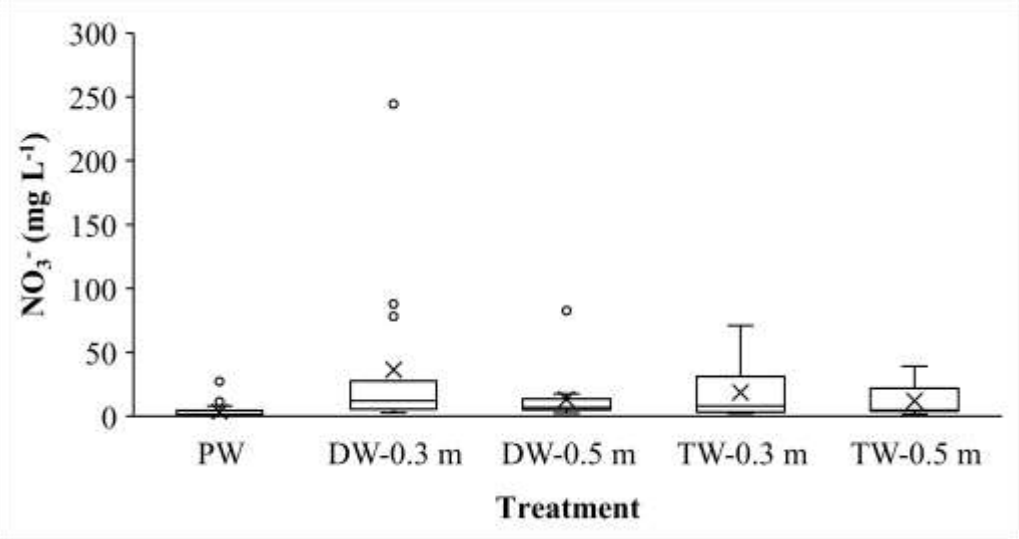

Figure 7: Interquartile ranges with outliers (o) and means (x) for NO_3^- concentrations (combined for all the sampling periods) of the perched water table (PW) and from wetting front detectors in two irrigation treatments (DW: DEWATS effluent: TW: tap water + fertiliser treatment) at two soil depths (0.3 and 0.5 m).

3.6. Crop nutrient uptake

The mean values for N and P taken up by banana were: N (DEWATS, 553 kg ha^{-1}; tap water + fertiliser, 533 kg ha^{-1}) and P (DEWATS, 35 kg ha^{-1}; tap water + fertiliser, 34 kg ha^{-1}). In the taro crop 250 kg N ha^{-1} were taken up in the DEWATS treatment and 173 kg N ha^{-1} in the tap water + fertiliser treatment. Taro P uptake was 55 kg ha^{-1} (DEWATS treatment) and 46 kg ha^{-1} (tap water + fertiliser treatment). There were no significant differences ($p > 0.05$) in N and P uptake and dry biomass between the irrigation treatments for both banana and taro (results not shown).

4. Discussion

4.1. Soil chemical properties

A significantly higher soil pH in soil fertigated with DEWATS effluent (Figure 3) could have been due to basic cations supplied by the effluent, as reported by several authors (Bame et al., 2014; Mulidzi et al., 2016; Singh et al., 2012). However, the soil pH did not significantly differ ($p > 0.05$) over time (results not shown). This could have been due to the short experimental period as slight changes have been reported over long-term studies (Al Omron et al., 2012; Rattan et al., 2005; Xu et al., 2010).

Organic carbon decreased with soil depth regardless of irrigation treatments (Table 3) and this is expected in all soils (Fink et al., 2016; Souza et al., 2014). Non-significant differences in organic C between irrigation treatments shows that the effluent did not add much dissolved organic matter due to DEWATS treatment which removes dissolved organic matter (Reynaud and Buckley, 2016).

Soil extractable P decreased with soil depth (Table 3) due to precipitation and adsorption processes within the upper soil layers. These processes are driven by different factors including soil pH (Barrow, 2016),

mineralogy and management practices (Fink et al., 2016). The soil at Newlands-Mashu has a clay loam topsoil (Musazura et al., 2015) which has a high P sorption capacity. Due to P retention in the top 0.3 m of the soil, its movement to deeper soil layers was low as reported by Bame et al. (2013).

The NO_3^--N concentrations increased significantly in the 0.3 m depth (Table 4). This could be attributed to the low hydraulic conductivity of the soil (Musazura et al., 2015) allowing nutrients to accumulate in the upper layers. A decrease in NO_3^--N concentrations from planting to 554 days after planting (Table 4) showed that the HFCW effluent did not provide excess N. The large increase from 504 to 992 days after planting was attributed to fertigation using AF effluent. Furthermore, AF effluent could have supplied more dissolved organic matter which stimulated microbial activity and thus increased the nitrification process. The ability of treated wastewater to increase soil NO_3^--N is well documented (Bame et al., 2013; Darwesh, 2015; Sahrawat, 2008).

Soil total N (organic + inorganic N) content significantly increased 504 days after planting compared to before planting (initial) and 992 days after planting (Table 4). Considering the experimental time frame such changes were not expected over such a short period (Brady and Weil, 2016) and the causes remain to be investigated.

Increased soil NH_4^+-N and total inorganic N over time in all irrigation treatments were found (Figure 4). The concentrations were significantly higher in the DEWATS treatment (0.3 m) after the second season (992 days after planting). Application of urea (tap water + fertiliser) and increased irrigation with AF effluent which contained high NH_4^+-N content (DEWATS treatment; Table 2) were the main causes. The Sepane soil at Newlands-Mashu has a high cation exchange capacity and hence retains positively charged

cations such as NH_4^+ (Bame et al., 2013) allowing its accumulation in the upper layer (0.3 m) of the soil profile.

4.2. Nitrogen and phosphorus leaching

Irrigation using DEWATS effluent commenced from 201 days after planting and leachates were collected from 295 days after planting. High N concentrations in all treatments were observed (Figure 4) during the period between 295 and 331 days after planting. This is attributed to mineralisation and nitrification after soil disturbance around the WFDs and low uptake by plants as described by Fessehazion et al. (2011). As the growing period progressed, concentrations stabilised in all treatments until 853 days after planting when they began to increase, especially in DEWATS effluent plots (0.3 m depth). Heavy rainfall events in July and August 2016 coupled with the applied irrigation did not increase N concentrations in leachates collected at lower soil depths (0.5 m depth) indicating restricted deep percolation. These findings are consistent with results for residual NO_3^--N (Figure 4). A high soil N concentration that exceeds crop requirements is a potential environmental pollutant and can be leached to lower depths depending on irrigation and rainfall (Brady and Weil, 2016; Pescod, 1992; USEPA, 2012). It is therefore important to consider on-farm practices such as use of high efficiency irrigation systems. Drip irrigation efficiently supplies water to meet crop water requirements without loading excess nutrients, if a correct scheduling is done.

Variations in leachate P concentrations over time (Figure 6) were probably driven by P desorption from the soil colloids. Souza et al. (2014) associated P desorption rates with concentrations of organic acids, especially citrate, which compete with P for sorption sites on the soil colloids. The formation of organic acids is driven by several factors including temperatures which vary seasonally (Brady and Weil, 2016),

however, this is not the case with the Durban climate. Therefore, soil P dynamics were driven by precipitation and adsorption processes while its increase in soil solution were due to dissolution and desorption leading to subsequent uptake by crops.

4.3. Groundwater monitoring

Water levels (Table 5) ranged between 0.1 and 0.8 m below ground being deeper in piezometers P1 and P2, upslope from the experimental site, than those within the field (P3 – P5). This was attributed to the continuous irrigation within the field, the high clay content of the subsoil and the presence of 2:1 expanding clays (Bame et al., 2013) resulting in accumulation of water. The soil at the site has low saturated hydraulic conductivity (K_{sat}), especially in layers between 0.3 – 1 m some negligible K_{sat} values have been reported (Musazura et al., 2015) and, this coupled with the continuous irrigation which prevented shrinking of the 2:1 clay implies that pollutant movement towards the groundwater was less likely to occur. The restricted deep percolation of water provides adequate time for losses through evapotranspiration and increased uptake of N and P by the crops, as well as other losses through denitrification.

The average NO_3^--N concentration (3 mg L^{-1}) found in the piezometers (Figure 7) was below the WHO (2017) minimum standard for drinking water of 10 mg L^{-1}. However, this may be affected in other instances by the area of the irrigated land and the volume of irrigation applied. The leaching of NO_3^- is aggravated by high rainfall. It is therefore of utmost importance to consider irrigation management practices such as leaving room for rain, as well as installation of subsurface drainage systems to harvest the drained water and nutrients for recycling by irrigation (Pescod, 1992).

High concentrations of pathogens (coliforms) in the effluent (Table 2) are of environmental concern. Their attenuation in the soil depends on residence time in the soil, adsorption and deactivation rate which are

affected by transport processes as well as their concentration in the effluent. Therefore, the potential for surface water and groundwater contamination is influenced by factors that affect soil water infiltration and erosion i.e. soil texture, structure, and erodibility, topography (slope, surface roughness), rainfall (amount and intensity), vegetation cover, and management practices (tillage, residue management). The impact on surface water bodies will be greater in areas prone to erosion due to high soil erodibility, poor vegetation cover, steep slope and poor agricultural management practices when exposed to high rainfall intensity. The effect of these factors will be compounded if the surface water bodies are close to the site of irrigation. On the other hand, areas dominated by sandy soils and receiving high rainfall are prone to groundwater contamination from wastewater irrigation with high pathogen concentrations. The effluent after the HFCW had a significantly reduced microbial load (Table 2) to close to, but still above, the WHO (2006) irrigation water quality guideline for unrestricted use (1000 cfu 100 ml^{-1}) (Category A). Storage of effluent can further influence significant pathogen reduction (WHO, 2006). Therefore, it would currently be categorized as Category B, where the usage of such water should employ special management practices such as crop selection (not for use for vegetables consumed raw), wastewater application measures (such as drip irrigation systems), and human exposure control (wearing protective clothing).

Although the presence of heavy metals in DEWATS effluents has been shown to be negligible (Bame et al., 2013) and thus were not considered in this study they may pose health risks when wastewater in general is used for irrigation on agricultural lands. Heavy metals are usually prevalent when domestic wastewater is mixed with industrial wastewater (Elgallal et al., 2016). A review by Elgallal et al. (2016) reported that, based on information from several studies, treated or partially treated domestic wastewater can be used safely for up to a century without negative impacts to crops, groundwater or the food chain from heavy metal contamination. Despite this, the use of treated domestic wastewater having heavy metal

concentrations within the FAO acceptable limits for irrigation may gradually accumulate within the soil in the long-term (Balkhair and Ashraf, 2016). Such gradual accumulation may compromise human health, food production and the environment in general. It is therefore of utmost importance to set rules and regulations which provide systematic heavy metal monitoring mechanisms on soils irrigated with wastewater.

4.4. Crop nutrient analysis

The lack of significant differences in plant tissue N and P and dry biomass between the irrigation treatments for both banana and taro showed that the DEWATS effluent supplied adequate nutrients for these crops. These field results confirm the findings of Bame et al. (2014) who used a similar effluent in pot experiments with maize and Musazura et al. (2015) in a field trial with Swiss chard.

5. Conclusions

There were no significant differences in N and P uptake by the two crops (banana and taro) regardless of the irrigation treatment. Irrigation with DEWATS effluent significantly increased inorganic N and P, especially in the 0.3 m depth of the soil. Phosphorus leaching did not significantly differ between the two irrigation treatments during the growing seasons. Very high concentrations of inorganic N were found in leachates from the DEWATS treatment within the 0.3 m soil depth. The soil water level within the field could reach up to 0.1 m below ground level showing presence of an impervious layer at the site. Based on a field scale investigation, fertigation using DEWATS effluent did not pose any groundwater contamination risk as the deep percolation was low in the clay soil. However, low drainage could cause pollution to nearby rivers through surface runoff hence management practices such as irrigation to meet crop water requirements with room for rainfall and installation of surface and subsurface drainage can be

employed with the drained water recycled for irrigation. Health risks from microbial contamination of near-surface water and food (especially vegetables consumed raw) may be a concern as the effluent used was Category B according to WHO (2006). Hence, improvement of the effluent from the HFCW is warranted to reduce the microbial count to an acceptable level for its unrestricted agricultural use. The study has provided reference information that can be used for modelling studies in the development of robust, environmentally safe, practical guidelines for the use of DEWATS effluent for irrigation of agricultural crops. Furthermore, there is room for further investigations on potential for groundwater and surface water contamination at catchment and regional scale using models such as DRASTIC.

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7. References

Al Omron, A.M., El-Maghraby, S.E., Nadeem, M.E.A., El-Eter, A.M., Al-Mohani, H., 2012. Long term effect of irrigation with the treated sewage effluent on some soil properties of Al-Hassa Governorate, Saudi Arabia. Journal of the Saudi Society of Agricultural Sciences 11, 15-18. https://doi.org/10.1016/j.jssas.2011.04.004.

Allen, R.G., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO, Rome, Italy.www.fao.org/docrep/X0490E/X0490E00.htm (Accessed on 28/01/2018).

APHA, 2005. Standard methods for the examination of water and wastewater. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA. ISBN 9780875530475.

Ashipala, N., Armitage, N., 2011. Impediments to the adoption of alternative sewerage in South African urban informal settlements. Water Science and Technology 64, 1781-1789. https://doi.org/10.2166/wst.2011.746.

Balkhair, K.S., Ashraf, M.A., 2016. Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. Saudi Journal of Biological Sciences 23, S32-S44. https://doi.org/10.1016/j.sjbs.2015.09.023.

Bame, I.B., Hughes, J.C., Titshall, L.W., Buckley, C.A., 2013. Leachate characteristics as influenced by application of anaerobic baffled reactor effluent to three soils: a soil column study. Chemosphere 93, 2171-2179. http://dx.doi.org/10.1016/j.chemosphere.2013.07.080.

Bame, I.B., Hughes, J.C., Titshall, L.W., Buckley, C.A., 2014. The effect of irrigation with anaerobic baffled reactor effluent on nutrient availability, soil properties and maize growth. Agricultural Water Management 134, 50-59. https://doi.org/10.1016/j.agwat.2013.11.011.

Barrow, N.J., 2016. The effects of pH on phosphate uptake from the soil. Plant and Soil 410, 401-410. https://doi.org/10.1007/s11104-016-3008-9.

Brady, N.C., Weil, R.R., 2016. The Nature and Properties of Soils, 15th ed. Pearson Prentice Hall, New York, USA. ISBN 9780135133873.

Crous, P., Haarhoff, J., Buckley, C., 2013. Water demand characteristics of shared water and sanitation facilities: Experiences from community ablution blocks in eThekwini Municipality, South Africa. Water SA 39, 211-220. http://dx.doi.org/10.4314/wsa.v39i3.3.

Darwesh, D.A., 2015. Assessment of nitrification and ammonia volatilization in different soils texture irrigated by Wastewater. International Journal of Science and Research 4, 945-948. ISSN (Online): 2319-7064.

DWA, 2013. Revision of general authorisations in terms of Section 39 of the National Water Act, 1998. Government Gazette Pretoria. https://www.greencape.co.za/assets/Water-Sector-Desk-Content/DWS-Revision-of-general-authorisation-in-terms-of-the-National-Water-Act-notice-169-2013.pdf (Accessed on 28/02/2018).

Elgallal, M., Fletcher, L., Evans, B., 2016. Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: A review. Agricultural Water Management 177, 419-431. http://dx.doi.org/10.1016/j.agwat.2016.08.027.

Fessehazion, M.K., Stirzaker, R.J., Annandale, J.G., Everson, C.S., 2011. Improving nitrogen and irrigation water use efficiency through adaptive management: A case study using annual ryegrass. Agriculture, Ecosystems & Environment 141, 350-358. http://dx.doi.org/10.1016/j.agee.2011.03.018.

Fink, J.R., Inda, A.V., Bavaresco, J., Barrón, V., Torrent, J., Bayer, C., 2016. Adsorption and desorption of phosphorus in subtropical soils as affected by management system and mineralogy. Soil and Tillage Research 155, 62-68. http://dx.doi.org/10.1016/j.still.2015.07.017.

Foxon, K., Pillay, S., Lalbahadur, T., Rodda, N., Holder, F., Buckley, C., 2005. The anaerobic baffled reactor (ABR): an appropriate technology for on-site sanitation. Water SA 30, 44-50. http://dx.doi.org/10.4314/wsa.v30i5.5165.

Hunter, A., 1974. Tentative ISFE soil extraction procedure. University, N.C.S., Raleigh, USA,

Kalra, Y., 1997. Handbook of Reference Methods for Plant Analysis. CRC Press, New York, USA. https://doi.org/10.1201/9781420049398.

Levy, G., Fine, P., Bar-Tal, A., 2011. Treated Wastewater in Agriculture: Use and impacts on the soil environments and crops. Wiley, New York, USA. ISBN 9781444322514.

Mulidzi, A., Clarke, C., Myburgh, P., 2016. Effect of Irrigation with Diluted Winery Wastewater on Phosphorus in Four Differently Textured Soils. South African Journal of Enology and Viticulture 37, 79-84. https://doi.org/10.21548/37-1-761.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27, 31-36. https://doi.org/10.1016/S0003-2670(00)88444-5.

Musazura, W., Odindo, A., Bame, I., Tesfamariam, E., 2015. Effect of irrigation with anaerobic baffled reactor effluent on Swiss chard (Beta vulgaris cicla.) yield, nutrient uptake and leaching. Journal of Water Reuse and Desalination 5, 592-609. https://doi.org/10.2166/wrd.2015.011.

Mynard, D.G., Kalra, Y.P., 2008. Nitrate and Exchangeable Ammonium Nitrogen, in: Carter, M.R. (Ed.), Soil Sampling and Methods for Analysis, 2nd ed. Lewis Publishers, London, UK, pp. 71-80. ISBN: 9781420005271.

Non-Affiliated Soil Analysis Work Committee, Soil Science Society of South Africa, 1990. Handbook of standard soil testing methods for advisory purposes. Soil Science Society of South Africa, Pretoria. ISBN: 9780620148009.

Ogbazghi, Z.M., Tesfamariam, E.H., Annandale, J.G., 2016. Modelling N mineralisation from sludge-amended soils across agro-ecological zones: A case study from South Africa. Ecological Modelling 322, 19-30. http://dx.doi.org/10.1016/j.ecolmodel.2015.11.019.

Pedrero, F., Kalavrouziotis, I., Alarcón, J.J., Koukoulakis, P., Asano, T., 2010. Use of treated municipal wastewater in irrigated agriculture - Review of some practices in Spain and Greece. Agricultural Water Management 97, 1233-1241. https://doi.org/10.1016/j.agwat.2010.03.003.

Pescod, M.B., 1992. Wastewater treatment and use in agriculture. Food and Agriculture Organisation Rome, Italy. ISBN 92-5-103135-5.

Raschid-Sally, L., Jayakody, P., 2009. Drivers and characteristics of wastewater agriculture in developing countries : results from a global assessment, Colombo, Sri Lanka, http://www.unwater.org/downloads/RR127.pdf (Accessed on 08/01/2017)

Rasiah, V., Armour, J.D., Cogle, A.L., 2005. Assessment of variables controlling nitrate dynamics in groundwater: Is it a threat to surface aquatic ecosystems? Marine Pollution Bulletin 51, 60-69. http://dx.doi.org/10.1016/j.marpolbul.2004.10.024.

Rattan, R.K., Datta, S.P., Chhonkar, P.K., Suribabu, K., Singh, A.K., 2005. Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. Agriculture, Ecosystems & Environment 109, 310-322. https://doi.org/10.1016/j.agee.2005.02.025.

Reynaud, N., Buckley, C.A., 2016. The anaerobic baffled reactor (ABR) treating communal wastewater under mesophilic conditions: a review. Water Science and Technology 73, 463-478. https://doi.org/10.2166/wst.2015.539.

Riekert, S., Bainbridge, S., 1998. Analytical methods of the Cedara plant and soil laboratory, Pietermaritzburg, South Africa, https://www.kzndard.gov.za/images/Documents/SOIL%20ANALYSIS/ANALYTICAL_METHODS_USED_BY_THE_SOIL_FERTILITY_AND_ANALYTICAL_SERVICES_SECTION.pdf (Accessed on 19/11/2018).

Rowell, D.L., 2014. Soil science: methods and applications. Longman Scientific & Technical, New York, USA. ISBN: 9780582087842.

Sahrawat, K.L., 2008. Factors Affecrting Nitrification in Soils. Communications in Soil Science and Plant Analysis 39, 1436-1446. http://dx.doi.org/10.1080/001036208020042.

Sasse, L., 1998. DEWATS : decentralised wastewater treatment in developing countries. Bremen Overseas Research and Development Association (BORDA), Bremen, Germany. cctps://sswm.info/sites/default/files/reference_attachments/SASSE%201998%20DEWATS%20Decentralised%20Wastewater%20Treatment%20in%20Developing%20Countries_0.pdf *(accessed 05/11/2018).

Schulze, R.E., 1997. South African Atlas of Agrohydrology and Climatology. WRC, Pretoria, South Africa,

Scott, C.A., Drechsel, P., Raschid-Sally, L., Bahri, A., Mara, D., Redwood, M., Jiménez, B., 2010. Wastewater irrigation and health: challenges and outlook for mitigating risks in low-income countries, in: Drechsel, P. (Ed.), Assessing and mitigating risks in low-income countries. International Water Management Instsitute (IWMI), London, UK., pp. 381-395. ISBN 9781844077960.

Singh, P.K., Deshbhratar, P.B., Ramteke, D.S., 2012. Effects of sewage wastewater irrigation on soil properties, crop yield and environment. Agricultural Water Management 103, 100-104. https://doi.org/10.1016/j.agwat.2011.10.022.

Soil Classification Working Group, 1991. Soil classification: A taxonomic system for South Africa. Department of Agricultural Development, Pretoria, South Africa. ISBN 9780621107845.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA, Washington DC, USA.,

Souza, M.F.d., Soares, E.M.B., Silva, I.R.d., Novais, R.F., Silva, M.F.d.O., 2014. Competitive sorption and desorption of phosphate and citrate in clayey and sandy loam soils. Revista Brasileira de Ciência do Solo 38, 1153-1161. http://dx.doi.org/10.1590/S0100-06832014000400011

USEPA, 2012. Guidelines for Water Reuse, Washington DC, USA.https://watereuse.org/wp-content/uploads/2015/04/epa-2012-guidelines-for-water-reuse.pdf (accessed on 17 August 2017).

VSN International, 2015. Genstat for windows 19th ed. VSN International, Hemel Hempstead, UK. , www.Genstat.co.uk (Accessed on 3/01/2018)

WHO, 2006. Guidelines for the safe use of wastewater, excreta and greywater: Exctreta and greywater use in agricuture. Organisation, W.H., Geneva, Switzerland,

WHO, 2017. Guidelines for Drinking-water quality, Guidelines for drinking-water quality: first addendum to the fourth edition. World Health Organisation, Geneva, Switzerland., p. 120 pp. ISBN 978-92-4-155001-7.

WWAP, 2017. The United Nations World Water Development Report 2017. UNESCO, W.W.A.P., Paris, France.ISBN: 978-92-3-100201-4.

Xu, J., Wu, L., Chang, A.C., Zhang, Y., 2010. Impact of long-term reclaimed wastewater irrigation on agricultural soils: A preliminary assessment. Journal of Hazardous Materials 183, 780-786. https://doi.org/10.1016/j.jhazmat.2010.07.094.