

**CROP FERTIGATION (NITROGEN AND PHOSPHORUS) WITH  
DECENTRALISED WASTEWATER TREATMENT SYSTEM  
EFFLUENTS AND EFFECTS ON SOILS AND GROUNDWATER.**

**by**

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in

Crop science

School of Agricultural, Earth and Environmental Sciences

College of Agriculture, Engineering and Science

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## PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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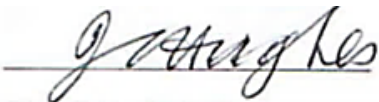
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## DECLARATION 1: PLAGIARISM

I, William Musazura, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

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(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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## DECLARATION 2: PUBLICATIONS

- 1 Musazura W, Odindo AO, Tesfamariam EH, Hughes JC and Buckley CA. (2016). Irrigating banana and taro with decentralised wastewater treatment effluent. WISA Biennial Conference and Exhibition 15<sup>th</sup> to 19<sup>th</sup> May 2016, Durban, South Africa. Presented by W Musazura.
- 2 Musazura W, Odindo AO, Tesfamariam EH, Hughes JC and Buckley CA. (2018). Decentralised wastewater treatment effluent fertigation: Preliminary technical assessment. *Water SA* 44 (2), 250 - 257. <http://dx.doi.org/10.4314/wsa.v43i3.01>.
- 3 Musazura W, Odindo AO and Buckley CA. (2018). Modelling nitrogen and phosphorus dynamics in soil fertigated with decentralised wastewater treatment effluent. Paper presented by W Musazura at 41st WEDC International Conference: Transformation towards sustainable and resilient wash services, Egerton University, Nakuru, Kenya, 2018. Paper 3028, 5 pp. <https://dspace.lboro.ac.uk/2134/35871>
- 4 Musazura W, Odindo AO, Tesfamariam EH, Hughes JC and Buckley CA. (2019). Nitrogen and phosphorus dynamics in plants and soil fertigated with decentralised wastewater treatment effluent. *Agricultural Water Management* (215) 55-62. <https://doi.org/10.1016/j.agwat.2019.01.005>.
- 5 Musazura W, Odindo AO, Tesfamariam EH, Hughes JC and Buckley CA. (2019). Nitrogen and phosphorus fluxes in three soils fertigated with decentralised wastewater treatment effluent to field capacity. *Journal of Water Reuse and Desalination*. <https://doi.org/10.2166/wrd.2019.025>.

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## ABSTRACT

Urbanisation is contributing to increased informal settlements in peri-urban areas and municipalities are facing challenges in providing sanitation. The decentralised wastewater treatment system (DEWATS) is a low cost, water-borne, onsite sanitation technology that can potentially serve peri-urban areas. The DEWATS treats human excreta to produce effluent that contains mineral nutrients, especially nitrogen (N) and phosphorus (P). Discharging treated wastewater into water bodies may cause pollution. Considering water scarcity, poverty and hunger issues in most developing countries, reuse of treated wastewater in agriculture promotes sustainable development if done in an environmentally friendly manner. This study therefore aimed at understanding the effects on crops, soils and the environment of fertigating with DEWATS effluent. All the studies were conducted at Newlands-Mashu experimental site (30°57'E, 29°58'S), Durban, South Africa. A field experiment investigated the effects of DEWATS effluent on tissue cultured banana (*Musa paradisiaca* var *Williams*) and taro (*Caucasia esculenta*). The study was carried out in a randomised complete block design with two irrigation treatments (DEWATS effluent without fertiliser vs tap water + fertiliser). Two crops were grown in an intercrop over two cropping cycles using drip irrigation. Two sources of effluent from the DEWATS were used. Effluent after treatment through a horizontal flow constructed wetland (HFCW) was used during the first cropping cycle and anaerobic filter effluent (AF) was used in the second cropping cycle. Data was collected on soil leachates, soil chemical properties, water table level, crop growth, yield and nutrient uptake, with a focus on N and P. Fertigation with DEWATS significantly ( $p < 0.05$ ) increased taro growth during the first cropping cycle. No significant differences ( $p > 0.05$ ) were reported for crop yield, N and P uptake and leaching between treatments showing its potential to substitute for inorganic fertilisers. The AF effluent significantly ( $p > 0.05$ ) increased soil inorganic N in the 0.3 m soil depth (rooting zone) after the second cropping cycle thereby acting as important N fertiliser source. Based on the findings no water table hazards due to low deep percolation and subsurface lateral flow was detected. However, subsurface drainage must be constructed in areas where water table rises to prevent groundwater pollution. A pot experiment was conducted to investigate fertigation of banana using DEWATS effluent on three different soil types. A factorial study was conducted in a complete randomised design. The treatments were three soil types (Inanda (Ia); Rhodic Hapludox / acidic clay soil, Sepane (Se); Aquic Haplustalf / clay loam soil and Cartref (Cf); Typic Haplaquept / sandy loam soil) \* two irrigation sources (DEWATS effluent vs tap water + fertiliser) \* four replicates. The Ia soil was collected from Worlds View, Pietermaritzburg (29°35'S, 30°19'E), the Cf soil from KwaDinabakubo, Hillcrest

(29°44'S; 30°51'E) and the Se was from the field trial site at Newlands-Mashu. Soils for the tap water + fertiliser treatment were mixed with inorganic fertilisers based on recommended crop requirements before being packed in a 90 L pot. The study was carried out over 728 days and all soils were irrigated to field capacity. Data was collected on banana growth (total leaf area and plant height), yield, N and P uptake and leaching, and soil chemical properties. Use of DEWATS effluent significantly ( $p < 0.05$ ) increased banana growth and yield in the Cf soil thereby showing ability of effluent to improve productivity in nutrient deprived soils. The  $\text{NH}_4^+$ -N and P concentrations significantly increased in all DEWATS effluent fertigated soils. Therefore, the effluent is a source of fertiliser that can potentially be used in place of conventional inorganic fertilisers. The N leached from the DEWATS treatment was significantly ( $p < 0.05$ ) lower than from the tap water + fertiliser treatment hence its use is environmentally sustainable. In all soils fertigated with DEWATS effluent, N leaching was significantly high in Ia soil hence fertigation in such a soil needs proper scheduling. The soil water balance (SWB-Sci) model was used to simulate water, and N and P dynamics in DEWATS effluent fertigated soil. The model was calibrated and validated based on data collected in the field studies. The crop growth model was successfully validated as it met all the standard statistical criteria required (i.e.  $r^2 > 0.8$ ,  $\text{MAE} < 20\%$  and  $D > 0.8$ ). High concentrations of inorganic N and P in topsoil fertigated with DEWATS effluent were simulated. Nitrate leaching was comparably higher in DEWATS effluent fertigated soils but without significant impact on ground water contamination in the respective soil. Therefore, the use of DEWATS effluent in clay soils is sustainable. The calculated land area required to fertigate banana and taro in an intercrop using effluent from each DEWATS was  $117 \text{ m}^2 \cdot \text{household}^{-1}$  ( $23.3 \text{ m}^2 \cdot \text{person}^{-1}$ ). If banana is grown as a sole crop land requirement could have been Cf ( $290 \text{ m}^2 \text{ household}^{-1}$ ;  $58 \text{ m}^2 \text{ person}^{-1}$ ), Ia ( $260 \text{ m}^2 \text{ household}^{-1}$ ;  $52 \text{ m}^2 \text{ person}^{-1}$ ) and Se ( $200 \text{ m}^2 \text{ household}^{-1}$ ;  $40 \text{ m}^2 \text{ person}$ ). Based on these findings it can be concluded that DEWATS effluent increases crop growth, yield, nutrient uptake and soil inorganic N and P within the rooting zone like more conventional practices. On-farm irrigation management practices such as scheduling with room for rainfall helps to prevent N and P leaching and rising water table. The SWB-Sci model is an irrigation scheduling and nutrient (N and P) management tool which may be used by decision makers and local governments in producing practical guidelines for sustainable wastewater use projects.

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## **DEDICATION**

I dedicate this work to:

My parents who took great care of me throughout my academic life. My siblings who gave me priceless support. My wife Everjoy and my daughters; Jamila and Ruvarashe, you kept me motivated.



## TABLE OF CONTENTS

PREFACE.....	i
DECLARATION 1: PLAGIARISM .....	ii
DECLARATION 2: PUBLICATIONS .....	iii
ABSTRACT.....	iv
ACKNOWLEDGMENTS .....	vi
DEDICATION.....	vii
TABLE OF CONTENTS.....	viii
LIST OF TABLES .....	xiii
LIST OF FIGURES .....	xvi
LIST OF PLATES .....	xviii
LIST OF APPENDICES.....	xix
CHAPTER 1: GENERAL INTRODUCTION .....	1
CHAPTER 2: EFFECT OF WASTEWATER FROM HUMAN EXCRETA-DERIVED MATERIALS ON SOILS, CROPS AND THE ENVIRONMENT: A REVIEW.....	5
2.1 Introduction .....	5
2.2 Wastewater treatment processes for agricultural use and nutrient recovery.....	6
2.2.1 Dry sanitation technologies.....	6
2.2.2 Decentralised wastewater treatment system.....	7
2.3 Effects of wastewater on soil .....	8
2.3.1 Chemical properties.....	8
2.3.2 Physical properties .....	15
2.3.3 Microbial properties.....	17
2.4 Crop growth, development and biomass production.....	17
2.4.1 N and P uptake mechanisms.....	17
2.4.2 N and P crop requirements.....	18
2.4.3 Effect of wastewater irrigation on crop growth, biomass and yield .....	18

2.5	Implications for human health of using treated wastewater.....	19
2.5.1	Pathogens in treated domestic wastewater .....	19
2.5.2	Heavy metal accumulation in plants.....	20
2.5.3	Emerging contaminants in treated wastewater .....	22
2.5.4	Sanitation safety plans .....	23
2.6	Challenges in the implementation and upscaling of wastewater use projects.....	24
2.6.1	Policies and institutional aspects of wastewater use.....	24
2.6.2	Cost benefit analysis .....	26
2.6.3	Social and cultural aspects .....	27
2.7	Modelling as a decision support tool .....	27
2.7.1	Modelling irrigation management and water and nutrient movement.....	28
2.7.2	Determining land area requirements.....	30
2.8	Summary and conclusions.....	32
CHAPTER 3: MATERIALS AND METHODS .....		34
3.1	Experimental site.....	34
3.2	Field experiments .....	36
3.2.1	Experimental design and field layout.....	36
3.2.2	Experimental installations .....	37
3.2.3	Trial establishment and management .....	42
3.2.4	Data collection.....	43
3.3	Pot experiment.....	47
3.3.1	Experimental design .....	47
3.3.2	Trial establishment and management .....	47
3.3.3	Data collection.....	50
3.4	Laboratory analyses.....	50
3.4.1	Effluent characterisation.....	50
3.4.2	Soil analysis .....	51

3.4.3	Plant tissue analyses.....	54
3.5	Data analysis .....	54
3.6	Modelling water and nutrient (N and P) balances in soil.....	54
3.6.1	The weather unit.....	54
3.6.2	Growth sub model calibration .....	55
3.6.3	Model validation .....	55
3.6.4	Land area determination.....	56
CHAPTER 4: CROP GROWTH, AND NITROGEN AND PHOSPHORUS DYNAMICS IN SOIL IRRIGATED WITH DEWATS EFFLUENT IN THE FIELD. ....		57
4.1	Introduction .....	57
4.2	Materials and Methods .....	58
4.3	Results .....	58
4.3.1	Effluent characterisation.....	58
4.3.2	Crop growth and yield.....	60
4.3.3	Soil properties.....	62
4.3.4	N and P leaching .....	66
4.3.5	Groundwater monitoring.....	67
4.3.6	Soil N and P loading and crop uptake.....	68
4.3.7	Crop water requirements.....	69
4.4	Discussion .....	70
4.4.1	Effluent characterisation.....	70
4.4.2	Crop growth and yield.....	71
4.4.3	Soil properties.....	72
4.4.4	N and P leaching .....	73
4.4.5	Groundwater monitoring.....	73
4.4.6	Soil N and P loading and crop uptake.....	74
4.4.7	Crop water requirements and land area .....	74

4.5	Conclusions .....	75
CHAPTER 5: NITROGEN AND PHOSPHORUS FLUXES, AND CROP UPTAKE IN THREE SOILS FERTIGATED WITH DEWATS EFFLUENT TO FIELD CAPACITY. ....		
5.1	Introduction .....	76
5.2	Materials and methods .....	77
5.3	Results .....	77
5.3.1	Crop growth and yield.....	77
5.3.2	Soil properties.....	80
5.3.3	N and P leaching .....	82
5.3.4	Soil N and P loading and crop uptake.....	84
5.4	Discussion .....	86
5.4.1	Crop growth and yield.....	86
5.4.2	Soil properties.....	86
5.4.3	N and P leaching .....	87
5.4.4	Soil N and P loading and crop uptake.....	87
5.5	Conclusions .....	88
CHAPTER 6: MODELING WATER, N AND P DYNAMICS IN SOIL FERTIGATED WITH DEWATS EFFLUENT. ....		
6.1	Introduction .....	89
6.2	Materials and methods .....	90
6.3	Results .....	90
6.3.1	Model calibration .....	90
6.3.2	Model validation .....	92
6.3.3	N and P modelling .....	94
6.3.4	Land area determination.....	96
6.4	Discussion .....	96
6.4.1	Model calibration and validation.....	96
6.4.2	Residual inorganic N and P.....	97

6.4.3	Nitrate leaching over time .....	98
6.4.4	Land area requirements .....	98
6.5	Conclusions .....	98
CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS .....		100
7.1	Introduction .....	100
7.2	General discussion.....	101
7.2.1	Effects on crop growth, yield and N and P uptake .....	101
7.2.2	Nitrogen and P dynamics in DEWATS effluent fertigated soils.....	102
7.2.3	Land area requirements and N and P loading .....	104
7.3	Conclusions .....	105
7.4	Recommendations and future studies.....	106
REFERENCES .....		108
APPENDICES .....		130

## LIST OF TABLES

Table 2.1: Nutrients required by selected crops for canopy formation and fruit production/yield (adapted and modified from FAO 2003). .....	18
Table 2.2: Threshold levels of heavy metals for crop production .....	22
Table 2.3: Pathogen reduction achievable by various health protection measures (from WHO 2006) .....	25
Table 3.1: Nitrogen (N), phosphorus (P) and potassium (K) fertiliser requirements for banana and taro during the growing period for cropping cycle 1 (Nov 2013 - May 2015) and cropping cycle 2 (Jun 2015 - July 2016) in respective irrigation treatments plots. ....	42
Table 3.2: Nitrogen (N), phosphorus (P), potassium (K) and lime (dolomite) fertiliser requirements for the three different soils used.....	48
Table 3.3: Soil chemical and physical properties of the Sepane soil at the Newlands-Mashu field site before planting. ....	53
Table 3.4: Physical and chemical properties for the different soil types used for the pot experiment at Newlands-Mashu. ....	53
Table 4.1: The chemical and physical properties of DEWATS effluents (after HFCW and AF) used during the study. ....	59
Table 4.2: Analysis of variance showing the probability values for banana and taro growth between the two irrigation treatments over two growing seasons. ....	60
Table 4.3: Mean squares for taro yield and total dry mass during the first season.....	61
Table 4.4: Taro growth variables between the two growing cropping cycles and fertigation treatments (n = 6; mean ± standard error of mean).....	61
Table 4.5: Mean squares for banana yield and dry mass between the two cropping cycles and irrigation treatments collected after harvest (728 days after planting). ....	61
Table 4.6: Mean squares for soil chemical properties between the two irrigation treatments sampled from two different depths over the three growing seasons.....	63
Table 4.7: Concentrations (mean ± standard error of mean differences; n = 3) of total N (organic + inorganic N), NO <sub>3</sub> <sup>-</sup> -N, NH <sub>4</sub> <sup>+</sup> -N, extractable P and total inorganic N (NO <sub>3</sub> <sup>-</sup> -N +NH <sub>4</sub> <sup>+</sup> -N) between the two soil depth, irrigation treatments over three different periods of the study....	65
Table 4.8: Analysis of variance table showing the mean and sum of squares for inorganic N and P in leachates collected from the wetting front detectors (WFDs) in the field. ....	66
Table 4.9: Nitrogen (N) and phosphorus (P) supplied by irrigation with effluent from the two different sources (Anaerobic filter; AF and Horizontal flow constructed wetland; HFCW) based	

on actual amounts applied over 992 days in comparison to crop nutrient requirements for both crops.....	68
Table 4.10: Mean squares for N and P concentrations from banana leaf tissues between two irrigation treatments over the two growing cycles.....	69
Table 4.11: Mean squares for N and P concentrations from taro corm tissues between two irrigation treatments during the first growing cycle. ....	69
Table 5.1: Mean squares banana growth rate (plant height and total leaf area) between the two irrigation treatments in three different soils over the experimental period (992 days).....	78
Table 5.2: Mean squares for banana fresh and dry biomass between the two irrigation treatments and three contrasting soil recorded after harvesting (728 days after planting). ....	79
Table 5.3: Banana plant height, total leaf area and fresh and dry biomass (728 days after planting) on three soils under different irrigation treatments (n=3; mean $\pm$ standard error of mean differences).....	79
Table 5.4: Means squares for soil chemical properties in the tunnel 728 days after planting amongst the three contrasting soils and two irrigation treatments.....	80
Table 5.5: Concentrations of total N, organic C and P in the soils after harvesting (n = 8; mean $\pm$ standard error of mean differences).....	80
Table 5.6: Analysis of variance table showing mean squares for inorganic N and P leached from the pots. ....	82
Table 5.7: The volumes of effluent from the horizontal flow constructed wetland (HFCW) and the anaerobic filter (AF) and the amounts of total nitrogen (N) and phosphorus (P) supplied during the growth period (728 days).....	84
Table 5.8: The N and P applied through fertigation using DEWATS effluent over 728 days in comparison to crop fertiliser requirements. ....	85
Table 5.9: Mean squares for banana leaf tissue N and P concentration between the two irrigation treatments at 728 days after planting. ....	85
Table 5.10: Banana plant tissue nitrogen (N) and phosphorus (P) concentrations as a function of irrigation treatment and soil type (n=9; mean $\pm$ standard error of mean differences).....	85
Table 6.1: Calibration of the SWB-Sci model based on banana leaf area index, top and harvestable dry mass, crop height and N uptake from tap water + fertiliser treatment. ....	90
Table 6.2: Validation of the SWB-Sci model based on banana leaf area index, top and harvestable dry mass, crop height and N uptake using an independent dataset from DEWATS treatment. ....	93

Table 6.3: Land area requirements in three different soils based on crop water requirements ( $E_{t_{crop}}$ ) and DEWATS effluent production capacity. ....96



## LIST OF FIGURES

Figure 2.1: Nitrogen cycle in soil fertigated with treated wastewater (based on information from Feigin et al. (2012) and Levy et al. (2011)).	9
Figure 2.2: Phosphorus dynamics in wastewater fertigated soils (based on information by Shen et al. (2011), Brady and Weil (2016) and Lusk et al. (2017)).	11
Figure 2.3: Sanitation safety plan modules (from WHO (2016)).	24
Figure 3.1: Map showing the study site and areas where some of the soils used during the study were collected (sourced and modified from AfriGIS, Google earth, 2018).	35
Figure 3.2: Diagram showing different modules of the DEWATS and the two sources of effluent used for fertigation during the study.	36
Figure 3.3: Field layout showing the irrigation treatments, cropping plan and the piezometers and wetting front detectors (WFD).	37
Figure 3.4: The Newlands-Mashu experimental site showing positions of the piezometers used in the study (P1 – P6 are different piezometers).	39
Figure 3.5: Sampling area in each plot for all the crop and soil data collected during the field experiment.	43
Figure 3.6: Pot experiment layout in a complete randomised design in the growing tunnel.	47
Figure 4.1: Banana plant height between the two cropping cycles for two irrigation treatment (n = 3; mean ± standard error of mean differences).	60
Figure 4.2: Banana yield (n = 6; mean ± standard error of mean differences) in different irrigation treatments and cropping cycles.	62
Figure 4.5: Concentrations of inorganic N (n = 3, mean ± standard error of mean differences) in leachates collected from the two irrigation treatments at two depths from 295 to 992 days after planting.	67
Figure 4.6: Boxplots showing concentration of inorganic 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.	67
Figure 4.7: Water levels in different locations of the experimental field. P1 and P2 upslope from the field plots; P3, P4 and P5 within the field plots; P6 downslope from the field plots.	68
Figure 4.6: Rainfall and crop evapotranspiration (ET <sub>crop</sub> for both banana and taro) and irrigation deficits at the Newlands-Mashu field site showing irrigation water demands for the period between November 2013 and July 2016.	70

Figure 5.1: Total leaf area and plant height of banana (n = 4; mean ± standard error of mean differences) on the three soils used during the study at four sampling times. ....	78
Figure 5.2: Boxplots showing mean (x) and distribution of quartiles in orthophosphate P concentrations (n = 12; mean ± standard error of mean differences) between the two irrigation treatments. ....	81
Figure 5.3: Concentrations (n = 4; mean ± standard error of means) of ammonium N in the three soils after harvesting from the two irrigation treatments. ....	81
Figure 5.4: Drainage rates for the three soils, monitored during the banana growing cropping cycle (n = 6; mean ± standard error of mean differences). ....	82
Figure 5.5: Amounts of orthophosphate (P) leached from the three soils between the two irrigation treatments (n=24; mean ± standard error of mean differences). ....	83
Figure 5.6: Interaction between irrigation treatment and soil type on the amount of nitrogen (N) leached during the study (n=4; mean ± standard error of mean differences). ....	83
Figure 5.7: Irrigation applied (depth) and crop water requirements for banana plants in the tunnel. ....	84
Figure 6.1: Soil profile water content measured by the CS 650 Campbell soil moisture reflectometers and simulated profile water content at the Newlands-Mashu field experiment. ....	91
Figure 6.2: Simulated and measured nitrate (NO <sub>3</sub> <sup>-</sup> ) concentrations at 0.3 and 0.5 m soil depths for the tap water + fertiliser treatment. ....	92
Figure 6.3: Simulated and measured mobile NO <sub>3</sub> <sup>-</sup> and labile P concentrations at 0.3 and 0.5 m soil depths for the DEWATS effluent fertigated soil. ....	94
Figure 6.4: Simulated residual N (NO <sub>3</sub> <sup>-</sup> ) and P (PO <sub>4</sub> <sup>3-</sup> ) concentrations for irrigation with DEWATS effluent and tap water + fertiliser at different depths (0.1 to 1.1 m) in the Sepane soil at Newlands-Mashu over 992 days. ....	95
Figure 6.5: Simulated concentration of NO <sub>3</sub> <sup>-</sup> leached from the Sepane soil fertigated with DEWATS effluent and tap water + fertiliser over a period of 992 days. ....	96

## LIST OF PLATES

Plate 3.1: Wetting front detectors inserted at different soil depths (0.3m, yellow top and 0.5m, red top).....	38
Plate 3.2: (A) The automated weather station and (B) the soil moisture reflectometers at three depths at Newlands Mashu. ....	41
Plate 3.3: (A) Collecting leachates from the wetting front detectors and (B) water Table samples.....	46
Plate 3.4: Measuring soil moisture content by weighing the pots in the growing tunnel. ....	49

## LIST OF APPENDICES

Appendix 1: Sensors connected to the weather station.....	130
Appendix 2: Newlands-Mashu weather station information used to create the simulated weather station for the Soil Water Balance model.....	131
Appendix 3: Banana crop specific parameters included in the SWB-Sci model based on measured and literature data. ....	132
Appendix 4: Nitrogen (N) and phosphorus (P) uptake crop parameters for banana. ....	136
Appendix 5: Soil physical properties used in the Soil Water Balance model. ....	137
Appendix 6: Field management practices for the Soil Water Balance model. ....	138
Appendix 7: Initial soil nitrogen (N) and phosphorus (P) parameters for the SWB-Sci model. ....	139
Appendix 8: Land area calculations for three different soils.....	140
Appendix 9: Mean squares for inorganic N and P in perched water table and WFD samples collected during the field study period. ....	141
Appendix 10: Irrigation data at Newlands-Mashu field experiment for the period June 2014 to July 2016.....	142
Appendix 11: Field studies raw data.....	144
Appendix 12: Tunnel raw data.....	150
Appendix 13: Soil water mass balance for banana simulated by the SWB model over a period of 992 days at Newlands-Mashu.....	153

## CHAPTER 1: GENERAL INTRODUCTION

About 54 % of the global population live in urban areas and the proportion is expected to increase to 60 % by the year 2050 (United Nations Department of Economic and Social Affairs Population Division 2014). Projections have also shown that more than 90 % of the general population increase is expected in Asia and Africa (United Nations Department of Economic and Social Affairs Population Division 2014). These population dynamics have impacts on sanitation demands as 61 % of the global population do not have access to safely managed sanitation and 72 % of the population in sub-Saharan Africa do not have access to at least basic sanitation, thus exposing them to health risks (WHO/UNICEF, 2017). The United Nations general assembly established Millennium Development Goals (MDGs) to, *inter alia*, secure global coverage of access to basic services such as water and sanitation by the year 2030 (WHO/UNICEF, 2017).

The South African government had the task to provide sanitation to unserved areas during the post-apartheid era (WWF-SA 2016). Although significant progress has been made much work remains to be done as about 4.9 % of South Africans still do not have toilets and about 19.5 % are living without improved sanitation services (Statistics South Africa 2016). The greatest challenge is within rural and informal settlements where connections to main sewage systems are difficult to achieve (Foxon et al. 2005). In South Africa, ventilated improved pit (VIP) latrines are recognised as minimum basic sanitation and in areas where they were constructed the major challenge was emptying them and subsequent management of the faecal sludge (WWF-SA 2016). Lack of proper care of VIP toilets, faecal sludge treatment and management expose people to health risks, as some of the faecal matter contaminants may leach and cause pollution of water table or surface water resources. The choice of appropriate sanitation technologies must consider cost, environmental sustainability and social acceptability (Crous et al. 2013). Water-borne sewage systems are more preferred by residents in informal settlements of South Africa as dry technologies are considered to be associated with poverty (Roma et al. 2010).

To address these immediate sanitation challenges in South African informal settlements interim measures have had to be taken and the eThekweni (Durban) Municipality in KwaZulu-Natal, is one of those involved. The Municipality has embarked on projects to construct community ablution blocks (CABs) to serve about 800 000 inhabitants in informal settlements around

eThekwini (Crous et al. 2013). Currently about 1 350 CABs have been erected in 350 informal settlements around the Municipality (Constable 2015, Crous et al. 2013). The eThekwini Municipality has also considered the Decentralised Wastewater Treatment System (DEWATS) as an on-site sanitation method to treat human excreta as part of housing development projects in urban and peri-urban areas of Durban and some of these have been connected to the CABs in some informal settlements (WRC 2014).

The DEWATS is defined as a modular system that consists of a biogas settler, anaerobic baffled reactor, anaerobic filter and sometimes planted gravel filters (horizontal and vertical flow constructed wetlands) (Sasse 1998). The technology anaerobically degrades organic compounds in human excreta and produces effluent rich in mineral nutrients, especially nitrogen (N) and phosphorus (P) (Gutterer et al. 2009). This effluent is expected to meet the standards set by the South African Department of Water Affairs (2013) for discharge into water courses. However, based on findings reported by the WRC (2014), the effluent does not, currently, meet these limits and hence some other disposal mechanisms need to be considered such as reuse as fertigation for agriculture.

South Africa is characterised by erratic rainfall patterns, high evapotranspiration and shallow dams and is the world's 30<sup>th</sup> most water scarce country (Hedden and Cilliers 2014). It has been reported that South Africa receives an average of about 495 mm of annual rainfall, which is half of the world's average annual rainfall of 1 033 mm (Hedden and Cilliers 2014, WWF-SA 2016). Based on recent data, the agriculture sector is the largest water consumer using about 69 % of the total water consumption in South Africa (AQUASTAT 2016). Also based on information collected by the eThekwini Municipality about 20 % of all its residents are food insecure and live at or below the poverty datum point thereby making it a threat to the future prosperity of the area (eThekwini Municipality 2017). These issues related to poor sanitation, water scarcity and food insecurity require that sustainable solutions be found as a matter of urgency. The use of treated wastewater in agriculture reduces pressure on scarce freshwater resources and promotes sustainable agriculture. This is in accordance with the United Nations Sustainable Development Goal 6.3, which emphasised protection of freshwater resources by refraining from discharging wastewater into rivers and increasing its use in agriculture (WWAP 2017). Any practice that involves agricultural use of treated wastewater must be done in an environmentally sustainable manner which does not negatively affect soils, aquatic life and water table resources (FAO 2013, Keraita et al. 2015, WWAP 2017). It is these principles that underlie the present study.

## **Study aim**

- To gain an understanding of the factors and processes that may influence the use of DEWATS effluent as a fertigation source of N and P and its effects on crops, soils and groundwater.

## **Specific objectives**

1. To investigate the effect of using DEWATS effluent on crop growth, yield, and N and P uptake.
2. To investigate N and P dynamics in the field and under controlled environment conditions when using DEWATS effluent for crop production.
3. To use the data collected to investigate the potential of the soil water balance model (SWB-Sci) to determine water and N and P mass balances as an irrigation and environmental management tool.

## **Thesis structure:**

### **Chapter 1: General introduction**

Summarises the background information and justification of the study.

### **Chapter 2: Use of decentralised wastewater treatment effluent on crops, soils and the environment: A review.**

The chapter reviews the status of the benefits, limitations and mitigation strategies for using treated wastewater as a source of N and P in agriculture.

### **Chapter 3: Materials and methods**

- Field studies of the effects of DEWATS effluent on banana and taro growth, nutrient uptake and yield and on N and P dynamics in soil, leachates and water table.
- A controlled environment study investigated fertigation using DEWATS effluent to field capacity and monitored its effects on the growth, yield, N and P uptake by banana, and N and P dynamics in three soils and leachates.
- Modelling using the SWB-Sci model to simulate N and P movement in soils under DEWATS effluent irrigation.

**Chapter 4: Crop growth, and nitrogen and phosphorus dynamics in soil irrigated with DEWATS effluent in the field.**

Field study to investigate the effects of DEWATS effluent on crop growth, N and P dynamics in soils, leaching and groundwater contamination.

**Chapter 5: Nitrogen and phosphorus fluxes, and crop uptake in three soils fertigated with DEWATS effluent to field capacity.**

The study investigated the N and P dynamics, uptake and leaching in three different soils following irrigation to field capacity.

**Chapter 6: Modelling water, N and P dynamics in soil fertigated with DEWATS effluent.**

The chapter focused on calibration and validation of the SWB-Sci model. The banana growth model was simulated to generate water balances for three different soils and the information was used to estimate land requirements in respective soils. The N and P movement in the soils were also simulated and the results explained the potential for environmental pollution and agronomic benefits for using DEWATS effluent.

**Chapter 7: General discussion and conclusions.**



## **CHAPTER 2: EFFECT OF WASTEWATER FROM HUMAN EXCRETA-DERIVED MATERIALS ON SOILS, CROPS AND THE ENVIRONMENT: A REVIEW**

### **2.1 Introduction**

Wastewater is defined as water the quality of which has been changed due to anthropological activities (Levy et al. 2011). Treated wastewater is the water that has undergone a series of physical, chemical and biological processes to remove solids, nutrients and organic matter (Pescod 1992). Wastewater can undergo different degrees of treatment such as preliminary, primary, secondary and tertiary which determine its final quality (Pescod 1992). Treated wastewater can be categorised into industrial, agricultural and domestic wastewater (Hussain et al. 2002, WWAP 2017). Industrial sources of wastewater include textiles, abattoirs, olive mills and wineries (Matheyarasu et al. 2015). Piggery and dairy wastewaters are examples of agricultural wastewaters (Matheyarasu et al. 2015). Domestic wastewater comes from household activities and is constituted of greywater (laundry, kitchen and bath water) and blackwater (faeces and urine) depending on the sewerage system design (Lüthi et al. 2011, Matheyarasu et al. 2015). The focus of this review will be the wastewater (blackwater) from human excreta-derived materials (HEDMs) that has been treated by various processes.

Use of wastewater in agriculture is an ancient practice. Humans have used wastewater for irrigation since the Bronze Age, (ca. 3 200 – 1 100 BC) (Angelakis and Snyder 2015). Fertigation is the application of plant nutrients dissolved in water to crops. The first evidence on fertigation using wastewater was from the Greeks who used wastewater from toilet storage tanks around the periphery of major cities (Jaramillo and Restrepo 2017). The practice then extended to farms in England, Germany and Scotland between 1500 and 1700 (Angelakis and Snyder 2015, Jaramillo and Restrepo 2017). During the 19<sup>th</sup> century the use of wastewater in agriculture contributed to outbreaks of waterborne diseases such as typhoid and cholera (Ashton and Ubido 1991). This prompted authorities to introduce sanitary control measures such as sanitary border controls and the development of underground sewerage systems (Angelakis and Snyder 2015). Currently, several countries are formally and informally irrigating crops with wastewater (Keraita and Drechsel 2015). Considering the benefits associated with fertigation using treated wastewater and continued research on developing ways of minimising its risks the practice is expected to significantly intensify by the year 2030 (Jaramillo and Restrepo 2017, WWAP 2017).

There are several factors driving the use of treated wastewater in agriculture and one of them is the increasing volumes of wastewater generated in urban and peri-urban settlements (WWAP 2017). Urban populations are increasing rapidly and outpacing current municipal infrastructural capacity to manage them. This is coupled with increasing per person water consumption and subsequent wastewater production (Thebo et al. 2017). Instead of discharging wastewater into water bodies, its use for fertigrating crops promotes sustainable agriculture.

Treated wastewater contains mineral nutrients (notably nitrogen (N) and phosphorus (P)), which are two of the most important macronutrients required for crop growth and yield. Although there are some other macro and micronutrients in wastewater, this review mainly focuses on N and P. Mateo-Sagasta et al. (2015) estimated that all the excreta produced daily worldwide could replace about 25 % of N and 15 % of P currently used as inorganic fertilisers in agriculture. In addition the cost of inorganic fertilisers are limiting agricultural productivity in low income communities (Andersson et al. 2016). Therefore, use of treated wastewater that supplies nutrients could save the costs of fertilisers (especially N and P) required for agriculture (Hussain et al. 2002, Keraita and Drechsel 2015, WWAP 2017).

## **2.2 Wastewater treatment processes for agricultural use and nutrient recovery**

Ecological sanitation (Ecosan) is an integrated approach that considers human excreta not as waste but as a valuable resource that can be used sustainably in agriculture (Lüthi et al. 2011, WHO 2009, WWAP 2017). Ecological sanitation systems are very important in densely populated, low-income communities where they provide onsite sanitation and at the same time produce resources that can be used in agriculture (WHO 2009). Onsite technologies can either be dry sanitation systems or waterborne sewerage systems (WHO 2009). Examples of dry sanitation systems are urine diverting dry toilets (UDDTs) and ventilated improved pit latrines (VIPs) while the decentralised wastewater treatment system (DEWATS) is one of the waterborne sanitation technologies (WWAP 2017).

### **2.2.1 Dry sanitation technologies**

The UDDT is defined as an onsite toilet which works without water and has a divider to separate urine from faeces. The VIP also operates without water but does not have any divider to separate urine and faeces (Tilley 2014).

Faecal sludge collected from the UDDT and VIP toilets is further processed using the latrine dehydration and pasteurisation (LaDePa) process, which pelletises it into a valuable product (Nikiema et al. 2013). The LaDePa pellets are smell free and sterile making their handling less

risky for farmers (Andersson et al. 2016). These pellets are used as a soil conditioner and source of mineral nutrients required by crops.

Urine separated from the UDDT toilets is processed into different products that recover nutrients (N and P). The processed products are struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ), nitrified urine concentrate (NUC) and urine effluent. Struvite is a crystalline phosphate mineral that is formed by adding a Mg source to urine at a pH of around nine (Andersson et al. 2016, Etter et al. 2011, Jönsson and Vinnerås 2004). The urine effluent is a by-product from struvite production and can be applied directly to crops (Etter et al. 2011). Nitrogen can be recovered from urine after stabilisation through the process of nitrification followed by concentration through distillation (Fumasoli et al. 2016).

### **2.2.2 Decentralised wastewater treatment system**

The DEWATS is an approach for treating wastewater at a source point. The DEWATS is based on four treatment modules which are the settling tank (primary treatment), anaerobic baffled reactor (ABR; secondary treatment), anaerobic filter (AF; secondary treatment) and the planted gravel filters (PGFs) for secondary aerobic or tertiary treatment (horizontal flow constructed wetland; HFCW and vertical flow constructed wetland; VFCW) (Gutterer et al. 2009).

The treatment process starts in the settling chamber where scum and suspended solids are removed. The wastewater then passes through the hanging and standing baffles of the ABR in an up and down motion, where sludge is retained (Reynaud and Buckley 2016). The dissolved and suspended organic matter are anaerobically degraded to inorganic compounds. The wastewater then passes to the AF which mechanically removes solids and facilitates digestion of dissolved organic compounds (Gutterer et al. 2009).

The wastewater effluent from the treatment process is further polished in PGFs. The PGFs are subsurface systems with porous materials such as sand or gravel as substrate and these also prevent clogging (Lavrova and Koumanova 2013). Hybrid constructed wetlands consist of a combination of HFCW and VFCW to maximise the advantages of each treatment system (Kadlec and Wallace 2008). In a VFCW wastewater is discharged onto the surface and flows vertically through the porous media, carrying oxygen with it, until it reaches the outlet at the bottom. The effluent then moves to the HFCW where it flows horizontally in a basin allowing filter materials to remove microorganisms and degradation of organic material before moving out through the outlet (Lavrova and Koumanova 2013). Nitrogen is mostly lost through annamox reactions while P is removed through adsorption and precipitation processes (Vymazal 2007). Phosphorus removal depends on the substrate used being higher in high

sorption capacity material (Vymazal 2007). Nitrogen and P removal is high in systems with frequent harvesting and lightly loaded wetland systems (Vymazal 2007). The effluent produced from such systems is generally clear but still contains some nutrients such as N and P (Vymazal 2007).

## **2.3 Effects of wastewater on soil**

### **2.3.1 Chemical properties**

Treated wastewater is mainly constituted of 99.9 % water with the balance present as dissolved and suspended substances (Pescod 1992). These substances are mainly nutrients (macro and micronutrients), organic matter and microorganisms (Pescod 1992).

Irrigation using wastewater significantly influences the soil physicochemical properties and microbial activity which control processes such as nutrient transformations, uptake by plants and leaching out of the root zone (Feigin et al. 2012, Levy et al. 2011). An understanding of the mechanisms controlling these processes is essential to provide sustainable management of wastewater irrigation (Levy et al. 2011).

#### *2.3.1.1 Nitrogen and phosphorus dynamics*

Nitrogen and P are the most important macronutrients in wastewater required for crop production (Andersson et al. 2016, Fonseca et al. 2007, Pedrero et al. 2010). Nitrogen is the dominant macronutrient in treated wastewater and it undergoes a series of transformations in the soil which makes it available for crop uptake or it is lost from the soil system (Feigin et al. 2012). Phosphorus is often unavailable to plants as it is either adsorbed to soil particles or precipitated as insoluble compounds (Brady and Weil 2016).

##### 2.3.1.1.1 Nitrogen dynamics

The dynamics of N in wastewater fertigated soils are shown in Figure 2.1. Wastewater contains organic and inorganic forms of N (Feigin et al. 2012). The most dominant forms of N in wastewater are ammonium ( $\text{NH}_4^+\text{-N}$ ) and organic N (Feigin et al. 2012, Fonseca et al. 2007). Some other N forms such as nitrites ( $\text{NO}_2^-$ ) and nitrates ( $\text{NO}_3^-$ ) are relatively lower (Feigin et al. 2012) especially when wastewater has been treated under anaerobic conditions (Feigin et al. 2012, Levy et al. 2011, Reynaud and Buckley 2016).

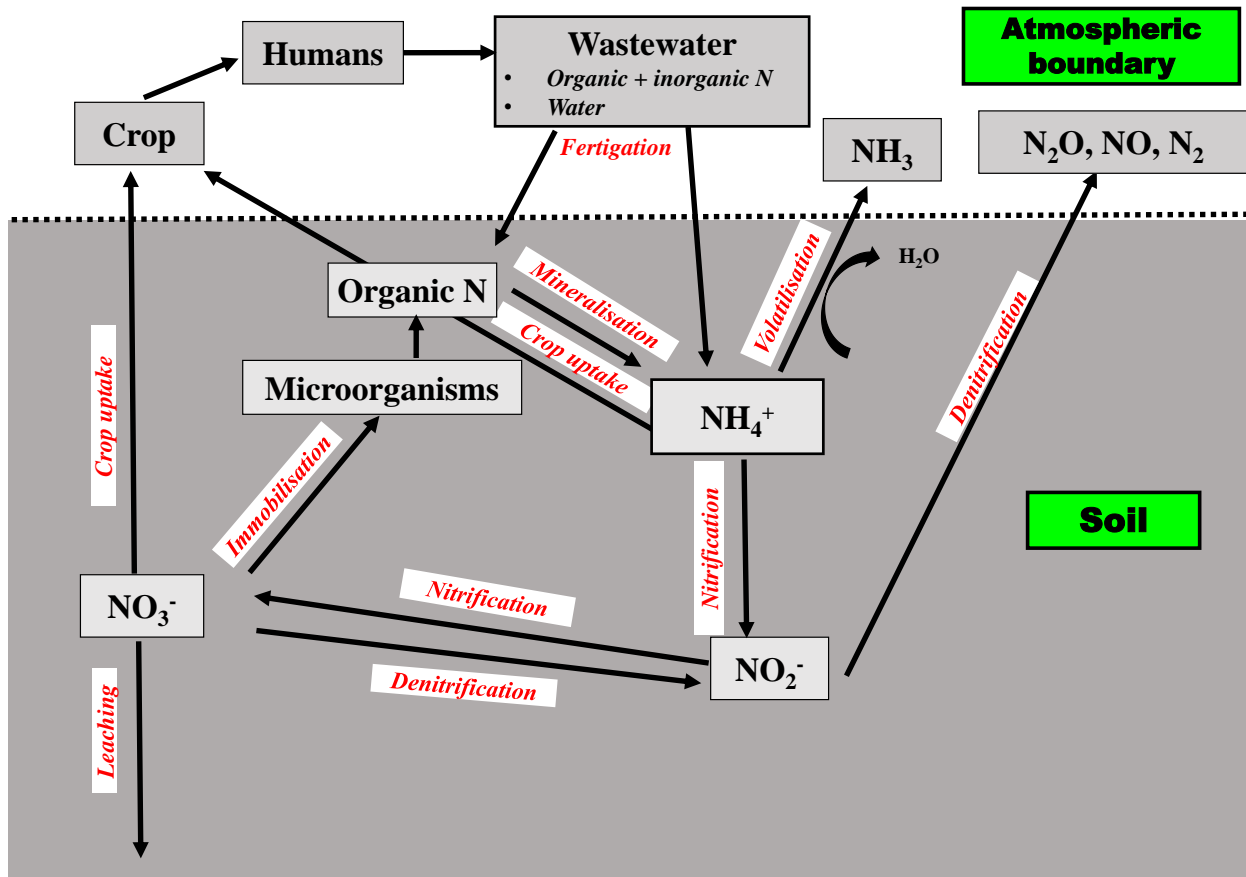


Figure 2.1: Nitrogen cycle in soil fertiligated with treated wastewater (based on information from Feigin et al. (2012) and Levy et al. (2011)).

Soil microorganisms consume inorganic N when the C:N ratio is high and incorporate it into their biomass (Chen et al. 2014), and therefore immobilised N is part of the organic N pool. Organic N in the soil is broken down to inorganic forms ( $\text{NH}_4^+$  and then  $\text{NO}_3^-$ ) in the presence of microorganisms through mineralisation (Feigin et al. 2012). Volatilisation of  $\text{NH}_4^+$  occurs at high pH, temperatures and wind speed (Smith et al. 1996). Smith et al. (1996) investigated  $\text{NH}_3$  fluxes in pasture fertiligated with sewage effluent at Wagga Wagga, Australia and reported 24 % loss of  $\text{NH}_4^+$  through volatilisation due to the high evapotranspiration rate.

Soil  $\text{NH}_4^+$  can be converted to  $\text{NO}_2^-$  and then  $\text{NO}_3^-$  through a series of oxidative reactions by a microbially driven process called nitrification (Norton 2008) that is affected by edaphic factors such as soil pH and temperature (Ogbazghi et al. 2016, Sahrawat 2008). The conversion of  $\text{NH}_4^+$  to  $\text{NO}_2^-$  is controlled by *Nitrosomonas* bacteria and the conversion of  $\text{NO}_2^-$  to  $\text{NO}_3^-$  by *Nitrobacter* species. The formation of  $\text{NO}_3^-$  is very important as it is a form that is taken up by plants and is also subject to losses through leaching and denitrification (Levy et al. 2011). Irrigation with wastewater increases nitrification in soils due to enhanced microbial activity (Sahrawat 2008). Darwesh (2015) conducted incubation studies by irrigating three soil types (light, heavy textured and silty loam soils) up to 60 % soil field

capacity using treated wastewater and reported an increased nitrification rate in all soils. Bame et al. (2013) conducted column leaching studies using three soils (a clay, a sand and a soil with high organic matter) and reported increased nitrification in all the soils treated with DEWATS effluent.

The residual soil  $\text{NO}_3^-$  undergoes a series of processes which lead to its loss from the soil. The  $\text{NO}_3^-$  is denitrified to  $\text{N}_2\text{O}$ ,  $\text{NO}$  and  $\text{N}_2$  (Hu et al. 2017); a process driven by bacteria such as *Pseudomonas spp.* and *Clostridium spp.* (Brady and Weil 2016). Denitrification occurs under anaerobic conditions caused by excess irrigation as reported by several authors using wastewater (Barton et al. 2000, Feigin et al. 2012, Hernández-Martínez et al. 2016). Denitrification was faster in heavy textured soils when wastewater fertigation was applied (Barton et al. 2000).

#### 2.3.1.1.2 Phosphorus dynamics

Phosphorus behaviour in soils fertigated with treated wastewater is shown in Figure 2.2. Elemental phosphorus is highly reactive and does not exist in nature hence it reacts with oxygen to form orthophosphates ( $\text{PO}_4^{3-}$ ) (Lusk et al. 2017). Orthophosphates in water are converted to  $\text{HPO}_4^{2-}$  under alkaline conditions and  $\text{H}_2\text{PO}_4^-$  under acidic conditions (Brady and Weil 2016). Phosphorus inorganic forms in wastewater come from detergents (orthophosphates;  $\text{H}_3\text{PO}_4$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{HPO}_4^{2-}$ , and  $\text{PO}_4^{3-}$  and polyphosphates;  $\text{P}_2\text{O}_7^{4-}$  and  $\text{P}_3\text{O}_{10}^{5-}$ ) and organic forms are predominantly from faecal matter (phospholipids, nucleotides and sugars) (Lusk et al. 2017).

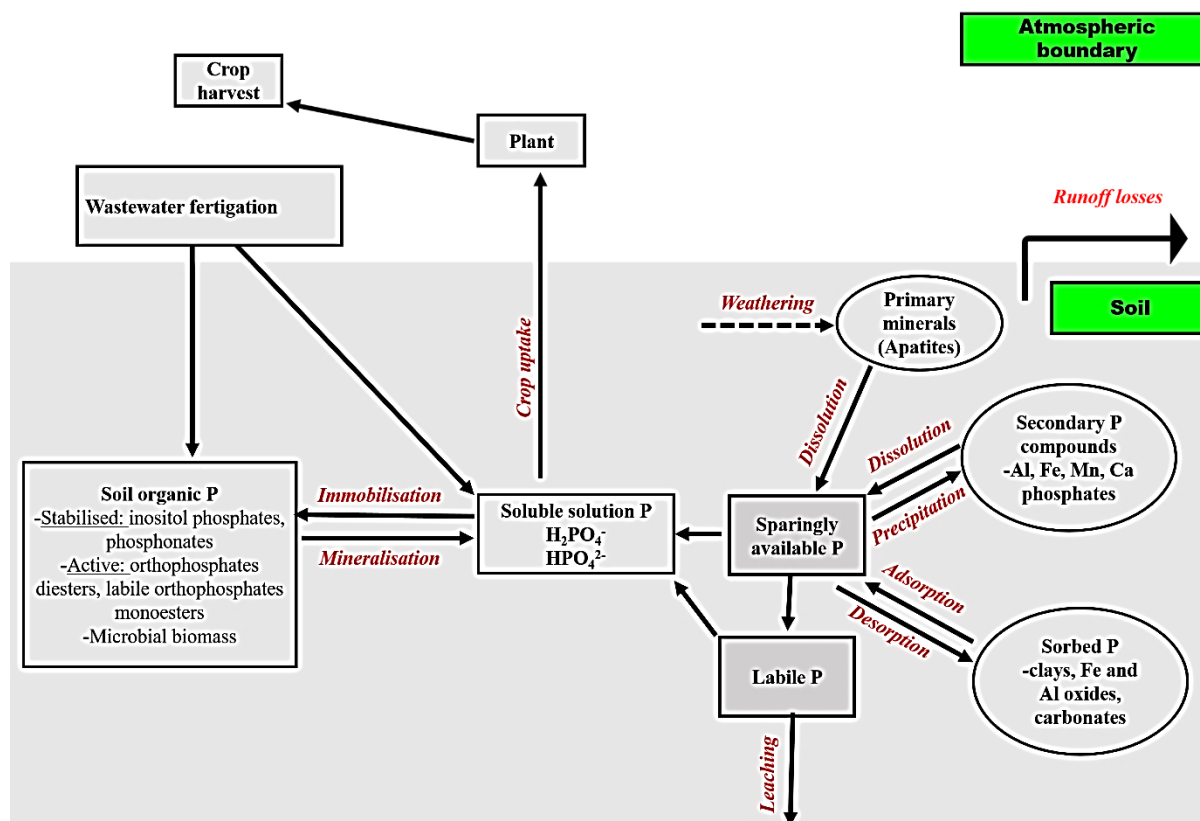


Figure 2.2: Phosphorus dynamics in wastewater fertigated soils (based on information by Shen et al. (2011), Brady and Weil (2016) and Lusk et al. (2017)).

Soil P occurs as solution P, labile P and non-labile P (Brady and Weil 2016). Solution P is the smallest fraction and is available for plant uptake. Although it constitutes a small portion of the total soil P, labile P is more than solution P, is not strongly bound to soil colloids and is in direct equilibrium with solution P. Non-labile P is a stable portion that is unavailable for plant uptake and constitutes the largest part of total soil P. Non-labile P can undergo chemical reactions to produce labile and soluble P but most of it remains permanently inactive (Brady and Weil 2016).

Irrigation using wastewater supplies soils with both organic and inorganic P (Figure 2.2). Organic phosphates such as pyrophosphates in wastewater undergo mineralisation to produce inorganic forms of P (Stewart and Tiessen 1987); a process that is biologically mediated. (Lusk et al. 2017). Zohar et al. (2010) investigated transformations of inorganic P in different fractions of a clay soil using isotopic oxygen in orthophosphate. They reported isotopic alterations of different P pools due to intense biological activity in their wastewater irrigated soils.

Several studies reported increased P content within the top layers of soils irrigated with wastewater due to its immobile nature in soil (Bame et al. 2013, Mulidzi et al. 2016, Yadav et al. 2002). This immobility is caused by processes such as adsorption, immobilisation and precipitation (Levy et al. 2011). Phosphorus

adsorption occurs when orthophosphates tightly bind to soil colloids such as clay minerals and Al/Fe oxides or hydroxides (Brady and Weil 2016, Fink et al. 2016, Lusk et al. 2017). Phosphorus adsorption capacities depend on soil mineral type and pH (Shen et al. 2011). Highly weathered soils with high goethite content were reported to have very high surface area for P adsorption (Brady and Weil 2016, Fink et al. 2016, Lusk et al. 2017). High P adsorption occurs in acidic soils due to increased concentrations of Al and Fe which form very strong bonds with P (Levy et al. 2011). In neutral to calcareous soils, P can be precipitated as dicalcium phosphate which may be transformed to stable compounds such as hydroxyapatite at alkaline pH (Shen et al. 2011).

Phosphorus availability for plant uptake is affected by its desorption rate from the soil colloids as well as its dissolution rate from P precipitates (Shen et al. 2011). The P desorption rate depends on the organic matter content, soil pH and the presence of other anions (Brady and Weil 2016). Soil organic acids such as citrate increase P desorption from soil colloids as they compete with P for sorption sites and modify the bonding energy of adsorbed P (Antelo et al. 2007, Souza et al. 2014). The solubility and desorption of soil P in wastewater irrigated soils is more affected by the buffering action of basic cations ( $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ) than the effluent pH (Bame et al. 2014, Mulidzi et al. 2016).

#### 2.3.1.1.3 Leaching and environmental impacts of wastewater irrigation

Environmental pollution through nutrient (especially N and P) leaching and runoff losses in wastewater fertigated soils, is a major issue of concern (USEPA 2012). Movement of nutrients down the soil profile through leaching may affect water table quality (Hamdi et al. 2013) while losses through surface runoff contribute to contamination of surface water resources (Sharpley et al. 2001).

The nitrate anion is not adsorbed by the soil colloids and hence easily leaches down the soil profile (Feigin et al. 2012) especially when in excess of plant requirements (Vazquez-Montiel et al. 1996). The leaching of  $\text{NO}_3^-$  is affected by irrigation management practices, climatic conditions and soil type (Feigin et al. 2012, Levy et al. 2011, Tesfamariam et al. 2015). High rainfall regimes and excessive irrigation increase  $\text{NO}_3^-$  fluxes down the soil especially in coarse textured soils. Insignificant effects of treated wastewater fertigation on  $\text{NO}_3^-$  leaching were reported in some studies (Lal et al. 2015, Musazura et al. 2015). Musazura et al. (2015) reported higher concentrations of  $\text{NO}_3^-$  in the top 0.3 m compared to 0.5 m depth of a clay loam soil fertigated with ABR effluent over a short period (May 2012 to April 2013). An eight year study by Lal et al. (2015) showed higher concentrations of  $\text{NO}_3^-$  in the top 0.3 m and its leaching was very low under an agroforestry production system.

Several studies have confirmed low P leaching in treated wastewater fertigated soils (Bame et al. 2013, Johns and McConchie 1994, Musazura et al. 2015). Phosphorus losses through leaching are less expected



due to sorption and precipitation processes which retain it within the soil profile (Bame et al. 2013, Sharpley et al. 2001, Shen et al. 2011). Column leaching studies by Bame et al. (2013) using ABR effluent showed high concentrations of P in the three different soils due to effluent loading. A similar low leaching rate agreed with Musazura et al. (2015) on the same clay loam soil under field conditions. Johns and McConchie (1994) investigated the effects of fertigating banana plants with treated wastewater in lysimeters at Woolgoolga, Australia. They reported accumulation of P in the soil with negligible concentrations in leachates.

Phosphorus losses through runoff are a major contributor to surface water contamination (Sharpley et al. 2001). High concentrations of P in heavy clay soils can be lost through surface runoff and lead to algal blooms (Heckrath et al. 1995). Fertigation with treated wastewater can increase soil P content due to adsorption and precipitation in the soil (Bame et al. 2013, Bame et al. 2014). Phosphorus is lost through surface runoff especially when management practices such as frequent tillage and excessive irrigation are used (Sharpley 2016). A study by Wang et al. (2015) on the effectiveness of conservation tillage and optimised fertilisation showed that both reduced the amount of P lost by runoff.

Nitrogen and P leaching in agricultural soils can be managed through irrigation scheduling that allows for rainfall (Tesfamariam et al. 2013). Blum et al. (2013) investigated nutrient dynamics in a treated wastewater fertigated tropical Brazilian soil under sugarcane. They reported increased  $\text{NO}_3^-$  leaching at 100 % crop water demand but there were no threats to the water table quality.

#### 2.3.1.2 Other macronutrients (Ca, Mg, K and S)

Most of the macronutrients in treated wastewater (about 53 - 99 %) exist as cations in solution and are readily available for plant uptake (Jaramillo and Restrepo 2017, Pedrero et al. 2010, Qadir et al. 2015). These nutrients have specific roles in the metabolism of plants and crops cannot grow or complete their life cycle in their absence, hence they are referred to as essential elements (Brady and Weil 2016).

Fertigation using treated wastewater has been reported to increase soil concentrations of macronutrients (Alghobar and Suresha 2016, Bame et al. 2013, Barreto et al. 2013). Barreto et al. (2013) in Brazil reported increased macronutrient concentrations within the top layers of a Fluvic Neosol planted with castor bean (*Ricinus communis*) and fertigated with treated wastewater. Column leaching studies by Bame et al. (2013) showed higher K concentrations in a clay soil leached with ABR effluent compared to the high organic matter soil and a sandy soil. Increased macronutrients in wastewater fertigated soils may result in nutrient imbalances (Pedrero et al. 2010) but according to Kiziloglu et al. (2008) this might not occur when using treated wastewater as it may not provide excessive macronutrients. To manage nutrient imbalances Pedrero et al. (2010) suggested that periodic monitoring be done.

### 2.3.1.3 Micronutrients (Mn, Cu, Zn, Bo, Fe)

Treated wastewater contains very low concentrations of micronutrients (Alghobar 2014, Bame et al. 2013, Levy et al. 2011, Musazura et al. 2015). Bame et al. (2013) and Musazura et al. (2015) also reported very low concentrations of micronutrients in ABR effluent. Several authors reported variable results on the accumulation of micronutrients in wastewater fertigated soils (Jaramillo and Restrepo 2017, Mohammad and Mazahreh 2003, Yadav et al. 2002). Mohammad and Mazahreh (2003) reported increased soil Fe and Mn but no changes in Cu and Zn concentrations after fertigation with secondary treated wastewater in a relay cropping system with maize (*Zea mays*) and vetch grass (*Vicia sativa*). Asgharipour and Azizmoghaddam (2012) investigated the effects of wastewater on mineral nutrients in foxtail millet plant (*Setaria italica*) and reported that the soil Mn and Zn concentrations were too low to meet crop demands. Alghobar (2014) and Khaskhoussy et al. (2015) reported only increased Cu and Cl concentrations in fields under treated wastewater fertigation. Therefore, not all micronutrients are supplied by treated wastewater to meet crop requirements. Alghobar and Suresha (2016) reported lower growth and yield of rice fertigated with treated wastewater due to a high concentration of soil micronutrients, although the effluent complied with the Food and Agriculture Organisation (FAO) water quality guidelines for leaching and irrigation of short season crops (Pescod 1992).

Most of the heavy metals in domestic sewage are adsorbed onto sewage sludge and therefore are less likely to be found in wastewater unless it has been contaminated by industrial activities (Levy et al. 2011). The ABR effluent used by Bame *et al.* (2013) and Musazura *et al.* (2015) was also reported to contain heavy metals below the FAO maximum permissible levels, indicating its potential for agricultural use. Some studies reported increased heavy metal concentrations in soils fertigated with wastewater (Al Omron et al. 2012, Bedbabis et al. 2010, Khaskhoussy et al. 2015). This can be due to their not being bioavailable resulting from soil properties such as high soil pH and clay content (Christou et al. 2014). According to Xu et al. (2010) heavy metals are expected to increase in the top layers of the soil over a long period (> 20 years) of fertigation. On the other hand, Rusan et al. (2007) investigated heavy metal concentrations in fields fertigated with treated wastewater but no significant amounts of Pb, Ni, Cd, Zn and Fe were detected in comparison to non-fertigated fields over a short period (two years) to a longer period (10 years). Some heavy metals are mobile so they accumulate in lower layers of the soil. Khaskhoussy et al. (2015) reported increased Cu, Cd and Ni in a treated wastewater fertigated field but the concentrations of Zn, Co and Pb did not significantly change. They further found that Zn and Co increased with soil depth due to leaching by fertigation water. Mojiri and Hamidi (2011) attributed heavy metal increase in the soil to either the composition of the treated wastewater or increased solubility of inherent insoluble soil heavy metal fractions from the chelation action of irrigated wastewater. Uzen et al. (2016) investigated the effects of treated wastewater (after anaerobic stabilisation) on cotton yield in

South Eastern Anatolia, Turkey and they did not observe any changes in soil heavy metals due to their absence in the wastewater used.

#### *2.3.1.4 Long term effects of fertigating with treated wastewater*

Long term use of treated wastewater has significant effects on soil properties such as pH, organic C, nutrients and microbial activity (Bedbabis et al. 2015, Mollahoseini 2013, Rusan et al. 2007). Soil pH is defined as the master variable in the soil which controls processes such as bioavailability of mineral nutrients, cation exchange capacity (CEC) and mineralisation of organic compounds (Jaramillo and Restrepo 2017, Saldías et al. 2016). Studies have reported variable effects of treated wastewater (primary, secondary and tertiary) on soil pH (Jaramillo and Restrepo 2017). Some long-term studies reported a slight decline in soil pH of soils fertigated with treated wastewater (Al Omron et al. 2012, Angin et al. 2005, Rattan et al. 2005, Xu et al. 2010) and others have reported an increase in soil pH (Christou et al. 2014, Galal 2015, Santos et al. 2017). Changes in soil pH due to fertigation with treated wastewater have been attributed to its buffering effect (Adrover et al. 2010, Bame et al. 2014, Belaid et al. 2012, Herpin et al. 2007). Treated wastewater increases soil pH in acidic soils (Adrover et al. 2010) and lowers it in alkaline soils (Fonseca et al. 2007). Increased soil pH has not been attributed to the wastewater pH but to the addition of exchangeable cations (Adrover et al. 2010, Bame et al. 2014, Mulidzi et al. 2016) and denitrification which removes H<sup>+</sup> ions (Friedel et al. 2000). On the other hand, a decline in soil pH in alkaline soils is due to leaching of basic cations (Solís et al. 2005) and the nitrification of N in the wastewater applied (Pound et al. 1978).

Treated wastewater contains very low concentrations of organic carbon compared to biosolids and it occurs as dissolved organic matter (DOM) (Chen et al. 2011b). Long term irrigation with treated wastewater has been reported to increase soil organic matter (SOM) in the topsoil (Al Omron et al. 2012, Angin et al. 2005, Friedel et al. 2000, Hentati et al. 2014, Xu et al. 2010). This occurs when large volumes of treated wastewater is used for fertigation (Friedel et al. 2000). However, it has also been shown that with continued fertigation the easily degradable SOM tends to decrease (Jueschke et al. 2008). This occurs due to increased microbial activity leading to breakdown of the SOM (Adrover et al. 2010, Homem et al. 2014, Jueschke et al. 2008, Minz et al. 2011).

#### **2.3.2 Physical properties**

Fertigation with treated wastewater has benefits and drawbacks on soil physical properties such as aggregate stability, hydraulic conductivity, water and nutrient retention (Jaramillo and Restrepo 2017).

### 2.3.2.1 Aggregate stability

Soil aggregate stability (AS) refers to the ability of soil aggregates to resist disruption by external forces (Pescod 1992). It is regarded as an essential property that controls physicochemical and biological processes as well as SOM, moisture holding capacity and nutrient retention (Brady and Weil 2016). There are many factors that affect AS and these can be environmental (soil temperature and moisture), biotic or abiotic. Biotic factors include plant roots, soil fauna and microorganisms while abiotic factors include clay minerals, sesquioxides and exchangeable cations (Brady and Weil 2016).

Fertigation using wastewater with high sodium adsorption ratio (SAR) was reported to reduce AS especially in tropical soils (Schacht and Marschner 2015). Most studies have confirmed that application of treated wastewater improves AS due to the influence of organic matter (Hentati et al. 2014, Jaramillo and Restrepo 2017, Levy et al. 2014b, Tarchitzky et al. 2007). Soil organic matter can reduce soil bulk density and promote aggregation of soil particles. According to Guerif (1994) AS depends on the chemical composition of the SOM. Dissolved organic matter increases AS by lowering soil wettability and increasing cohesion of aggregates due to its binding action and microbial activity (Vogeler 2009).

A combination of SOM and sodicity may contribute to slaking of soil aggregates. According to Levy (2011) decreasing AS in clay soils results from a combination of a high concentration of humic substances and sodicity. The influence of wastewater on AS of clay soils is also more pronounced in cultivated soils than under zero tillage (Bhardwaj et al. (2007).

### 2.3.2.2 Hydraulic conductivity

Saturated hydraulic conductivity ( $K_{sat}$ ) is a measure of the soil's ability to transmit water when subjected to a hydraulic gradient and this is affected by AS (Vogeler 2009). Decreased  $K_{sat}$  in treated wastewater fertigated soils is well documented (Levy et al. 2014a, Qian and Meham 2005, Sepaskhah and Karizi 2011). The  $K_{sat}$  is affected by several factors such as high SAR (Lado and Ben-Hur 2009, Schacht and Marschner 2015) and the composition of DOM (Levy et al. 2014b).

The effects of DOM on  $K_{sat}$  is more pronounced in fine textured soils than coarse textured soils since the aggregate stability of the former soil is more sensitive to the composition of DOM (Levy et al. 2014b). According to Lado and Ben-Hur (2009),  $K_{sat}$  can be reduced through the blockage of soil pores by the suspended solids as the effluent moves down the soil profile of a clay loam soil. On the other hand, this is less likely to happen on sandy loam soils due to their larger average pore size. This was also confirmed by Vogeler (2009) who did not find any significant changes in hydraulic conductivity of light textured soils fertigated with treated wastewater over periods of 12 and 22 years.

### 2.3.3 Microbial properties

Soil microbial populations are the major indicators of soil quality as they are very dynamic and easily affected by anthropogenic activities (Friedel et al. 2000). Treated wastewater can increase beneficial microorganisms in the soil which are responsible for different processes such as organic matter degradation, nutrient transformations and indirect enhancement of nutrient bioavailability (Zdenek and Demnerova 2007). Soil microbial populations and compositions are affected by many factors such as organic matter, soil pH, temperature, texture, salinity and heavy metals (Guo et al. 2017).

Fertigation with wastewater can increase or alter microorganism populations in the soil (Hentati et al. 2014). This occurs over a long period of fertigation as confirmed by several authors (Friedel et al. 2000, Hentati et al. 2014, Sklarz et al. 2013). Organic matter is the main contributor to microbial populations in the soil (Friedel et al. 2000, Sklarz et al. 2013, Tsiknia et al. 2014).

## 2.4 Crop growth, development and biomass production

Treated wastewater is an important source of mineral nutrients and water required for optimum growth of crops. Fertigation with treated wastewater must be done following irrigation scheduling that aims to meet crop water demands at the same time providing nutrients and avoiding loss of especially N and P.

### 2.4.1 N and P uptake mechanisms

One of the ways in which N is removed from wastewater fertigated fields is through uptake by plants (FAO 2003). Nitrogen uptake by crops depends on crop type as those adapted to anaerobic soils take up  $\text{NH}_4^+$  while those in aerobic soils take up  $\text{NO}_3^-$  (Masclaux-Daubresse et al. 2010). The  $\text{NO}_3^-$  is taken up from the soil solution through the plasma membrane of the root cortex by an active process (Mitra 2016). The N is distributed into different plant parts where it is utilised in plant biochemical reactions such as protein synthesis (Mitra 2016). Wastewater fertigation increases crop N uptake as reported by several authors. Hernández-Martínez et al. (2016) reported 65 % N uptake by rye grass (*Lolium rigidum*) and oats (*Avena sativa* L.) from soil fertigated with wastewater under field conditions. Bame et al. (2014) conducted pot experiments with three different soils and reported high plant tissue N concentrations in maize irrigated with DEWATS effluent. Bedbabis et al. (2010) reported high N concentrations in leaves of olive trees fertigated with treated wastewater over two years compared to trees irrigated with well water under field conditions. Musazura et al. (2015), however, reported insignificant differences in N uptake between the Swiss chard fertigated with DEWATS effluent, and inorganic fertiliser amended treatments under field conditions.

Phosphorus is absorbed by plant roots in two forms which can either be  $\text{H}_2\text{PO}_4^-$  or  $\text{HPO}_4^{2-}$  (Shen et al. 2011). These nutrients are taken up through high affinity active transport systems against a steep chemical

potential gradient through the plasma membrane of root cortical and root epidermal cells (Shen et al. 2011). Phosphorus is generally less mobile hence its uptake is enhanced by root architecture or mycorrhizal fungi (Marschner 2011). In case of P starvation plants alter their root morphology, topology and distribution patterns to increase surface area for P uptake. Arbuscular mycorrhizal fungi form symbiotic relationships with plant roots and increase their P absorption surface area. The rhizosphere is the critical zone for the interaction of plants, soil and microorganisms. Different processes that ensure P bioavailability within the rhizosphere are affected by microorganisms, root exudates and acidification. Plants exude chemicals in the rhizosphere which acidify the sparingly available P (Marschner 2011). Rhizosphere and soil microorganisms can enhance acquisition of plant P by influencing solubilisation of P to plants or through hormonal induced plant growth.

#### 2.4.2 N and P crop requirements

Nutrient requirements of crops vary with crop type and stage of growth (Table 2.1). Leaf vegetables take up N and P continuously to promote vegetative growth but most fruiting crops take up nutrients during the vegetative growth and assimilate them to reproductive organs during the reproductive stage (Bar-Tal et al. 2015). Most grass crops such as reed canary grass, sudan grass, bermuda grass, rye grass and Johnson grass have high nutrient uptake capacity (Pescod 1992, Seshadri et al. 2014b, Tesfamariam et al. 2009, Zhang et al. 2017). This is because of their deep root systems which can utilise more nutrients from the soil (FAO 2003). Nutrients provided in excess of crop requirements may reduce yields. For example, excess N may delay flowering and indirectly cause plant diseases (Pedrero et al. 2010). Excessive nutrients in the soil depend on effluent loading, concentrations and bioavailability (Bar-Tal et al. 2015). Excess nutrients in the soil can be managed through monitoring soil nutrient status, choice of crop and crop rotation systems with deep rooted crops (FAO 2003).

*Table 2.1: Nutrients required by selected crops for canopy formation and fruit production/yield (adapted and modified from FAO 2003).*

Plant part	Nutrient	Potato	Tomato	Eggplant	Pepper	Strawberry	Lettuce	Mango	Banana	Citrus
Canopy (kg ha <sup>-1</sup> )	N	86	95	105	90	85	*115	70	250	85
	P	7	12	13	6	5	*14	6	26	8
Fruit (kg ton <sup>-1</sup> )	N	**3.2	1.8	1.96	2	1.17	-	1.35	2	1.44
	P	**0.54	0.17	0.17	0.26	0.22	-	0.19	0.22	0.19

\*Whole plant

\*\*Potato tuber

#### 2.4.3 Effect of wastewater irrigation on crop growth, biomass and yield

Fertigation using treated wastewater was reported to increase crop growth and yield in forage (Mohammad and Ayadi 2004), arable (Bame et al. 2014, Guo et al. 2016), fruit trees (Bedbabis et al.

2015) and vegetable crops (Musazura et al. 2015). Treated wastewater can thus increase crop growth and yield comparably to conventional fertilisers. Musazura et al. (2015) investigated the effects of ABR effluent on Swiss chard growth over three cropping cycles. The Swiss chard growth and yield results were comparable between the effluent and recommended practice (tap water + fertiliser) due to its high N and P content. This also confirmed a study by Castro et al. (2013) who reported higher lettuce yield in wastewater fertigated soil compared to conventional fertilisers. Treated wastewater may improve crop growth and yield in poor soils since it provides nutrients and improves soil properties (Section 2.3). The glasshouse study by Bame et al. (2014) on the effects of ABR effluent on maize biomass in three different soils investigated inorganic fertiliser applied at three levels (no fertiliser, half and full recommended rate) and two irrigation water sources (ABR vs tap water). They reported a significantly higher maize biomass in the sandy soil under ABR effluent fertigation compared to tap water irrigation at full fertiliser recommended rate. They attributed the high crop growth in ABR effluent to its liming action and nutrient content. Despite these reported benefits of treated wastewater on crop growth, yield and quality, some negative results on reduced growth and yield have also been reported and have been attributed to presence of chemicals such as detergents (Day and Tucker 1959), excessive N (Feigin et al. 1984) and salts (Alghobar and Suresha 2016).

Forage crops have been used extensively for wastewater irrigation due to their ability to uptake more nutrients, their high water consumption in all seasons and their ability to prevent soil erosion (Pescod 1992). Treated wastewaters have been reported to improve the growth, yield, and nutritive value of forage crops (Mohammad and Ayadi 2004, Muklada et al. 2017, Pescod 1992, Rusan et al. 2007). Increased crop growth was attributed to increased nutrients in the soil and their subsequent uptake by crops. Mohammad and Ayadi (2004) carried out a study on the effects of treated wastewater on forage yield and nutrient uptake under field conditions. The yield of both vetch and maize grass increased with wastewater fertigation due to its nutrient content. These findings agreed with studies by Guo et al. (2016) who reported increased maize yield in wastewater fertigated soil in both pot and field experiments.

## **2.5 Implications for human health of using treated wastewater**

Irrigation of crops with treated wastewater must comply with human safety in terms of pathogens, heavy metals and emerging contaminants (WHO 2006).

### **2.5.1 Pathogens in treated domestic wastewater**

Bacteria are microbes with a length of between 0.2 and 10  $\mu\text{m}$ . Wastewater contains both harmless and pathogenic bacteria (USEPA 2012). Pathogenic bacteria are usually found in lower concentrations

compared to coliform groups (Pescod 1992). The bacterial species found in wastewater include *Escherichia coli*, *Salmonella spp.*, *Shigella spp.* and *Vibrio cholerae*. The faecal coliform *E. coli* is used as an indicator of faecal contamination because of its simplicity to isolate and identify. Other pathogen of concern belongs to the *Streptococcus* group. *Streptococcus bovis* and *S. equinus* are found in animals alone, *S. faecalis* and *S. faecium* occur both humans and animals, and other species such as *S. faecalis var liquefaciens* occur in both polluted and unpolluted water (Pescod 1992). *Clostridium perfringens* forms spores and thus has survival characteristics like viruses and helminths. *Salmonella spp.* include pathogenic bacteria such as *S. typhi* (typhoid causing) which are spread through ingestion of contaminated food (Blumenthal et al. 2000).

Viruses in treated wastewater include hepatitis A virus, hepatitis E virus, adenovirus, rotavirus and norovirus (WHO 2006). Enteroviruses are viruses which cause diseases such as meningitis and poliomyelitis and they are common in tropical climates (Blumenthal et al. 2000). Rotaviruses are responsible for most gastro- intestinal diseases although they exist in lower concentrations than enteroviruses. Most viruses are resistant to environmental stresses although there are some which have a short life span outside a human host (USEPA 2012). Viruses are very difficult to remove through conventional wastewater treatment processes such as sedimentation and filtration due to their relatively small size and they need high doses of ultraviolet (UV) treatment (USEPA 2012).

Helminths are a group of intestinal parasites which include flatworms (*Schistosoma spp.*), tapeworms (*Taenia solium*) and roundworms (*Ascaris spp.* and *Trichuris spp.*). Roundworms (*Ascaris lumbricoides*) are of major concern as they easily spread in wastewater irrigated lands. The eggs of *A. lumbricoides* are large (45-70  $\mu$  m \* 35-50  $\mu$  m) (WHO 2006). Children under the age of 15 are at higher risk to *Ascaris* compared to adults (Blumenthal et al. 2000). They produce eggs which are resistant to harsh environments and can survive over ten years in soil making them one of the most ubiquitous parasites (WHO 2006). Different groups of people are at different risk of infections. Workers who do not wear shoes, consumers eating raw food which was in contact with untreated wastewater and nearby communities where sprinkler irrigation is used are most vulnerable. One of the risk management methods suggested by WHO (2016) is the use of wastewater treated to < 1 egg per litre of helminths.

### **2.5.2 Heavy metal accumulation in plants**

Heavy metals in plants can be of health concern. The main heavy metals of concern in wastewater used for irrigation are given in Table 2.2. Cadmium and Cr are examples of heavy metals of concern due to their non-essentiality to both animals and crops (Levy et al. 2011). Some heavy metals such as Se are



beneficial especially in South Africa, where it is deficient in many pastures where it is supplemented through fertilisers (Müller and Engelbrecht 2018).

The bioavailability of heavy metals by plants is affected by several factors including soil pH, organic matter and soil type (Hass et al. 2011, Jaramillo and Restrepo 2017). The presence of organic matter allows chelation of heavy metals thereby contributing to their bioavailability (Levy et al. 2011). Bioavailability of heavy metals is also very high in low clay content soils at low pH (Mojiri and Hamidi 2011). Plants fertigated with treated wastewater may take up heavy metals which can be health hazardous (Flores-Márgez et al. 2013, Hass et al. 2011, Kiziloglu et al. 2008, WHO 2006). However, several studies confirmed plant concentrations that were within the WHO permissible levels for safe human consumption (Christou et al. 2014, Rattan et al. 2005, Yadav et al. 2002). Despite this fact a study by Balkhair and Ashraf (2016) reported increased heavy metals in okra fertigated with treated domestic wastewater and the effluent used was the main cause of contamination. Uzen et al. (2016) reported insignificant uptake of heavy metals by cotton fertigated with treated wastewater since the effluent used had low concentrations of heavy metals. Sometime heavy metals may be taken up by plants but not translocated to edible parts. Lu et al. (2015) investigated long term fertigation with treated wastewater on accumulation of heavy metals in plant residues and maize cobs. The authors reported lower concentrations of heavy metals in maize cobs compared to roots and leaves. This may be a problem if the crop is used for forage.

The uptake of heavy metals by forage crops may allow their transfer along the food chain (crop-animal-humans) thereby posing health risks (Flores-Márgez et al. 2013). Even though heavy metals are expected to accumulate in the soil over a long period sometimes their bioaccumulation in plant tissues might not reach toxic levels for human consumption (Rusan et al. 2007). There is not much evidence of heavy metal transfer from fodder to animals and then humans. Flores-Márgez et al. (2013) investigated the uptake of heavy metals (Cd, Cr, Ni and Pb) from treated wastewater to oats (*Avena sativa L.*) and to sheep tissues. The authors reported insignificant bioaccumulation of heavy metals in sheep tissues and they concluded that treated wastewater fertigation did not pose heavy metal contamination risks.

Table 2.2: Threshold levels of heavy metals for crop production

Element	Recommended maximum thresholds in wastewater (mg L <sup>-1</sup> )	Remarks
<b>Aluminium (Al)</b>	5.0	Reduces productivity in soils (pH < 5.5), it is precipitated at more alkaline soil (> 7) and eliminate its toxicity.
<b>Arsenic (As)</b>	0.10	Variable toxicity, ranging from 12 mg L <sup>-1</sup> (Sudan grass) to 0.05 mg L <sup>-1</sup> (rice).
<b>Beryllium (Be)</b>	0.1	Variable toxicity to plants; 5 mg L <sup>-1</sup> (kale) to 0.5 mg L <sup>-1</sup> (bush beans).
<b>Cadmium (Cd)</b>	0.01	Beans, beets and turnips are very susceptible at concentrations as low as 0.1 mg L <sup>-1</sup> in wastewater. Conservative limits are recommended due to its potential for accumulation in plants and soils to concentrations harmful to humans.
<b>Cobalt (Co)</b>	0.05	Toxic to tomato plants at 0.1 mg L <sup>-1</sup> in wastewater. It is inactivated be neutral to alkaline pH in soils.
<b>Chromium (Cr)</b>	0.01	It is not an essential growth element. Conservative limits recommended due to limited knowledge about its toxicity to plants.
<b>Fluoride (F)</b>	1	Inactivated in neutral to alkaline soils.
<b>Lead (Pb)</b>	5.0	Can inhibit cell growth at very high concentrations.
<b>Lithium (Li)</b>	2.5	Tolerated by most crops up to 5 mg L <sup>-1</sup> ; mobile in soils. Just like Bo it is toxic to citrus at low concentrations (< 0.075 mg L <sup>-1</sup> ).
<b>Molybdenum (Mo)</b>	0.01	Non-toxic to plants at normal concentrations in the soil and wastewater. Can be toxic to livestock if forage is grown in soils with high concentrations of available Mo.
<b>Nickel (Ni)</b>	0.2	Can be toxic to many plants at 0.5 to 1 mg L <sup>-1</sup> ; reduced toxicity at neutral to alkaline pH.
<b>Selenium (Se)</b>	0.02	Toxic to plants at concentrations as low as 0.025 mg L <sup>-1</sup> and toxic to livestock if forage is grown in soils with relatively high levels of added Se. It is an essential element to animals at very low concentrations.
<b>Titanium (Ti)</b>	-	Effectively excluded by plants and specific tolerance is not known.
<b>Vanadium (V)</b>	0.10	Can be toxic many plants at relatively low concentrations.

The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m<sup>3</sup> hectare<sup>-1</sup> year<sup>-1</sup>). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10 000 m<sup>3</sup> hectare<sup>-1</sup> year<sup>-1</sup>. The values given are for water used on a continuous basis at one site.

Source: Adapted from National Academy of Sciences and National Academy of Engineering (1972) and Pratt (1972) and cited by Pescod (1992).

### 2.5.3 Emerging contaminants in treated wastewater

Emerging pollutants are defined as chemicals (synthetic or naturally occurring) found in very minute quantities (micropollutants) in wastewater that are resistant to wastewater treatment (Clarke and Cummins 2015). These are described as new chemicals with no regulatory status and their impacts on human health and the environment are poorly understood (Deblonde et al. 2011). Examples of micropollutants include hormones such as oestrogen (Adeel et al. 2017), pharmaceutical compounds (Chen et al. 2011a,

Riemenschneider et al. 2016) and endocrine disruptors (WHO 2006). Some of their adverse effects such as reproductive abnormalities have been reported in several animal species (WHO 2006). Therefore, in recent years there has been a focus on their transmission and dynamics in the food chain (Jaramillo and Restrepo 2017, Malchi et al. 2014). Fertigation with treated wastewater has been identified as one of the ways in which they are introduced into the food chain (Daso et al. 2012, Riemenschneider et al. 2016). Several studies have investigated their occurrence in treated wastewater, dynamics in the soil, uptake by plants and their transmission within the food chain (Chen et al. 2011a, Deblonde et al. 2011, Malchi et al. 2014). Chen et al. (2011a) investigated the accumulation of different endocrine disruptors and pharmaceuticals in treated wastewater fertigated soils. They found that these micropollutants accumulated in soils but, except for triclocarban, they posed minimal risks to animals. Dissolved organic matter from treated wastewater was reported to be responsible for the sorption of organic micropollutants in soils (Ilani et al. 2005). Riemenschneider et al. (2016) studied the uptake of different micropollutants in various vegetable crops fertigated with treated wastewater and some of them including new micropollutants were detected even in edible parts of the vegetables. Most of them were concentrated in the leaves and roots with fewer in the fruits. They also carried out a risk assessment and found that most were not hazardous to health.

#### **2.5.4 Sanitation safety plans**

A sanitation safety plan (SSP) is defined as a risk based management tool for sanitation systems which assists in the implementation of the WHO (2006) guidelines for safe use of wastewater, excreta and greywater in agriculture and aquaculture (WHO 2016, Winkler et al. 2017). These plans provide a structure to bring different stakeholders to identify health risks in the sanitation system and come up with improvements and monitoring strategies. A diagram showing a sanitation safety plan's modules is shown in Figure 2.3. Different stakeholders involved within the system include local authorities, wastewater utility managers, sanitation enterprises, farmers, community based organisations, non-governmental organisations, health authorities and regulators, and policy makers (WHO 2016). The SSP manual assists users to (i) identify and manage health risks within the sanitation chain, (ii) maximise health benefits and reduce health risks, and (iii) give a guarantee to authorities and the public on the safety of sanitation related products and services (Winkler et al. 2017). After its introduction in 2010, several pilot projects have been implemented and regional workshops held in south Asia, and based on these the tool was shown to be promising in promoting the safe use of wastewater in agriculture (Winkler et al. 2017).

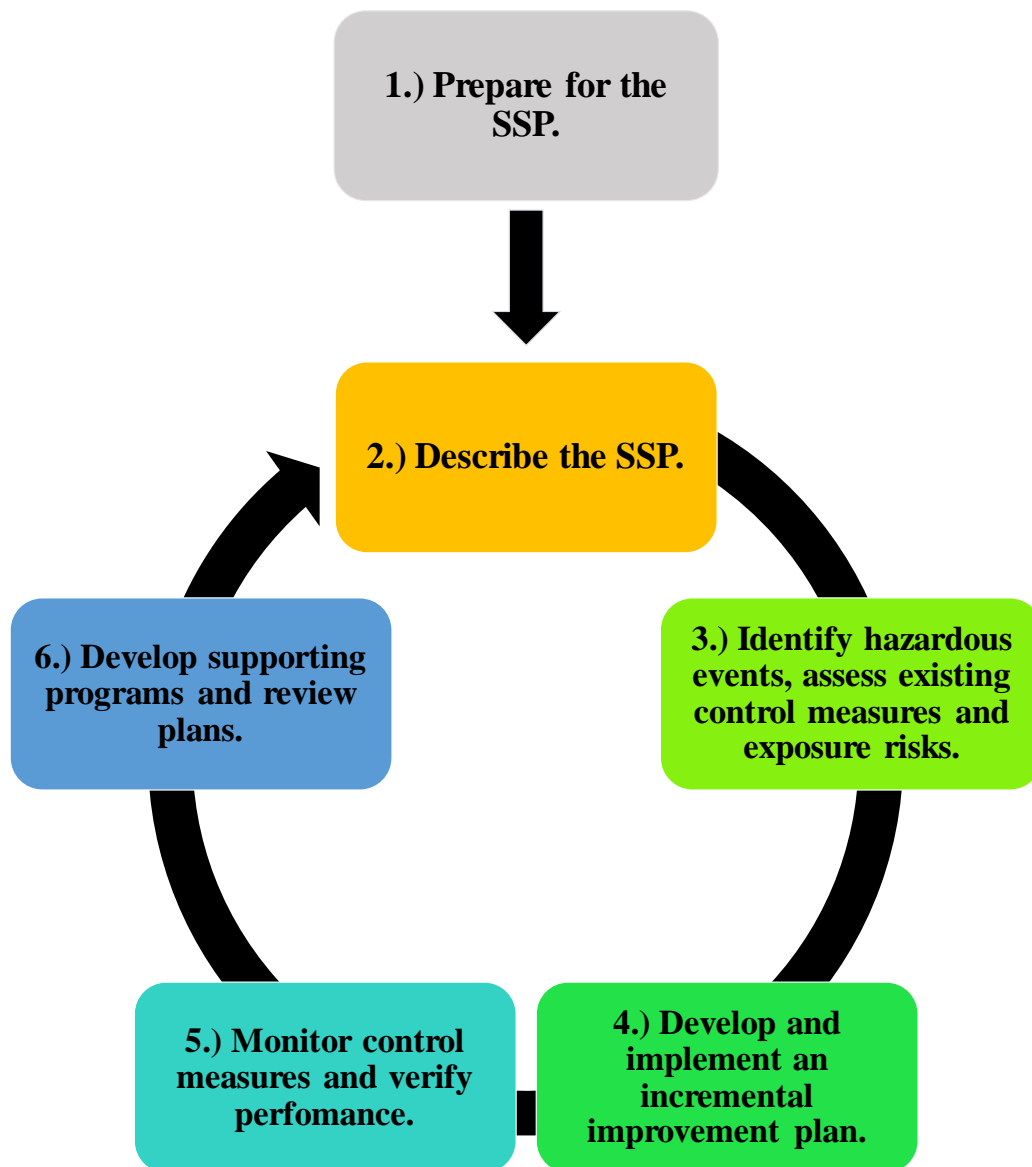


Figure 2.3: Sanitation safety plan modules (from WHO (2016))

## 2.6 Challenges in the implementation and upscaling of wastewater use projects

The use of treated wastewater in agriculture must be done in a way to maximise the benefits and minimise risks (WHO 2006, WWAP 2017). To achieve safe and sustainable wastewater use projects, practical, country-specific guidelines must be developed based on experimental data, models and existing international guidelines (Pescod 1992).

### 2.6.1 Policies and institutional aspects of wastewater use

Use of treated wastewater in agriculture is increasingly becoming a global practice despite its problems of health and environmental safety (Jaramillo and Restrepo 2017). Several guidelines have been produced by different international organisations with special focus on health aspects (WHO 2006), environmental

protection (USEPA 2012) and impact on crops (FAO 1985, Pescod 1992). These guidelines have been used as a reference for the development of wastewater use practical guidelines for different countries (Jaramillo and Restrepo 2017).

Each country must abide with the international policy on wastewater use in agriculture. This has an impact especially on the international export of food products where they should comply with the WHO guidelines for wastewater, excreta and greywater reuse in agriculture and aquaculture (WHO 2006). The WHO (2006) guidelines identified two different groups to be at risk to microbial contamination i.e., consumers and field workers (WHO 2006). Pathogen risk preventive measures included the development of Monte Carlo-based quantitative microbial risk assessment (QMRA) models which were used to generate estimates of a range of wastewater qualities. The QMRA model is generated based on information provided in Table 2.3. An estimated risk will be compared with the microbial quality guidelines.

*Table 2.3: Pathogen reduction achievable by various health protection measures (from WHO 2006)*

<b>Control measure</b>	<b>Pathogen reduction (log units)</b>	<b>Notes</b>
Wastewater treatment	1-6	Required pathogen to be achieved by wastewater treatment depends on the combination of health protection measures selected (pathogen reductions for different wastewater treatment options).
Localized (drip irrigation for low growing crops)	2	Root crops and crops such as lettuce that grow just above but partially in contact with the soil
Localized (drip irrigation for high growing crops)	4	Crops such as tomatoes, the harvested parts of which are not in contact with the soil
Spray drift control (spray irrigation)	1	Use of micro-sprinklers, anemometer-controlled direction switching sprinklers, inward-throwing sprinklers etc
Spray buffer zone (spray irrigation)	1	Protection of residents near spray or sprinkler irrigation. The buffer zone should be 50-100 m.
Pathogen die off	0.5-2 day <sup>-1</sup>	Die off on crop surfaces that occurs between last irrigation and consumption. The log unit reduction achieved depends on climate (temperature, sunlight intensity, humidity), time, crop type, etc.
Produce washing with water	1	Washing salad crops, vegetable and fruit with clean water.
Produce disinfection	2	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruit, root crops.
Produce cooking	6-7	Immersion in boiling or close to boiling water until the food is cooked ensures pathogen destruction.

In 1987 the Food and Agriculture Organisation (FAO) published water quality guidelines of agricultural significance (FAO 1985). The guidelines focused on issues such as the degree of restriction of water use with reference to salinity, infiltration and specific ion toxicity. Subsequently the FAO published suggested guidelines where the type of agricultural reuse was classified based on the type of crop to be irrigated (FAO 1999).

The United States Environmental Protection Agency (USEPA 1980) agricultural use of treated wastewater guideline had a special focus on preventing environmental pollution. The USEPA (2012) guidelines were updated to facilitate wastewater use projects based on global experiences. Some aspects included are the improvements in wastewater treatment technologies to promote health and environmental sustainability of wastewater irrigation.

The international guidelines provide opportunities for safe and sustainable wastewater use in countries like South Africa where a legal framework for water reuse has been developed. The South African Department of Water and Sanitation (DWS) formerly the Department of Water Affairs (DWAF) has included water reuse in their policies as an option for waste and wastewater management (Saldías et al. 2016). The recent DWS sanitation policy emphasised that human wastewater and excreta reuse in agriculture must comply with the National Environmental Management: Waste Act No. 59 of 2008 (NEMA) (DWS 2016). The NEMA focuses on reducing the amount of waste generated and where it may be reused, recycled and recovered in an environmentally sustainable manner. The DWAF (1996) is available for use as a primary source and a decision support tool for assessing the fitness of water quality for agricultural use. The National Water Act of 1998 (Act No. 36 of 1998) also provides water quality guidance for reuse or disposal into the environment with special focus on industrial, domestic and agricultural wastewaters (DWA 2013). Therefore, the South African policies provide an opportunity for water reuse in agriculture which, in conjunction with international regulations, ensure that safe and sustainable reuse projects are feasible.

### **2.6.2 Cost benefit analysis**

A comprehensive cost-benefit analysis on the reuse of treated wastewater in agriculture is recommended to ensure the long term environmental, economic and social sustainability of the practice (Arborea et al. 2017). Treated wastewater contains mineral nutrients and organic matter which can increase crop productivity thereby improving the livelihoods of society (WWAP 2017). Furthermore, agricultural systems are bio-filters which absorb water and nutrients for crop uptake thereby reducing costs required for expensive advanced wastewater treatments that enable it to be released into water bodies (Andersson et al. 2016, Keraita and Drechsel 2015, WWAP 2017). On the other hand, wastewater may release toxins into the environment, which may jeopardise public health and environmental safety (Hussain et al. 2002). It is crucial for policymakers to assess ways of minimising any negative impacts while maximising the benefits of using treated wastewater in agriculture (Hussain et al. 2002).

Several studies have been done on the cost-benefit analysis of using treated wastewater in agriculture (Arborea et al. 2017, Haruvy 1997, Hussain et al. 2002). Haruvy (1997) investigated ways of tackling

decision-making issues on the economic viability of disposing of treated wastewater and offsite use. Molinos-Senante et al. (2011) developed a theoretical methodology to assess internal and external economic impacts which was applied to various wastewater treatments in Valencia, Spain.

### **2.6.3 Social and cultural aspects**

Public acceptance is one of the major factors to be considered when a new technology or programme is to be introduced in an area (Roma and Buckley 2011). Social perceptions of handling human excreta and wastewater are variable across different communities (WWAP 2017). In high-income communities, the use of wastewater is considered undesirable due to its health impacts and unpleasant smell while in poor communities it is considered important as it improves their livelihoods (WWAP 2017). Most people in African and Asian countries consume vegetables fertigated with either treated or untreated wastewater (Keraita and Drechsel 2015, Mateo-Sagasta et al. 2015, WWAP 2017). Religious perceptions can also play a role in the acceptance of using wastewater in agriculture, for example some religions are sceptical about handling human excreta thereby making the practice difficult in such areas (WWAP 2017).

One of the challenges in the use of wastewater can be variations in perceptions across different stakeholders. Policymakers, local governments, regulators, politicians, academics and the public have different expectations and obligations. Sershen et al. (2016) conducted a multidisciplinary colloquium on water security in South Africa with special focus on perceptions amongst different stakeholders. Based on their study some of the drawbacks in acceptance of water reuse projects were lack of skills and will in government, loss of trust by citizens in the government and failure to upscale reuse projects.

Several measures can be taken to change peoples' perceptions towards handling of human excreta. One of the ways can be by educating the community about the benefits of using wastewater and how to implement health and safety methods to minimise risks (Keraita and Drechsel 2015, Raschid-Sally and Jayakody 2009, WWAP 2017). Peoples' trust in their government can be restored through improving government and public understanding of the water sector, by the provision of incentives on water reuse and environmental protection, and improving public capacity building in the sector (Sershen et al. 2016).

## **2.7 Modelling as a decision support tool**

Understanding the complexities of the dynamics occurring in agricultural systems can be assisted by models. Modelling is generally defined as the art of simulating a real situation (Dourado-Neto et al. 1998). According to Rimmington and Charles-Edwards (1987) models are simplified descriptions of a system, made to better understand the operation of a real system and interaction of its main components. Models can be classified as either static, mechanistic or empirical (Thornley and France 2007). Static models are

defined as steady state models which calculate the system in equilibrium where time is not variable. Empirical models describe the responses of a system using statistical or mathematical equations without any scientific content while mechanistic models give more details on the phenomena being modelled (van der Laan et al. 2014). Mechanistic models provide more knowledge on the phenology and responses to environmental changes (Steduto et al. 2009). Sometimes some models may contain aspects of the different approaches thereby serving both purposes (Singels et al. 2010).

Some of the decision-making processes on agricultural and environmental management as well as generating new knowledge in scientific research requires a lot of evidence-based information (Bellocchi et al. 2015). Such information can be obtained through a series of controlled and field experiments in different environments and over long periods. This is laborious and expensive considering that often immediate decisions must be made, therefore models are used as tools for extrapolating systems to new environments (Singels et al. 2010). Therefore, calibration and validation of models must be done based on experimental data, which might be complex and therefore one of the considerations made when choosing a model is its simplicity (van der Laan et al. 2014).

### **2.7.1 Modelling irrigation management and water and nutrient movement**

Water and nutrient management can be modelled at a number of different spatial scales (Kersebaum et al. 2007). According to Quinn (2004) these can be point ( $\sim 1 \text{ m}^2$ ), plot ( $\sim 25 \text{ m}^2$ ), hillslope ( $\sim 10\,000 \text{ m}^2$ ), small catchment ( $\sim 1 \text{ km}^2$ ) and large catchment ( $\sim 1\,000 \text{ km}^2$ ). Spatial variability in soil properties, geology, topography and management practices are the major factors driving different processes such as nutrient dynamics, fluxes, leaching and runoff processes (Rowlings et al. 2012). Therefore, to understand these processes better and generate information that will help in decision making by scientists and farmers, modelling should be done at a local scale (van der Laan 2009). van der Laan (2009) referred to local scale modelling as between plot and field scales. The influence of several processes occurring at field level have impacts on the larger areas such as catchments (Lu et al. 2016). Therefore, modelling can be upgraded from local to catchment scale. This can help decision makers (policymakers and Municipalities) when deciding on land use planning and implementation of environmentally sustainable agricultural practices (Styczen and Storm 1993). Several models have been used to simulate water and nutrient dynamics at different scales and these include the soil water balance (SWB-Sci) model (Annandale et al. 1999b, Ogbazghi et al. 2016, Tesfamariam et al. 2015), the soil-plant-atmosphere continuum system (SPACSYS) (Liu et al. 2018), HYDRUS (Šimůnek et al. 2008), the cropping systems simulating model (CropSyst) (Stöckle et al. 2003), the agricultural production systems simulator (APSIM) (Keating et al. 2003) and the soil and water assessment tool (SWAT) (Lu et al. 2016).



### 2.7.1.1 *Soil water balance model*

This is a mechanistic, irrigation and nutrient simulation model which gives a description of the soil-plant-atmosphere continuum making use of soil, crop and weather databases (Jovanovic et al. 1999). The model was derived from a simple irrigation scheduling crop model (NEWSWB) by Campbell and Diaz (1988) to a more complex scientific version (SWB-Sci), which has other components of the nutrient and salt sub-models (van der Laan 2009).

The crop unit of the SWB-Sci model simulates crop growth and development mechanistically in a way that will separate soil evaporation from transpiration thereby giving a clear estimate of crop water use (Jovanovic et al. 1999). This makes it an irrigation scheduling tool as it accurately calculates crop water requirements. The soil unit simulates water movement using a simple cascading (Campbell and Diaz 1988) or finite difference approach (Annandale et al. 1999a).

The N simulation and algorithms are based on CropSyst (Stöckle et al. 2003) and for P on GLEAMS (water table loading effects of agricultural management systems) (Muller and Gregory 2003). The ClimGen weather generator allows the SWB-Sci model to simulate long term crop growth, and nutrient and salt balances. The model has been used in many studies including N management in sludge amended soils (Ogbazghi et al. 2016, Tesfamariam et al. 2015), irrigation scheduling and salt balance using gypsiferous water (Annandale et al. 1999b).

### 2.7.1.2 *HYDRUS model*

HYDRUS is generally defined as a numerical model that simulates single or multidimensional variables of saturated flow and transport processes within the vadose zone (Šimůnek et al. 2008). The model was developed through collaborative research between the United States Salinity Laboratory and the University of California Riverside (Šimůnek et al. 2008). HYDRUS models water and nutrient fluxes through solving the Richards' equation for saturated water flow. The convection-dispersion equation is solved for solute transport in the liquid phase while diffusion equations are solved for solute transport in the vapour phase.

Some of the weaknesses of using HYDRUS is its inability to simulate mechanistic crop growth or soil-plant interactions (Han et al. 2015, Hu et al. 2008, Liang et al. 2016). A study by Li et al. (2005) used HYDRUS-2D to simulate water and N fluxes in the soil from a surface point source of  $\text{NH}_4\text{NO}_3$  but they could not investigate crop water and nutrient uptake since this module is not available in the model. Despite its inability to model crop growth, recently the root growth model software as a function of environmental stress was added to HYDRUS (Hartmann et al. 2017). One of the considerations when

choosing a model is its simplicity but HYDRUS is very sophisticated and requires a lot of inputs for accurate simulations (van der Laan et al. 2014).

Despite these weaknesses use of the model has been widespread due to its high accuracy resulting from its mechanistic nature (van der Laan et al. 2014). The HYDRUS model has, therefore, been used extensively to simulate N and water dynamics in different irrigation systems such as drip irrigation (Dudley et al. 2008, El-Nesr et al. 2014, Mekala and Nambi 2016), drainage fluxes and water table depths (Han et al. 2015, Karandish and Šimůnek 2017) and soil hydraulic conductivity due to wastewater fluxes in soils (Agah et al. 2016).

### 2.7.1.3 *Other models*

There are several other models used to simulate biophysical processes in agricultural systems under different management practices. The RZWQM is a 1-D model that simulates solute movement down the soil through macropores and preferential transport along mobile-immobile zones (Ma 2000). It simulates soil water redistribution following a mass conservative numerical solution of the Richards' equation.

The APSIM model allows plug in and plug out of various modules to simulate different cropping systems (Mok et al. 2014). The model uses different sub-models which are the crop module, soil water balance (SoilWat) and the solute balance (SWIM3). The SoilWat uses a cascading approach while the SWIM3 follows the Richards' and convection-dispersion equations (Probert and Verburg 1996). One of the problems associated with the model is its inability to account for soil cracking and preferential flows thereby decreasing its accuracy in accounting for solute balance (Stewart et al. 2006).

CropSyst is a multi-crop, multi-year and daily step model that simulates soil water, crop growth, NT balance, soil erosion and salinity (Stöckle et al. 2003). Just like the SWB-Sci, it uses the cascading soil water balance approach to account for incomplete solute mixing (Corwin et al. 1991). The cascading approach allows all solutes to be accounted for using active samplers (suction cups) to collect nutrients and passive samplers (wetting front detectors) to collect draining solutes (van der Laan et al. 2014).

## 2.7.2 **Determining land area requirements**

Some challenges in implementing a wastewater use project include technical issues such as effluent management in different seasons, nutrient loading in different soils and, leading from these, the calculation of land area requirements (DEC 2004).

### *2.7.2.1 Effluent volumes*

Fertigation with treated wastewater is done following crop water requirements in different seasons and at different stages of crop growth and development (FAO 2003). During wet seasons crop water requirements are low and excess effluent is produced (DEC 2004). The management of excess effluent is very important to avoid environmental pollution. On the other hand, there may be seasonal periods when the irrigation demand exceeds effluent supply.

It is therefore important to consider effluent storage during wet seasons and its use during dry seasons (Feigin et al. 2012). According to the DEC (2004) guidelines wastewater use can be done as either partial reuse or full reuse. In partial reuse schemes excess effluent may be discharged into rivers while in full reuse schemes wet weather storage is considered. In full reuse schemes storage may not be required if enough land is available to assimilate all the effluent during periods of lower crop water demand (AE 2000).

Storage requirements are calculated based on water balance to account for crop requirements, evaporation, runoff and drainage losses (DEC 2004). This is done using irrigation scheduling models (DEC 2004) such as SWB-Sci (Annandale et al. 1999a).

### *2.7.2.2 Nutrient and water loading on different soil types*

The nutrient (N and P) loading over a certain area irrigated with wastewater is of environmental concern (Matheyarasu et al. 2015). Nutrient loading rates are affected by crop type and crop nutrient requirements (Pescod 1992).

Approaches to wastewater fertigation management are variable. There are scenarios when nutrients (N and P) are limiting factors. Irrigation may be done to meet either N or P requirements (AE 2000).

Irrigation scheduling allows effluent to be applied according to crop requirements without necessarily loading nutrients to excess and at the same time prevents leaching and runoff losses (Ogbazghi et al. 2016, Tesfamariam et al. 2015, van der Laan 2009). In general heavy textured soils accumulate nutrients faster due to less leaching losses while the major environmental threat is loss through runoff (Levy et al. 2011). The reverse is true for light textured soils which lose nutrients through leaching. Therefore, before the commencement of wastewater irrigation long term water and nutrient balances are required to develop nutrient management strategies (DEC 2004). The SWB-Sci model has been widely used to assess long term water, and N and

P balances in sludge amended soils (Ogbazghi et al. 2016, Tesfamariam et al. 2015, van der Laan 2009). Therefore, the model can be applied to wastewater fertigation projects.

### 2.7.2.3 *Land area requirements*

A sufficient and sustainable land area for a wastewater fertigation scheme is very important in the identification of aspects such as buffer zones, leaching requirements and runoff controls (AE 2000, DEC 2004, USEPA 2012). Land area can be determined from the effluent production capacity of the treatment system, and knowledge of soil water and nutrient (N and P) budgets (DEC 2004). The optimum land area must be able to absorb all the water and nutrients from a specific treatment system design capacity without any environmental issues (AE 2000). According to Pescod (1992), land area can be estimated based on a water balance which considers crop water requirements, as provided by the SWB-Sci model (Annandale et al. 1999a). Nutrients can be managed through several approaches such as use of deep rooted crops, frequent harvesting and even dilution of the effluent when necessary (Pescod 1992).

## **2.8 Summary and conclusions**

Ecological sanitation (EcoSan) systems encourage sustainable reuse of human excreta-derived materials rather than disposing of them to the environment. The DEWATS is one of these systems which produces effluent from which water and nutrients (N and P) can be recovered. The effects of treated wastewater on soils, crops and the environment have been studied in both controlled environment and field studies. Nitrogen and P are the two most important macronutrients in treated wastewater which may limit crop productivity. On the other hand, they are also the most important contributors to environmental pollution. Application of treated wastewater increases soil N and P content and influences their subsequent dynamics into plant available forms. Besides N and P, treated wastewater provides other essential macro and micronutrients for crops. Long term fertigation using treated wastewater increases SOM, microbial populations and improves soil pH. These contribute to improved hydraulic conductivity, soil aggregate stability, moisture and nutrient retention. There is substantial evidence that treated wastewater can increase growth and yield in forage, grain, vegetable, fruit and ornamental crops. Despite these positive effects of treated wastewater there are drawbacks in terms of specific toxic ions, micropollutants, heavy metals, pathogens and their environmental effects. Heavy metals and pathogens can be managed following the WHO (2006) and USEPA (2012) guidelines. The FAO (1985) water quality guidelines for agricultural use are available to advise on controlling problems with specific toxic ions, salinity and sodicity. These guidelines encourage proper post-harvest handling and recently sanitation safety plans have been established. Upscaling wastewater use projects is the major challenge due to policy,

institutional, economic, cultural and social perception issues. South Africa has not yet developed water reuse practical guidelines although the legal framework based on current policies and institutional guidelines exists. To achieve this, technical aspects such as land area, effluent management in different seasons and N and P movement in the environment need consideration. Mechanistic models such as the SWB-Sci can be used as decision making tools to estimate land area requirements, storage capacity and nutrient dynamics in soils for environmental protection. The DEWATS effluent has potential to promote sustainable agriculture, therefore its impacts on soils, crops and the environment need investigation.

## CHAPTER 3: MATERIALS AND METHODS

### 3.1 Experimental site

The experimental site and other locations from which soils used during the study were collected are shown in Figure 3.1. The experimental site was Newlands-Mashu Research Facility located in Durban, South Africa (30°57'E, 29°58'S; altitude 14 m above sea level). The climate of the study site falls under the humid sub-tropical agro-ecological region of South Africa with cool, dry winters which are frost-free and hot, wet summers. The site receives an annual rainfall of approximately 800 to 1 000 mm and has a mean daily temperature of 20.5°C (Schulze 1997). The soil at the site is a clay of the Sepane form (Soil Classification Working Group 1991); an Aquic Haplustalf (Soil Survey Staff 2014).

A pilot DEWATS designed by Bremen Overseas Research and Development Association (BORDA) following recommendations by Sasse (1998) was installed at the site by the eThekweni Water and Sanitation Department (EWS) (Figure 3.2). The pilot plant was connected to the main sewer of 83 houses close to the research site to allow research in a safely managed environment where treated effluent passes back into the trunk sewer. The DEWATS plant consists of three treatment steps: (i) settling chambers and biogas collectors, (ii) three parallel ABR streets, (iii) two AF modules and (iv) a VFCW (9.8 m length \* 9.8 m breadth \* 0.75 m depth) and a HFCW (8.15 m length \* 8.11 m breadth \* 0.9 m depth) to further polish the effluent. Street 2 supplies almost one third of the total design effluent to the VFCW and then to the HFCW.

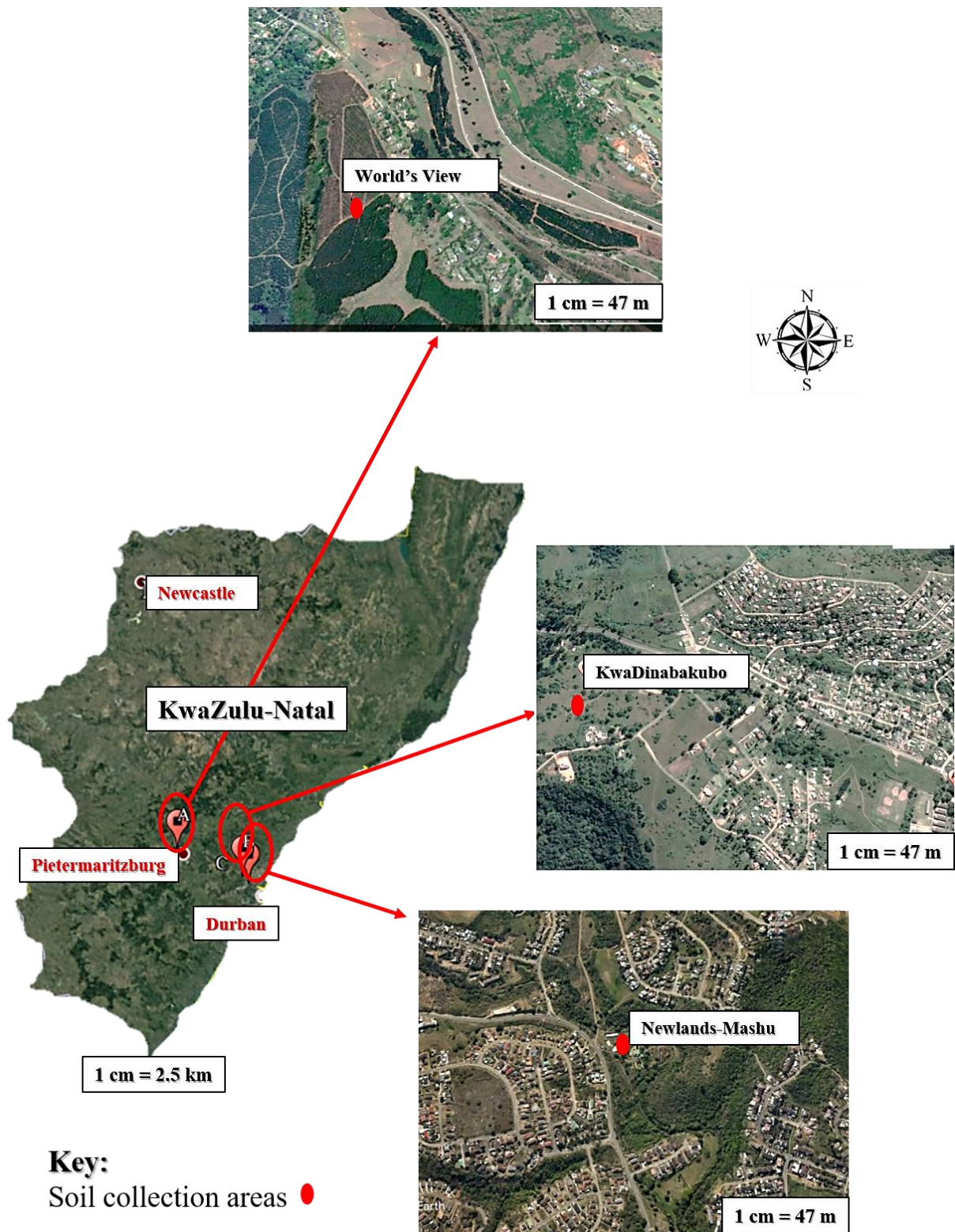


Figure 3.1: Map showing the study site and areas where some of the soils used during the study were collected (sourced and modified from AfriGIS, Google earth, 2018)

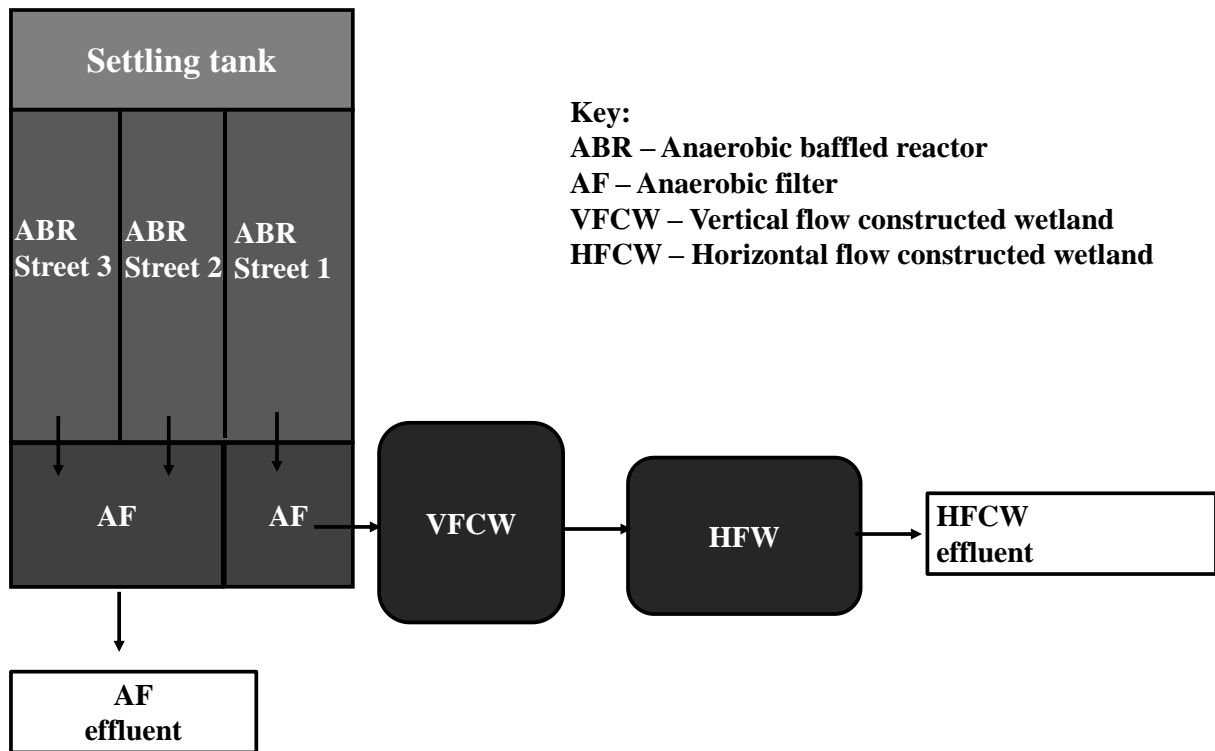


Figure 3.2: Diagram showing different modules of the DEWATS and the two sources of effluent used for fertigation during the study.

### 3.2 Field experiments

#### 3.2.1 Experimental design and field layout

The field plan at Newlands-Mashu is shown in Figure 3.3. The experiment was laid out in a Randomised Complete Block Design with three blocks (replicates). There was a total of six ridged plots of 10 m \* 9 m (90 m<sup>2</sup>) that were planted to 20 banana and 42 taro plants. The two irrigation treatments were irrigation with DEWATS effluent and no fertiliser applied and tap water irrigation with fertiliser application. Banana (*Musa acuminata* var Williams) and taro (*Colocasia esculentum*) were grown in an intercrop, with taro as the minor crop between the banana rows.

Tissue cultured banana seedlings were purchased from Zululand Nurseries, Eshowe, KwaZulu-Natal and taro seed (Dumbe lomfula) was obtained from Ukulinga, University of KwaZulu-Natal Agricultural Research Farm. The two crops were selected due to the ability of the banana to bear fruits which are high above the ground and hence less likely to be contaminated by the effluent while taro is a crop that is commonly grown in South Africa and must be cooked before eating.



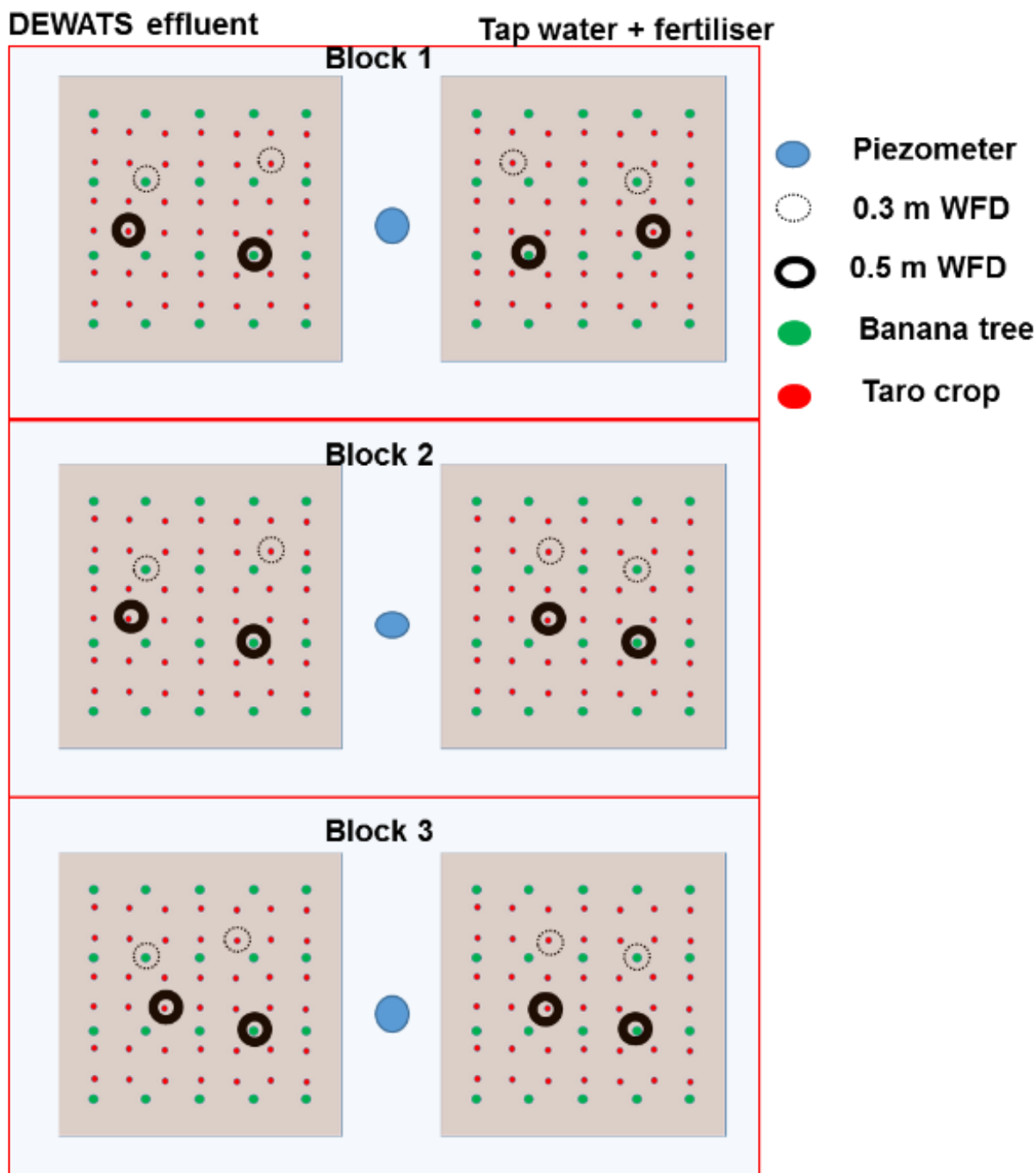


Figure 3.3: Field layout showing the irrigation treatments, cropping plan and the piezometers and wetting front detectors (WFD).

### 3.2.2 Experimental installations

Four Fullstop™ wetting front detectors (WFDs) (Commonwealth Scientific and Industrial Research Organisation, Canberra, Australia) were installed in each plot at two soil depths (0.3 and 0.5 m) before planting (Plate 3.1).

Six piezometers were installed in different locations around the study field site according to methods described by Rasiah et al. (2005). Polyvinyl chloride pipes (50 mm diameter \* 1.2 m long) were perforated and the bottom of the pipe covered with 250  $\mu$ m polyester cloth to filter the water entering. They were then inserted into holes bored with a bucket auger (50 mm diameter).



*Plate 3.1: Wetting front detectors inserted at different soil depths (0.3m, yellow top and 0.5m, red top).*



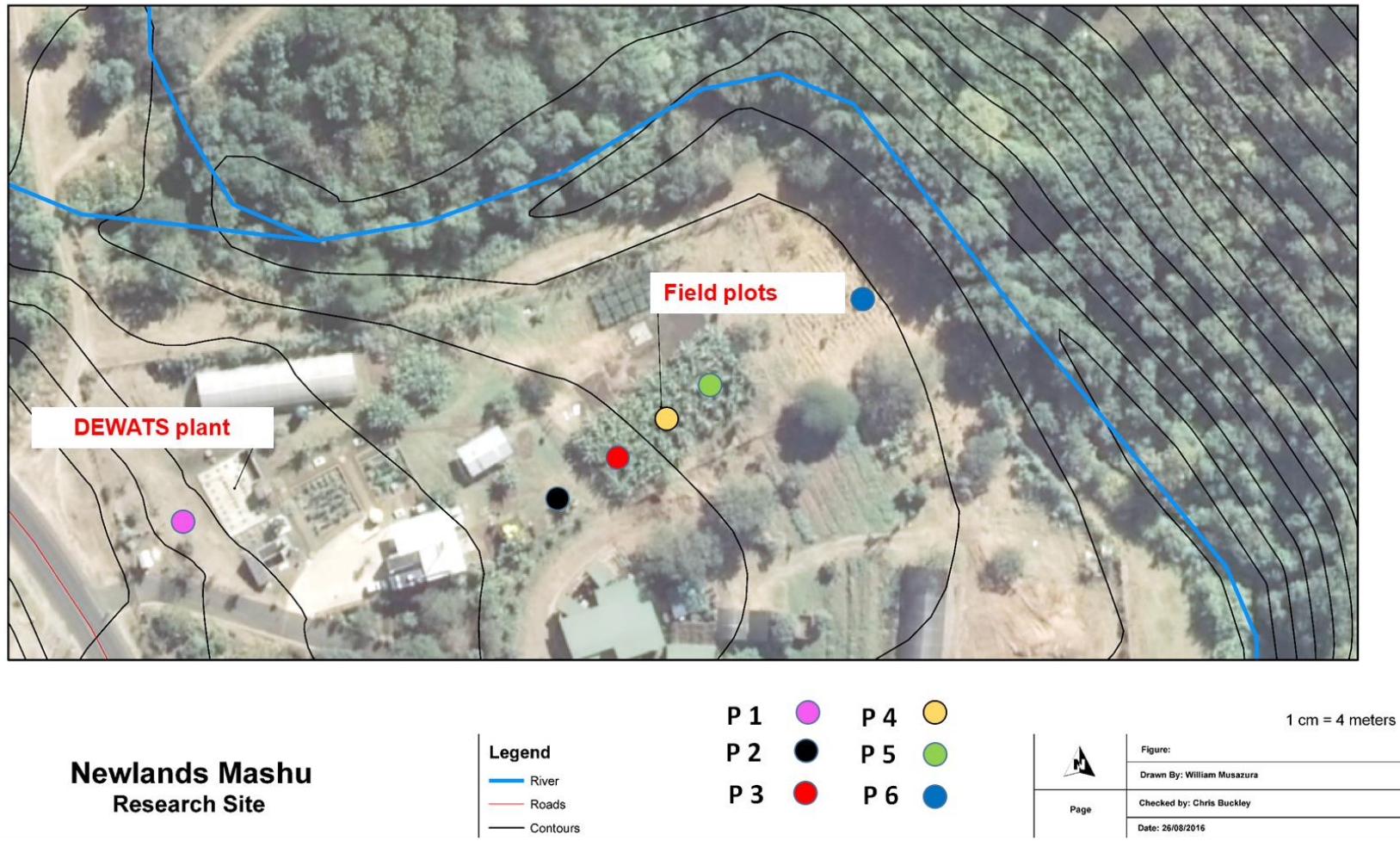
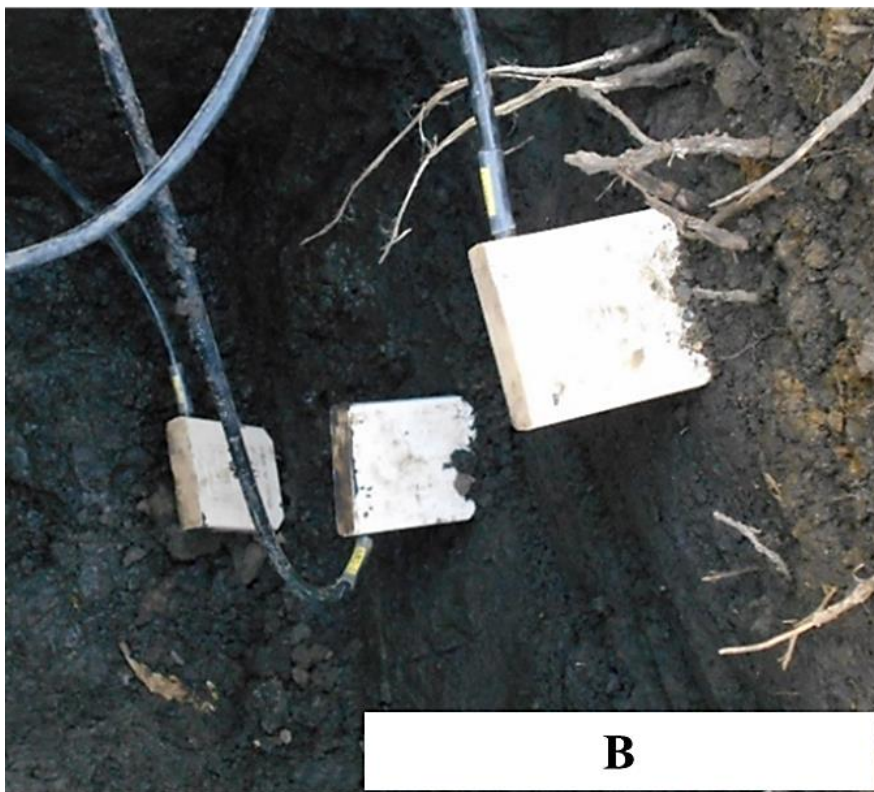
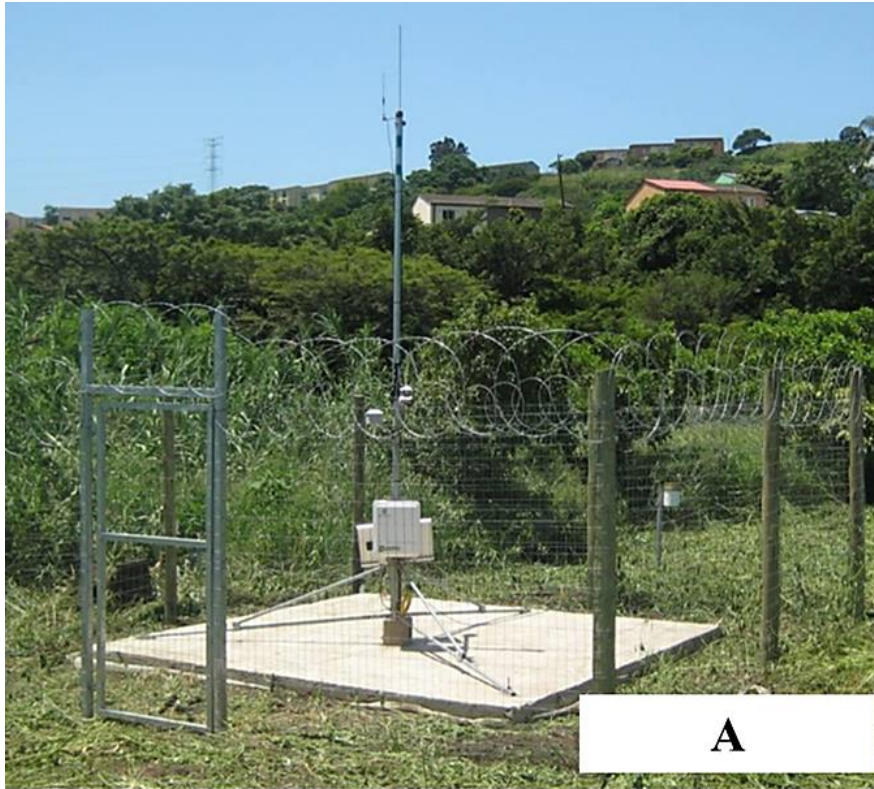


Figure 3.4: The Newlands-Mashu experimental site showing positions of the piezometers used in the study (P1 – P6 are different piezometers).

A Rainbird ESP- Me ® controller (Rain bird, California, USA) was installed to control irrigation scheduling. A submersible pump was submerged in effluent from either the AF or HFCW in different cropping cycles to pump effluent to a 10 m<sup>3</sup> capacity tank which supplied the agricultural field. The irrigation pipes were connected to Netafim® drippers (Netafim, Kraaifontein, South Africa) and calibrated to deliver 2 L h<sup>-1</sup> with four irrigation cycles day<sup>-1</sup>, totalling 8 L plant<sup>-1</sup> day<sup>-1</sup>.

An automated weather station with a CR 1 000 (Campbell Scientific Inc., Utah, USA) data logger was installed about 10 m away from the experimental field (Plate 3.2A) to monitor a number of weather variables (Appendix 1). The CS 650 soil moisture reflectometers (Campbell Scientific Inc., Utah, USA) for monitoring soil volumetric water content, temperature and electrical conductivity were installed at three soil depths (0.3, 0.6 and 0.9 m) as shown in Plate 3.2B. The Precision Infrared Temperature Sensor (IRTS-P) (Campbell Scientific Inc., Utah, USA) connected to the CR 1 000 data logger was installed to monitor canopy temperature.



*Plate 3.2: (A) The automated weather station and (B) the soil moisture reflectometers at three depths at Newlands Mashu.*

### 3.2.3 Trial establishment and management

Banana was planted on 13 November 2013 at a spacing of 3 m \* 1.5 m and taro on 18 December 2013 at a spacing of 1 m \* 1 m in an intercrop. Straight fertilisers were applied to the tap water + fertiliser treated main crop (banana) based on soil chemical analysis results prior to the beginning of each cropping cycle to meet the crop fertiliser requirements described in Table 3.1. Urea (46 % N) was applied at a rate of 544 kg ha<sup>-1</sup> over eight split applications (February to October of each year) on monthly basis until the flowering stage of each cropping cycle. Potassium chloride (Muriate of potash; 52 % K) was applied over three split applications (November, March and July of each year) at a rate of 600 kg ha<sup>-1</sup> (cropping cycle 1) and 87 kg ha<sup>-1</sup> (cropping cycle 2). The soil P test was greater than the target soil test, hence P fertiliser was not applied (Table 3.1).

*Table 3.1: Nitrogen (N), phosphorus (P) and potassium (K) fertiliser requirements for banana and taro during the growing period for cropping cycle 1 (Nov 2013 - May 2015) and cropping cycle 2 (Jun 2015 - July 2016) in respective irrigation treatments plots.*

Crop	Treatment	Cropping cycle	N P K		
			(kg ha <sup>-1</sup> year <sup>-1</sup> )		
Banana	*HFCW effluent	1	250	0	262
	#AF effluent	2	250	0	232
	Tap water + fertiliser	1	250	0	312
		2	250	0	45
Taro	HFCW effluent	1	160	80	80
	AF effluent	2	160	80	80
	Tap water + fertiliser	1	160	80	80
		2	160	80	80

\*Horizontal flow constructed wetland

#Anaerobic filter

The experiments were done over two cropping cycles whereby cropping cycle 1 was from banana planting to first harvest (November 2013 – May 2015; 0 - 504 days after planting) and cropping cycle 2 was the first banana ratoon crop growing period until harvesting (July 2015 - July 2016; 504 - 992 days after planting). During the experimental period, the DEWATS effluent used for irrigation was obtained from two different sources of the treatment system. The effluent was obtained from the HFCW (cropping cycle 1) and the AF (cropping cycle 2). This was done because the HFCW underwent a technical breakdown during the experimental period such that irrigation was continued using AF effluent.



### 3.2.4 Data collection

The sampling area for all crop and soil data collected during the study is described in Figure 3.5. All the data were collected from plants within the central 42 m<sup>2</sup> quadrant of each 90 m<sup>2</sup> plot. Sampling was done from six banana (30% sample size) and eight taro plants (20% sample size).

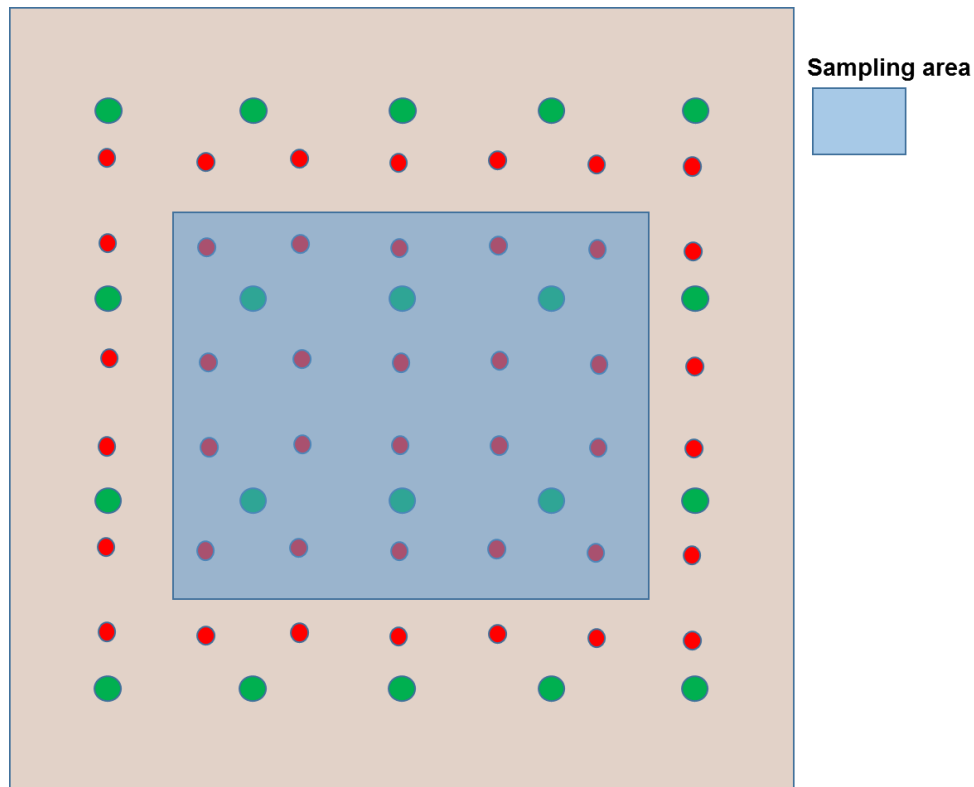


Figure 3.5: Sampling area in each plot for all the crop and soil data collected during the field experiment.

#### 3.2.4.1 Plant growth and yield data collection

Crop growth parameters measured for both crops during the study were plant height, leaf area index (LAI), chlorophyll content and biomass.

In banana growth measurement was done from planting until flowering at a three months interval. Plant height was measured from the base of the stem to the third uppermost open leaf. Leaf length and width were also measured from the same third uppermost open leaf. Leaf area index was determined following methods by Ghoreishi et al. (2012) according to Equation 3.1 and 3.2.

$$TLA = L * W * N * C$$

Equation 3.1

$$LAI = \frac{TLA}{TA} \quad \text{Equation 3.2}$$

Where: LAI is the leaf area index ( $m^2 m^{-2}$ ); TLA is the total leaf area ( $m^2$ ); L is the leaf length (m); W is the leaf width (m); N is the number of leaves; C is the regression coefficient generated from the independent variables of leaf length and width (dimensionless); TA is the total area occupied by the crop ( $m^2$ ).

Banana crop (main crop) was harvested on 15 May 2015 and the first ratoon crop on 25 July 2016. Fresh mass was measured immediately after harvesting using the WA3002L floor digital scale with a maximum measurement of 300 kg (Weighing Instrument Co., Ltd, Suzhou, China). Banana is a very succulent plant and the whole plant is difficult to dry, therefore different plant parts were subsampled (leaves, stem and bunch) and dried at 70°C for several days until a constant mass was attained. The proportion of subsample dry mass to subsample fresh mass was determined and used to calculate banana total dry mass from total fresh mass following Equation 3.3.

$$TDM = \left[ \frac{SDM}{SFM} * TFM \right] \quad \text{Equation 3.3}$$

Where: TDM is the total dry mass ( $kg ha^{-1}$ ); SDM is the subsample dry mass ( $kg ha^{-1}$ ); SFM is the subsample fresh mass ( $kg ha^{-1}$ ); TFM is the total fresh mass ( $kg ha^{-1}$ ).

Banana yield was determined according to Equation 3.4.

$$Y = FNB * BHA * FM \quad \text{Equation 3.4}$$

Where: Y is the yield ( $kg ha^{-1}$ ); FNB is the number of fruits per bunch (dimensionless); BHA is the total number of bunches (dimensionless); FM is the total fruit mass ( $kg ha^{-1}$ ).

In taro, crop growth measurements were done over the last three months before harvesting at a monthly interval. Plant height was measured from the base to the apex of the second youngest leaf. The leaf length and width of the youngest mature leaf were also measured. Leaf area index was determined following Equations 3.1 and 3.2 as for banana crop. Taro vegetative growth index was calculated from LAI, plant height (PH), and the number of suckers and stolons according to Equation 3.5.

$$VGI = \left( \frac{LAI * PH}{100} \right) - (\text{suckers-stolons})^2 \quad \text{Equation 3.5}$$

Whereby: VGI is the vegetative growth index (dimensionless); LAI is the leaf area index ( $m^2 m^{-2}$ ); PH is the plant height (m).



Taro crops were harvested on 10 May 2015 for the first season crop while the second season crop was harvested on 22 July 2016. Since taro plants are less succulent the whole corms were oven dried as for banana. Yield was determined following Equation 3.6.

$$Y = NC * NP * CM \quad \text{Equation 3.6}$$

Where: Y is the yield ( $\text{kg ha}^{-1}$ ); NC is the number of corms per plant (dimensionless); NP is the number of plants (dimensionless); CM is the corm mass ( $\text{kg ha}^{-1}$ ).

The chlorophyll content index (dimensionless) was measured on taro and banana plants using the CCM 200-plus chlorophyll meter (Opti-Sciences, Inc., Hudson, USA).

#### *3.2.4.2 Leachates sampling for N and P analysis*

Due to some technical delays on irrigating with wastewater, leachates were collected from WFDs from 295 days after planting. This was done after heavy rainfall and when the WFDs were full as signalled by the visual indicators. Water samples from the WFDs were collected by sucking water through a 2 mm diameter pipe connected to the below-ground water collector using a 60 mL syringe as shown in Plate 3.3A.

#### *3.2.4.3 Soil sampling*

In the field studies soil samples were then collected from two depths (0.3 and 0.6 m) before the beginning and after each crop cycle to monitor changes in soil chemical properties over time. Undisturbed soil cores were collected to determine bulk density. Sampling was done randomly from five different places in each plot, within a 0.4 m radius from the banana stem using a Dutch auger (50 mm diameter).

#### *3.2.4.4 Groundwater monitoring*

The water table levels were monitored at random intervals using a homemade electric sounding device (water level meter). The device responds to contact with water by emitting light and a beep sound. The distance from the ground surface to the end of the device sensor was measured using a measuring tape and recorded as water level below ground.

Water table samples were collected at random intervals and during heavy rainfall events. Collection was done using the same procedure as for the WFDs as shown in Plate 3.3B. These were analysed for  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and  $\text{PO}_4^{3-}\text{-P}$  following standard methods (APHA 2005).



*Plate 3.3: (A) Collecting leachates from the wetting front detectors and (B) water Table samples.*

#### *3.2.4.5 Crop nitrogen and phosphorus uptake*

Banana plant tissue analysis was done after each harvest (at 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 (Hue et al. 2000). Taro tissue samples were collected from the corms after the first crop harvest. Taro tissue samples were not collected during the second cropping cycle since they did not establish well under the banana canopy. The collected

samples were bulked to form a composite sample for each plot and oven dried at 70°C for 72 hours (Kalra 1997).

### 3.3 Pot experiment

#### 3.3.1 Experimental design

A 2 \* 3 \* 4 factorial experiment was carried out in a complete randomised design (Figure 3.6). The experiment comprised of two irrigation treatments (DEWATS effluent vs Municipal tap water + fertiliser) \* three soil types \* four replicates.

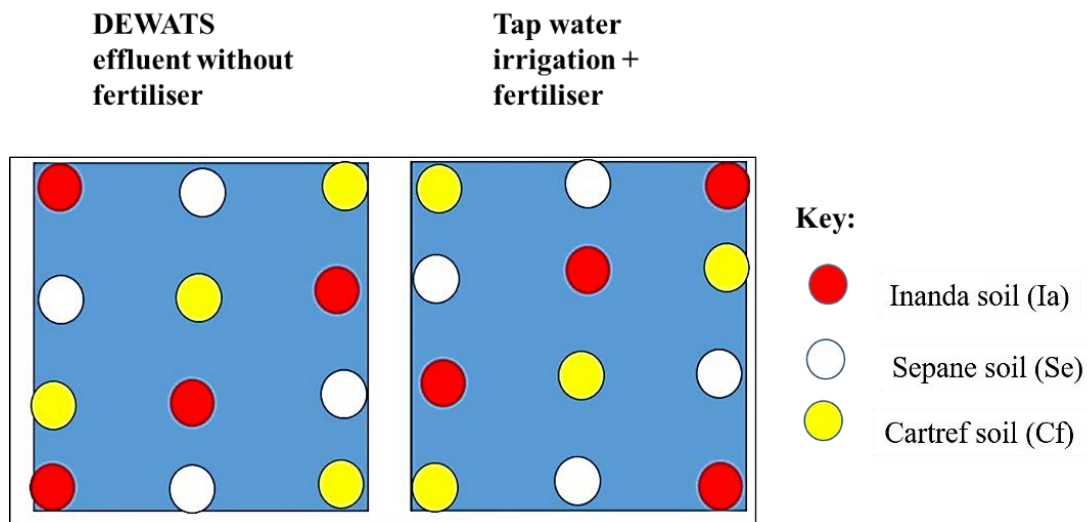


Figure 3.6: Pot experiment layout in a complete randomised design in the growing tunnel.

#### 3.3.2 Trial establishment and management

The soils used for the pot experiment were collected from three different locations in the province of KwaZulu-Natal, South Africa as shown in Figure 3.1. Three contrasting topsoil (0 - 0.3 m) horizons were collected from a Cartref form (Cf; Typic Haplaquept), an Inanda form (Ia; Rhodic Hapludox) and a Sepane form (Se; Aquic Haplustalf) (Soil Classification Working Group 1991, Soil Survey Staff 2014). The Cf soil is generally a coarse textured soil with low nutrient concentrations, which is likely to benefit from irrigation using wastewater although susceptible to nutrient leaching. Sepane soil was chosen on its ability to retain water and nutrients but susceptible to surface runoff. The Cf was sampled from KwaDinabakubo (29°44'S; 30°51'E) near Durban, KZN under natural grassland. The Ia was collected from World's View (29°35'S, 30°19'E), Pietermaritzburg under commercial forestry and the Se from the Newlands-Mashu Research Centre. Chemical and physical properties for soils used during the study are shown in Table 3.4. Freshly collected soils were air dried and sieved using a 2 mm

mesh. Inorganic fertilisers used during the study: urea (46% N), single superphosphate (10.5% P) and potassium chloride (52% K), were applied to the tap water + fertiliser treatment soils (Table 3.2) based on soil fertility recommendations described in Table 3.2. Dolomitic lime was added at a rate of 1.03 g kg<sup>-1</sup> to the Ia and Cf soils to adjust soil pH to a permissible acid saturation of 1%. Fertilisers and dolomitic lime were then mixed using a Baumax BS361 concrete mixer. The soils were packed at a rate of 60 kg per pot based on their bulky densities (Ct; 1.44 g cm<sup>-3</sup>, Ia; 0.8 g cm<sup>-3</sup> and Se; 1.2 g cm<sup>-3</sup>). The pots were perforated underneath to allow free drainage and dishes were placed underneath to collect the leachates which were analysed, and the rest were recycled back into the pot.

*Table 3.2: Nitrogen (N), phosphorus (P), potassium (K) and lime (dolomite) fertiliser requirements for the three different soils used.*

Soil type	N	P	K	Lime
		(mg kg <sup>-1</sup> )		
Inanda	100	10	104	1 030
Cartref	58	4.6	79	1 030
Sepane	70	0	51	0

Wetting front detectors (WFDs) were inserted in each pot to passively collect leachates. Single banana (*M. paradisiaca*) suckers of 4 - 5 kg mass was planted in each pot on 3 April 2015. For the first 210 days after planting (3 April to 29 October 2015), the pots were irrigated with HFCW effluent and thereafter AF effluent was used. Irrigation was done once or twice a week and a total of 2 770 mm of effluent per pot was applied over a period of 718 days (10 days before final harvesting). Soil moisture content was determined by weighing the pot before each irrigation event (Plate 3.4). Temperature and relative humidity were monitored using iMini escort (CB-USB2-MINI5P) data loggers and the values were used to calculate reference evapotranspiration using the SWB-Sci model following algorithms by Allen (1998). Irrigation was done exceeding the crop water requirements while maintaining the soils moisture content at field capacity, aiming to absorb as much effluent as possible. Crop water requirements (ET<sub>crop</sub>) were calculated according to the Food and Agriculture Organisation (FAO) formula as a product of banana crop factors (K<sub>c</sub>) and reference evapotranspiration (ET<sub>o</sub>) (Allen 1998, FAO 2015).





*Plate 3.4: Measuring soil moisture content by weighing the pots in the growing tunnel.*

### **3.3.3 Data collection**

All the data were collected from four replicates.

#### *3.3.3.1 Plant growth and yield*

Banana growth variables described in Section 3.2.4.1 were measured following similar procedures. Plant fresh and dry biomass were determined at 728 days after planting.

#### *3.3.3.2 Soil sampling*

Soil samples were collected at 728 days after planting when the plants were harvested. Five subsamples per pot were collected from different points (upper, middle and bottom) using a Dutch auger. These were bulked to form a composite sample per pot and they were analysed for chemical properties.

#### *3.3.3.3 Soil drainage*

Soil drainage rate was monitored at random intervals by measuring the volume of leachate in the collecting plate four hours after irrigation.

#### *3.3.3.4 Nitrogen and phosphorus leaching*

Leachates within each pot were collected from the WFDs following procedures described in Section 3.2.4.2. The total amount of inorganic N and P leached were calculated following Equation 3.7.

$$LC = \frac{V * C}{1\ 000} \quad \text{Equation 3.7}$$

Where: LC is the amount leached (g); V is the volume leached (L), C is the leachate concentration (mg L<sup>-1</sup>).

#### *3.3.3.5 Crop nutrient and phosphorus uptake*

Banana plant samples were collected following methods described in Section 3.2.4.5.

## **3.4 Laboratory analyses**

### **3.4.1 Effluent characterisation**

About 50 mL aliquots of treated effluent used during the study were collected from the HFCW (n = 3) and the AF (n = 10) and analysed for chemical and physical properties following

standard methods for water and wastewater analysis (APHA 2005). The total N,  $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N and  $\text{PO}_4^{3-}$ -P were analysed using a NOVA 60 Spectroquant® (Merck Millipore, Germany).

Suspended solids were analysed by filtering a well-mixed sample through a 0.45  $\mu\text{m}$  glass fibre filter. The filter residue was dried to a constant mass at 103 – 105 °C. Suspended solids were determined as an increase in the mass of a filter.

The chemical oxygen demand (COD) was analysed by digesting a wastewater sample in a strongly acidic potassium dichromate solution with silver sulphate (catalyst) and mercuric sulphate. The dichromate was oxidised, and excess dichromate was titrated with ammonium (II) sulphate. The COD value was calculated from the amount of dichromate titrated.

### 3.4.2 Soil analysis

Soil particle size analysis was done following the hydrometer method described by Rowell (2014). The soil (25 – 50 g) and 100 ml of dispersing solution was added were added to the dispersing cup. The dispersing cup was attached to the mixer and mixed for 30 – 60 seconds. The suspension was quantitatively transferred from the dispersing cup to 1 000 ml cylinder, which was filled to 1 000 ml mark using deionised water. This was left overnight to equilibrate. At the beginning of each set, the temperature and the hydrometer reading were recorded. The density was determined by inserting the plunger into suspension and mixing for 30 seconds until the suspension was uniform. The plunger was removed (the 40 seconds timer was beginning) and the hydrometer was gently inserted into the suspension. Hydrometer reading was recorded at 40 seconds interval to determine the amount of silt plus clay after sand has settled to the bottom. The hydrometer was recorded again after 6 hours 52 minutes to determine the amount of clay in suspension after silt has settled to the bottom. Different particle size proportions were determined according to calculations from Equations 3.8 – 3.10 below:

$$\text{Clay (\%)} = \text{Corrected hydrometer reading at 6 hrs 52 mins.} * \frac{100}{\text{mass of sample}} \quad \text{Equation 3.8}$$

$$\text{Silt (\%)} = \text{Corrected hydrometer reading at 40 sec.} * \frac{100}{\text{mass of sample}} - \text{clay (\%)} \quad \text{Equation 3.9}$$

$$\text{Sand (\%)} = 100 \% - (\text{Silt} + \text{clay} \%) \quad \text{Equation 3.10}$$

The soil water contents at field capacity and permanent wilting points were calculated from the SWB-Sci model calculator using the soil texture data (Annandale et al. 1999a). The bulk

density was determined from the undisturbed soil cores following methods described by Rowell (2014). A smooth vertical soil surface was prepared at the depth of the soil to be sampled. The sampler was driven into the soil without compressing and disturbing the soil. The sampler was removed while retaining the undisturbed soil in the inner cylinder. The soil sample was carefully trimmed, and two metal disks were placed at each end of the cylinder. The soil sample was packed in a plastic bag to preserve moisture content. The soil sample was dried in an oven at 105 °C for 72 hours. The bulk density was determined according to Equation 3.11 below:

$$\text{Bulk density} = \frac{W1-W2-W3}{\text{Volume of cylinder}} \quad \text{Equation 3.11}$$

Whereby: W1 is the mass of wet soil plus tin cylinder; W2 is the mass of the tin and W3 is the mass after drying.

Soil extractable P was done using Ambic-2 solution (Hunter 1974) followed by the molybdenum blue procedure (Hunter 1974, Murphy and Riley 1962). Soil total inorganic N ( $\text{NH}_4^+\text{-N} + \text{NO}_3^-\text{-N}$ ) was extracted from freshly collected soils in a 1:5 soil :2M KCl followed by filtering using Whatman ® No. 2 paper according to Mynard and Kalra (2008). The filtrates were then analysed using a Nova 60 Spectroquant® (Merck Millipore, Germany) according to standard methods (APHA 2005). All other soil analyses reported in Table 3.3 and 3.4 were conducted according to standard methods from the Non-Affiliated Soil Analysis Work Committee (1990).



Table 3.3: Soil chemical and physical properties of the Sepane soil at the Newlands-Mashu field site before planting.

Soil parameter	Depth (m)	
	0-0.3	0.3-0.6
Bulk density (g cm <sup>-3</sup> )	1.25	1.43
Clay (%)	35	43
Silt (%)	42	31
Sand (%)	23	26
Field capacity (m m <sup>-1</sup> )	0.424	0.413
Permanent wilting point (m m <sup>-1</sup> )	0.309	0.298
Organic C (%)	2.9	2.6
Total N (%)	0.29	0.27
Inorganic N (mg kg <sup>-1</sup> )	24.2	23
Extractable P (mg kg <sup>-1</sup> )	39.3	11.9
Exchangeable K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.30	0.18
Exchangeable Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	12.2	8.1
Exchangeable Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	7.8	7.4
Exchangeable acidity (cmol <sub>c</sub> kg <sup>-1</sup> )	0.05	0.07
Total cations (cmol <sub>c</sub> kg <sup>-1</sup> )	20.4	15.7
Acid saturation (%)	0	0
pH (KCl)	5.2	5.1
Extractable Zn (mg kg <sup>-1</sup> )	22.8	6.9
Extractable Mn (mg kg <sup>-1</sup> )	3.7	11.1
Extractable Cu (mg kg <sup>-1</sup> )	9.5	5.8

Table 3.4: Physical and chemical properties for the different soil types used for the pot experiment at Newlands-Mashu.

Property	Inanda	Cartref	Sepane
Bulky density (g cm <sup>-3</sup> )	0.80	1.43	1.20
Clay (%)	23	12	37
Silt (%)	48	15	41
Sand (%)	29	73	22
Field capacity (m m <sup>-1</sup> )	0.40	0.24	0.43
Permanent wilting point (m m <sup>-1</sup> )	0.29	0.12	0.31
Organic C (%)	6	0.5	2.9
Total N (%)	0.56	0.05	0.29
Extractable P (mg kg <sup>-1</sup> )	12.0	0.7	39.3
pH (KCl)	4.11	4.21	5.20
Total cations (cmol <sub>c</sub> kg <sup>-1</sup> )	5.9	1.2	20.4
Acid saturation (%)	30	18	0
Exchangeable K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.07	0.01	0.30
Exchangeable Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	3.2	0.4	12.2
Exchangeable Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	0.0	0.4	7.8
Exch. acidity (cmol <sub>c</sub> kg <sup>-1</sup> )	1.80	0.18	0.05
Extractable Zn (mg kg <sup>-1</sup> )	2.8	0.1	22.8
Extractable Mn (mg kg <sup>-1</sup> )	10.7	0.7	3.7
Extractable Cu (mg kg <sup>-1</sup> )	3.6	0.2	9.5

### 3.4.3 Plant tissue analyses

All the plant tissue samples were analysed following standard methods for plant analysis (Riekert and Bainbridge 1998). Plant tissue samples were bulked to form a composite sample and oven dried at 70°C for 72 hours. Dried plant tissues were then crushed and sieved through a 1 mm sieve. These were subjected to wet acid digestion prior to analysis for N and P. The leaf tissues were analysed for total N using a LECO ® TruSpec Micro CNS 2000 analyser (Leco Corporation, Michigan, USA) and P using inductively coupled plasma optical emission spectroscopy (ICP-OES) Vista MPX (SpectroFlame Modula; Spectro, Kleve, Germany). The total nutrients removed by plants were then determined following Equation 3.12.

$$NR = \frac{TDM * C}{1000\ 000} \quad \text{Equation 3.12}$$

Where: NR is the nutrients removed by crops (kg ha<sup>-1</sup>); TDM is the total dry mass (kg ha<sup>-1</sup>); C is the concentration in plant tissues (mg kg<sup>-1</sup>).

### 3.5 Data analysis

All the data collected were analysed using GenStat 18<sup>th</sup> Edition (VSN International, UK). Analysis of variance (ANOVA) was conducted to test for significant differences between the main factors and their interactions (where applicable) at the 5% significance level. Contrasts were done where there were three or more treatments to compare treatment means. Means were separated using standard error of mean differences (P < 0.05). Significantly different treatments were presented through bar graphs, boxplots and tables showing standard error of mean differences.

### 3.6 Modelling water and nutrient (N and P) balances in soil

The SWB-Sci model was used to determine land area and to simulate N and P dynamics in DEWATS effluent fertigated soils. The model has three different units i.e. the weather unit, the crop growth unit, and the soil unit (Annandale et al. 1999a, Jovanovic et al. 2000, Jovanovic et al. 1999).

#### 3.6.1 The weather unit

The weather station installed at the experimental site (Section 3.2.1) was used to measure different variables which were included in the model. Information on the weather station was created as shown in Appendix 2.

### **3.6.2 Growth sub model calibration**

Crop growth parameters for calibrating the banana growth model were collected from the tap water + fertiliser treatment from the experiments conducted over a period of 992 days as described in Section 3.2. Some of the parameters not measured were obtained from Literature. The parameters included in the model are given in Appendix 3.

#### *3.6.2.1 Model calibration of crop parameters for N and P uptake*

Crop parameters for nutrient uptake were based on the CropSyst algorithms (Boote et al. 2013). These simulate crop nutrient uptake based on root N concentration and aboveground N concentrations at different stages of growth (van der Laan et al. 2010). The model was calibrated using the data collected from the tap water + fertiliser treatment and some parameters were obtained from literature (Appendix 3 and 4).

#### *3.6.2.2 Soil parameters*

Soil physical properties given in Appendix 5 were included in the model.

#### *3.6.2.3 Field management*

All the field management practices are given in Appendix 6.

#### *3.6.2.4 Nitrogen and phosphorus model initialisation*

The SWB-Sci was calibrated for N and P modelling using literature and measured data. The rain and irrigation water quality ( $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N and  $\text{PO}_4^{3-}$  in  $\text{mg L}^{-1}$ ) were entered with regards to DEWATS effluent. The fertiliser and tillage management were entered for the tap water + fertiliser treatment. The plant residue parameters were also included in the sub-model. Other additional physical and chemical properties used to parameterize the model are given in Appendix 7.

### **3.6.3 Model validation**

The model was validated using an independent data of leaf area index (LAI), crop height, N uptake and mobile N and P from DEWATS effluent. Model sensitivity was tested following five statistical parameters suggested by De Jager (1994): root mean standard error (RMSE), sample size (N), mean absolute error (MAE), correlation coefficient ( $r^2$ ) and Willmott's coefficient of agreement (D). The significance levels for accurate simulations were RMSE (non-applicable),  $r^2 > 0.8$ ,  $\text{MAE} < 20\%$  and  $D > 0.8$

#### **3.6.4 Land area determination**

Land area required per each DEWATS plant, household and individual was calculated according to calculations in Appendix 8. The calculations were based on  $E_{t_{crop}}$  (evaporation + transpiration) simulated by the SWB-Sci model for each soil type (Cf, Ia and Se) see Appendix 13.

## **CHAPTER 4: CROP GROWTH, AND NITROGEN AND PHOSPHORUS DYNAMICS IN SOIL IRRIGATED WITH DEWATS EFFLUENT IN THE FIELD.**

### **4.1 Introduction**

Erratic rainfall patterns due to climate change are contributing to water scarcity thereby jeopardising food security in countries such as South Africa (WWAP 2017). Furthermore, as the population continues to increase so does the generation of wastewater contribute to pollution of available fresh water resources. The use of wastewater on agricultural soils is one of the mitigation strategies to climate change and a way of conserving fresh water resources while improving livelihoods in most developing countries (Fonseca et al. 2007, Pedrero et al. 2010).

Irrigation with wastewater allow soil to act as a medium for nutrient-retention and subsequent uptake by crops (Bame et al. 2013) such that water draining down the ground water is less contaminated. Several studies evidenced the ability of wastewater to increase crop growth, nutrient uptake and improve soil chemical and physical properties (Bame et al. 2013, Hussain et al. 2002, Mousavi et al. 2015).

Although wastewater is a valuable agricultural resource there are some limitations associated with its use. Some of these limitations include the effects of excessive nutrients on crop yield, soil nutrient imbalances and environmental pollution (Pedrero et al. 2010). Nutrients (N and P) from wastewater added to the soil undergo different transformation processes driven by various biotic and abiotic factors including, but not limited to, soil factors such as texture, mineralogy, structure, pH, temperature, and water content (Levy et al. 2011, Ogbazghi et al. 2016, Sahrawat 2008). The N and P may be leached down the soil profile depending on irrigation management practices and rainfall intensity leading to groundwater pollution.

Upscaling of water reuse program needs proper planning. The planning process considers various technical aspects such as the site's physical characteristics, the effluent quality and quantity, land area and storage requirements during wetter periods and most importantly environmental sustainability. However, this information is often not available. This field study therefore, investigated the amount of DEWATS effluent that can be irrigated per unit area to a banana/taro intercrop, storage requirements in rainy season and N and P dynamics in a soil

planted to banana and taro. Specific objectives were to (i) characterise the DEWATS effluent (after the AF and again after a HFCW); (ii) determine its effects on the growth and yield of banana and taro in an intercrop; (iii) calculate banana/taro irrigation requirements with special reference to the study site; (iv) use the information to determine land requirements for irrigating banana/taro intercrop with DEWATS effluent; (v) N and P loading in soil and uptake by the two crops; (vi) soil chemical properties; (vii) soil N and P leaching and effects on groundwater  $\text{NO}_3^-$  pollution.

## **4.2 Materials and Methods**

These have been described in Sections 3.1 – 3.2 in Chapter 3.

## **4.3 Results**

### **4.3.1 Effluent characterisation**

The chemical and physical characteristics of effluents from two different points of DEWATS (AF and HFCW) are reported in Table 4.1. Higher concentrations of mineral nutrients (total N,  $\text{PO}_4^{3-}$ -P and  $\text{NH}_4^+$ -N) and chemical oxygen demand (COD) were reported in AF effluent than HFCW except for  $\text{NO}_3^-$ -N which was very low in AF. There were very low concentrations of suspended solids in AF than in HFCW effluent. The pH for AF effluent was slightly alkaline (mean value of 7.65) than HFCW effluent (mean value of 6.73).

Table 4.1: The chemical and physical properties of DEWATS effluents (after HFCW and AF) used during the study.

Effluent source	NO <sub>3</sub> -N (mg L <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N (mg L <sup>-1</sup> )	PO <sub>4</sub> <sup>3-</sup> (mg L <sup>-1</sup> )	Tot. N (mg L <sup>-1</sup> )	COD (mg O <sub>2</sub> L <sup>-1</sup> )	Suspended solids (mg L <sup>-1</sup> )	pH	EC (mS m <sup>-1</sup> )	
	n	9	9	9	3	6	9	9	
AF	Mean ± SE	2.1 ± 0.5	54.8 ± 1.6	10.5 ± 1.5	60.6 ± 2.7	524.5 ± 391.1	0	7.65 ± 0.06	1.2 ± 0.1
	Median	1.8	55.6	8.7	59.8	133.6	0	7.68	1.2
	Range	0.2 - 4.1	48.1 - 60.1	5.9 - 19.5	51.2 - 68.4	81.2 - 2470	0	7.33 - 7.98	0.9 - 1.4
	n	3	3	3	3	19	19	19	
HFCW	Mean ± SE	12.7 ± 6.4	6.7 ± 7.	4.1 ± 0.5	19.4 ± 7	67.9 ± 7.5	4 ± 1.3	6.73 ± 0.09	74.1 ± 2.8
	Median	10.2	7.2	3.9	18.1	66	2	6.57	70
	Range	3.1 - 24.9	5 - 7.9	5.9 - 19.5	8.1 - 32.1	31 - 159	1.0 - 26	6.24 - 7.71	54 - 99

AF is anaerobic filter effluent, HFCW is the horizontal flow constructed wetland effluent

### 4.3.2 Crop growth and yield

The F-probability values for banana growth variables over the two cropping cycles are reported in Table 4.2. No significant differences ( $p > 0.05$ ) were reported between the two irrigation treatments over the two cropping cycles for banana growth variables except for banana plant height, which significantly differed between the two cropping cycles at 5 % significance level.

Table 4.2: Analysis of variance showing the probability values for banana and taro growth between the two irrigation treatments over two growing seasons.

Source of variation	D.F.	Banana			Taro		
		PH (m)	CCI (n/a)	LAI (m <sup>2</sup> m <sup>-2</sup> )	PH (m)	VGI (n/a)	LAI (m <sup>2</sup> m <sup>-2</sup> )
Block	2						
Cropping cycle	1	0.005**	0.868	0.574	0.034*	0.012*	0.008**
Treatment	1	0.621	0.123	0.877	< 0.001***	< 0.001***	< 0.001***
Season x treatment	1	0.648	0.765	0.854	0.064	0.022*	0.03**

DF = degrees of freedom; PH = plant height; CCI = chlorophyll content index; LAI = leaf area index; VGI = vegetative growth index; n/a = dimensionless.

The differences in banana plant height between the two cropping seasons are reported in Figure 4.1. Banana plant height was higher during the second cropping cycle compared to the first one.

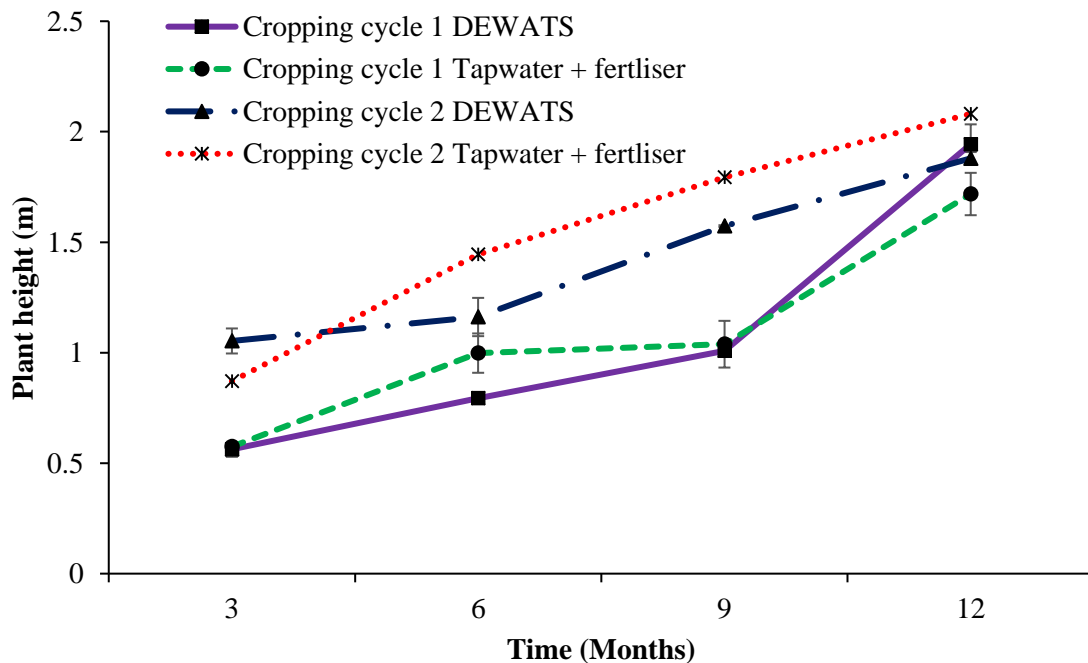


Figure 4.1: Banana plant height between the two cropping cycles for two irrigation treatment ( $n = 3$ ; mean  $\pm$  standard error of mean differences).

A significant ( $p < 0.01$ ) interaction was found between treatment and cropping cycle on taro growth (leaf area index, vegetative growth index and plant height) (Table 4.3).



Table 4.3: Mean squares for taro yield and total dry mass during the first season.

Source of variation	Degrees of freedom	Total dry mass	Yield
Block stratum	2	3.79	9.01
Treatment	1	4.46	18.73
Residual	2	15.87	41.51
Total	5		

The differences in taro growth variables between the two irrigation treatments over two cropping cycles are presented in Table 4.4. Use of DEWATS effluent increased all taro growth variables during the first cropping cycle compared to tap water + fertiliser treatment. Taro growth was lower during the second cropping cycle regardless of the irrigation treatment.

Table 4.4: Taro growth variables between the two growing cropping cycles and fertigation treatments ( $n = 6$ ; mean  $\pm$  standard error of mean).

Cropping cycle	Treatment	Leaf area index	Vegetative growth index	Plant height
1	DEWATS	0.06 $\pm$ 0.007 <sup>a</sup>	1676 $\pm$ 290 <sup>a</sup>	0.45 $\pm$ 0.03 <sup>a</sup>
	Tap water +fertiliser	0.04 $\pm$ 0.005 <sup>b</sup>	774 $\pm$ 171 <sup>b</sup>	0.37 $\pm$ 0.02 <sup>b</sup>
2	DEWATS	0.02 $\pm$ 0.003 <sup>c</sup>	276 $\pm$ 65 <sup>c</sup>	0.20 $\pm$ 0.01 <sup>c</sup>
	Tap water + fertiliser	0.02 $\pm$ 0.003 <sup>c</sup>	230 $\pm$ 50 <sup>c</sup>	0.19 $\pm$ 0.01 <sup>c</sup>

Superscripts that are different within a column indicate significant differences ( $p < 0.05$ )

The mean squares for banana yield and dry mass are reported in Table 4.5. No significant differences ( $p > 0.05$ ) were reported for taro yield in all treatments. Significant differences in banana yield was found between the irrigation treatments ( $p < 0.05$ ) and cropping cycles ( $p < 0.01$ ).

Table 4.5: Mean squares for banana yield and dry mass between the two cropping cycles and irrigation treatments collected after harvest (728 days after planting).

Source of variation	Degrees of freedom	Yield	Total dry mass
Block stratum	2	48.1	12
Block*Units* stratum			
Cropping cycle	1	162.9 **	81
Treatment	1	96.6 *	2
Season*Treatment	1	41.6	3
Residual	6	8.6	20
Total	11		

\* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .

The effects of irrigation treatments on banana yield over two cropping seasons were presented in Figure 4.2. Banana yield was higher in DEWATS effluent compared to tap water + fertiliser treatment, during the first cropping cycle than the second one (Figure 4.2).

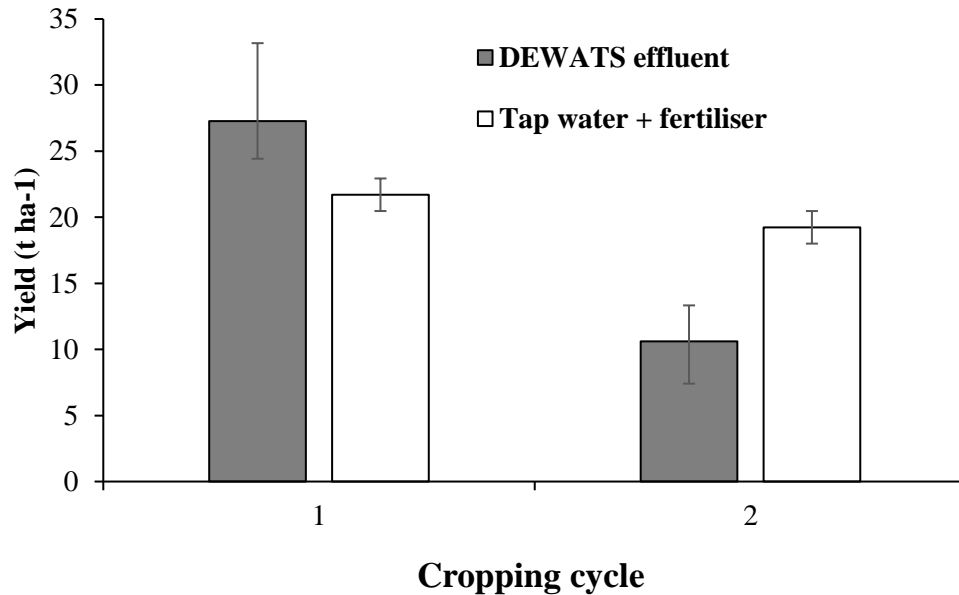


Figure 4.2: Banana yield ( $n = 6$ ; mean  $\pm$  standard error of mean differences) in different irrigation treatments and cropping cycles.

#### 4.3.3 Soil properties

Mean squares for soil chemical properties at two different soil depths (0.3 and 0.6 m) after three sampling periods are reported in Table 4.6. Soil pH significantly ( $p < 0.01$ ) differed between irrigation treatments. There were significant differences between different soil depths with respect to soil organic C ( $p < 0.01$ ), extractable P ( $p < 0.001$ ),  $\text{NO}_3^-$ -N ( $p < 0.05$ ) and total N ( $p < 0.01$ ). Significant changes in soil total N ( $p < 0.01$ ) and  $\text{NO}_3^-$ -N ( $p < 0.001$ ) were observed over time. A significant interaction between soil depth and time occurred with regards to total inorganic N and  $\text{NH}_4^+$ -N ( $p < 0.05$ ).

Table 4.6: Mean squares for soil chemical properties between the two irrigation treatments sampled from two different depths over the three growing seasons.

Source of variation	Degrees of freedom	Missing values	Total N	Org. C	Tot. Inorg. N	NH <sub>4</sub> <sup>+</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	Ext. P	Soil pH
				(%)		(mg kg <sup>-1</sup> )			
Block stratum	2		0.2	0.4	93	44	142	744	0.6
Irrigation treatment	1		0.1	0.1	398 *	66	141	110	1.3
Soil depth	1		1.1 **	1.5 **	903 ***	163	299 *	19605 ***	0.1
Time	2		0.7 **	0	6805	3066 ***	1056 ***	263	0.2
Irrigation treatment * soil depth	1		0	0.1	79	84	0.14	344	0
Irrigation treatment * time	2		0.1	0	390 *	38	186	107	0.3
Soil depth * time	2		0.1	0.2	665	339 *	71.93	835	0.1
Irrigation treatment * soil depth * time	2		0.2	0.3	63	63	0.31	55	0
Residual	20	-2	0.1	0.1	147	72	54.47	322	0.1
Total	33	-2							

Ext. P is the extractable phosphorus.

Org. C is the organic C

Tot. Inorg. N is the total inorganic nitrogen

\*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001

The concentrations of extractable P and  $\text{NO}_3^-$ -N at different depths between the two irrigation treatments and different sampling times are shown in Table 4.7. Higher concentrations of P and  $\text{NO}_3^-$ -N content were reported in the 0.3 m soil depth compared to 0.6 m.

The total soil N concentrations at three different sampling times are given in Table 4.7. A significantly higher ( $p < 0.05$ ) concentration of total N was found 504 days after planting (DAP) compared to the initial concentration and 992 DAP. There was a consistent pattern in soil total inorganic N and  $\text{NH}_4^+$ -N concentrations, both increased with time and attained the highest concentration at 0.3 m soil depth 992 DAP (Table 4.7).

Table 4.7: Concentrations (mean  $\pm$  standard error of mean differences;  $n = 3$ ) of total N (organic + inorganic N),  $\text{NO}_3^-$ -N,  $\text{NH}_4^+$ -N, extractable P and total inorganic N ( $\text{NO}_3^-$ -N +  $\text{NH}_4^+$ -N) between the two soil depth, irrigation treatments over three different periods of the study.

Irrigation treatment	Soil depth	Time	Total N	Extractable P	$\text{NO}_3^-$ -N	$\text{NH}_4^+$ -N	Total inorganic N
			(%)		mg kg <sup>-1</sup>		
DEWATS	0.3 m	Initial	0.30 $\pm$ 0.01 <sup>ab</sup>	37.7 $\pm$ 1.8 <sup>abcd</sup>	4.9 $\pm$ 1.4 <sup>bc</sup>	10.4 $\pm$ 2.1 <sup>e</sup>	15.3 $\pm$ 3.3 <sup>d</sup>
		504 DAP	0.34 $\pm$ 0.01 <sup>a</sup>	52.2 $\pm$ 2 <sup>abcd</sup>	4.9 $\pm$ 1 <sup>bc</sup>	20.8 $\pm$ 2.4 <sup>d</sup>	25.7 $\pm$ 1.4 <sup>d</sup>
		992 DAP	0.29 $\pm$ 0.03 <sup>ab</sup>	58.7 $\pm$ 22.4 <sup>abc</sup>	33.1 $\pm$ 12.5 <sup>a</sup>	57.4 $\pm$ 2 <sup>a</sup>	90.4 $\pm$ 10.8 <sup>a</sup>
	0.6 m	Initial	0.27 $\pm$ 0.01 <sup>ab</sup>	11.9 $\pm$ 4.6 <sup>bcd</sup>	3.4 $\pm$ 1.2 <sup>bc</sup>	10.2 $\pm$ 2 <sup>e</sup>	13.6 $\pm$ 2.2 <sup>d</sup>
		504 DAP	0.30 $\pm$ 0.01 <sup>ab</sup>	5.2 $\pm$ 0.8 <sup>d</sup>	1.2 $\pm$ 0.8 <sup>c</sup>	32.6 $\pm$ 3.5 <sup>b</sup>	33.8 $\pm$ 2.7 <sup>cd</sup>
		992 DAP	0.27 $\pm$ 0.02 <sup>ab</sup>	10 $\pm$ 6.9 <sup>cd</sup>	22.4 $\pm$ 2.2 <sup>ab</sup>	41.9 $\pm$ 9.4 <sup>bc</sup>	64.4 $\pm$ 10.7 <sup>abc</sup>
Tap water + fertiliser	0.3 m	Initial	0.28 $\pm$ 0.02 <sup>ab</sup>	41 $\pm$ 2.4 <sup>abcd</sup>	4.2 $\pm$ 0.8 <sup>bc</sup>	8.9 $\pm$ 2.4 <sup>e</sup>	13.1 $\pm$ 2.6 <sup>d</sup>
		504 DAP	0.32 $\pm$ 0.03 <sup>ab</sup>	72.5 $\pm$ 24.4 <sup>a</sup>	6.1 $\pm$ 1.9 <sup>bc</sup>	29.2 $\pm$ 9.5 <sup>bcd</sup>	35.3 $\pm$ 11.4 <sup>cd</sup>
		992 DAP	0.32 $\pm$ 0.01 <sup>ab</sup>	64.2 $\pm$ 15.4 <sup>a</sup>	20.3 $\pm$ 6.4 <sup>abc</sup>	51.5 $\pm$ 6.6 <sup>ab</sup>	71.8 $\pm$ 10.7 <sup>ab</sup>
	0.6 m	Initial	0.25 $\pm$ 0.03 <sup>ab</sup>	11.9 $\pm$ 3.4 <sup>bcd</sup>	3.5 $\pm$ 0.7 <sup>bc</sup>	8.8 $\pm$ 1.8 <sup>e</sup>	12.4 $\pm$ 2.3 <sup>d</sup>
		504 DAP	0.32 $\pm$ 0.0 <sup>ab</sup>	5.3 $\pm$ 0.5 <sup>d</sup>	2.8 $\pm$ 0.4 <sup>bc</sup>	24.3 $\pm$ 0.8 <sup>c</sup>	27.0 $\pm$ 0.3 <sup>d</sup>
		992 DAP	0.24 $\pm$ 0.03 <sup>b</sup>	1.8 $\pm$ 0.1 <sup>d</sup>	9.2 $\pm$ 3.1 <sup>bc</sup>	34.3 $\pm$ 0.3 <sup>b</sup>	43.5 $\pm$ 3.1 <sup>bcd</sup>

Superscripts that are different within a column indicate significant differences ( $p < 0.05$ ).

#### 4.3.4 N and P leaching

The mean squares for N and P leaching within the soil are reported in Table 4.8. Significant differences ( $p < 0.001$ ) over time were found with respect to P leaching. No significant differences ( $p > 0.05$ ) of orthophosphate P concentrations in leachates were reported between the two irrigation treatments. There were significant interactions between irrigation treatments, depth and time ( $p < 0.05$ ) on inorganic N concentrations leached.

Table 4.8: Analysis of variance table showing the mean and sum of squares for inorganic N and P in leachates collected from the wetting front detectors (WFDs) in the field.

##### Variate: Inorganic N

Source of variation	Degrees of freedom	Missing values	Sum of squares	Mean squares	F	Probability
Block stratum	2		519	260		
Block*Units* stratum						
Time	14		72852	5204	***	< 0.001
Depth	1		10291	10291	*	0.014
Treatment	1		2661	2661		0.206
Time*Depth	14		45213	3229	*	0.027
Time*Treatment	14		52550	3754	**	0.009
Depth*Treatment	1		2152	2152		0.255
Time*Depth*Treatment	13	-1	39972	3075	*	0.042
Residual	111	-7	182758	1646		
Total	171	-8	351888			

##### Variate: Orthophosphate P

Source of variation	Degrees of freedom	Missing values	Sum of squares	Mean squares	F	Probability
Block stratum	2		70	35		
Block*Units* stratum						
Time	14		2118	151	***	<.001
Depth	1		23	23		0.23
Treatment	1		15	14		0.34
Time*Depth	14		26	2		1
Time*Treatment	14		316	23		0.153
Depth*Treatment	1		1	1		0.824
Time*Depth*Treatment	13	-1	134	10		0.805
Residual	109	-9	1722	16		
Total	169	-10	4327			

\* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

From 295 to 331 DAP there were generally high N concentrations in leachates from all treatments and at both sampled depths (Table 4.8). As the growing period progressed, concentrations stabilised in all treatments until 853 DAP. The N concentrations in the DEWATS effluent treatment and at 0.3 m began to rise at 899 DAP reaching a significantly high value of 244 mg L<sup>-1</sup> at 992 DAP (Figure 4.3).

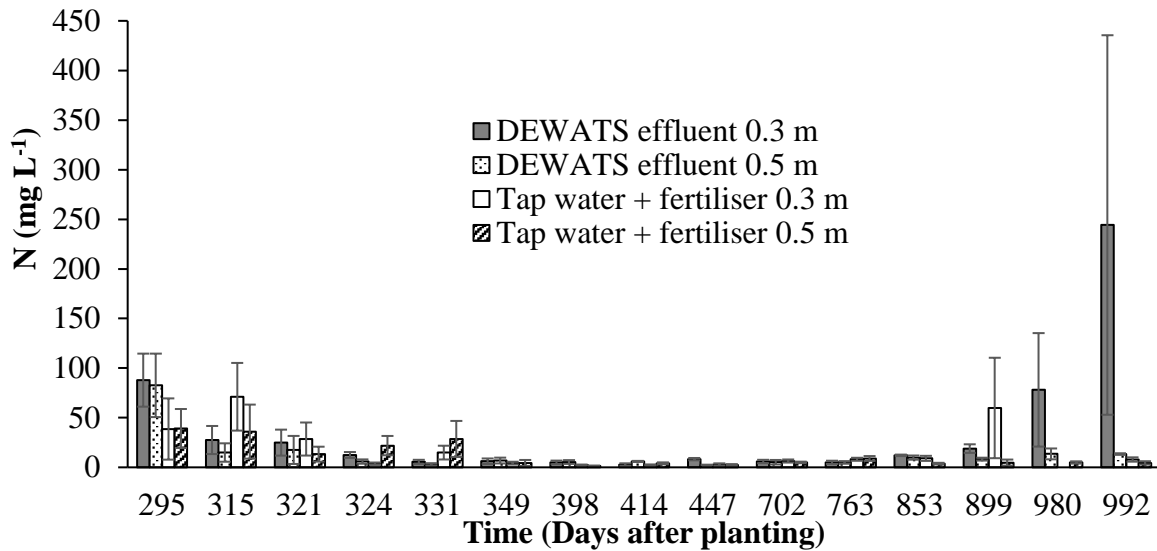


Figure 4.3: Concentrations of inorganic N ( $n = 3$ , mean  $\pm$  standard error of mean differences) in leachates collected from the two irrigation treatments at two depths from 295 to 992 days after planting.

The average concentration of inorganic P in soil leachates monitored over the period between 295 and 992 DAP are shown in Figure 4.4. Phosphorus increased from  $0.1 \text{ mg L}^{-1}$  (295 DAP) to reach a maximum concentration of  $9.97 \text{ mg L}^{-1}$  (702 DAP), which later declined to a concentration of  $< 2.5 \text{ mg L}^{-1}$ .

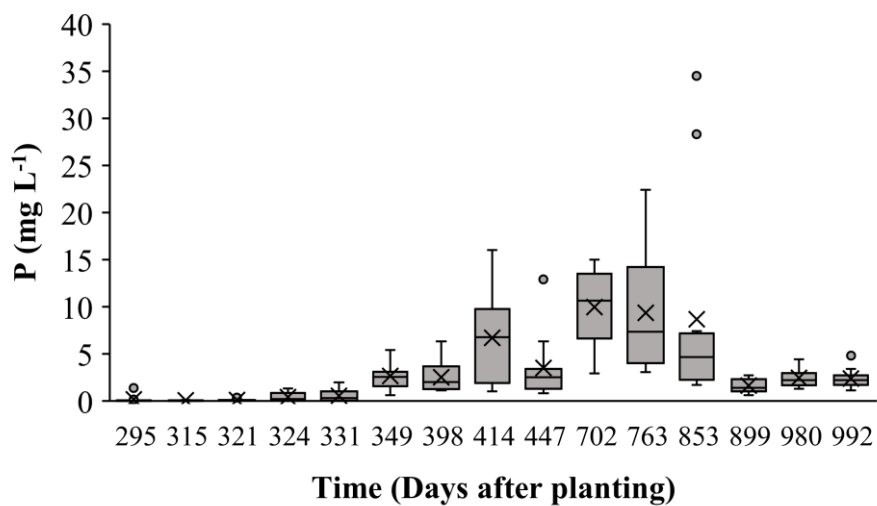


Figure 4.4: Boxplots showing concentration of inorganic P in leachates collected from the wetting front detectors between 295 and 992 days after planting; means combined for all soil depths and irrigation treatments.

#### 4.3.5 Groundwater monitoring

The water table levels measured during the experimental period are shown in Figure 4.5. The average water level was generally deeper in piezometer 1 (0.7 m below ground level) and

piezometer 2 (0.59 m below ground level) compared to the field plots piezometers (P3, 0.35 m; P4, 0.37 m; and P5, 0.36 m). The water levels varied in the different locations at the site i.e. P1 (0.4 – 0.81 m below ground level), P2 (0.44 – 0.77 m below ground level), P3 (0.1 – 0.5 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 piezometer P6 downslope from the field plots.

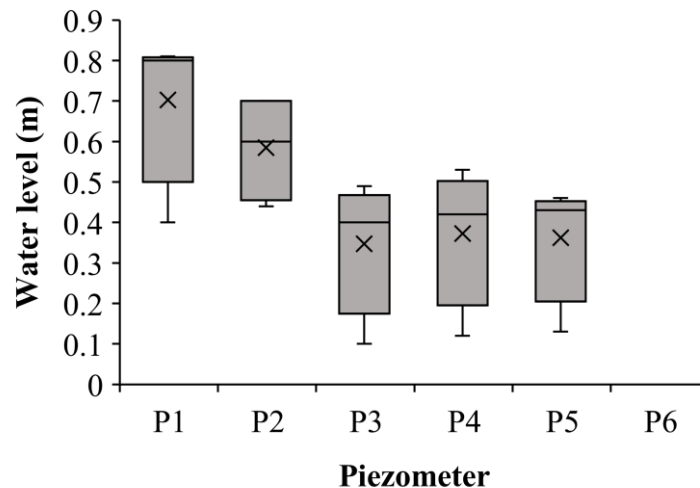


Figure 4.5: Water levels in different locations of the experimental field. P1 and P2 upslope from the field plots; P3, P4 and P5 within the field plots; P6 downslope from the field plots.

#### 4.3.6 Soil N and P loading and crop uptake

The N and P supplied by fertigating the banana and taro crops with DEWATS effluent is given in Table 4.9. During the whole cropping period, the N and P requirements for both crops were met. Although there was a deficit of about 742 mm when irrigation was not done (Nov 2013 to May 2014), the total applied still met the crop nutrient requirements.

Table 4.9: Nitrogen (N) and phosphorus (P) supplied by irrigation with effluent from the two different sources (Anaerobic filter; AF and Horizontal flow constructed wetland; HFCW) based on actual amounts applied over 992 days in comparison to crop nutrient requirements for both crops.

Water source	N	P
	(kg ha <sup>-1</sup> )	
AF	1 000	220
HFCW	239	47
<b>Total applied</b>	<b>1 239</b>	<b>267</b>
<b>Total required</b>	<b>1 128</b>	<b>220</b>

The mean squares values for banana and taro plant tissue N and P concentrations are reported in Table 4.10 and Table 4.11. There were no significant differences ( $p > 0.05$ ) in N and P uptake between the irrigation treatments for both banana (Table 4.10) and taro (Table 4.11). The



mean values for nutrients (N and P) taken up by the banana were: N (DEWATS; 3.3 % or 553 kg ha<sup>-1</sup> and tap water + fertiliser; 3.1 % or 533 kg ha<sup>-1</sup>) and P (DEWATS; 0.21 % or 35 kg ha<sup>-1</sup> and tap water + fertiliser; 0.20 % or 34 kg ha<sup>-1</sup>). In the taro crop 250 kg N ha<sup>-1</sup> were taken up under DEWATS while 173 kg N ha<sup>-1</sup> under tap water + fertiliser treatment. Taro P uptake was 55 kg ha<sup>-1</sup> (DEWATS treatment) and 46 kg ha<sup>-1</sup> (tap water + fertiliser treatment).

*Table 4.10: Mean squares for N and P concentrations from banana leaf tissues between two irrigation treatments over the two growing cycles.*

<b>Source of variation</b>	<b>Degrees of freedom</b>	<b>N</b>	<b>P</b>
Block stratum	2	0.02	0.0005
Block*Units* stratum			
Season	1	0.09	0.0004
Treatment	1	0.10	0.0004
Season*Treatment	1	0.16	0.0004
Residual	6	0.04	0.0004
Total	11		

*Table 4.11: Mean squares for N and P concentrations from taro corm tissues between two irrigation treatments during the first growing cycle.*

<b>Source of variation</b>	<b>Degrees of freedom</b>	<b>N</b>	<b>P</b>
Block stratum	2	0.132	0.0001
Block*Units* stratum			
Treatment	1	0.196	0.0001
Residual	2	0.103	0
Total			

\*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001

#### **4.3.7 Crop water requirements**

The rainfall and total evapotranspiration for the two crops (banana and taro) between planting (November 2013) and final harvest (July 2016) are presented in Figure 4.6. The graph shows a seasonal variation in rainfall and crop water demands typical of the sub-tropical climate at the experimental site. Higher crop water requirements were recorded during the summer months (September to April) compared to winter (May to August). During the study, the highest winter rainfall was recorded in July 2016. In July 2015 and again in July 2016 irrigation deficits were very low (rainfall higher than evapotranspiration). Although crop water demand was high in summer, rainfall sometimes supplemented irrigation requirements.

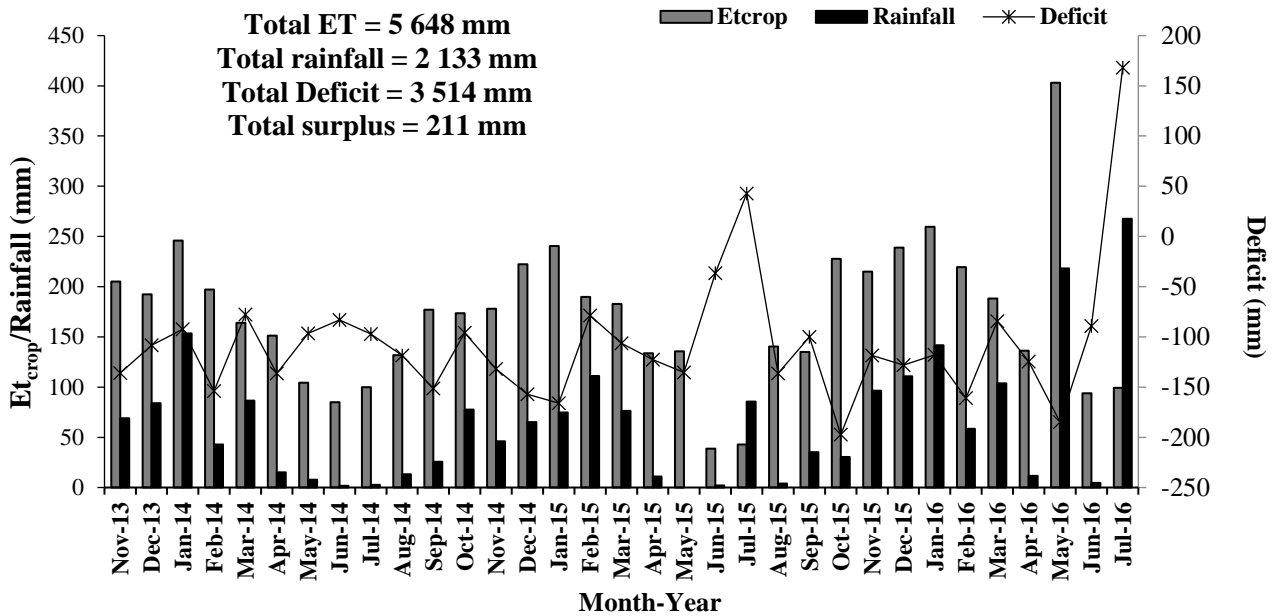


Figure 4.6: Rainfall and crop evapotranspiration ( $ET_{crop}$  for both banana and taro) and irrigation deficits at the Newlands-Mashu field site showing irrigation water demands for the period between November 2013 and July 2016.

The data recorded for actual water applied with regards to the respective DEWATS effluent sources (AF and HFCW) is given in Appendix 10. The total amount of HFCW effluent used to irrigate the main banana crop and the taro first-year crop (June 2014 to May 2015) was 1 130 mm, and thereafter AF effluent was used for irrigation (June 2015 to July 2016) such that 1 642 mm was applied (Appendix 10). During the entire growing period (November 2013 to July 2016), including 6 months of no irrigation (November 2013 to May 2014), the total effluent used for irrigation was 2 772 mm instead of the 3 514 mm required by the crops.

## 4.4 Discussion

### 4.4.1 Effluent characterisation

The characterisation of effluent from two components of the DEWATS plant reported in Table 4.1 showed high concentrations of mineral nutrients (N and P) in the AF effluent. These later decreased in the HFCW effluent due to further treatment through the planted gravel filters, which remove N through anammox reactions and P through adsorption reactions (Kadlec and Wallace 2008). Increased  $NO_3^-$ -N in the HFCW was attributed to aerobic treatment as the effluent passed through the vertical flow constructed wetland (VFCW) and then the HFCW (Jasper 2014). The AF effluent therefore falls within the FAO ‘no restriction category for

agricultural use' while the HFCW effluent is within the slight to moderate restriction in terms of  $\text{NO}_3^-$ -N concentrations (Pescod 1992).

The AF effluent average COD test value of  $524.5 \text{ mg L}^{-1}$  reported in were within the South African Department of Water and Sanitation (DWS) acceptable limits of  $5\,000 \text{ mg L}^{-1}$  for irrigating with  $50 \text{ m}^3$  of wastewater on any given day (DWA 2013). The values did not conform to the limits for using  $500$  and  $2\,000 \text{ m}^3$  of wastewater on any given day which is supposed to be  $400$  and  $75 \text{ mg L}^{-1}$  respectively. Large variation of COD in AF effluent was reported; the median was  $133.6 \text{ mg L}^{-1}$  and the range  $81.2 - 2\,470 \text{ mg L}^{-1}$ . As expected, wastewater treatment through the anaerobic baffled reactor (ABR) and AF remove about  $84 - 88 \%$  of COD from domestic wastewater + blackwater (Reynaud and Buckley 2016). Therefore, large variations were due to variations in wastewater flow in terms of quality and quantity as reported by Reynaud and Buckley (2016). The COD removal in HFCW was very high, attaining a value acceptable for unrestricted use in agriculture according to the DWA (2013) standards, although there are no limits for COD in FAO standards for irrigation water quality (Pescod 1992).

The effluent pH values were within the DWA (2013) and FAO standard limits for irrigation wastewater (Pescod 1992). High pH in effluent is related to increased alkalinity (Foxon 2009) and pH above  $7.33 - 7.98$  is expected in ABR and AF treatment since the anaerobic treatment is stopped by pH below  $6.5$  as reported by Reynaud and Buckley (2016).

The FAO standard limit for unrestricted wastewater irrigation in terms of electrical conductivity (EC), according to FAO (1985), is  $70 \text{ mS m}^{-1}$  and this also applies to South African department of water and sanitation standards (DWA 2013). Based on wastewater characterisation results the EC for HFCW effluent was within the limit (Average  $74 \text{ mS m}^{-1}$ ; Median  $70 \text{ mS m}^{-1}$ ) although it fell within the slight to moderate degree of reuse according FAO standards by FAO (1985).

#### **4.4.2 Crop growth and yield**

Fertigation using DEWATS effluent significantly ( $p < 0.05$ ) increased taro and banana growth during the first cropping cycle (Figure 4.1 and Table 4.4). This agreed with several studies on fertigating with wastewater (Shahalam et al. 1998, Tak et al. 2013, Uzen et al. 2016). Taro did not perform well during the second cropping cycle as shown by low vegetative growth rate (Table 4.4) due to full banana canopy cover shading. Although the banana plant height was higher during second cropping cycle, lower yields were reported (Figure 4.2). This could have been probably due to high N application using large volumes of AF effluent (Appendix 10). It

has been confirmed that less treated wastewater with high N concentrations may lead to delayed flowering and reduced yield (Hernández-Martínez et al. 2016, Mojid et al. 2016, Pedrero et al. 2010).

#### 4.4.3 Soil properties

Soil extractable P decreased with depth (Table 4.7). Phosphorus is highly immobile in most soils except in sands due to adsorption in the topsoil by organic matter and/or clay minerals, though the latter tend to be more prevalent in the B horizon, especially of acid soils. Phosphorus that leach from topsoil is then held lower in the profile. As a result, there is little P leaching except in sand soils as reported by Bame et al. (2014) using a sandy soil type.

The  $\text{NO}_3^-$ -N concentrations significantly increased over the experimental period and highest concentrations were reported in the 0.3 m soil depth (Table 4.7). This could be attributed to the poor drainage of the clay soil allowing nutrients to accumulate in the top layers. A decrease in  $\text{NO}_3^-$ -N concentrations from planting to 504 DAP (Table 4.7) was due to low N concentrations from HFCW effluent used during that period. Since the AF effluent was then used from 504 to 992 DAP, a significant increase in soil  $\text{NO}_3^-$ -N was reported as the effluent was applied in high volumes (Appendix 10). Furthermore, the AF effluent could have supplied more dissolved organic matter which stimulated microbial activity that controls the nitrification process as reported by several authors (Bame et al. 2013, Darwesh 2015, Sahrawat 2008).

Soil total N (organic + inorganic N) content significantly increased at 504 DAP compared to before planting (initial) and at 992 DAP (Table 4.7). Soils contain about 99 % of N as organically bound (Brady and Weil 2016). The degradation of organically bound N occurs over a long period of time depending on other factors such as soil type, climatic conditions, topography and vegetation type. Considering the experimental time frame such changes were not expected over such a short period and the reasons behind this observation were unclear.

Increased soil  $\text{NH}_4^+$ -N and total inorganic N occurred over time in both irrigation treatments (Table 4.7). The concentrations were significantly higher in the DEWATS treatment (0.3 m) after the second cropping cycle (992 DAP). Application of urea (tap water + fertiliser) and increased irrigation with AF effluent (DEWATS treatment) were the main causes. High  $\text{NH}_4^+$ -N concentrations in the DEWATS treatment (0.3 m) during the second cropping cycle were caused by the high  $\text{NH}_4^+$ -N content in the AF effluent used (Table 4.1) and high irrigation depth from 778 DAP (Appendix 10). Clay loam soils have high cation exchange capacity (CEC)

hence retain positively charged cations such as  $\text{NH}_4^+$  (Levy et al. 2011), allowing its accumulation in the upper layer (0.3 m) of the soil profile. Bame et al. (2013) used the same soil and reported high  $\text{NH}_4^+$ -N retention in their laboratory column study. The authors attributed  $\text{NH}_4^+$ -N retention in the Se soil to fixation by clay soils due to their high CEC.

#### **4.4.4 N and P leaching**

Fertigation using DEWATS effluent commenced from 201 DAP and leachates were collected from 295 DAP. High N concentrations in all treatments were reported during the period between 295 and 331 DAP (Figure 4.3). This was attributed to mineralisation and nitrification after soil disturbance around the WFDs and low uptake by plants as reported by Fessehazion et al. (2011). As the growing period progressed, concentrations stabilised in all treatments until 853 DAP before they began to increase, especially in the DEWATS effluent plots (0.3 m depth), due to increased fertigation using AF effluent (Appendix 10). High rainfall events in July and August 2016 (Figure 4.6; Appendix 10) coupled with high irrigation depth (Figure 4.6) did not move N concentrations downwards as expected. Low N movement to lower soil depths was attributed to low solute movement in the clayey soil and other losses ( $\text{N}_2$ ,  $\text{N}_2\text{O}$  and  $\text{NO}$  gases by the process of denitrification, and  $\text{NH}_3$  gas through volatilisation). Comparable results have also been reported by Musazura et al. (2015) on the same site.

Variations in leachate P concentrations over time were found (Figure 4.4). Soil P can either be sparingly available or permanently fixed. The sparingly available P (precipitated or adsorbed) is in equilibrium with solution P. The dissolution and adsorption of P from the soil colloids is affected by soil pH, mineralogy, presence of competing anions as well as P concentrations in the soil and uptake by crops (Fink et al. 2016). Changes in soil solution P concentration from leachates over time could have been attributed to variations in uptake demands by plants over the growing cycle. Phosphorus uptake by plants trigger replenishment through dissolution and desorption from soil colloids.

#### **4.4.5 Groundwater monitoring**

Groundwater levels (Figure 4.5) ranged between 0.1 – 0.8 m below ground. Whereby the upslope (P1 and P2) were much deeper than within the field (P3 – P5). This was attributed to high clay content of the subsoil and the presence of 2:1 expanding clays (Bame et al. 2013) and continuous irrigation within the field, which increased the perched water table. The accumulation water in the perched water table can be controlled through irrigation scheduling

considering crop water requirements with room for rainfall. If the water in the perched water table percolates down the soil it contaminates the groundwater. This is less likely to happen due to the clay soil nature and continuous irrigation which prevent cracking of expanding clays at the site. Low deep percolation of water provides adequate time for losses through evapotranspiration and increase uptake of N and P by crops. The risk to nearby surface water pollution is through downslope subsurface flow during rainy season towards the low point on the landscape, which is the river. This can be alleviated by installation of subsurface drainage to remove away excess water. However, in this study water was not detected in the piezometer outside the field near the river (P6), implying that the water table was deeper than the piezometer.

#### **4.4.6 Soil N and P loading and crop uptake**

The N and P applied met all the crop fertiliser requirements (Table 4.9). According to DEC (2004) if nutrients exceed crop requirements they become environmentally hazardous. As for P, it might meet the crop requirements but not bio-available due to precipitation and adsorption reactions in the soil. Therefore, the application of DEWATS effluent was environmentally sustainable.

The lack of significant differences in plant tissue N and P and dry biomass between the two irrigation treatments for both banana and taro is a further evidence that the DEWATS effluent supplied adequate nutrients for these crops. These results conform to studies by other authors who worked with different effluents and crops (Almukhtar et al. 2015, Bame et al. 2014, Fonseca et al. 2007).

#### **4.4.7 Crop water requirements and land area**

The total amount of effluent production by the DEWATS plant at Newlands Mashu is  $35 \text{ m}^3 \text{ day}^{-1}$  ( $12.5 \text{ ML year}^{-1}$ ). If the crops could have been irrigated during the whole experimental period, an amount of  $3\,514 \text{ mm}$  ( $1\,277 \text{ mm year}^{-1}$ ) was required. Thus, to use all the effluent produced based on crop water requirements about  $0.97 \text{ ha}$  of land would be required. Considering that there are 83 households and five people per household,  $1\,170 \text{ m}^2 \text{ household}^{-1}$  ( $23.3 \text{ m}^2 \text{ person}^{-1}$ ) would be needed. During wet periods effluent can be stored for later use and based on the calculations made in Figure 4.6 with reference to the climate at Newlands-Mashu about  $211 \text{ mm year}^{-1}$  ( $770 \text{ m}^3$ ) of excess effluent will be produced. Therefore, storage requirements needed translated to  $9.2 \text{ m}^3 \text{ household}^{-1}$  ( $1.9 \text{ m}^3 \text{ person}^{-1}$ ).

#### 4.5 Conclusions

The AF effluent contains high concentrations of N and P than the HFCW. The effluent complies with the DWS and the FAO standards for wastewater irrigation in terms of COD, N and P, pH and EC. There were no significant differences in N and P uptake, crop growth and yield by the two crops (banana and taro) regardless of the irrigation treatment. Use of 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 N were found in leachates from the DEWATS treatment within the 0.3 m soil depth. The site water table was generally shallow, ranging from 0.1 - 0.8 m below ground level. The occurrence of a perched water table as shallow as 0.1 m below ground level was of environmental benefit since the water was not draining deeper and moving laterally. Risks to surface water contamination can be minimised through on farm management practices such as installation of subsurface drainage, irrigation scheduling with room for rainfall and the use of high efficiency irrigation systems such as drip irrigation. Over the 992 days period banana and taro required 3 514 mm of effluent. An area of  $117 \text{ m}^2 \cdot \text{household}^{-1}$  ( $23.3 \text{ m}^2 \cdot \text{person}^{-1}$ ) is needed under the conditions studied at Newlands-Mashu. Storage requirements needed during wet periods were calculated to be about  $767 \text{ m}^3$  ( $9.2 \text{ m}^3 \cdot \text{household}^{-1}$  or  $1.9 \text{ m}^3 \cdot \text{person}^{-1}$ ). The HFCW effluent is an important source of irrigation water than nutrients (N and P) required by banana and taro in an intercrop.

## **CHAPTER 5: NITROGEN AND PHOSPHORUS FLUXES, AND CROP UPTAKE IN THREE SOILS FERTIGATED WITH DEWATS EFFLUENT TO FIELD CAPACITY.**

### **5.1 Introduction**

The use of treated wastewater in agriculture has been recommended as a major way to fulfil MDG number seven of fighting against hunger (WWAP 2017). Practical guidelines that will be used to inform policy makers on how to maximise benefits and mitigate risks must be developed for an effective wastewater use programme in agriculture (Pescod 1992). Practical guidelines consider technical aspects such as land area requirements, soil types, buffer zones, storage and transportation of the effluent (Pescod 1992, USEPA 2012).

Fertigation using wastewater can be done following scheduling which considers crop water requirements at different stages of growth (Pescod 1992, Qadir et al. 2013, USEPA 2012). There are different approaches for scheduling irrigation. These can be room for rainfall, maintenance of field capacity, leaching requirement and application of fixed amount (Annandale et al. 1999a). Different scheduling methods are applicable in different scenarios, for example in areas where water is scarcely available application to meet crop water requirements while giving room for rainfall can be used. However, there are some situations in which water is in excess, for example, during wet seasons the effluent production is high and crop water requirements are low. There is need for ways in which effluent can be managed. Irrigation methods such as maintenance of field capacity may be opted for.

The DEWATS effluent contains nitrogen (N) and phosphorus (P) (Gutterer et al. 2009), which may accumulate in the soil with continuous irrigation. Nitrogen and phosphorus dynamics in the soil are affected by variable soil conditions, driven by numerous soil physical, chemical and microbiological properties (Brady and Weil 2016, Feigin et al. 2012), which influence their accumulation, transformation and movement in the soil (Bame et al. 2014). Accumulation of nutrients in the soil is also driven by effluent quality and quantity (Pescod 1992). Poor on-farm irrigation management practices using wastewater may pose environmental risks due to nutrient leaching and/or surface runoff to nearby rivers (Qadir et al. 2013, Sharpley et al. 2001, USEPA 2012).

Some studies have been conducted on the behaviour of DEWATS effluent in three soils of KZN under laboratory column conditions (Bame et al. 2013), and with maize (Bame et al. 2014) and Swiss chard (Musazura 2014) in pot experiments. The nutrient (N and P) movement



in soil under DEWATS effluent irrigation were investigated in field studies (Chapter 4). Studies were limited to one site hence extrapolation of field investigation to other areas with contrasting soils is achievable through pot studies.

According to Canadian (AE 2000) and Australian governments guidelines (DEC 2004) wastewater fertigation may be done following different approaches which are (i) semi reuse that considers discharge when wastewater is excess, (ii) full reuse considers storage of excess wastewater and its use later (iii) full reuse that considers over-application when effluent is in excess followed by nutrient monitoring schemes. Furthermore, more information on fertigating crops with DEWATS effluent to field capacity, aiming to utilise excess effluent and influence of different soil type to environmental pollution is required and forms the major aim of this study. Specific objectives of the study were to (i) investigate growth and nutrient uptake of banana irrigated with DEWATS effluent, (ii) investigate the effects of irrigating with DEWATS effluent to field capacity on N and P loading in soils, and (iii) determine the effect on soil chemical properties and N and P leaching.

## **5.2 Materials and methods**

These have been described in Section 3.3 in Chapter 3.

## **5.3 Results**

### **5.3.1 Crop growth and yield**

Mean squares for the effects of different irrigation treatments and soil type on banana growth (plant height and total leaf area) are given in Table 5.1. There were significant differences in total leaf area ( $p < 0.05$ ) and plant height ( $p < 0.001$ ) between the three soils and both irrigation treatments.

Table 5.1: Mean squares banana growth rate (plant height and total leaf area) between the two irrigation treatments in three different soils over the experimental period (992 days).

Source of variation	Degrees of freedom	Missing values	Plant height	Total leaf area
Time	3		1.9 ***	35 ***
Treatment	1		0.4 ***	0
Soil	2		1.4 ***	46.7 ***
Time*Treatment	3		0	0.3
Time*Soil	6		0	7.3 ***
Treatment*Soil	2		0.3 ***	3.4 *
Time*Treatment*Soil	6		0	1
Residual	63	-9	0	0.7
Total	86	-9		

Significant difference at 5 % level\*, 1 % level\*\*, 0.01 level\*\*\*

The banana growth rate (total leaf area and plant height) during the vegetative stage is shown in Figure 5.1. Growth rate was higher in the Se soil compared to Ia and Cf soil for all irrigation treatments. The total leaf area declined from 588 days after planting but remained higher in Se followed by Ia and Cf soils.

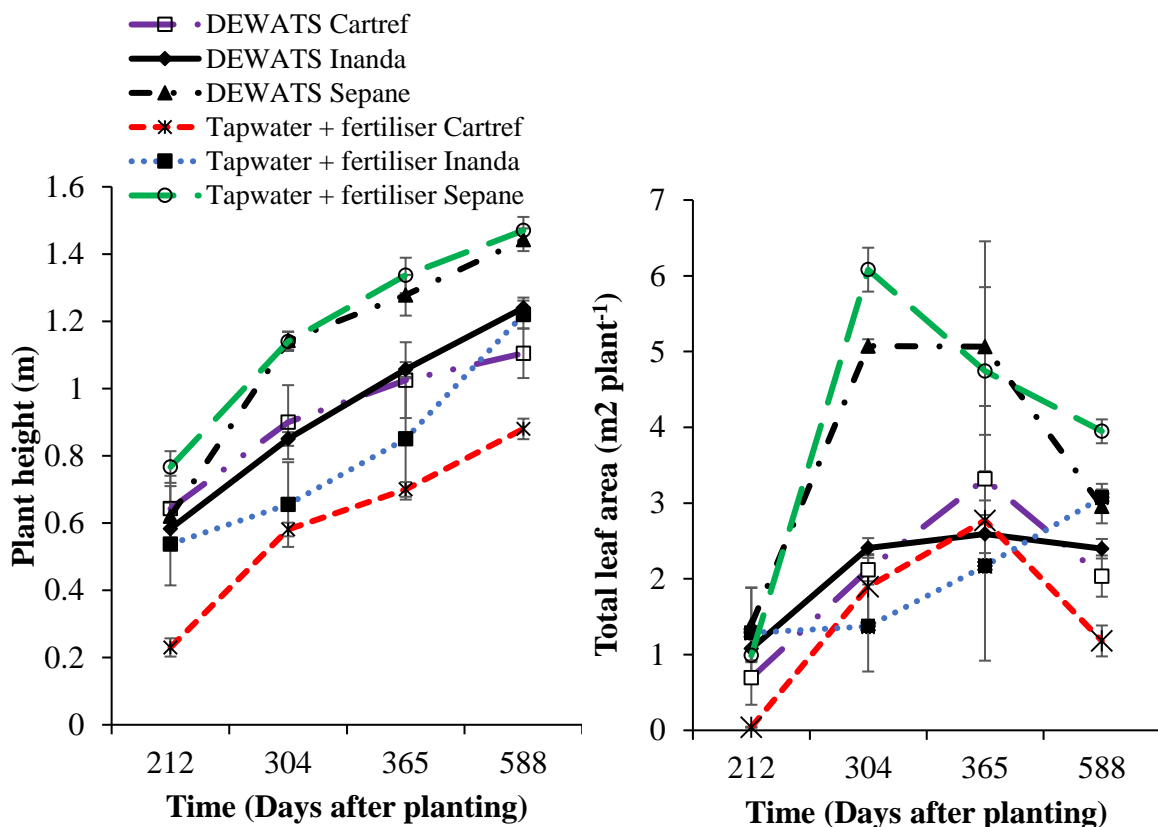


Figure 5.1: Total leaf area and plant height of banana ( $n = 4$ ; mean  $\pm$  standard error of mean differences) on the three soils used during the study at four sampling times.

The analysis of variance table for the effects of different irrigation treatments and soil types on banana biomass over the 728 days growing period is shown in Table 5.2. The fresh mass differed significantly (p < 0.05) between the two irrigation treatments and three soil type. Dry mass also showed a significant difference (p < 0.001) among three soils (Table 5.2).

Table 5.2: Mean squares for banana fresh and dry biomass between the two irrigation treatments and three contrasting soil recorded after harvesting (728 days after planting).

Source of variation	Degrees of freedom	Missing values	Fresh mass	Dry mass
Treatment	1		467604	62763
Soil type	2		38120676 ***	1049322 ***
Treatment*Soil type	2		4815376 *	138195
Residual	14	-4	837615	38471
Total	19	-4		

The interaction between soil type and irrigation treatment on banana plant height, total leaf area, fresh and dry biomass after harvesting is presented in Table 5.3. The plant height and total leaf area were significantly high in Se compared to other soils for both irrigation treatments. These plant growth variables were also comparable between the two irrigation treatments under Ia soil as well as to Cf soil fertigated with DEWATS effluent. Least plant height and total leaf area were reported in Cf soil in tap water + fertiliser treatment.

The fresh and dry biomass of banana measured at harvest (728 days after planting) are also reported in Table 5.3. Both fresh and dry biomass were significantly high in Se soil under tap water + fertiliser treatment. Dry biomass in Ia soil was significantly higher in tap water + fertiliser treatment compared DEWATS treatment. On the other hand, both fresh and dry biomass were significantly higher in Cf fertigated with DEWATS effluent compared to tap water + fertiliser treated.

Table 5.3: Banana plant height, total leaf area and fresh and dry biomass (728 days after planting) on three soils under different irrigation treatments (n=3; mean ± standard error of mean differences).

Treatment	Soil type	Plant height (m)	Total leaf area (m <sup>2</sup> )	Fresh biomass (g plant <sup>-1</sup> )	Dry biomass (g plant <sup>-1</sup> )
DEWATS	Cartref	0.92 ± 0.06 <sup>b</sup>	2.04 ± 0.29 <sup>b</sup>	4 480 ± 559 <sup>d</sup>	560 ± 65 <sup>d</sup>
	Inanda	0.90 ± 0.07 <sup>b</sup>	2.07 ± 0.19 <sup>b</sup>	6 500 ± 284 <sup>c</sup>	911 ± 124 <sup>c</sup>
	Sepane	1.12 ± 0.08 <sup>a</sup>	3.62 ± 0.45 <sup>a</sup>	7 188 ± 210 <sup>b</sup>	1 001 ± 69 <sup>bc</sup>
Tap water + fertiliser	Cartref	0.56 ± 0.08 <sup>c</sup>	1.29 ± 0.31 <sup>c</sup>	2 450 ± 401 <sup>e</sup>	359 ± 70 <sup>e</sup>
	Inanda	0.78 ± 0.09 <sup>b</sup>	1.88 ± 0.37 <sup>cb</sup>	6 767 ± 775 <sup>abc</sup>	1 171 ± 131 <sup>ab</sup>
	Sepane	1.15 ± 0.08 <sup>a</sup>	4.22 ± 0.64 <sup>a</sup>	8 113 ± 633 <sup>a</sup>	1 249 ± 186 <sup>a</sup>

Superscripts that are different within a column indicate significant differences (p < 0.05).

### 5.3.2 Soil properties

Mean squares for soil chemical properties after harvesting (728 days after planting) are given in Table 5.4. Significant differences ( $p < 0.001$ ) between soils were found with respect to total N, organic C and P. Soil P content also significantly differed ( $p < 0.01$ ) between the irrigation treatments. There was a significant ( $p < 0.01$ ) interaction between irrigation treatments and soil type on soil  $\text{NH}_4^+$ -N content.

Table 5.4: Means squares for soil chemical properties in the tunnel 728 days after planting amongst the three contrasting soils and two irrigation treatments.

Source of variation	Degrees of freedom	Total N	$\text{NO}_3^-$ -N	$\text{NH}_4^+$ -N	Org. C	Extr. P	Soil pH
Soil	2	0.3***	206	103	37***	11915***	0.1
Treatment	1	0	223	2078	0.1	1393**	0
Soil*Treatment	2	0	6	439.3**	0.1	178	0
Residual	12	0	183	139	0.4	99	0
Total	17						

\*  $P < 0.05$ ; \*\*  $P < 0.01$ ; \*\*\*  $P < 0.001$

Org. C is the organic carbon

Extr. P is the extractable P

Comparison of total N, P and organic C concentrations in the three soils after harvest and before planting are presented for all irrigation treatments in Table 5.5. Total N and organic C contents followed the order Ia > Se > Cf. Soil P content was significantly ( $p < 0.001$ ) higher in the Se compared to the Ia and Cf soils. The soil P did not significantly increase in Ia soil compared to other soils.

Table 5.5: Concentrations of total N, organic C and P in the soils after harvesting ( $n = 8$ ; mean  $\pm$  standard error of mean differences).

Soil type	Treatment	N %	P mg/kg	Org. C %
Cartref	Initial	0.05 $\pm$ 0 <sup>a</sup>	0.7 $\pm$ 0.2 <sup>a</sup>	0.5 $\pm$ 0.03 <sup>a</sup>
	DEWATS	0.06 $\pm$ 0.01 <sup>a</sup>	28.5 $\pm$ 8.8 <sup>c</sup>	0.9 $\pm$ 0.2 <sup>b</sup>
	Tap water + fertiliser	0.06 $\pm$ 0.01 <sup>a</sup>	9.5 $\pm$ 1.1 <sup>b</sup>	0.9 $\pm$ 0.2 <sup>b</sup>
Inanda	Initial	0.6 $\pm$ 0.03 <sup>d</sup>	11.7 $\pm$ 3.5 <sup>b</sup>	6 $\pm$ 0 <sup>e</sup>
	DEWATS	0.6 $\pm$ 0.04 <sup>d</sup>	19.9 $\pm$ 1.5 <sup>c</sup>	6 $\pm$ 0 <sup>e</sup>
	Tap water + fertiliser	0.5 $\pm$ 0.09 <sup>d</sup>	13.8 $\pm$ 2.0 <sup>b</sup>	5.6 $\pm$ 0.4 <sup>e</sup>
Sepane	Initial	0.29 $\pm$ 0.04 <sup>b</sup>	39.3 $\pm$ 3.0 <sup>c</sup>	2.9 $\pm$ 0.2 <sup>c</sup>
	DEWATS	0.34 $\pm$ 0.04 <sup>c</sup>	108 $\pm$ 3.8 <sup>d</sup>	3.9 $\pm$ 0.6 <sup>d</sup>
	Tap water + fertiliser	0.31 $\pm$ 0.05 <sup>bc</sup>	81.2 $\pm$ 10.0 <sup>d</sup>	3.7 $\pm$ 0.5 <sup>d</sup>

Superscripts that are different within a column indicate significant differences ( $p < 0.05$ ).

A boxplot for soil P concentrations in the two irrigation treatments is shown in Figure 5.2. The mean and median values for P content in the DEWATS treatment were higher than in the tap water + fertiliser treatment. This also applied to the ranges which were 10.9 - 116 mg L<sup>-1</sup> (DEWATS) and 7.4 - 94.8 mg L<sup>-1</sup> (tap water + fertiliser).

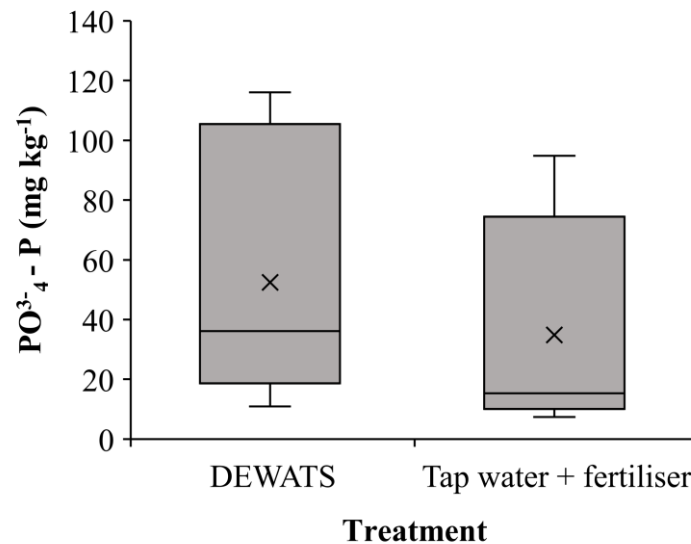


Figure 5.2: Boxplots showing mean (x) and distribution of quartiles in orthophosphate P concentrations ( $n = 12$ ; mean  $\pm$  standard error of mean differences) between the two irrigation treatments.

The NH<sub>4</sub><sup>+</sup>-N concentrations in the three different soils and irrigation treatments are described in Figure 5.3. Fertigation with DEWATS effluent significantly increased NH<sub>4</sub><sup>+</sup>-N content in all soils compared to tap water + fertiliser treatment. The least NH<sub>4</sub><sup>+</sup>-N concentrations values were found in the Cf and Se soils under the tap water + fertiliser treatment.

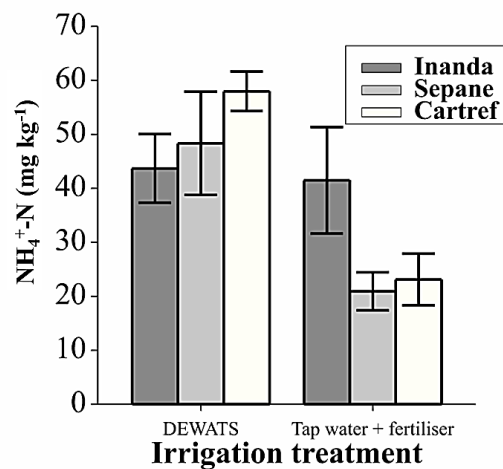


Figure 5.3: Concentrations ( $n = 4$ ; mean  $\pm$  standard error of means) of ammonium N in the three soils after harvesting from the two irrigation treatments.

### 5.3.3 N and P leaching

Significant differences ( $p < 0.001$ ) in the drainage rates between the three soils are shown in Figure 5.4. The sandy Cf had the highest drainage rate followed by Ia and the Se.

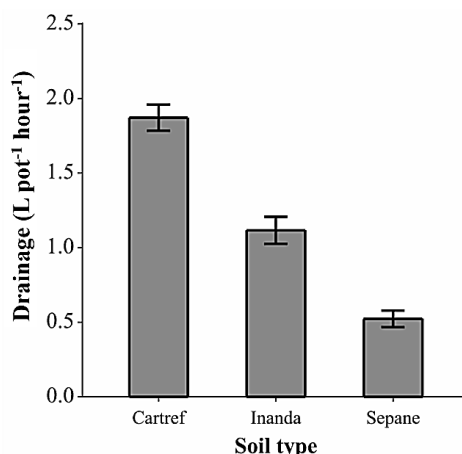


Figure 5.4: Drainage rates for the three soils, monitored during the banana growing cropping cycle ( $n = 6$ ; mean  $\pm$  standard error of mean differences).

The analysis of variance table in Table 5.6 shows the N and P leaching results for the different soils and irrigation treatments during the experimental period. There were significant differences in P leaching between the soils ( $p < 0.05$ ). A significant interaction ( $p < 0.001$ ) between soil type and irrigation treatment on N leaching over time was also reported.

Table 5.6: Analysis of variance table showing mean squares for inorganic N and P leached from the pots.

Source of variation	Degrees of freedom	Missing values	Volumes leached	N		P	
Time	5		0.1	8.9	***	0.004	***
Soil	2		21.7	***	1.5	*	0.001
Treatment	1		0	6.2	***	0	
Time*Soil	10		0.1	1.6	***	0	
Time*Treatment	5		0.4	5.1	***	0	
Soil*Treatment	2		0.5	1.8	*	0.001	
Time*Soil*Treatment	10		0.3	2.1	***	0.001	
Residual	72	-36	0.3	0.4		0	
Total	107	-36					

\*  $P < 0.05$ ; \*\*  $P < 0.01$ ; \*\*\*  $P < 0.001$

The P leached from each pot amongst the three soils are therefore shown in Figure 5.5. In soils fertigated with DEWATS effluent more P was leached from Cf soil compared to both Ia and Se.

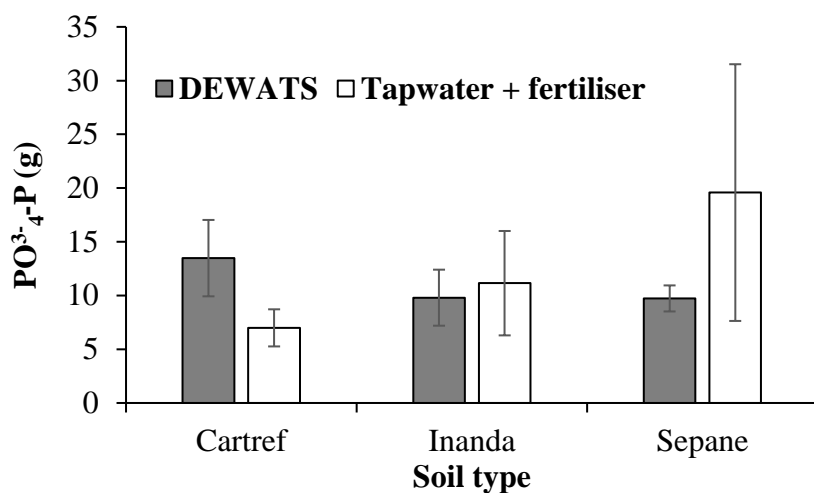


Figure 5.5: Amounts of orthophosphate (P) leached from the three soils between the two irrigation treatments ( $n=24$ ; mean  $\pm$  standard error of mean differences).

The interaction between soil type and irrigation treatment over time on N leached is shown in Figure 5.6. Very high N leaching occurred in Se soil under the tap water + fertiliser treatment compared to DEWATS effluent. Comparisons amongst different soils within the DEWATS effluent treatment showed that N leaching was higher in Ia than the Se and Cf soils.

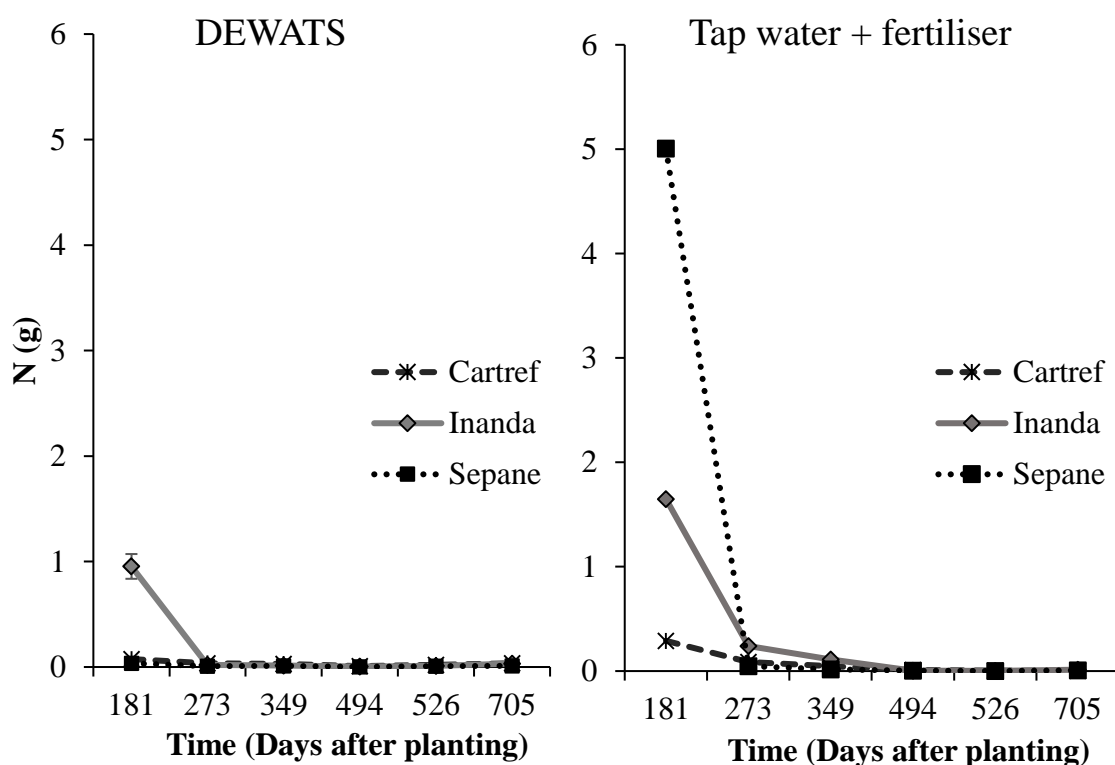


Figure 5.6: Interaction between irrigation treatment and soil type on the amount of nitrogen (N) leached during the study ( $n=4$ ; mean  $\pm$  standard error of mean differences).

### 5.3.4 Soil N and P loading and crop uptake

The irrigation depth for effluent applied to banana in the growing tunnel compared to crop water requirements are described in Figure 5.7. The irrigation was generally higher than the crop water requirements ( $ET_{crop}$ ) throughout the whole growing period.

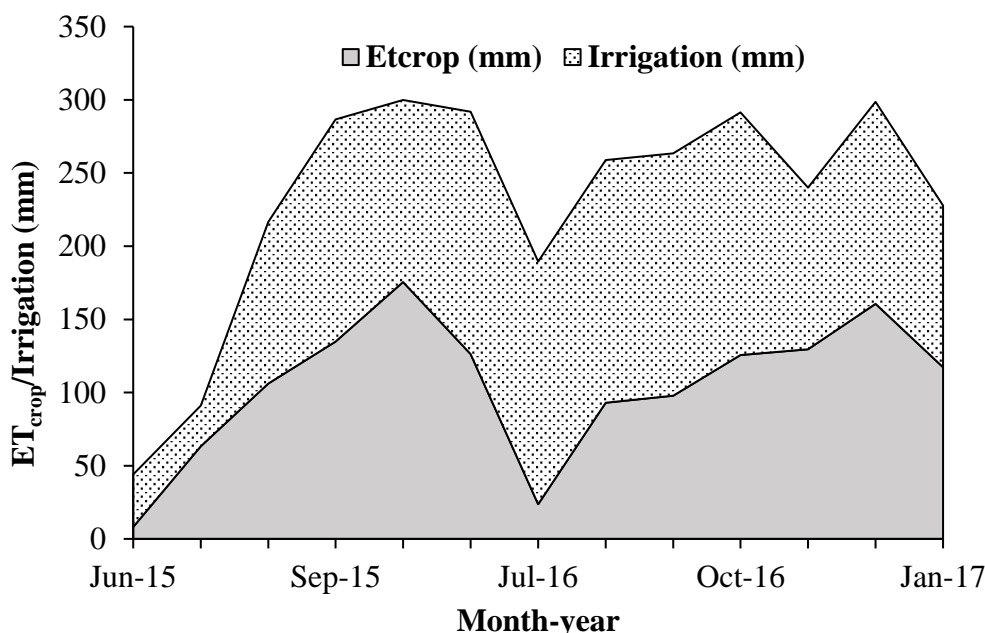


Figure 5.7: Irrigation applied (depth) and crop water requirements for banana plants in the tunnel.

The volumes of effluent applied during the banana growing period and respective contribution to N and P are given in Table 5.7. More AF effluent was applied compared to HFCW effluent. The use of AF effluent provided more N and P than HFCW.

Table 5.7: The volumes of effluent from the horizontal flow constructed wetland (HFCW) and the anaerobic filter (AF) and the amounts of total nitrogen (N) and phosphorus (P) supplied during the growth period (728 days).

Time	Effluent source	Irrigation (L)	N (mg kg <sup>-1</sup> of soil in pots)	P (mg kg <sup>-1</sup> of soil in pots)
April 2015 - October 2015	HFCW	178	58	13
November 2015 - February 2017	AF	815	779	135
Total	HFCW + AF	993	837	148

The amounts of N and P applied through fertigation using DEWATS effluent in relation to the crop fertiliser requirements are shown in Table 5.8. During the study period more N and P were applied compared to crop fertiliser requirements based on initial soil analysis results.



Table 5.8: The N and P applied through fertigation using DEWATS effluent over 728 days in comparison to crop fertiliser requirements.

Soil type	Required		Applied	
	N	P	N	P
	(mg kg <sup>-1</sup> of soil in pots)			
Cartref	58	4.6	837	148
Inanda	100	10	837	148
Sepane	70	0	837	148

The banana plant tissue nutrient concentrations in all soils and irrigation treatments are reported in Table 5.9. There was a significant difference ( $p < 0.001$ ) in P uptake between soils. A significant ( $p < 0.001$ ) difference in N and P uptake between the irrigation treatments was also reported.

Table 5.9: Mean squares for banana leaf tissue N and P concentration between the two irrigation treatments at 728 days after planting.

Source of variation	Degrees of freedom	Missing values	N	P
Soil type	2		0.3	0.01 ***
Treatment	1		3.4 ***	0.01 ***
Soil type*Treatment	2		0.2	0
Residual	12	-6	0.1	0
Total	17	-6		

\*  $P < 0.05$ ; \*\*  $P < 0.01$ ; \*\*\*  $P < 0.001$

Table 5.10 shows the concentrations of banana leaf tissue N and P concentrations between the two irrigation treatments. There were significantly ( $p < 0.01$ ) higher banana plant tissue N and P concentrations in crops fertigated with DEWATS effluent compared to the tap water + fertiliser. Very high P concentrations were reported under sepane soil under DEWATS effluent fertigation.

Table 5.10: Banana plant tissue nitrogen (N) and phosphorus (P) concentrations as a function of irrigation treatment and soil type ( $n=9$ ; mean  $\pm$  standard error of mean differences).

Treatment	Soil type	N (%)	P (mg kg)
DEWATS effluent	Cartref	0.029 $\pm$ 0.002 <sup>c</sup>	17 $\pm$ 1.5 <sup>c</sup>
	Inanda	0.030 $\pm$ 0.002 <sup>c</sup>	18 $\pm$ 1.5 <sup>c</sup>
	Sepane	0.028 $\pm$ 0.002 <sup>c</sup>	22 $\pm$ 0.6 <sup>d</sup>
Tap water + fertiliser	Cartref	0.018 $\pm$ 0.001 <sup>a</sup>	13 $\pm$ 1.2 <sup>a</sup>
	Inanda	0.025 $\pm$ 0.002 <sup>b</sup>	12 $\pm$ 0.6 <sup>b</sup>
	Sepane	0.022 $\pm$ 0.001 <sup>b</sup>	19 $\pm$ 1.5 <sup>c</sup>

Superscripts a and b that are different within a column indicate significant differences ( $p < 0.05$ ).

## **5.4 Discussion**

### **5.4.1 Crop growth and yield**

The DEWATS effluent increased banana vegetative growth (plant height, dry mass and leaf area) in the Cf soil, although highest growth occurred in the Se soil (Figure 5.1 and Table 5.3). This was due to nutrients supplied through fertigation (Table 5.8) and their subsequent uptake by crops (Table 5.10), which agreed with several studies using the same type of wastewater (Bame et al. 2014) and other types of wastewaters (Herpin et al. 2007, Khurana and Singh 2012, Mohammad and Ayadi 2004). Banana yield could not be determined due to delayed and erratic flowering exceeding the experimental time frame. Delayed flowering is caused by excess N and this has been reported in literature as one issue of concern when using treated wastewater for irrigation (Jaramillo and Restrepo 2017, Pedrero et al. 2010, Pescod 1992). In this case the reasons behind delayed flowering was not well understood and could not be attributed to excessive N from DEWATS effluent since this was also evidenced in tap water + fertiliser treatment, which received recommended amounts of N.

### **5.4.2 Soil properties**

Total N and organic C were very high in Ia than Se and Cf soils regardless of irrigation treatment (Table 5.5). About 99 % of the total soil N is organically bound and its degradation is a long-term process which may occur over 10 or more years (Brady and Weil 2016). The same applies to the soil organic matter, whose degradation time depend on its nature. Therefore, differences in total N and organic C concentrations in these three soils were attributed to their initial concentrations (Table 3.4). The same applies to results reported in Chapter 4 under Se soil.

High soil P content in Se soil compared to Ia and Cf reported in Table 5.5 was probably due to low drainage of the soil and retention by soil Al/Mn/Fe minerals. According to findings by Bame et al. (2013) Ia soils retain more P due to their high organic matter and Al oxide content while Cf loses more due to its coarse texture, but Table 5.5 showed that P content was comparable between Ia and Cf soils. Comparisons between the irrigation treatments showed that soil P content significantly increased in the DEWATS treatment compared to tap water + fertiliser treatment regardless of soil type (Figure 5.2). Soil P content were comparably higher after harvesting than respective initial values (Table 5.5) due to volumes of effluent used for

irrigation (DEWATS treatment) and application of inorganic fertiliser (tap water + fertiliser treatment) as well as the immobile nature of P in soils.

The  $\text{NH}_4^+$ -N concentrations increased significantly in all soils under DEWATS effluent irrigation (Figure 5.3). This is expected in soils with high cation exchange capacity (CEC) due to adsorption by the soil colloids as reported in Chapter 4 and other authors (Bame et al. 2013, Hernández-Martínez et al. 2016). On the other hand,  $\text{NH}_4^+$ -N content also increased in the low CEC Cf, probably due to AF effluent loading (Table 5.7). Similar findings were reported by Tsiknia et al. (2014) using olive mill wastewater. Volatilisation of soil  $\text{NH}_4^+$  occurs at pH above 7 (Dendooven et al. 1998). The pH values for all soils used in the study ranged between 4.11 and 5.20 (Table 3.4) hence pH driven volatilisation losses were very low.

### **5.4.3 N and P leaching**

Soil drainage rates monitored during the study showed, as expected, that the Se (clayey) had the least drainage followed by the Ia and the Cf (sandy) (Figure 5.4).

The leaching of P was high in Cf compared to the other two soils (Figure 5.5) due to higher P sorption capacity of Se expanding soils as reported in Chapter 4. High organic matter in Ia soils retains soil P thereby leaving less available for leaching as reported by Bame et al. (2013).

More N was leached from the tap water + fertiliser treatment in the Se soil at 181 DAP (Figure 5.6). This could have been attributed to fast hydrolysis of the urea and N leaching due to water applied soon after application of urea, which was split applied. In DEWATS effluent fertigated soil low N leaching losses from the Se and Cf soils compared to the Ia were probably due to the lower N content in these soils (Table 3.4). According to Egiarte et al. (2006) high concentrations of  $\text{NO}_3^-$  in leachates results from nitrification especially in acidic soils. Therefore, high N leaching from the Ia soil (DEWATS) was likely to be caused by fast nitrification resulting from acidity of that particular soil as explained by Bame et al. (2013).

### **5.4.4 Soil N and P loading and crop uptake**

High banana leaf tissue N and P concentrations in DEWATS effluent treatment (Table 5.10) are directly linked to nutrients applied through fertigation (Table 5.8) and retained in the soil (Figure 5.3 and Table 5.5). This agreed with studies by Johns and McConchie (1994) using treated domestic wastewater. Critical ranges for banana plant tissue nutrient sufficiency are 2.7 – 3.6 % N and 0.16 – 0.27 % P (de Mello Prado and Caione 2012). Despite receiving high

amounts of N and P through DEWATS irrigation (Table 5.7), the N and P concentrations in banana did not exceed 2.9 and 0.19%, respectively. This may be because plants take up nutrients during their growing period until an optimum concentration is attained (de Mello Prado and Caione 2012), as well as leaching and volatilisation of N and non-availability of P (Bame et al. 2013, Bame et al. 2014).

## **5.5 Conclusions**

Crop growth significantly increased in Cf soil fertigated with DEWATS effluent. Fertigation with AF effluent up to soil field capacity loaded more N and P to the soil, which even exceeded crop fertiliser requirements. Soil extractable P and  $\text{NH}_4^+$ -N increased significantly in all DEWATS effluent fertigated soils. Soil P leaching differed between soils, Cf soil losing more compared to Ia and Se. There was a significantly high N leaching in tap water + fertiliser treatment than in DEWATS effluent treatment. Nitrogen leaching differed amongst three soils under DEWATS effluent irrigation, highest leaching was reported in Ia soil compared to other soils. Therefore, acidic and sandy soils are at high risk to environmental pollution when fertigated with DEWATS effluent to field capacity. To manage nutrient leaching in such soils, irrigation practices such as applying to meet crop water requirements giving room for rainfall are recommended than maintaining field capacity. The banana leaf tissue N and P concentrations were significantly higher in DEWATS effluent compared to tap water + fertiliser implying that banana plants may remove nutrients supplied by the effluent.

## **CHAPTER 6: MODELING WATER, N AND P DYNAMICS IN SOIL FERTIGATED WITH DEWATS EFFLUENT.**

### **6.1 Introduction**

The use of wastewater in agriculture is done following robust practical guidelines. Practical guidelines are developed using information such on technical feasibility of water reuse, impacts on the environment, human health and social acceptance (DEC 2004, FAO 2013, Pescod 1992, Seshadri et al. 2014a). As discussed in Chapter 4 and 5, technical information required includes land area, annual effluent production, crops and effects on different soils. The behaviour of N and P in soils under wastewater irrigation and their effects on the environment must continuously be monitored (DEC 2004, Qadir et al. 2013, USEPA 2012).

Some work has been done on technical assessments for irrigation with DEWATS effluent and potential environmental effects based on nutrient dynamics in the soil (Chapter 4), and the ability of different soils to absorb effluent volumes and environmental impacts (Chapter 5). However, the development of robust guidelines for the use of wastewater in agriculture can be done through a series of experiments in different locations (contrasting soils, weather patterns and locational dynamics) and different crop types, which is expensive (Pescod 1992). Tools that can be used by policy makers to assist in decision making process are required.

Crop models are used as extrapolation tools to explain different systems based on experimental data (Chanter 1981, Probert et al. 1995) and they must be calibrated and validated for accurate simulations (Arnold et al. 2012). Different models have been used for simulating water and nutrient processes in agricultural systems to mention a few; Hydrus (Šimunek et al. 2012), agricultural production systems simulator model (APSIM) (Keating et al. 2003), CROPWAT (Stancalie et al. 2010) and the Soil Water Balance (SWB-Sci) (Tesfamariam et al. 2015).

The SWB-Sci is a water, salt and nutrient balance, irrigation scheduling model which make use of the soil-plant-atmosphere continuum (Jovanovic et al. 1999). The model has been used extensively in water, salt and nutrient monitoring studies (Annandale et al. 2001, Fessehazion et al. 2014, Tesfamariam et al. 2015). Its ability to calculate water balances and simulate nutrient dynamics makes it a vital tool for determining land area requirements and potential environmental risks in crops fertigated with wastewater.

The SWB-Sci model has never been calibrated and validated to simulate water and nutrient dynamics in soils fertigated with DEWATS effluent under banana cropping. This study therefore, aimed to calibrate and validate the SWB-Sci model for the simulation of water, N and P dynamics in soil fertigated with DEWATS effluent. The specific objectives of the study were to (i) calibrate and validate the SWB-Sci model, (ii) use nutrient (N and P) balance results to explain the potential environmental effects of fertigating with DEWATS effluent, (iii) the water balance results in determining land area requirements.

## 6.2 Materials and methods

Model description and methodologies followed to calibrated and validate the SWB-Sci model are reported in Chapter 3 (Section 3.6).

## 6.3 Results

### 6.3.1 Model calibration

#### 6.3.1.1 Crop growth

Simulation results for the leaf area index, total harvestable dry mass, crop height and crop N uptake in tap water + fertiliser treated banana are given in Table 6.1. All the growth variables and nutrient uptake met all statistical criteria for model accuracy proposed by De Jager (1994).

*Table 6.1: Calibration of the SWB-Sci model based on banana leaf area index, top and harvestable dry mass, crop height and N uptake from tap water + fertiliser treatment.*

<b>Variable</b>	<b>n</b>	<b>r<sup>2</sup></b>	<b>D</b>	<b>RMSE</b>	<b>MAE (%)</b>
Leaf area index	6	0.93	0.97	0.3	19
Top and harvestable dry mass	6	0.99	0.99	0.7	14
Crop height	7	0.9	0.96	0.2	11
Crop N uptake	6	0.99	0.99	14.5	13

N is the sample number; r<sup>2</sup> is the correlation coefficient, D is the Willmott's coefficient of agreement, RMSE is the root mean standard error; MAE is the mean absolute error.

#### 6.3.1.2 Profile water content

The measured soil profile water content during the banana growing period was plotted against the simulated water content (Figure 6.1). The model showed a good fit between simulated and measured profile water content.

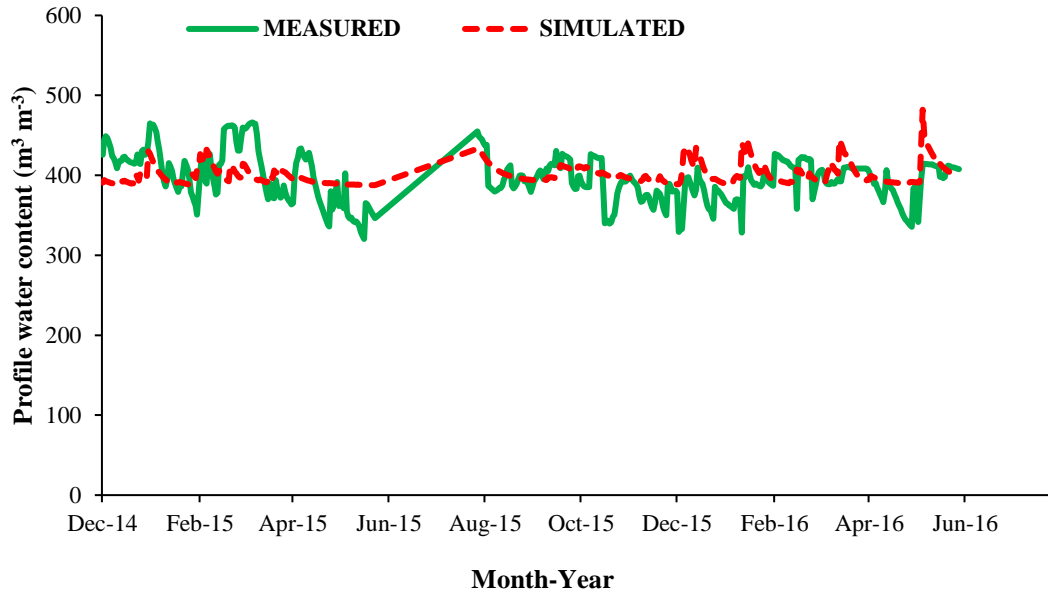


Figure 6.1: Soil profile water content measured by the CS 650 Campbell soil moisture reflectometers and simulated profile water content at the Newlands-Mashu field experiment.

#### 6.3.1.3 Mobile N and P

The SWB-Sci calibration results for  $\text{NO}_3^-$  and labile P in tap water + fertiliser treatment are reported in Figure 6.2. The  $\text{NO}_3^-$  concentrations were initially well simulated, however as the season progressed the model began to overestimate. There were some other periods when the simulated and measured data agreed with each other and other periods where they followed a similar pattern.

The labile P was initially underestimated but the model began to overestimate as from 447 days after planting. Similarly, to  $\text{NO}_3^-$  concentration observations, there were other periods when there was agreement between simulated and measured data.

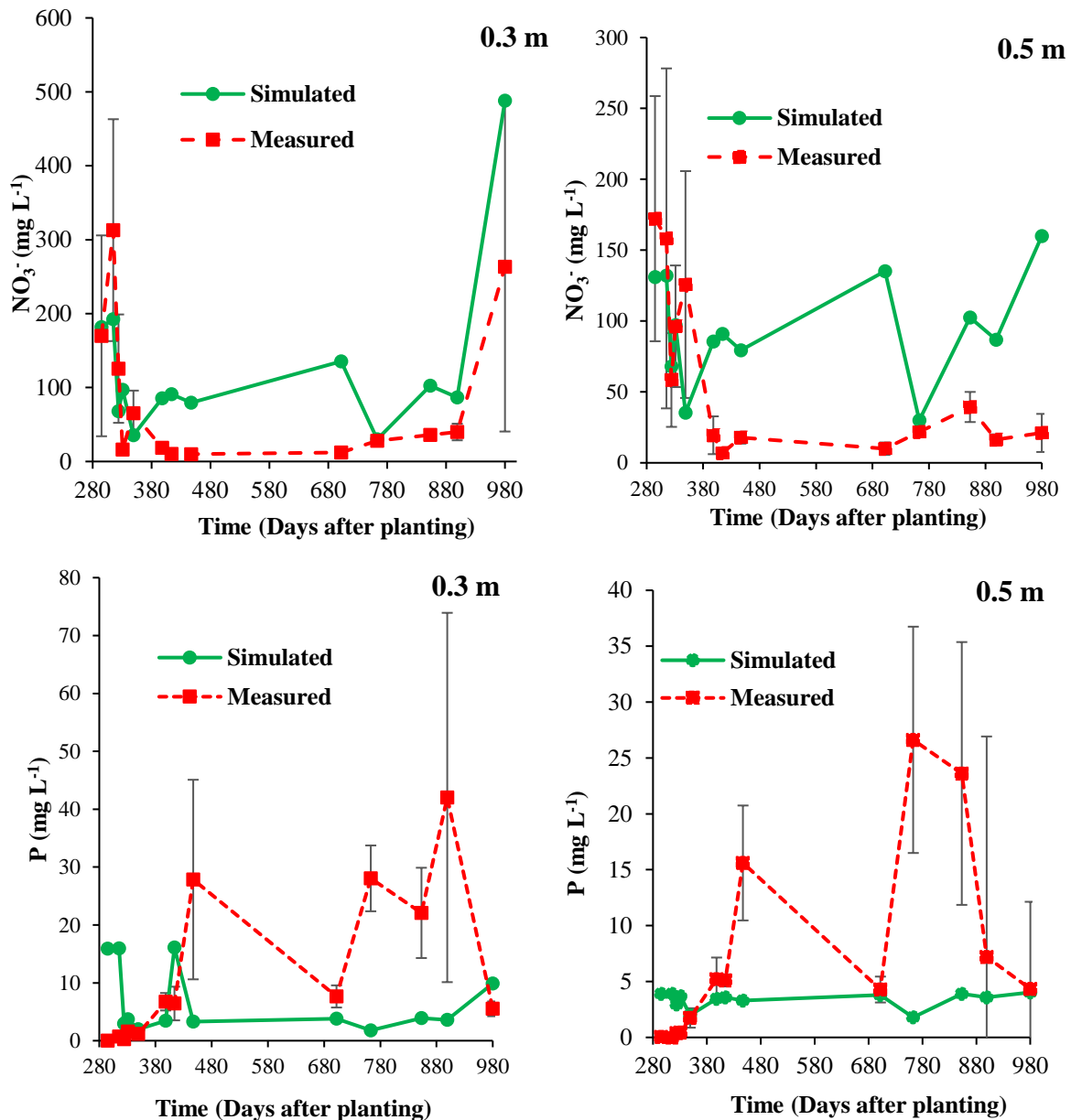


Figure 6.2: Simulated and measured nitrate ( $\text{NO}_3^-$ ) concentrations at 0.3 and 0.5 m soil depths for the tap water + fertiliser treatment.

### 6.3.2 Model validation

#### 6.3.2.1 Crop growth

An independent set of data from the DEWATS treatment was used to validate the SWB-Sci model. The statistical analyses results of the measured vs simulated data are reported in Table 6.2. The statistical parameters for almost all the parameters of interest (leaf area index, top and harvestable dry mass) were within the ranges of the prescribed statistical parameters (Table 6.2).



Table 6.2: Validation of the SWB-Sci model based on banana leaf area index, top and harvestable dry mass, crop height and N uptake using an independent dataset from DEWATS treatment.

<b>Variable</b>	<b>n</b>	<b>r<sup>2</sup></b>	<b>D</b>	<b>RMSE</b>	<b>MAE (%)</b>
Leaf area index	6	0.91	0.97	0.3	22
Top and harvestable dry mass	6	0.98	0.99	0.8	16
Crop height	7	0.9	0.96	0.3	20
Crop N uptake	6	0.95	0.98	19.9	13

### 6.3.2.2 Mobile N and P

The validation of the SWB-Sci model using N and P concentrations from the DEWATS effluent treated soil measured at Newlands-Mashu are presented in Figure 6.3. The NO<sub>3</sub> concentrations were sometimes overestimated for instance 315, 815 and 980 days after planting (0.3 m depth) and from 349 days after planting at 0.5 m depth.

The labile P concentrations were initially overestimated. These were then underestimated as the experiment progressed. There were some periods when the measured data agreed with simulated data especially from 349 – 702 days after planting (0.3 m) and 398 days after planting (0.5 m depth). There were also other periods when the simulated labile P concentrations agreed with measured data which had very large standard errors especially from 447 days after planting (0.5 m).

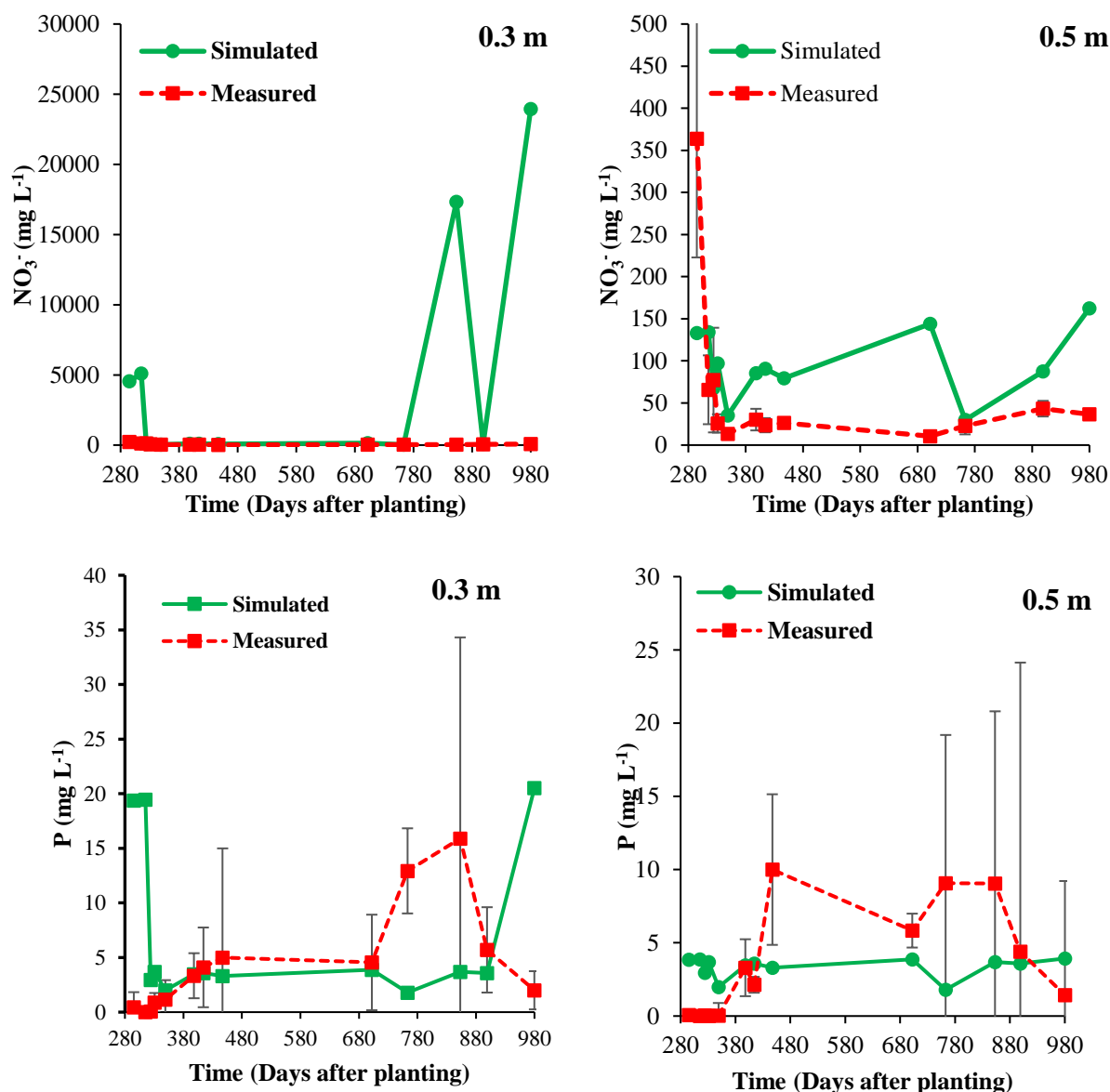


Figure 6.3: Simulated and measured mobile  $\text{NO}_3^-$  and labile P concentrations at 0.3 and 0.5 m soil depths for the DEWATS effluent fertigated soil.

### 6.3.3 N and P modelling

#### 6.3.3.1 Residual N and P

Accumulation of residual inorganic N ( $\text{NO}_3^-$ ) and labile P concentrations in the soil was also simulated (Figure 6.4). Residual  $\text{NO}_3^-$  and P concentrations increased rapidly as time progressed in soils treated with DEWATS effluent compared with tap water + fertiliser treatment. The build-up of  $\text{NO}_3^-$  concentrations in the DEWATS treated soils was more imminent at 0.2 m depth below the soil surface than other layers. Similarly, the  $\text{NO}_3^-$  concentrations in the tap water + fertiliser treated soil was also higher in the 0.2 m depth below the soil surface while P was higher at the top 0.1 m depth.

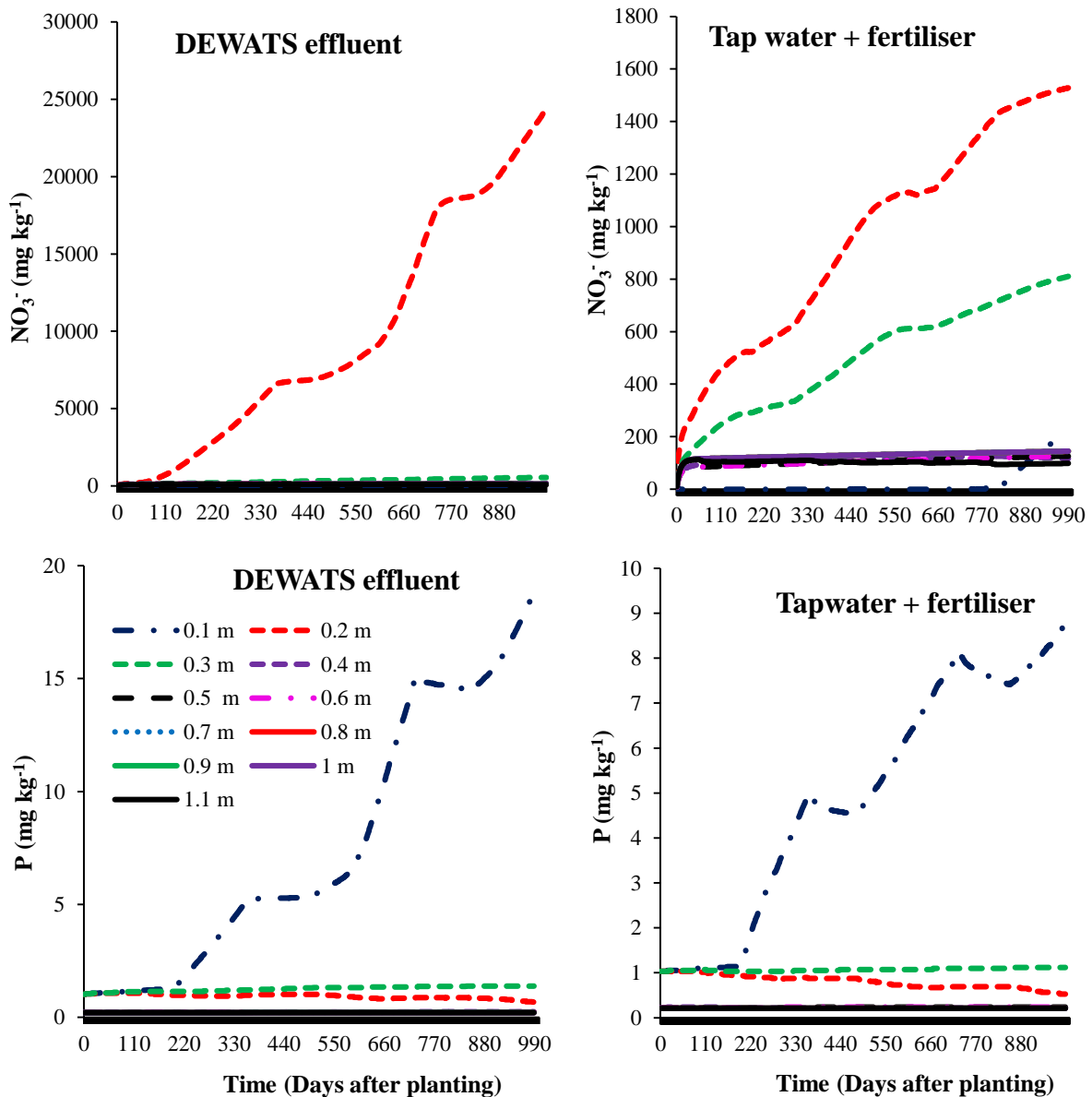


Figure 6.4: Simulated residual N ( $\text{NO}_3^-$ ) and P ( $\text{PO}_4^{3-}$ ) concentrations for irrigation with DEWATS effluent and tap water + fertiliser at different depths (0.1 to 1.1 m) in the Sepane soil at Newlands-Mashu over 992 days.

### 6.3.3.2 Nitrate leaching

The SWB-Sci simulated cumulative  $\text{NO}_3^-$  (N) leached from the soil for the two irrigation treatments over a period of 992 days was reported (Figure 6.5). High concentrations of nitrate leaching were found in DEWATS treated soils than tap water + fertiliser treated.

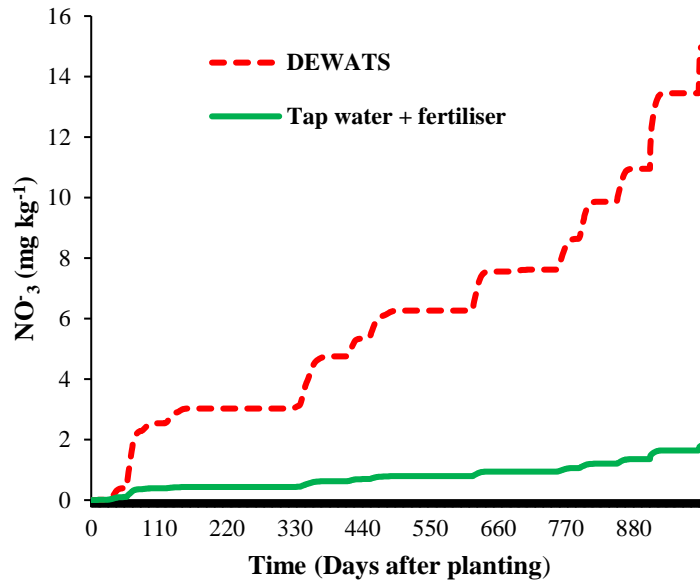


Figure 6.5: Simulated concentration of  $\text{NO}_3^-$  leached from the Sepane soil fertigated with DEWATS effluent and tap water + fertiliser over a period of 992 days.

### 6.3.4 Land area determination

The land area requirement for three different soils to absorb the volumes of effluent produced by the DEWATS based on crop water requirements are shown in Table 6.3. More land is required for cartref (Cf) and inanda (Ia) soils than sepane (Se) soil.

Table 6.3: Land area requirements in three different soils based on crop water requirements ( $E_{t_{crop}}$ ) and DEWATS effluent production capacity.

Soil type	Evapotranspiration (mm)	Land area per each DEWATS (m <sup>2</sup> )	Household <sup>-1</sup> (m <sup>2</sup> )	Person <sup>-1</sup> (m <sup>2</sup> )
Cartref	1 473	23 900	290	58
Inanda	1 616	21 700	260	52
Sepane	2 111	16 700	200	40

## 6.4 Discussion

### 6.4.1 Model calibration and validation

The reliability of a model depend on its sensitivity (van der Laan et al. 2014). The statistical criteria for model accuracy proposed by De Jager (1994) were met with regards to crop growth, N uptake and profile water content. According to van der Laan et al. (2014) soil profile volumetric water content has a significant effect on inorganic N leaching than the drainage factor. This therefore relate to the ability of the model to accurately simulate N movement in the soil profile. However, based on the findings reported in Figure 6.2 and Figure 6.3, the simulated mobile N and P concentrations showed variable differences

to measured ones. This is typical of these variables due to complexities in their transformations and soil heterogeneity as reported by van der Laan et al. (2010) and Fessehazion et al. (2014).

According to van der Laan et al. (2010) different sensors are used to sample different components of soil  $\text{NO}_3^-$ . Suction cups measure  $\text{NO}_3^-$  in resident water and WFDs measure draining water. The authors found better estimates if suction cups are used together with WFDs. They concluded that the SWB-Sci model can be used for accurately simulating long term  $\text{NO}_3^-$  leaching after calibration using site specific data set. Even though there are limitations in calibrating the model using measured  $\text{NO}_3^-$  concentrations, the authors further reported that soil water content, crop N uptake and crop growth simulations are adequate. Therefore, the model was used reliably to simulate effects of DEWATS effluent on residual N and P and  $\text{NO}_3^-$  leaching.

#### **6.4.2 Residual inorganic N and P**

Very high concentrations of simulated resident  $\text{NO}_3^-$  –N in DEWATS effluent compared to tap water + fertiliser (Figure 6.4) were due to high concentrations of inorganic N applied through fertigation (Appendix 10). The high accumulation of  $\text{NO}_3^-$  at 0.2 m depth below the soil surface for both the DEWATS and inorganic fertiliser treated soils indicate the low drainage losses of water from high clay content soils at the study site. The soils in the study site are rich in clay minerals with high expanding capacity (montmorillonite and smectite) as reported in Chapter 4. Despite heavy rainfalls and high irrigation application around 880 days after planting (June and July 2016) see Appendix 10,  $\text{NO}_3^-$  concentrations continued to increase at 0.2 m depth below the soil surface. This also agreed with increased inorganic N in 0.3 m depth of soil reported in Chapter 4 (Figure 4.3).

An increase in residual labile P concentrations reported in 0.1 m layer of the soil compared to other layers agreed with extractable P concentrations in 0.3 m soil depth reported in Chapter 4 (Table 4.7). This is mainly due to P adsorption by the soil as reported by Bame et al. (2014). Therefore, there is low risk of P leaching to the groundwater. The only possible long-term potential risk is high accumulation of P on the soil surface, which could lead to surface water contamination from runoff losses.

Nutrients accumulating in the soil may be potential sources of environmental pollution depending on irrigation and rainfall, which either leach nutrients or wash them away through surface runoff (FAO 2013, Fessehazion et al. 2014, Ogbazghi et al. 2016, Tesfamariam et al. 2015). In the short term, the accumulation of N and P within the root zone is beneficial for crop

production especially in soils with low drainage capacity. In the long term however, accumulation at such rates could lead to high plumes of  $\text{NO}_3^-$  leaching to the ground water when plants do not utilise them timely especially during low intensity but high volume of rainfall events.

#### **6.4.3 Nitrate leaching over time**

The model simulated high leaching of  $\text{NO}_3^-$  in soil fertigated with DEWATS effluent (Figure 6.5). This was due to large irrigation depth using DEWATS effluent (Appendix 10). This shows that high accumulation of residual  $\text{NO}_3^-$  at the 0.2 m depth does not necessarily imply that there was no leaching rather the cascading of  $\text{NO}_3^-$  from the upper 0.1 m soil layer to the lower 0.2 m layer in large quantities as a function of time. This implies that it is a matter of time for the  $\text{NO}_3^-$  accumulated in the 0.2 m soil layer to move deeper into the soil below the reach of the plant roots. Besides, nutrient leaching in a soil occurs through a cascading approach which depends on volumetric water content and drainage factor in different soil layers (Fessehazion et al. 2014, van der Laan et al. 2010). Besides, since most of the  $\text{NO}_3^-$  is retained in micro and meso pores of the soil, which is in equilibrium with the micro pores and soil exchange sites, as water moves down the soil profile, a significant amount of  $\text{NO}_3^-$  drains along. Therefore, this calls for considering nutrient based application rather than crop water requirement-based application of DEWATS on agricultural land.

#### **6.4.4 Land area requirements**

One of the SWB-Sci model purpose is to schedule irrigation in a way that maximises crop water requirements while minimising losses through leaching and runoff. Based on the SWB-Sci model calculations, land area requirements were lower for Se soil followed by Ia and Cf soils. This was due to high water retention capacity for Se soil coupled with its low hydraulic conductivity (Figure 5.4) than the other two soils. Therefore, Se soil can assimilate more effluent per unit area. More land area is required for Cf and Ia soils to assimilate all the effluent produced. In soils with higher drainage irrigation is done at a lesser rate but more frequently while in poorly drained soils the reverse is true.

### **6.5 Conclusions**

The SWB-Sci model was successfully calibrated and validated, and met the statistical criteria ( $r^2 > 0.8$ ,  $D > 0.9$ ,  $\text{MAE} < 20\%$ ) for simulating banana growth, top N uptake and soil profile volumetric content. Although there are limitations in the calibration and validation of SWB-

Sci model based on soil leached N and P concentrations, crop growth, nutrient uptake and soil profile volumetric water content are most important variables in testing model sensitivity. The simulated increase in residual inorganic N and P concentrations within the root zone (upper 0.3 m) of the soil under DEWATS effluent fertigation shows the potential of effluent as an important fertiliser source. The simulated  $\text{NO}_3$  leaching from the soil was higher in DEWATS effluent fertigation compared to tap water + fertiliser but without any risk to the ground water contamination. Land area requirements for each DEWATS plant in Cf soil was 23 900 m<sup>2</sup> (290 m<sup>2</sup> household<sup>-1</sup>; 58 m<sup>2</sup> person<sup>-1</sup>), Ia was 21 700 m<sup>2</sup> (260 m<sup>2</sup> household<sup>-1</sup>; 52 m<sup>2</sup> person<sup>-1</sup>) and for Se was 16 700 m<sup>2</sup> (200 m<sup>2</sup>household<sup>-1</sup>; 40 m<sup>2</sup> person).

## CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS

### 7.1 Introduction

The decentralised wastewater treatment system (DEWATS) potentially provides onsite sanitation to residents living in the peripheries of cities. However, management of treated wastewater from the DEWATS is important since disposal into water bodies can be environmental unsustainable. Therefore, agricultural systems may be used; soils act as media for nutrient (N and P) retention allowing plants to take them up such that water percolating deep the soil does not contaminate the groundwater.

Fertigation with wastewater may improve soil chemical and physical properties, which increase crop growth and yield. Studies have also confirmed that DEWATS effluent comply with the FAO and WHO standard wastewater quality for agricultural use in terms of its chemical and physical properties, and heavy metals, respectively. Furthermore, WHO guidelines to manage pathogenic risks are available. Despite beneficial use of wastewater in agriculture, some negative aspects of concern include impacts on the environment if not well managed.

Upscaling of the wastewater used by local governments and policy makers, who are considering integration of urban sanitation with agriculture should be done using practical guidelines. Development of practical guidelines consider technical issues such as land area requirements for specific soils, nutrient loading, effects on various crops and environmental sustainability of the practice. This information is not adequately available with reference to South Africa. Therefore, this study was a step in investigating the impacts of DEWATS effluent on N and P uptake, transformations and impacts on the environment. The study generated information required to develop practical guidelines for safe and sustainable water reuse projects in South Africa.

The study aim was to understand the factors and processes that may influence the use of DEWATS effluent as a fertigation source of N and P and its effects on crops, soils and the environment. The following questions were addressed with regards to fertigation using DEWATS:

- What are the effects on crop growth, yield, and N and P uptake?
- What is the N and P dynamics in soils in terms of retention within the rooting zone and leaching?



- Can the SWB-Sci model be calibrated and validated to simulate crop growth, N and P dynamics and water balance in DEWATS fertigated soil?
- Based on simulations, what are land area requirements in different soils and N and P retention and leaching from soil?
- Can the DEWATS effluent be used without contaminating the groundwater with N and P? If there are risks how can they be managed?

The following sections discuss major findings from chapter 4 to 6 about the effects of DEWATS effluent on crop growth, N and P uptake, retention and leaching under field and controlled conditions. The importance of the SWB-Sci as a tool in calculating land area requirements and effects of N and P on the environment is also discussed.

## **7.2 General discussion**

### **7.2.1 Effects on crop growth, yield and N and P uptake**

Crop growth in DEWATS effluent fertigated soils increased under field conditions (Chapter 4) and in three different soil types (Chapter 5). High crop growth in field conditions were attributed to interaction of initial soil fertility and N and P applied through fertigation using effluent, especially after second cropping cycle when AF effluent was used. The influence of initial nutrients on crop growth in effluent fertigated soils was observed in Se and Cf soils. Sepane (Se) showed high banana growth compared to other soils in pot experiments although same types and volumes of effluents were applied to all soils. Furthermore, banana growth was comparably higher in Cf under effluent fertigation than tap water + fertiliser (Chapter 5), confirming the ability of wastewater to improve crop growth in poor soils as reported in several studies (Bame et al. 2014, Mohamed Sa et al. 2017, Musazura 2014).

Crop growth variables such as leaf area index (LAI) and chlorophyll content are important aspects in the photosynthetic capacity of the plants and yield. Despite higher LAI in DEWATS fertigated taro plants the final yield was comparable to tap water + fertiliser treatment (Chapter 4). Although wastewater has the capacity to increase crop vegetative growth, yield may not be affected. Even several authors have shown that wastewater might increase vegetative growth at the expense of economic yield due to excessive N (Alghobar and Suresha 2016, Pedrero et al. 2010). This was confirmed by banana grown under pot experiments which did not flower probably due to N loading through fertigation with effluent thereby exceeding crop fertiliser requirements (Table 5.8). In tap water + fertiliser treatment from which adequate N amounts

were applied, delayed flowering also occurred thereby nullifying an assumption that delayed flowering was associated with DEWATS effluent irrigation. Field studies reported in Chapter 4 showed that plants managed to flower and fruit despite addition of nutrients in recommended amounts. This implies that even though high amounts of N are applied through fertigation, not all is taken up plants. Nitrogen in the soil may not be bioavailable or lost through other transformations such as denitrification, immobilisation or leaching.

The plant tissue N and P uptake was comparable between irrigation treatments under the field conditions (Chapter 4) while DEWATS effluent fertigated crop were higher under controlled studies (Chapter 5). Higher N and P concentrations reported in DEWATS effluent treated crops compared to tap water + fertiliser (Table 5.10), showed the ability of banana plants to remove N from soils. Nutrient uptake by banana in both field and tunnel studies conformed with findings by several authors using wastewater (Almuktar et al. 2015, Bame et al. 2014, Fonseca et al. 2007).

Fertigation with AF effluent exceeding crop water requirements (Table 5.7) and loaded a lot of N and P onto the soils. The optimum nutrient sufficiency levels for banana foliar analysis are: N (2.7 – 3.7 %) and P (0.16 – 0.27 %) (de Mello Prado and Caione 2012). According to studies in Chapter 4 and 5 the foliar concentrations for N and P in banana were within the sufficiency ranges hence both effluent and tap water + fertiliser provided plant required nutrients. Since plants have a limited capacity to take up N and P, excessive N and P can be managed through populating plants over an area, irrigation scheduling to meet crop water needs without loading nutrients or expansion of land area.

## **7.2.2 Nitrogen and P dynamics in DEWATS effluent fertigated soils**

### *7.2.2.1 N and P retention*

The effluent significantly increased soil  $\text{NH}_4^+$ -N in all three soils than the inorganic fertiliser (Figure 5.3). The DEWATS effluent contains N as  $\text{NH}_4^+$ -N especially after anaerobic treatment (Foxon 2009). Fertigation with effluent applies  $\text{NH}_4^+$ -N to the soil, which is fixed by soils such as 2:1 clays. However, pot trials done in Chapter 5 showed a significant  $\text{NH}_4^+$ -N increase even in Cf as reported by Bame et al. (2014). On the other hand, the  $\text{NH}_4^+$ -N in field studies (Chapter 4) did not significantly differ between the irrigation treatments. Implying that high  $\text{NH}_4^+$ -N concentrations in pot trials were attributed to high effluent loading (Table 5.7).

The soil  $\text{NO}_3^-$ -N concentrations were comparable between the DEWATS effluent and tap water + fertiliser (Chapter 4 and 5). Therefore, the effluent can be assimilated by soil microorganisms to produce plant available N ( $\text{NO}_3^-$ ) just like other inorganic fertilisers. It has been confirmed that fertigation with wastewater increases nitrification process (Bame et al. 2013, Darwesh 2015).

Significant differences in  $\text{NO}_3^-$  concentrations were reported between soil depths. The  $\text{NO}_3^-$  was concentrated within the 0.3 than the 0.6 m depth (Chapter 4) as reported by the SWB-Sci model in Chapter 6. Based on the model simulation, more  $\text{NO}_3^-$  were expected to accumulate in the top 0.2 m of the soil (plant rooting zone) (Figure 6.4), further confirming the potential of DEWATS effluent as a source of N fertiliser in clay soils.

Despite having high concentrations of  $\text{NH}_4^+$ -N in DEWATS effluent fertigated soils under pot trials, the  $\text{NO}_3^-$ -N remained comparable between irrigation treatments (Table 5.4), implying that nitrification was low, which differed from findings by Bame et al. (2013). This could have been attributed to high water content which inhibited the nitrification process.

The soil P significantly increased in all soils applied effluent (Chapter 4 and 5). Even studies by Bame et al. (2014) reported increased P content in soils applied DEWATS effluent including the Cf soil despite its poor P sorption capacity. This means that DEWATS effluent is an important source of P especially in low P soils.

#### 7.2.2.2 *N and P leaching*

The concentrations of  $\text{NO}_3^-$ -N in soil leachates increased within the 0.3 m depth of the DEWATS fertigated soil as the cropping cycle progressed (Figure 4.3). The leachates did not significantly move down the soil profile due to low hydraulic conductivity of the clay soil. This also agreed with pot experiments where leaching was low in Se soil than Ia soil (Figure 5.6). The simulations by the SWB-Sci model showed high concentrations of  $\text{NO}_3^-$  within the top 0.2 m depth of the soil. Therefore, the use of DEWATS effluent in a clay loam soil increase plant available N within the rooting zone. Furthermore, the less likelihood of  $\text{NO}_3^-$ -N to leach in such soils prevents groundwater contamination risks. The problem occurs when the perched water tables could rise to shallow depths as reported in Figure 4.5. However, this could be managed through subsurface drainage to prevent subsurface lateral flows to nearby rivers. Care must be taken when draining water from the subsurface, its discharge into rivers may cause contamination. Therefore, it is recommended that the water can be recycled back into the field.

If the water is recycled back into the agricultural land, especially in wet season, surface runoff can be a problem especially on highly sloping sites. Based on studies at Newlands-Mashu the water table outside the field just before the river was deeper than the piezometer depth. This implies that lateral subsurface movement of water towards the river was low.

In well drained soils with high N content such as Ia, groundwater pollution is likely to occur through leaching as reported in Chapter 5. Care must be taken to prevent groundwater pollution in such soils and this is achievable through irrigation scheduling with room for rainfall.

Based on findings in Chapter 4, mobile P concentrations in leachates from soil applied DEWATS effluent were comparable to tap water + fertiliser although inorganic fertiliser was not applied. This shows that most of the P applied through fertigation was retained by soil colloids hence leaching was minimum as confirmed by the SWB-Sci model (Chapter 6). High labile P concentrations were shown in top 0.1 m soil depth (Figure 6.4). Soil type and irrigation depth contribute to P leaching (Chapter 5). More P leaching was reported in coarse textured Cf soil after irrigation to field capacity while exceeding crop water requirements due to its physical properties. Cartref soil has low P sorption capacity since it has low Fe oxides content and organic matter. Organic matter and Fe oxides interact together in increasing P adsorption as well as decreasing its leaching down the soil profile.

### **7.2.3 Land area requirements and N and P loading**

According to Pescod (1992), on farm effluent supply must be strategically managed. The total area to be irrigated depends on the total amounts of effluent available during the crop growing period. The use effluent to irrigate banana and taro in an intercrop required  $117 \text{ m}^2 \cdot \text{household}^{-1}$  ( $23.3 \text{ m}^2 \cdot \text{person}^{-1}$ ) (Chapter 4). This land area was calculated based on crop water requirements for both crops to maximise all the effluent produced by the DEWATS. Based on the findings in Chapter 4, the taro plants did not grow well during the second season. Therefore, calibration and validation of the SWB model for an intercrop could not be pursued, although the model is capable of simulating crop growth in a hedgerow intercrop (Annandale et al. 1999a). Banana has the same annual water requirements as taro, which is 1 500 - 2 200 mm for banana (FAO 2015) and  $\geq 1 500$  mm for taro (Onwueme 1999). Therefore, assuming irrigation was to be done only on either banana or taro, the land area required could have doubled the calculated one. The land area calculated by the SWB-Sci for banana cropping under the Se soil used in the field was  $200 \text{ m}^2 \text{ household}^{-1}$  ( $40 \text{ m}^2 \text{ person}^{-1}$ ) (Table 6.3), which is almost double the land area calculated in the field.

The land area requirements for different soils differed; Cf required more land area while Se required the least land area (Table 6.3). The aim of scheduling using the SWB-Sci, according to Annandale et al. (1999a), is to maximise crop water requirements while minimising losses through leaching and runoff. The production of effluent is a continuous process while crop water demands are variable across seasons especially in subtropical climates. Therefore excess effluent in different seasons can be stored for use when crop water demands are high (DWA 2013, Pescod 1992). In this study storage requirements calculated based on crop water requirements in Chapter 4 was 767 m<sup>3</sup> (9.2 m<sup>3</sup>·household<sup>-1</sup> or 1.9 m<sup>3</sup>·person<sup>-1</sup>). The excess effluent was found only in July 2015 and July 2016 (Figure 4.6), which might be unnecessary to invest in storage facilities. However, uncertainties in weather patterns calls for storage investment since effluent loading in soils such as Cf and Ia may cause pollution as reported in Chapter 5.

### 7.3 Conclusions

The study investigated the effects of fertigation with DEWATS effluent (AF and HFCW effluent) on crop growth, yield and nutrient uptake. The effects of DEWATS effluent on banana and taro growth were comparable to tap water + fertiliser treatment during the first cropping cycle under field conditions. Use of AF effluent increased vegetative growth at the expense of yield through irrigation to soil field capacity under controlled conditions. The DEWATS effluent increases productivity of poor nutrient soils as shown by high growth in Cf soils fertigated with effluent. Nutrient (N and P) uptake in banana and taro under field studies were comparable between the two irrigation treatments. Fertigation with effluent to soil field capacity increased banana leaf tissue N and P concentrations.

High irrigation depth using AF effluent increased soil inorganic N content in both field and pot experiments. Soil extractable P content significantly increased in all soils fertigated with effluent to field capacity and within the 0 – 0.3 m depth in the field. Although the soil inorganic N and P content increased, their subsequent leaching to groundwater was very low in clay soils. Nitrogen leaching in the soils irrigated to soil field capacity was higher in the tap water + fertiliser treatment than the DEWATS treatment. A comparison between three soils fertigated with DEWATS effluent showed higher N leaching from the Ia soil compared to the other soils. Moreover, more P leached from the sandy Cf soil compared to other soils under the same treatment. Although the NO<sub>3</sub>-N concentrations in the water table were far below international minimum standard concentrations for drinking water of 10 mg L<sup>-1</sup>, risks for contamination are

minimised if irrigation scheduling with room for rainfall, drip irrigation and subsurface drainage are provided in areas prone to rising water tables.

The SWB-Sci model was successfully calibrated and validated to simulate water and nutrient (N and P) balances in DEWATS effluent fertigated soils. The model calculated area requirements in Cf soil (290 m<sup>2</sup> household<sup>-1</sup>; 58 m<sup>2</sup> person<sup>-1</sup>), Ia soil (260 m<sup>2</sup> household<sup>-1</sup>; 52 m<sup>2</sup> person<sup>-1</sup>) and Se soil (200 m<sup>2</sup>household<sup>-1</sup>; 40 m<sup>2</sup> person). Storage is required during the wet weather to cater for excess effluent. Simulations by the SWB-Sci model showed the likelihood of increasing inorganic N and P within the top soil layers (0.3 m depth) of the clay soil with continuous fertigation especially if irrigation depth is high and the AF effluent is used. The model simulated lower N leaching in DEWATS effluent fertigated soils than tap water + fertiliser, showing the environmental sustainability of using DEWATS for fertigation compared to conventional fertilisers.

#### **7.4 Recommendations and future studies**

- DEWATS effluent can be used sustainably in agriculture where it promotes crop growth and improved yields. Care must be taken to avoid over application of N especially when using AF effluent. Optimisation of nutrients and water is recommended to ensure that adequate water is applied with no excess nutrients. This can be achieved through irrigation scheduling and monitoring soil nutrients.
- Use of DEWATS effluent from the AF loads more N and P into the soil. High inorganic N and P in the soil are potential environmental pollutants. There is need for more information on nutrient removal by other crops. Therefore, studies must broaden the scope to include fertigation of high nutrient demanding crops for forage or composting.
- Excess effluent exceeding crop water requirements especially during wet seasons needs to be managed accordingly. In case were storage investments are prohibitive, other uses of the effluent should be explored such as hydroponics and duck weed composting.
- Soil nutrient monitoring through fertility testing, monitoring leachate quality and plant tissue nutrient content are recommended management practices. Best methods to monitor soil nutrients in DEWATS fertigated soils must be investigated and included as part of practical guidelines.
- Use of HFCW effluent might not provide enough crop nutrients. More research is needed to understand the use of effluent in combination with other human excreta-derived materials as nutrient supplements for different crops.

- Irrigation scheduling considering room for rainfall is important to prevent N and P leaching especially in coarse textured soils.
- The SWB-Sci model was calibrated and validated to simulate long-term N and P dynamics in DEWATS effluent fertigated soil at Newlands-Mashu. Therefore, the model can be applied to different regions with contrasting soils and climatic conditions.
- The current study focused on banana with taro as an intercrop. The taro failed to grow during the second cropping cycle hence could not be used for model calibration. Therefore, modelling should be done with shorter season crops in different agricultural systems such as mono-cropping, relay cropping and crop rotation. This will add more information required in the development of practical guidelines.
- The SWB-Sci one dimensional model may not account for other lateral solute flows within the soil profile. Studies can be extended to consider three dimensional flows using other models such as HYDRUS 3D.
- The SWB-Sci has been very sensitive in simulating N dynamics in the soil under field study; the measured and simulated N concentrations were very variable. Improvement of the model should be considered in the future.
- Although N and P are major contributors to environmental pollution, more considerations should be given on emerging micropollutants and microbial contamination of groundwater resources in wastewater fertigated areas.

## REFERENCES

- Adeel, M., Song, X., Wang, Y., Francis, D. and Yang, Y. (2017) Environmental impact of estrogens on human, animal and plant life: A critical review. *Environment International* 99(Supplement C), 107-119. <https://doi.org/10.1016/j.envint.2016.12.010>
- Adrover, M., Edelweiss, F., Gabriel, M. and Jaume, V. (2010) Chemical properties and biological activity in soils of Mallorca following twenty years of treated wastewater irrigation. *Journal of Environmental Management* 99(2012), S188-s192. <https://doi.org/10.1016/j.jenvman.2010.08.017>
- AE (2000) Guidelines for wastewater irrigation, p. 30, Alberta Environment, Alberta, Canada. <https://extranet.gov.ab.ca/env/infocentre/info/library/7268.pdf> (accessed on 18 August 2017)
- Agah, A.E., Meire, P. and Deckere, E.d. (2016) Soil Contamination - Current Consequences and Further Solutions. Larramendy, M.L. and Soloneski, S. (eds), p. Ch. 09, InTech, Rijeka. Doi: 10.5772/66214
- Ahumuza, B., Basamba, T., Van Asten, P. and Tushemereirwe, W. (2015) Physiological nutrient use efficiency of banana hybrids across agro ecological regions in Uganda. *African Journal of Plant Science* 9(2), 97-105. <https://doi.org/10.5897/AJPS2014.1238>
- Al Omron, A.M., El-Maghraby, S.E., Nadeem, M.E.A., El-Eter, A.M. and 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(1), 15-18. <https://doi.org/10.1016/j.jssas.2011.04.004>
- Alghobar, M.A. (2014) Effect of Sewage Water Irrigation on Soil Properties and Evaluation of the Accumulation of Elements in Grass Crop in Mysore City, Karnataka, India. *American Journal of Environmental Protection* 3(5), 283. Doi: 10.11648/j.ajep.20140305.22
- Alghobar, M.A. and Suresha, S. (2016) Effect of Wastewater Irrigation on Growth and Yield of Rice Crop and Uptake and Accumulation of Nutrient and Heavy Metals in Soil. *Applied Ecology and Environmental Sciences* 4(3), 53-60. Doi:10.12691/aees-4-3-1
- Allen, R.G. (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, Food and Agriculture Organisation, Rome, Italy. [www.fao.org/docrep/X0490E/X0490E00.htm](http://www.fao.org/docrep/X0490E/X0490E00.htm) (accessed on 28 February 2018)
- Almuktar, S.A.A.A.N., Scholz, M., Al-Isawi, R.H.K. and Sani, A. (2015) Recycling of domestic wastewater treated by vertical-flow wetlands for irrigating Chillies and Sweet Peppers. *Agricultural Water Management* 149, 1-22. <https://doi.org/10.1016/j.agwat.2014.10.025>
- Andersson, K., Rosemarin, A., Lamizana, B., Kvarnström, E., McConville, J., Seidu, R., Dickin, S. and Trimmer, C. (2016) Sanitation, Wastewater management and sustainability from waste disposal to resource recovery, Nairobi and Stockholm. ISBN: 978-92-807-3488-1
- Angelakis, A.N. and Snyder, S.A. (2015) Wastewater treatment and reuse: Past, present, and future. *Water* 7(9), 4887-4895. <https://doi.org/10.3390/w7094887>



Angin, I., Yaganoglu, A. and Turan, M. (2005) Effects of Long-Term Wastewater Irrigation on Soil Properties. [https://doi.org/10.1300/J064v26n03\\_05](https://doi.org/10.1300/J064v26n03_05)

Annandale, J.G., Benadél, N., Jovanovic, N.Z., Steyn, J.M. and Du Sautoy, N. (1999a) Facilitating irrigation scheduling by means of the Soil Water Balance model. , Water Research Commission, Pretoria, South Africa. <http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/753-1-99.pdf> (accessed on 28 February 2018)

Annandale, J.G., Jovanovic, N.Z., Benadè, N. and Tanner, P.D. (1999b) Modelling the long-term effect of irrigation with gypsiferous water on soil and water resources. *Agriculture, Ecosystems & Environment* 76(2), 109-119. [https://doi.org/10.1016/S0167-8809\(99\)00079-1](https://doi.org/10.1016/S0167-8809(99)00079-1)

Annandale, J.G., Jovanovic, N.Z., Pretorius, J.J.B., Lorentz, S.A., Rethman, N.F.G. and Tanner, P.D. (2001) Gypsiferous mine water use in irrigation on rehabilitated open-cast mine land: Crop Production, soil water and salt balance. *Ecological Engineering* 17(2), 153-164. [https://doi.org/10.1016/S0925-8574\(00\)00155-5](https://doi.org/10.1016/S0925-8574(00)00155-5)

Antelo, J., Arce, F., Avena, M., Fiol, S., López, R. and Macías, F. (2007) Adsorption of a soil humic acid at the surface of goethite and its competitive interaction with phosphate. *Geoderma* 138(1), 12-19. <https://doi.org/10.1016/j.geoderma.2006.10.011>

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

AQUASTAT (2016) Water withdrawal by sector, around 2010, Rome, Italy. [http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal\\_eng.pdf](http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal_eng.pdf)

Arborea, S., Giannoccaro, G., de Gennaro, B., Iacobellis, V. and Piccinni, A. (2017) Cost–Benefit Analysis of Wastewater Reuse in Puglia, Southern Italy. *Water* 9(3), 175. Doi: 10.3390/w9030175

Arnold, J., Moriasi, D., Gassman, P., Abbaspour, K., White, M., Srivivasan, R., Santhi, C., Harmel, R., Griensven, A.V. and Van Liew, M. (2012) SWAT: Model use, calibration and validation. *Transactions of the ASABE* 55(4), 1491-1508.

Asgharipour, M.R. and Azizmoghaddam, H.R. (2012) Effects of raw and diluted municipal sewage effluent with micronutrient foliar sprays on the growth and nutrient concentration of foxtail millet in southeast Iran. *Saudi Journal of Biological Sciences* 19(4), 441-449. <https://doi.org/10.1016/j.sjbs.2012.06.001>

Ashton, J. and Ubido, J. (1991) The healthy city and the ecological idea. *Social History of Medicine* 4(1), 173-180. <https://doi.org/10.1093/shm/4.1.173>

Balkhair, K.S. and 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(1), S32-S44. <http://dx.doi.org/10.1016/j.sjbs.2015.09.023>

Bame, I.B., Hughes, J.C., Titshall, L.W. and Buckley, C.A. (2013) Leachate characteristics as influenced by application of anaerobic baffled reactor effluent to three soils: a soil column study. *Chemosphere* 93(9), 2171-2179. <http://dx.doi.org/10.1016/j.chemosphere.2013.07.080>

Bame, I.B., Hughes, J.C., Titshall, L.W. and 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>

Bar-Tal, A., Fine, P., Yermiyahu, U., Ben-Gal, A. and Hass, A. (2015) Managing water and fertilizer for sustainable agricultural intensification. Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R. and Wicheln, D. (eds), pp. 209-242, IFA, IWMI, IPNI and IPI, Paris, France. ISBN 979-10-92366-02-0

Barreto, A.N., Nascimento, J.J.V.R.d., Medeiros, E.P.d., Nóbrega, J.A.d. and Bezerra, J.R.C. (2013) Changes in chemical attributes of a Fluvent cultivated with castor bean and irrigated with wastewater. *Revista Brasileira de Engenharia Agrícola e Ambiental* 17, 480-486. <http://dx.doi.org/10.1590/S1415-43662013000500003>

Barton, L., Schipper, L.A., Smith, C.T. and McLay, C.D.A. (2000) Denitrification enzyme activity is limited by soil aeration in a wastewater-irrigated forest soil. *Biology and Fertility of Soils* 32(5), 385-389. <https://doi.org/10.1007/s003740000267>

Bedbabis, S., Ferrara, G., Ben Rouina, B. and Boukhris, M. (2010) Effects of irrigation with treated wastewater on olive tree growth, yield and leaf mineral elements at short term. *Scientia Horticulturae* 126(3), 345-350. <https://doi.org/10.1016/j.scienta.2010.07.020>

Bedbabis, S., Trigui, D., Ben Ahmed, C., Clodoveo, M.L., Camposeo, S., Vivaldi, G.A. and Ben Rouina, B. (2015) Long-terms effects of irrigation with treated municipal wastewater on soil, yield and olive oil quality. *Agricultural Water Management* 160, 14-21. <https://doi.org/10.1016/j.agwat.2015.06.023>

Belaid, N., Neel, C., Kallel, M., Ayoub, T., Ayadi, A. and Baudu, M. (2012) Long term effects of treated wastewater irrigation on calcisol fertility: A case study of Sfax-Tunisia. *Agricultural Sciences* 3(05), 702-713. <http://dx.doi.org/10.4236/as.2012.35085>

Bellocchi, G., Rivington, M., Matthews, K. and Acutis, M. (2015) Deliberative processes for comprehensive evaluation of agroecological models. A review. *Agronomy for Sustainable Development* 35(2), 589-605. <https://doi.org/10.1007/s13593-014-0271-0>

Bhardwaj, A.K., Goldstein, D., Azenkot, A. and Levy, G.J. (2007) Irrigation with treated wastewater under two different irrigation methods: Effects on hydraulic conductivity of a clay soil. *Geoderma* 140(1-2), 199-206. <https://doi.org/10.1016/j.geoderma.2007.04.003>

Blum, J., Melfi, A.J., Montes, C.R. and Gomes, T.M. (2013) Nitrogen and phosphorus leaching in a tropical Brazilian soil cropped with sugarcane and irrigated with treated sewage effluent. *Agricultural Water Management* 117(Supplement C), 115-122. <https://doi.org/10.1016/j.agwat.2012.11.010>

Blumenthal, J.U., Mara, D.D., Peasey, A., Ruiz-Palacios, G. and Stott, R. (2000) Guidelines for the microbiological quality of treated wastewater used in agriculture: recommendations for revising WHO guidelines pp. 1104-1116, Geneva, Switzerland. PMID: 2560847

Boote, K.J., Jones, J.W., White, J.W., Asseng, S. and Lizaso, J.I. (2013) Putting mechanisms into crop production models. *Plant, cell & environment* 36(9), 1658-1672. <https://doi.org/10.1111/pce.12119>

Brady, N.C. and Weil, R.R. (2016) *The Nature and Properties of Soils*, Pearson Prentice Hall, New York, USA. ISBN 9780135133873

Campbell, G. and Diaz, R. (1988) Simplified soil-water balance models to predict crop transpiration. Bidinger, F.R. and Johansen, C. (eds), pp. 15-27, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). Patancheru, India., <https://core.ac.uk/download/pdf/12102891.pdf#page=23> (Accessed on 19 May 2018)

Campbell, G. and Van Evert, F. (1994) *Light interception by plant canopies: efficiency and architecture. Resource capture by crops*. Nottingham University Press, Nottingham, 35-52. ISBN: 9781897676219

Castro, E., Mañas, P. and De Las Heras, J. (2013) Effects of Wastewater Irrigation in Soil Properties and Horticultural Crop (*Lactuca Satival.*). *Journal of Plant Nutrition* 36(11), 1659-1677. <https://doi.org/10.1080/01904167.2013.805221>

Chanter, D. (1981) *Mathematics and plant physiology*. ROSE, D.A. and CHARLES-EDWARDS, D.A. (eds), pp. 253-266, Academic Press, London, UK.

Chaves, C., Cayón, S. and Jones, J.W. (2009) Modeling plantain (*Musa AAB Simmonds*) potential yield. *Agronomía Colombiana* 27(3), 359-366. <https://revistas.unal.edu.co/index.php/agrocol/article/download/13279/14168> (Accessed on 19 May 2018)

Chen, B., Liu, E., Tian, Q., Yan, C. and Zhang, Y. (2014) Soil nitrogen dynamics and crop residues. A review. *Agronomy for Sustainable Development* 34(2), 429-442. <https://doi.org/10.1007/s13593-014-0207-8>

Chen, F., Ying, G.-G., Kong, L.-X., Wang, L., Zhao, J.-L., Zhou, L.-J. and Zhang, L.-J. (2011a) Distribution and accumulation of endocrine-disrupting chemicals and pharmaceuticals in wastewater irrigated soils in Hebei, China. *Environmental Pollution* 159(6), 1490-1498. <https://doi.org/10.1016/j.envpol.2011.03.016>

Chen, Y., Dosoretz, C.G., Katz, I., Jüeschke, E., Marschner, B. and Tarchitzky, J. (2011b) *Treated Wastewater in Agriculture*. Levy, G., Fine, P. and Bar-Tal, A. (eds), pp. 400-417, Wiley-Blackwell. <http://dx.doi.org/10.1002/9781444328561.ch13>

Christou, A., Eliadou, E., Michael, C., Hapeshi, E. and Fatta-Kassinou, D. (2014) Assessment of long-term wastewater irrigation impacts on the soil geochemical properties and the bioaccumulation of heavy metals to the agricultural products. *Environmental Monitoring and Assessment* 186(8), 4857-4870. <https://doi.org/10.1007/s10661-014-3743-4>

Clarke, R.M. and Cummins, E. (2015) Evaluation of “Classic” and Emerging Contaminants Resulting from the Application of Biosolids to Agricultural Lands: A Review. *Human and Ecological Risk Assessment: An International Journal* 21(2), 492-513. <https://doi.org/10.1080/10807039.2014.930295>

Constable, M.A. (2015) *Transitional sanitation: eThekwini Communal Ablution Blocks*, Young Africa Publishing, Cape Town, South Africa. <http://earthworksmagazine.co.za/transitional-sanitation-ethekwini-communal-ablution-blocks/> (Accessed on 10 February 2018).

- Corwin, D., Waggoner, B. and Rhoades, J. (1991) A functional model of solute transport that accounts for bypass. *Journal of environmental quality* 20(3), 647-658.  
Doi:10.2134/jeq1991.00472425002000030023x
- Crous, P., Haarhoff, J. and Buckley, C. (2013) Water demand characteristics of shared water and sanitation facilities: Experiences from community ablution blocks in eThekweni Municipality, South Africa. *Water SA* 39(3), 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(6), 945-948. <http://www.ijsr.net/archive/v4i6/SUB155316.pdf> (Accessed on 19 May 2018).
- Daso, A.P., Fatoki, O.S., Odendaal, J.P. and Olujimi, O.O. (2012) Occurrence of Selected Polybrominated Diphenyl Ethers and 2,2',4,4',5,5'-Hexabromobiphenyl (BB-153) in Sewage Sludge and Effluent Samples of a Wastewater-Treatment Plant in Cape Town, South Africa. *Archives of Environmental Contamination and Toxicology* 62(3), 391-402.  
<https://doi.org/10.1007/s00244-011-9720-9>
- Day, A.D. and Tucker, T.C. (1959) Production of Small Grains Pasture Forage Using Sewage Effluent as a Source of Irrigation Water and Plant Nutrients1. *Agronomy Journal* 51(9), 569-572. <http://dx.doi.org/10.2134/agronj1959.00021962005100090019x>
- De Jager, J. (1994) Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA* 20(4), 307-314.
- de Mello Prado, R. and Caione, G. (2012) Soil Fertility. Issaka, R. (ed), pp. 115 - 134, InTech, London, UK. <http://dx.doi.org/10.5772/53388>
- Deblonde, T., Cossu-Leguille, C. and Hartemann, P. (2011) Emerging pollutants in wastewater: A review of the literature. *International Journal of Hygiene and Environmental Health* 214(6), 442-448. <https://doi.org/10.1016/j.ijheh.2011.08.002>
- DEC (2004) Environmental Guidelines–Use of Effluent by Irrigation, p. 121, Department of Environment and Conservation (New South Wales), Sydney, Australia.  
<http://www.environment.nsw.gov.au/resources/water/effguide.pdf> (accessed on 28 February 2018)
- Dendooven, L., Bonhomme, E., Merckx, R. and Vlassak, K. (1998) N dynamics and sources of N<sub>2</sub>O production following pig slurry application to a loamy soil. *Biology and Fertility of Soils* 26(3), 224-228. <https://doi.org/10.1007/s003740050371>
- Department of Water Affairs (2013) Revision of general authorisations in terms of Section 39 of the National Water Act, 1998, Government Gazette Pretoria.
- Dourado-Neto, D., Teruel, D.A., Reichardt, K., Nielsen, D.R., Frizzone, J.A. and Bacchi, O.O.S. (1998) Principles of crop modeling and simulation: I. uses of mathematical models in agricultural science. *Scientia Agricola* 55, 46-50. <http://dx.doi.org/10.1590/S0103-90161998000500008>
- Dudley, L.M., Ben-Gal, A. and Lazarovitch, N. (2008) Drainage Water Reuse: Biological, Physical, and Technological Considerations for System Management *Journal of environmental quality* 37(5\_Supplement), S-25-S-35. <http://dx.doi.org/10.2134/jeq2007.0314>

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 February 2018)

DWAF (1996) South African Water Quality Guidelines. Forestry, D.o.W.A.a. (ed), Pretoria, South Africa.  
[http://www.dwaf.gov.za/iwqs/wq\\_guide/Pol\\_saWQguideFRESH\\_vol4\\_Irrigation.pdf](http://www.dwaf.gov.za/iwqs/wq_guide/Pol_saWQguideFRESH_vol4_Irrigation.pdf)  
(Accessed on 19 May 2018).

DWS (2016) National sanitation policy 2016, Department of Water and Sanitation, Pretoria, South Africa.  
[http://www.dwa.gov.za/Documents/sanitation/17005SC\\_POLICY\\_National%20Sanitation%20Policy%202016%20FINAL310117.pdf](http://www.dwa.gov.za/Documents/sanitation/17005SC_POLICY_National%20Sanitation%20Policy%202016%20FINAL310117.pdf) (Accessed on 10 January 2018).

Egiarte, G., C.M. , Arbostain, E., Ruiz-Romera and M.Pinto (2006) Study of the chemistry of an acid soil column and of the corresponding leachates after the addition of an anaerobic municipal sludge. *Chemosphere*. 65, 2456–2467.  
<https://doi.org/10.1016/j.chemosphere.2006.04.044>

El-Nesr, M.N., Alazba, A.A. and Šimůnek, J. (2014) HYDRUS simulations of the effects of dual-drip subsurface irrigation and a physical barrier on water movement and solute transport in soils. *Irrigation Science* 32(2), 111-125. <https://doi.org/10.1007/s00271-013-0417-x>

eThekweni Municipality (2017) Municipal Services and Living Conditions Survey 2016 – 2017, Research and Policy Advocacy Department, Durban, South Africa.  
[http://www.durban.gov.za/City\\_Government/Administration/city\\_manager/RAPA/Reports/2016-2017%20RAPA%20Quantitative%20Report%20Municipal%20Services%20and%20Living%20Conditions%20Survey%20Trends.pdf](http://www.durban.gov.za/City_Government/Administration/city_manager/RAPA/Reports/2016-2017%20RAPA%20Quantitative%20Report%20Municipal%20Services%20and%20Living%20Conditions%20Survey%20Trends.pdf) (Accessed on 19 May 2018).

Etter, B., Tilley, E., Khadka, R. and Udert, K.M. (2011) Low-cost struvite production using source-separated urine in Nepal. *Water Research* 45(2), 852-862.  
<https://doi.org/10.1016/j.watres.2010.10.007>

FAO (1985) Water quality for agriculture, Food and Agriculture Organisation, Rome, Italy. ISBN 92-5-102263-1

FAO (2003) Users Manual for Irrigation with Treated Wastewater, Cairo, Egypt.  
[http://www.fao.org/tempref/GI/Reserved/FTP\\_FaoRne/morelinks/Publications/English/Users\\_manual-en.pdf](http://www.fao.org/tempref/GI/Reserved/FTP_FaoRne/morelinks/Publications/English/Users_manual-en.pdf) (Accessed on 19 May 2018).

FAO (2013) Guidelines to control water pollution from agriculture in China: Decoupling water pollution from agricultural production, p. 197, Food and Agriculture Organisation of the United Nations, Rome, Italy. ISSN: 1020-1203

FAO (2015) Crop Water Information: Banana. Division, L.a.W. (ed), Food and Agriculture Organisation, Rome, Italy. <http://www.fao.org/land-water/databases-and-software/crop-information/banana/en/> (Accessed on 17 May 2016).

Feigin, A., Ravina, I. and Shalhevet, J. (2012) *Irrigation with Treated Sewage Effluent: Management for environmental Protection*, Springer, Heidelberg, Germany. ISBN 9783642744808

Feigin, A., Vaisman, I. and Bielorai, H. (1984) Drip Irrigation of Cotton with Treated Municipal Effluents: II. Nutrient Availability in Soil. *Journal of environmental quality* 13(2), 234-238. <http://dx.doi.org/10.2134/jeq1984.00472425001300020012x>

Fessehazion, M.K., Annandale, J.G., Everson, C.S., Stirzaker, R.J. and Tesfamariam, E.H. (2014) Evaluating of soil water balance (SWB-Sci) model for water and nitrogen interactions in pasture: Example using annual ryegrass. *Agricultural Water Management* 146, 238-248. <http://dx.doi.org/10.1016/j.agwat.2014.08.018>

Fessehazion, M.K., Stirzaker, R.J., Annandale, J.G. and Everson, C.S. (2011) Improving nitrogen and irrigation water use efficiency through adaptive management: A case study using annual ryegrass. *Agriculture, Ecosystems & Environment* 141(3-4), 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. and 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>

Flores-Márgez, J.P., Jaramillo-López, E., Assadian, N.W., Di Giovanni, G.D., Pérez-Casio, F. and Shukla, M.K. (2013) Heavy Metals in Oat and Soil Treated with Lime-Stabilized Biosolids and Reclaimed Wastewater. *Journal of Environmental & Analytical Toxicology* 3(4). <http://dx.doi.org/10.4172/2161-0525.S6-001>

Fonseca, A.F.d., Herpin, U., Paula, A.M.d., Victória, R.L. and Melfi, A.J. (2007) Agricultural use of treated sewage effluents: agronomic and environmental implications and perspectives for Brazil. *Scientia Agricola* 64, 194-209. <https://doi.org/10.1590/S0103-90162007000200014>

Foxon, K., Pillay, S., Lalbahadur, T., Rodda, N., Holder, F. and Buckley, C. (2005) The anaerobic baffled reactor (ABR): an appropriate technology for on-site sanitation. *Water SA* 30(5), 44-50. <http://dx.doi.org/10.4314/wsa.v30i5.5165>.

Foxon, K.M. (2009) Analysis of a pilot-scale anaerobic baffled reactor treating domestic wastewater. <http://researchspace.ukzn.ac.za/handle/10413/403> (Accessed on 19 May 2018).

Freitas, W.d.S., Ramos, M.M. and Costa, S.L.d. (2008) Demanda de irrigação da cultura da banana na bacia do Rio São Francisco. *Revista Brasileira de Engenharia Agrícola e Ambiental* 12, 343-349. [http://www.scielo.br/scielo.php?script=sci\\_arttext&pid=S1415-43662008000400002&nrm=iso](http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1415-43662008000400002&nrm=iso)

Friedel, J.K., Langer, T., Siebe, C. and Stahr, K. (2000) Effects of long-term waste water irrigation on soil organic matter, soil microbial biomass and its activities in central Mexico. *Biology and Fertility of Soils* 31(5), 414-421. Doi: 10.1007/s003749900188

Fumasoli, A., Etter, B., Sterkele, B., Morgenroth, E. and Udert, K.M. (2016) Operating a pilot-scale nitrification/distillation plant for complete nutrient recovery from urine. *Water Science and Technology* 73(1), 215-222. Doi: 10.2166/wst.2015.485

Galal, H.A.A. (2015) Long-term Effect of Mixed Wastewater Irrigation on Soil Properties, Fruit Quality and Heavy Metal Contamination of Citrus. *American Journal of Environmental Protection* 3(3), 100-105. <http://pubs.sciepub.com/env/3/3/6>

Ghoreishi, M., Hossini, Y. and Maftoon, M. (2012) Simple models for predicting leaf area of mango (*Mangifera indica* L.). *Journal of Biology and Earth Sciences* 2(2), 45-53. <https://doi.org/10.1016/j.scienta.2017.10.034>

Guerif, J. (1994) *Developments in Agricultural Engineering*. Soane, B.D. and van Ouwerkerk, C. (eds), pp. 191-214, Elsevier. <https://doi.org/10.1016/B978-0-444-88286-8.50017-9>

Guo, L., Li, J., Li, Y. and Xu, D. (2016) Balancing the Nitrogen Derived from Sewage Effluent and Fertilizers Applied with Drip Irrigation. *Water, Air, & Soil Pollution* 228(1), 12. <https://doi.org/10.1007/s11270-016-3192-5>

Guo, W., Andersen, M.N., Qi, X.-b., Li, P., Li, Z.-y., Fan, X.-y. and Zhou, Y. (2017) Effects of reclaimed water irrigation and nitrogen fertilization on the chemical properties and microbial community of soil. *Journal of Integrative Agriculture* 16(3), 679-690. Doi: 10.1016/s2095-3119(16)61391-6

Gutterer, B., Sasse, L., Panzerbieter, T. and Reckerzügel, T. (2009) *Decentralised wastewater treatment systems (DEWATS) and sanitation in developing countries, Bremen, Germany*. ISBN: 978 1 84380 128 3

Hamdi, W., Gamaoun, F., Pelster, D.E. and Seffen, M. (2013) Nitrate Sorption in an Agricultural Soil Profile. *Applied and Environmental Soil Science* 2013, 1-7. <http://dx.doi.org/10.1155/2013/597824>

Han, M., Zhao, C., Šimůnek, J. and Feng, G. (2015) Evaluating the impact of groundwater on cotton growth and root zone water balance using Hydrus-1D coupled with a crop growth model. *Agricultural Water Management* 160, 64-75. <https://doi.org/10.1016/j.agwat.2015.06.028>

Hartmann, A., Šimůnek, J., Aidoo, M.K., Seidel, S.J. and Lazarovitch, N. (2017) Implementation and Application of a Root Growth Module in HYDRUS. *Vadose Zone Journal*. <http://dx.doi.org/10.2136/vzj2017.02.0040>

Haruvy, N. (1997) Agricultural reuse of wastewater: nation-wide cost-benefit analysis. *Agriculture, Ecosystems & Environment* 66(2), 113-119. [https://doi.org/10.1016/S0167-8809\(97\)00046-7](https://doi.org/10.1016/S0167-8809(97)00046-7)

Hass, A., Mingelgrin, U. and Fine, P. (2011) *Treated Wastewater in Agriculture*. Levy, G., Fine, P. and Bar-Tal, A. (eds), pp. 247-285, Wiley-Blackwell. <http://dx.doi.org/10.1002/9781444328561.ch7>

Heckrath, G., Brookes, P.C., Poulton, P.R. and Goulding, K.W.T. (1995) Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment. *Journal of environmental quality* 24(5), 904-910. <http://dx.doi.org/10.2134/jeq1995.00472425002400050018x>

Hedden, S. and Cilliers, J. (2014) *Parched prospects: The emerging water crisis in South Africa*, Pretoria, South Africa. ISSN 1026-0404

- Hentati, O., Chaker, S., Wali, A., Ayoub, T. and Ksibi, M. (2014) Effects of long-term irrigation with treated wastewater on soil quality, soil-borne pathogens, and living organisms: case study of the vicinity of El Hajeb (Tunisia). *Environmental Monitoring and Assessment* 186(5), 2671-2683. <https://doi.org/10.1007/s10661-013-3570-z>
- Hernández-Martínez, J.L., Prado, B., Cayetano-Salazar, M., Bischoff, W.-A. and Siebe, C. (2016) Ammonium-nitrate dynamics in the critical zone during single irrigation events with untreated sewage effluents. *Journal of Soils and Sediments*, 1–14. <https://doi.org/10.1007/s11368-016-1506-2>
- Herpin, U., Gloaguen, T.V., da Fonseca, A.F., Montes, C.R., Mendonça, F.C., Piveli, R.P., Breulmann, G., Forti, M.C. and Melfi, A.J. (2007) Chemical effects on the soil–plant system in a secondary treated wastewater irrigated coffee plantation—A pilot field study in Brazil. *Agricultural Water Management* 89(1–2), 105-115. <http://dx.doi.org/10.1016/j.agwat.2007.01.001>
- Homem, B., de Almeida Neto, O., Condé, M., Silva, M. and Ferreira, I. (2014) Effect of prolonged use of swine wastewater on soil properties. *Científica (Jaboticabal)* 42(3), 299-309. ISSN: 1984-5529
- Hu, K., Li, B., Chen, D., Zhang, Y. and Edis, R. (2008) Simulation of nitrate leaching under irrigated maize on sandy soil in desert oasis in Inner Mongolia, China. *Agricultural Water Management* 95(10), 1180-1188. <https://doi.org/10.1016/j.agwat.2008.05.001>
- Hu, Y., Zhang, L., Deng, B., Liu, Y., Liu, Q., Zheng, X., Zheng, L., Kong, F., Guo, X. and Siemann, E. (2017) The non-additive effects of temperature and nitrogen deposition on CO<sub>2</sub> emissions, nitrification, and nitrogen mineralization in soils mixed with termite nests. *CATENA* 154, 12-20. <http://dx.doi.org/10.1016/j.catena.2017.02.014>
- Hue, N.V., Uchida, R. and Ho, M.C. (2000) Sampling and analysis of soils and plant tissues: How to take representative samples, how the samples are tested. Silva J.A. and Uchida R.S. (eds), pp. 23 - 30, University of Hawaii, Honolulu, USA. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.424.272&rep=rep1&type=pdf> (Accessed on 20 March 2018).
- Hunter, A. (1974) Tentative ISFE soil extraction procedure, Raleigh, N.C., USA.
- Hussain, I., Raschid, L., Hanjra, M.A., Marikar, F. and van der Hoek, W. (2002) A framework for analyzing socioeconomic, health and environmental impacts of wastewater use in agriculture in developing countries, p. 33, International Water Management Institute (IWMI) Colombo, Sri Lanka. ISBN: 92-9090-454-2
- Ilani, T., Schulz, E. and Chefetz, B. (2005) Interactions of Organic Compounds with Wastewater Dissolved Organic Matter. *Journal of environmental quality* 34(2), 552-562. <http://dx.doi.org/10.2134/jeq2005.0552>
- Jaramillo, F.M. and Restrepo, I. (2017) Wastewater Reuse in Agriculture: A Review about Its Limitations and Benefits. *Sustainability* 9(10), 1734. Doi: 10.3390/su9101734
- Jasper, J.T. (2014) Treatment of Trace Organic Contaminants and Nutrients in Open-Water Unit Process Wetlands. <http://www.escholarship.org/uc/item/560472zt>



Johns, G. and McConchie, D. (1994) Irrigation of bananas with secondary treated sewage effluent. II. Effect on plant nutrients, additional elements and pesticide residues in plants, soil and leachate using drainage lysimeters. *Australian Journal of Agricultural Research* 45(7), 1619-1638. <http://dx.doi.org/10.1071/AR9941619>

Jönsson, H. and Vinnerås, B. (2004) Adapting the nutrient content of urine and faeces in different countries using FAO and Swedish data. loop, E.C.t. (ed), pp. 623-626., International Water Association, Lübeck, Germany. ISBN 91 88714 94 2

Jovanovic, N., Annandale, J. and Hammes, P. (2000) Teaching crop physiology with the Soil Water Balance model. *Journal of Natural Resources and Life Sciences Education* 29, 23-30. <https://www.agronomy.org/files/jnrlse/issues/2000/e99-11.pdf> (Accessed on 19 May 2018).

Jovanovic, N., Annandale, J. and Mhlauli, N. (1999) Field water balance and SWB parameter determination of six winter vegetable species. *Water SA* 25(2), 191-196. <http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=4288&FromURL=%2FPages%2FDefault.aspx%3F> (Accessed on 19 May 2018).

Jueschke, E., Marschner, B., Tarchitzky, J. and Chen, Y. (2008) Effects of treated wastewater irrigation on the dissolved and soil organic carbon in Israeli soils. *Water Science and Technology* 57(5), 727-733. Doi: 10.2166/wst.2008.173

Kadlec, R. and Wallace, S. (2008) *Treatment wetlands*, CRC press. ISBN: 978-1-56670-526-4

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

Karandish, F. and Šimůnek, J. (2017) Two-dimensional modeling of nitrogen and water dynamics for various N-managed water-saving irrigation strategies using HYDRUS. *Agricultural Water Management* 193, 174-190. <https://doi.org/10.1016/j.agwat.2017.07.023>

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18(3), 267-288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)

Keraita, B., Dávila, J., Drechsel, P., Winkler, M. and Medlicott, K. (2015) *Alternative Water Supply Systems*. Memon, F.A. and Ward, S. (eds), pp. 367-369, IWA Publishing, London, UK., <https://cgspace.cgiar.org/handle/10568/65321>

Keraita, B. and Drechsel, P. (2015) Consumer perceptions of fruit and vegetable quality: certification and other options for safeguarding public health in West Africa. *IWMI Working Paper (No.164)*, 23 pp. ISBN: 978-92-9090-822-7

Kersebaum, K.C., Hecker, J.-M., Mirschel, W. and Wegehenkel, M. (2007) Modelling water and nutrient dynamics in soil–crop systems: Proceedings of the workshop on “Modelling water and nutrient dynamics in soil–crop systems” held on 14–16 June 2004 in Müncheberg, Germany. Kersebaum, K.C., Hecker, J.-M., Mirschel, W. and Wegehenkel, M. (eds), pp. 1-17, Springer Netherlands, Dordrecht. 10.1007/978-1-4020-4479-3\_1

Khaskhoussy, K., Kahlaoui, B., Nefzi, B.M., Jozdan, O., Dakheel, A. and Hachicha, M. (2015) Effect of treated wastewater irrigation on heavy metals distribution in a Tunisian soil. *Engineering, Technology & Applied Science Research* 5(3), 805-810.

Khurana, M. and Singh, P. (2012) Waste water use in crop production: a review. *Resources and Environment* 2(4), 116-131. DOI: 10.5923/j.re.20120204.01

Kiziloglu, F.M., Turan, M., Sahin, U., Kuslu, Y. and Dursun, A. (2008) Effects of untreated and treated wastewater irrigation on some chemical properties of cauliflower (*Brassica oleracea* L. var. botrytis) and red cabbage (*Brassica oleracea* L. var. rubra) grown on calcareous soil in Turkey. *Agricultural Water Management* 95(6), 716-724.  
<https://doi.org/10.1016/j.agwat.2008.01.008>

Lado, M. and Ben-Hur, M. (2009) Treated domestic sewage irrigation effects on soil hydraulic properties in arid and semiarid zones: A review. *Soil and Tillage Research* 106(1), 152-163.  
<http://dx.doi.org/10.1016/j.still.2009.04.011>

Lal, K., Minhas, P.S. and Yadav, R.K. (2015) Long-term impact of wastewater irrigation and nutrient rates II. Nutrient balance, nitrate leaching and soil properties under peri-urban cropping systems. *Agricultural Water Management* 156(Supplement C), 110-117.  
<https://doi.org/10.1016/j.agwat.2015.04.001>

Lavrova, S. and Koumanova, B. (2013) Applied Bioremediation - Active and Passive Approaches. Yogesh, B.P. and Prakash, R. (eds), pp. 69-99, Intech Open Science Online Publisher, Croatia. <http://dx.doi.org/10.5772/56245>

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

Levy, G.J. (2011) Review. *Israel Journal of Plant Sciences* 59(2), 95-104.  
Doi: 10.1560/ijps.59.2-4.95

Levy, G.J., Fine, P., Goldstein, D., Azenkot, A., Zilberman, A., Chazan, A. and Grinhut, T. (2014a) Long term irrigation with treated wastewater (TWW) and soil sodification. *Biosystems Engineering* 128, 4-10. Doi: 10.1016/j.biosystemseng.2014.05.004

Levy, G.J., Lordian, A., Goldstein, D. and Borisover, M. (2014b) Soil structural indices' dependence on irrigation water quality and their association with chromophoric components in dissolved organic matter. *European Journal of Soil Science* 65(2), 197-205.  
<http://dx.doi.org/10.1111/ejss.12116>

Li, J., Zhang, J. and Rao, M. (2005) Modeling of water and nitrate transport under surface drip fertigation. *Transactions of the ASAE* 48(2), 627. <https://doi.org/10.13031/2013.18336>

Liang, H., Hu, K., Batchelor, W.D., Qi, Z. and Li, B. (2016) An integrated soil-crop system model for water and nitrogen management in North China. *Scientific Reports* 6, 25755. Doi: 10.1038/srep25755

Liu, Y., Li, Y., Harris, P., Cardenas, L.M., Dunn, R.M., Sint, H., Murray, P.J., Lee, M.R.F. and Wu, L. (2018) Modelling field scale spatial variation in water run-off, soil moisture, N<sub>2</sub>O emissions and herbage biomass of a grazed pasture using the SPACSYS model. *Geoderma* 315, 49-58. <https://doi.org/10.1016/j.geoderma.2017.11.029>

- Lu, S., Andersen, H.E., Thodsen, H., Rubæk, G.H. and Trolle, D. (2016) Extended SWAT model for dissolved reactive phosphorus transport in tile-drained fields and catchments. *Agricultural Water Management* 175, 78-90. <https://doi.org/10.1016/j.agwat.2015.12.008>
- Lu, Y., Yao, H., Shan, D., Jiang, Y., Zhang, S. and Yang, J. (2015) Heavy Metal Residues in Soil and Accumulation in Maize at Long-Term Wastewater Irrigation Area in Tongliao, China. *Journal of Chemistry* 2015, 9. <http://dx.doi.org/10.1155/2015/628280>
- Lusk, M.G., Toor, G.S., Yang, Y.-Y., Mechtensimer, S., De, M. and Obreza, T.A. (2017) A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. *Critical Reviews in Environmental Science and Technology* 47(7), 455-541. <http://dx.doi.org/10.1080/10643389.2017.1327787>
- Lüthi, C., Panesar, A., Schütze, T., Norström, A., McConville, J., Parkinson, J., Saywell, D. and Ingle, R. (2011) *Sustainable Sanitation in Cities: A framework for action*, Papiroz Publishing House, Rijswijk, Netherlands.
- Ma, L., Ahuja, L.R., Ascough, J.C., Shaffer, M.J., Rojas, K.W., Malone, R.W., Cameira, M.R., (2000) Integrating system modeling with field research in agriculture: applications of the Root Zone Water Quality Model (RZWQM). *Advances in Agronomy* 71, 233–292.
- Malchi, T., Maor, Y., Tadmor, G., Shenker, M. and Chefetz, B. (2014) Irrigation of root vegetables with treated wastewater: evaluating uptake of pharmaceuticals and the associated human health risks. *Environ Sci Technol* 48(16), 9325-9333. 10.1021/es5017894
- Marschner, H. (2011) *Marschner's Mineral Nutrition of Higher Plants*, Elsevier Science. <https://books.google.co.za/books?id=yqKV3USG41cC>
- Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L. and Suzuki, A. (2010) Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. *Annals of Botany* 105(7), 1141-1157. Doi: 10.1093/aob/mcq028
- Mateo-Sagasta, J., Raschid-Sally, L. and Thebo, A. (2015) *Wastewater: Economic Asset in an Urbanizing World*. Drechsel, P., Qadir, M. and Wichelns, D. (eds), pp. 15-38, Springer Netherlands, Dordrecht. [https://doi.org/10.1007/978-94-017-9545-6\\_2](https://doi.org/10.1007/978-94-017-9545-6_2)
- Matheyarasu, R., Seshadri, B., Bolan, N.S. and Naidu, R. (2015) Impacts of Abattoir Waste-Water Irrigation on Soil Fertility and Productivity. Doi: 10.5772/59312
- Mekala, C. and Nambi, I.M. (2016) Experimental and Simulation Studies on Nitrogen Dynamics in Unsaturated and Saturated Soil Using HYDRUS-2D. *Procedia Technology* 25, 122-129. Doi: 10.1016/j.protcy.2016.08.089
- Minz, D., Karyo, R. and Gerstl, Z. (2011) *Treated Wastewater in Agriculture*. Levy, G., Fine, P. and Bar-Tal, A. (eds), pp. 351-381, Wiley-Blackwell. <http://dx.doi.org/10.1002/9781444328561.ch11>
- Mitra, G.N. (2016) *Regulation of nutrient uptake by plants : a biochemical and molecular approach*, Springer, New Delhi, India. Doi: 10.1007/978-81-322-2334-4

Mohamed Sa, J., Mohamed Ya, M. and Jamal Safi, M. (2017) Impact of Treated Wastewater Irrigation on Soil Properties and Production of Cucumis melo inodorus in Gaza Strip. *International Journal of Soil Science* 12(3), 104-112. Doi: 10.3923/ijss.2017.104.112

Mohammad, M.J. and Ayadi, M. (2004) Forage Yield and Nutrient Uptake as Influenced by Secondary Treated Wastewater. *Journal of Plant Nutrition* 27(2), 351-365. <http://dx.doi.org/10.1081/PLN-120027659>

Mohammad, M.J. and Mazahreh, N. (2003) Changes in Soil Fertility Parameters in Response to Irrigation of Forage Crops with Secondary Treated Wastewater. *Communications in Soil Science and Plant Analysis* 34(9-10), 1281-1294. <https://doi.org/10.1081/CSS-120020444>

Mojid, M., Wyseure, G. and Biswas, S. (2016) Effects of Municipal Wastewater Irrigation on Yield and Fertilizer Requirement of Wheat (*Triticum aestivum* L.) in Bangladesh. *The Agriculturists* 14(1), 01-14. <http://dx.doi.org/10.3329/agric.v14i1.29096>

Mojiri, A. and Hamidi, A. (2011) Effects of municipal wastewater on accumulation of heavy metals in soil and wheat (*Triticum aestivum* L.) with two irrigation methods. *Romanian Agricultural Research* 28, 217-222. <http://www.incda-fundulea.ro/rar/nr28/rar28.29.pdf> (Accessed on 19 May 2015).

Mok, H.-F., Dassanayake, K.B., Hepworth, G. and Hamilton, A.J. (2014) Field comparison and crop production modeling of sweet corn and silage maize (*Zea mays* L.) with treated urban wastewater and freshwater. *Irrigation Science* 32(5), 351-368. Doi: 10.1007/s00271-014-0434-4

Molinos-Senante, M., Hernández-Sancho, F. and Sala-Garrido, R. (2011) Cost–benefit analysis of water-reuse projects for environmental purposes: A case study for Spanish wastewater treatment plants. *Journal of Environmental Management* 92(12), 3091-3097. <https://doi.org/10.1016/j.jenvman.2011.07.023>

Mollahoseini, H. (2013) Long term effects of municipal wastewater irrigation on some properties of a semiarid region soil of Iran. *International Journal of Agronomy and plant production* 4(5), 1023-1028. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.678.4943&rep=rep1&type=pdf> (Accessed on 19 May 2018).

Monteith, J.L. and Moss, C.J. (1977) Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences* 281(980), 277-294. Doi: 10.1098/rstb.1977.0140

Mousavi, S.R., Tavakoli, M.T., Dadgar, M., Chenari, A.I., Moridiyan, A. and Shahsavari, M. (2015) Reuse of Treated Wastewater for Agricultural Irrigation with Its Quality Approach. *Biological Forum* 7(1), 814-822. <https://www.researchtrend.net/bfij/bf12/132%20SAYED%20ROHOLLA%20MOUSAVI.pdf> (Accessed on 19 May 2018).

Muklada, H., Klein, J.D., Glasser, T.A., Dvash, L., Azaizeh, H., Halabi, N., Davidovich-Rikanati, R., Lewinsohn, E. and Landau, S.Y. (2017) Initial evaluation of willow (*Salix acmophylla*) irrigated with treated wastewater as a fodder crop for dairy goats. *Small Ruminant Research*. <https://doi.org/10.1016/j.smallrumres.2017.10.013>

Mulidzi, A., Clarke, C. and 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(1), 79-84.  
[http://www.scielo.org.za/scielo.php?script=sci\\_arttext&pid=S2224-79042016000100002](http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2224-79042016000100002)  
(Accessed on 19 May 2018).

Müller, F.L. and Engelbrecht, W.L. (2018) Selenium addition affects early seedling growth of *Medicago polymorpha* and *Trifolium subterraneum*, but not seed germination: a preliminary study. *South African Journal of Plant and Soil* 35(1), 75-77.  
<https://doi.org/10.1080/02571862.2017.1324048>

Muller, S. and Gregory, J. (2003) *Ground Water Loading Effects of Agricultural Management Systems*, University of Florida, Florida, USA.

Murphy, J. and 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](https://doi.org/10.1016/S0003-2670(00)88444-5)

Musazura, W. (2014) Effect of ABR effluent irrigation on Swiss chard (*Beta vulgaris* subsp. *cicla*) growth and nutrient leaching. Msc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa. <http://prg.ukzn.ac.za/docs/default-source/dissertation/1-93-mb.pdf?sfvrsn=0> (accessed on 28 December 2016)

Musazura, W., Odindo, A., Bame, I. and 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(4), 592-609.  
<https://doi.org/10.2166/wrd.2015.011>

Mynard, D.G. and Kalra, Y.P. (2008) *Soil Sampling and Methods for Analysis*. Carter, M.R. (ed), pp. 71-80, Lewis Publishers, London, UK. ISBN: 9781420005271

National Academy of Sciences and National Academy of Engineering (1972) *Water quality criteria*, p. 529, Wahington DC, USA.

Nikiema, J., Cofie, O., Impraim, R. and Adamtey, N. (2013) Processing of Fecal Sludge to Fertilizer Pellets Using a Low-Cost Technology in Ghana. *Environment and Pollution* 2(4).  
<http://dx.doi.org/10.5539/ep.v2n4p70>

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

Norton, J.M. (2008) *Agronomy monogram 49*. Schepers, J.S.a.R., W.R. (ed), p. 173, American Society of Agronomy,, Madison, USA.

Nyombi, K., Van Asten, P.J.A., Leffelaar, P.A., Corbeels, M., Kaizzi, C.K. and Giller, K.E. (2009) Allometric growth relationships of East Africa highland bananas (*Musa* AAA-EAHB) cv. Kisansa and Mbwazirume. *Annals of Applied Biology* 155(3), 403-418.  
<http://dx.doi.org/10.1111/j.1744-7348.2009.00353.x>

- Ogbazghi, Z.M., Tesfamariam, E.H. and 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>
- Onwueme, I. (1999) Taro cultivation in Asia and the Pacific, p. 16, Bangkok, Thailand. <http://www.fao.org/docrep/005/ac450e/ac450e00.htm> (Accessed on 19 May 2018).
- Pedrero, F., Kalavrouziotis, I., Alarcón, J.J., Koukoulakis, P. and Asano, T. (2010) Use of treated municipal wastewater in irrigated agriculture—Review of some practices in Spain and Greece. *Agricultural Water Management* 97(9), 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 of the United Nations, Rome, Italy. ISBN 92-5-103135-5
- Pound, C.E., Crites, R.W., Olson, J.V. and Laboratory, R.S.K.E.R. (1978) Long-term Effects of Land Application of Domestic Wastewater: Hollister, California, Rapid Infiltration Site, Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory. <https://books.google.co.za/books?id=D-ui3Ag7NqkC>
- Pratt, P.F. (1972) Quality criteria for trace elements in irrigation waters., p. 46, California Agricultural Experiment Station.
- Probert, M., Keating, B., Thompson, J. and Parton, W. (1995) Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture* 35(7), 941-950. <http://dx.doi.org/10.1071/EA9950941>
- Probert, M.E. and Verburg, K. (1996) APSIM-SoilWat. Verburg, K. (ed), CSIRO Division of Soils Divisional Brisbane, Australia. ISBN 0643 058680.
- Qadir, M., Drechsel, P. and Raschid-Sally, L. (2013) Encyclopedia of environmental management. Jørgensen, S.E. (ed), pp. 2675-2680, CRS Press, Florida, USA. <http://dx.doi.org/10.1081/E-EEM-120046687>
- Qadir, M., Mateo-Sagasta, J., Jimenez, B., Siebe, C., Siemens, J. and Hanjra, M.A. (2015) Wastewater: Economic Asset in an Urbanizing World. Drechsel, P., Qadir, M. and Wichelns, D. (eds), pp. 55-74, Springer Netherlands. Doi: 10.1007/978-94-017-9545-6
- Qian, Y.L. and Mecham, B. (2005) Long-Term Effects of Recycled Wastewater Irrigation on Soil Chemical Properties on Golf Course Fairways *Agronomy Journal* 97(3), 717-721. <http://dx.doi.org/10.2134/agronj2004.0140>
- Quinn, P. (2004) Scale appropriate modelling: representing cause-and-effect relationships in nitrate pollution at the catchment scale for the purpose of catchment scale planning. *Journal of Hydrology* 291(3), 197-217. <https://doi.org/10.1016/j.jhydrol.2003.12.040>
- Raschid-Sally, L. and Jayakody, P. (2009) Drivers and characteristics of wastewater agriculture in developing countries : results from a global assessment, p. 35, International Water Management Institute (IWMI), Colombo, Sri Lanka. <http://www.unwater.org/downloads/RR127.pdf> (Accessed 08/01/2017)

Rasiah, V., Armour, J.D. and Cogle, A.L. (2005) Assessment of variables controlling nitrate dynamics in groundwater: Is it a threat to surface aquatic ecosystems? *Marine Pollution Bulletin* 51(1-4), 60-69. <http://dx.doi.org/10.1016/j.marpolbul.2004.10.024>

Rattan, R.K., Datta, S.P., Chhonkar, P.K., Suribabu, K. and 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(3), 310-322. <https://doi.org/10.1016/j.agee.2005.02.025>

Reynaud, N. and Buckley, C.A. (2016) The anaerobic baffled reactor (ABR) treating communal wastewater under mesophilic conditions: a review. *Water Science and Technology* 73(3), 463-478. Doi: 10.2166/wst.2015.539

Riekert, S. and Bainbridge, S. (1998) Analytical methods of the Cedara plant and soil laboratory, KwaZulu-Natal Department of Agriculture and Environmental Affairs, Pietermaritzburg, South Africa.

Riemenschneider, C., Al-Raggad, M., Moeder, M., Seiwert, B., Salameh, E. and Reemtsma, T. (2016) Pharmaceuticals, Their Metabolites, and Other Polar Pollutants in Field-Grown Vegetables Irrigated with Treated Municipal Wastewater. *Journal of Agricultural and Food Chemistry* 64(29), 5784-5792. <http://dx.doi.org/10.1021/acs.jafc.6b01696>

Rimmington, G. and Charles-Edwards, D. (1987) *Plant growth modeling for resource management: current models and methods*

Wisioł, K. and Hesketh, J. (eds), pp. 3-15, CRC Press, Florida, USA. ISBN: 9780849364907

Robinson, J.C. and Alberts, A.J. (1986) Growth and yield responses of banana (cultivar 'Williams') to drip irrigation under drought and normal rainfall conditions in the subtropics. *Scientia Horticulturae* 30(3), 187-202. [http://dx.doi.org/10.1016/0304-4238\(86\)90097-X](http://dx.doi.org/10.1016/0304-4238(86)90097-X)

Robinson, J.C. and Bower, J.P. (1988) Transpiration from banana leaves in the subtropics in response to diurnal and seasonal factors and high evaporative demand. *Scientia Horticulturae* 37(1), 129-143. [http://dx.doi.org/10.1016/0304-4238\(88\)90156-2](http://dx.doi.org/10.1016/0304-4238(88)90156-2)

Robinson, J.C. and Saúco, V.G. (2010) *Bananas and Plantains*, CABI. ISBN: 9781845937386

Roma, E. and Buckley, C. (2011) *Assessing Community Ablution Blocks and exploring sanitation market in informal settlements of eThekwin Municipality—South Africa*. Unpublished report for Unilever (UK).

Roma, E., Buckley, C., Jefferson, B. and Jeffrey, P. (2010) Assessing users' experience of shared sanitation facilities: a case study of community ablution blocks in Durban, South Africa. *Water SA* 36, 589-594. <http://dx.doi.org/10.4314/wsa.v36i5.61992>

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

Rowlings, D.W., Grace, P.R., Kiese, R. and Weier, K.L. (2012) Environmental factors controlling temporal and spatial variability in the soil-atmosphere exchange of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from an Australian subtropical rainforest. *Global Change Biology* 18(2), 726-738. Doi: 10.1111/j.1365-2486.2011.02563.x

Rusan, M.M.J., Hinnawi, S. and Rousan, L. (2007) Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. *Desalination* 215(1), 143-152. <https://doi.org/10.1016/j.desal.2006.10.032>

Sahrawat, K.L. (2008) Factors Affecting Nitrification in Soils. *Communications in Soil Science and Plant Analysis* 39(9-10), 1436-1446. <http://dx.doi.org/10.1080/001036208020042>

Saldías, C., Speelman, S., van Huylbroeck, G. and Vink, N. (2016) Understanding farmers' preferences for wastewater reuse frameworks in agricultural irrigation: Lessons from a choice experiment in the Western Cape, South Africa. *Water SA* 42, 26-37. [http://www.scielo.org.za/scielo.php?script=sci\\_arttext&pid=S1816-79502016000100004&nrm=iso](http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502016000100004&nrm=iso)

Santos, S.R., Ribeiro, D.P., Matos, A.T., Kondo, M.K. and Araújo, E.D. (2017) Changes in Soil Chemical Properties Promoted by Fertigation with Treated Sanitary Wastewater. *Engenharia Agrícola* 37(2), 343-352. Doi: 10.1590/1809-4430-eng.agric.v37n2p343-352/2017

Sasse, L. (1998) DEWATS : decentralised wastewater treatment in developing countries, Bremen Overseas Research and Development Association (BORDA), Bremen, Germany.

Schacht, K. and Marschner, B. (2015) Treated wastewater irrigation effects on soil hydraulic conductivity and aggregate stability of loamy soils in Israel. *Journal of Hydrology and Hydromechanics* 63(1). 10.1515/johh-2015-0010

Schulze, R.E. (1997) South African Atlas of Agrohydrology and–Climatology., Water Research Commission, Pretoria, South Africa.

Sepaskhah, A.R. and Karizi, A. (2011) Effects of alternate use of wastewater and fresh water on soil saturated hydraulic conductivity. *Archives of Agronomy and Soil Science* 57(2), 149-158. <http://dx.doi.org/10.1080/03650340903286430>

Sershen, S., Rodda, N., Stenström, T.A., Schmidt, S., Dent, M., Bux, F., Hanke, N., Buckley, C.A. and Fennemore, C. (2016) Water security in South Africa: perceptions on public expectations and municipal obligations, governance and water re-use. *Water SA* 42(3), 456. Doi: 10.4314/wsa.v42i3.11

Seshadri, B., Bolan, N.S., Kunhikrishnan, A., Chowdhury, S., Thangarajan, R. and Chuasavathi, T. (2014a) Recycled Water Irrigation in Australia. *Environmental Sustainability: Role of Green Technologies*, 39.

Seshadri, B., Kunhikrishnan, A., Bolan, N. and Naidu, R. (2014b) Effect of industrial waste products on phosphorus mobilisation and biomass production in abattoir wastewater irrigated soil. *Environ Sci Pollut Res Int* 21(17), 10013-10021. Doi: 10.1007/s11356-014-3030-5

Shahalam, A., Abu Zahra, B.M. and Jaradat, A. (1998) Wastewater Irrigation Effect on Soil, Crop and Environment: a Pilot Scale Study at Irbid, Jordan. *Water, Air, and Soil Pollution* 106(3), 425-445. <http://dx.doi.org/10.1023/A:1005046912234>

Sharpley, A. (2016) Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agrícola* 73(1), 1-8. Doi: 10.1590/0103-9016-2015-0107



Sharpley, A.N., McDowell, R.W. and Kleinman, P.J.A. (2001) Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and Soil* 237(2), 287-307. <http://dx.doi.org/10.1023/A:1013335814593>

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and Zhang, F. (2011) Phosphorus Dynamics: From Soil to Plant. *Plant Physiology* 156(3), 997-1005. 10.1104/pp.111.175232

Šimunek, J., van Genuchten, M.T. and Šejna, M. (2012) HYDRUS: Model Use, Calibration, and Validation. *Transactions of the ASABE* 55(4), 1263-1274.

Šimunek, J., van Genuchten, M.T. and Šejna, M. (2008) Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes *Vadose Zone Journal* 7(2), 587-600. <http://dx.doi.org/10.2136/vzj2007.0077>

Sinclair, T.R., Tanner, C. and Bennett, J. (1984) Water-use efficiency in crop production. *BioScience* 34(1), 36-40. <https://doi.org/10.2307/1309424>

Singels, A., Annandale, J.G., Jager, J.M.D., Schulze, R.E., Inman-Bamber, N.G., Durand, W., Rensburg, L.D.V., Heerden, P.S.V., Crosby, C.T., Green, G.C. and Steyn, J.M. (2010) Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *South African Journal of Plant and Soil* 27(1), 49-65. Doi: s10.1080/02571862.2010.10639970

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

Sklarz, M.Y., Zhou, M., Ferrando Chavez, D.L., Yakirevich, A., Gillor, O., Gross, A. and Soares, M.I. (2013) Effect of treated domestic wastewater on soil physicochemical and microbiological properties. *J Environ Qual* 42(4), 1226-1235. Doi: 10.2134/jeq2012.0416

Smith, C., Freney, J. and Bond, W. (1996) Ammonia volatilisation from soil irrigated with urban sewage effluent. *Soil Research* 34(5), 789-802. <https://doi.org/10.1071/SR9960789>

Smith, M. (1992) CROPWAT: A computer program for irrigation planning and management, Food & Agriculture Organisation, Rome, Italy.

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

Soil Survey Staff (2014) Keys to Soil Taxonomy, Natural Resources Conservation Service, Washington DC, USA.

Solís, C., Andrade, E., Mireles, A., Reyes-Solís, I.E., García-Calderón, N., Lagunas-Solar, M.C., Piña, C.U. and Flocchini, R.G. (2005) Distribution of heavy metals in plants cultivated with wastewater irrigated soils during different periods of time. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 241(1), 351-355. <https://doi.org/10.1016/j.nimb.2005.07.040>

Souza, M.F.d., Soares, E.M.B., Silva, I.R.d., Novais, R.F. and 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>

Stancalie, G., Marica, A. and Toullos, L. (2010) Using earth observation data and CROPWAT model to estimate the actual crop evapotranspiration. *Physics and Chemistry of the Earth, Parts A/B/C* 35(1), 25-30.

Statistics South Africa (2016) The state of basic service delivery in South Africa: In-depth analysis of the Community Survey 2016 data, Statistics South Africa, Pretoria, South Africa.

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. (2009) AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal* 101(3), 426-437. <http://dx.doi.org/10.2134/agronj2008.0139s>

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. (2012) Crop yield response to water, Food and Agriculture Organization of the United Nations Rome.

Stewart, J.W.B. and Tiessen, H. (1987) Dynamics of soil organic phosphorus. *Biogeochemistry* 4(1), 41-60. [10.1007/BF02187361](https://doi.org/10.1007/BF02187361)

Stewart, L., Charlesworth, P.B., Bristow, K. and Thorburn, P. (2006) Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. *Agricultural Water Management* 81(3), 315-334.

Stöckle, C.O., Donatelli, M. and Nelson, R. (2003) CropSyst, a cropping systems simulation model. *European Journal of Agronomy* 18(3), 289-307. [http://dx.doi.org/10.1016/S1161-0301\(02\)00109-0](http://dx.doi.org/10.1016/S1161-0301(02)00109-0)

Styczen, M. and Storm, B. (1993) Modelling of N-movements on catchment scale - a tool for analysis and decision making. *Fertilizer research* 36(1), 7-17. <https://doi.org/10.1007/BF00749943>

Tak, H.I., Babalola, O.O., Huyser, M.H. and Inam, A. (2013) Urban wastewater irrigation and its effect on growth, photosynthesis and yield of chickpea under different doses of potassium. *Soil Science and Plant Nutrition* 59(2), 156-167. <http://dx.doi.org/10.1080/00380768.2012.761570>

Tarchitzky, J., Lerner, O., Shani, U., Arye, G., Lowengart-Aycicegi, A., Brener, A. and Chen, Y. (2007) Water distribution pattern in treated wastewater irrigated soils: hydrophobicity effect. *European Journal of Soil Science* 58(3), 573-588. <https://doi.org/10.1111/j.1365-2389.2006.00845.x>

Tesfamariam, E.H., Annandale, J.G., Steyn, J.M. and Stirzaker, R.J. (2009) Exporting Large Volumes of Municipal Sewage Sludge through Turfgrass Sod Production. *Journal of environmental quality* 38, 1320-1328. <http://dx.doi.org/10.2134/jeq2008.0397>

Tesfamariam, E.H., Annandale, J.G., Steyn, J.M., Stirzaker, R.J. and Mbakwe, I. (2013) Municipal sludge as source of nitrogen and phosphorus in perennial pasture (*Eragrostis curvula*) production: Agronomic benefits and environmental impacts. *Water SA* 39(4). <http://dx.doi.org/10.4314/wsa.v39i4.9>

Tesfamariam, E.H., Annandale, J.G., Steyn, J.M., Stirzaker, R.J. and Mbakwe, I. (2015) Use of the SWB-Sci model for nitrogen management in sludge-amended land. *Agricultural Water Management* 152, 262-276. <http://dx.doi.org/10.1016/j.agwat.2015.01.023>

Thebo, A.L., Drechsel, P., Lambin, E. and Nelson, K. (2017) A global, spatially-explicit assessment of irrigated croplands influenced by urban wastewater flows. *Environmental Research Letters* 12(7). <http://iopscience.iop.org/article/10.1088/1748-9326/aa75d1> (Accessed on 19 may 2018).

Thornley, J.H.M. and France, J. (2007) *Mathematical Models in Agriculture: Quantitative Methods for the Plant, Animal and Ecological Sciences*, CABI Pub. ISBN: 9780851990101

Tilley, E. (2014) *Compendium of sanitation systems and technologies*, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf.

Tsiknia, M., Tzanakakis, V.A., Oikonomidis, D., Paranychianakis, N.V. and Nikolaidis, N.P. (2014) Effects of olive mill wastewater on soil carbon and nitrogen cycling. *Applied Microbiology and Biotechnology* 98(6), 2739-2749. <https://doi.org/10.1007/s00253-013-5272-4>

United Nations Department of Economic and Social Affairs Population Division (2014) *World Urbanization Prospects: The 2014 Revision*. ISBN 978-92-1-151517-6

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

Uzen, N., Cetin, O. and Unlu, M. (2016) Effects of domestic wastewater treated by anaerobic stabilization on soil pollution, plant nutrition, and cotton crop yield. *Environmental Monitoring and Assessment* 188(12), 664. <https://doi.org/10.1007/s10661-016-5680-x>

van Asten, P., Gold, C., Wendt, J., De Waele, D., Okech, S., Ssali, H. and Tushmereirwe, W. (2003) The contribution of soil quality to yield and its relationship with other factors in Uganda. Blomme, G., Gold, C. and Karamura, E. (eds), pp. 100 - 115, *International Network for the Improvement of Banana and Plantain Seeta*, Uganda. [https://www.biodiversityinternational.org/uploads/tx\\_news/Farmer-participatory\\_testing\\_of\\_integrated\\_pest\\_management\\_options\\_for\\_sustainable\\_banana\\_production\\_in\\_Eastern\\_Africa\\_1377.pdf](https://www.biodiversityinternational.org/uploads/tx_news/Farmer-participatory_testing_of_integrated_pest_management_options_for_sustainable_banana_production_in_Eastern_Africa_1377.pdf) (Accessed on 10 January 2018).

van der Laan, M. (2009) *Development, testing and application of a crop nitrogen and phosphorus model to investigate leaching losses at the local scale*. Thesis, University of Pretoria, Pretoria, South Africa., <http://hdl.handle.net/2263/25253>

van der Laan, M., Annandale, J.G., Bristow, K.L., Stirzaker, R.J., Preez, C.C.d. and Thorburn, P.J. (2014) Modelling nitrogen leaching: Are we getting the right answer for the right reason? *Agricultural Water Management* 133, 74-80. <http://dx.doi.org/10.1016/j.agwat.2013.10.017>

van der Laan, M., Stirzaker, R.J., Annandale, J.G., Bristow, K.L. and Preez, C.C.d. (2010) Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses. *Agricultural Water Management* 97(11), 1779-1786. <http://dx.doi.org/10.1016/j.agwat.2010.06.012>

Vazquez-Montiel, O., Horan, N.J. and Mara, D.D. (1996) Management of domestic wastewater for reuse in irrigation. *Water Science and Technology* 33(10), 355-362. [https://doi.org/10.1016/0273-1223\(96\)00438-6](https://doi.org/10.1016/0273-1223(96)00438-6)

Vogeler, I. (2009) Effect of Long-term Wastewater Application on Physical Soil Properties. *Water, Air, and Soil Pollution* 196(1), 385-392. <https://doi.org/10.1007/s11270-008-9785-x>

Vymazal, J. (2007) Removal of nutrients in various types of constructed wetlands. *Science of The Total Environment* 380(1), 48-65. <https://doi.org/10.1016/j.scitotenv.2006.09.014>

Wang, J., Lü, G., Guo, X., Wang, Y., Ding, S. and Wang, D. (2015) Conservation tillage and optimized fertilization reduce winter runoff losses of nitrogen and phosphorus from farmland in the Chaohu Lake region, China. *Nutrient Cycling in Agroecosystems* 101(1), 93-106. <https://doi.org/10.1007/s10705-014-9664-3>

WHO (2006) Guidelines for the safe use of wastewater, excreta and greywater: Excreta and greywater use in agriculture, p. 191, Geneva, Switzerland. ISBN: 9789241546829

WHO (2009) Ecosan Expert Training Course for the Introduction of Ecological Sanitation in Bhutan: Training Course Report. Organisation, W.H. (ed), p. 188, Geneva, Switzerland. [http://www.sswm.info/sites/default/files/reference\\_attachments/WHO%202009%20Ecosan%20Expert%20Training%20Course%20for%20the%20Introduction%20of%20Ecological%20Sanitation%20in%20Bhutan.pdf](http://www.sswm.info/sites/default/files/reference_attachments/WHO%202009%20Ecosan%20Expert%20Training%20Course%20for%20the%20Introduction%20of%20Ecological%20Sanitation%20in%20Bhutan.pdf) (Accessed on 10 January 2018).

WHO (2016) Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta, World Health Organisation, Geneva, Switzerland. [http://apps.who.int/iris/bitstream/10665/171753/1/9789241549240\\_eng.pdf](http://apps.who.int/iris/bitstream/10665/171753/1/9789241549240_eng.pdf)

Winkler, M., Jackson, D., Sutherland, D., P., Lim, J., Srikantaiah, V., Fuhrmann, S. and Medlicott, K. (2017) Sanitation safety planning as a tool for achieving safely managed sanitation systems and safe use of wastewater. *WHO South-East Asia Journal of Public Health* 6(2), 34-40. Doi: 10.4103/2224-3151.213790

WRC (2014) DEWATS process for Decentralised wastewater treatment: Technical Lessons From eThekweni Municipality, Gezina, South Africa.

WWAP (2017) The United Nations World Water Development Report 2017, p. 198, Paris, France. ISBN: 978-92-3-100201-4

WWF-SA (2016) Water: Facts and Futures Kim, W. and Sue, R. (eds), Cape Town, South Africa. [http://awsassets.wwf.org.za/downloads/wwf009\\_waterfactsandfutures\\_report\\_web\\_lowres\\_.pdf](http://awsassets.wwf.org.za/downloads/wwf009_waterfactsandfutures_report_web_lowres_.pdf) (Accessed on 19 May 2018).

Xu, J., Wu, L., Chang, A.C. and Zhang, Y. (2010) Impact of long-term reclaimed wastewater irrigation on agricultural soils: A preliminary assessment. *Journal of Hazardous Materials* 183(1), 780-786. <https://doi.org/10.1016/j.jhazmat.2010.07.094>

Yadav, R.K., Goyal, B., Sharma, R.K., Dubey, S.K. and Minhas, P.S. (2002) Post-irrigation impact of domestic sewage effluent on composition of soils, crops and ground water—A case study. *Environment International* 28(6), 481-486. [http://dx.doi.org/10.1016/S0160-4120\(02\)00070-3](http://dx.doi.org/10.1016/S0160-4120(02)00070-3)

Zdenek, F. and Demnerova, K. (2007) Wastewater Reuse–Risk Assessment, Decision-Making and Environmental Security. Zaidi, M.K. (ed), pp. 331-336, Springer Netherlands, Dordrecht. [https://doi.org/10.1007/978-1-4020-6027-4\\_33](https://doi.org/10.1007/978-1-4020-6027-4_33)

Zhang, J., Varco, J.J. and Adeli, A. (2017) Short-term and seasonal soil nitrogen dynamics and recovery by bermudagrass irrigated with <sup>15</sup>N labelled swine lagoon effluent. *Plant and Soil* 410(1), 437-451. <https://doi.org/10.1007/s11104-016-3041-8>

Zohar, I., Shaviv, A., Young, M., Kendall, C., Silva, S. and Paytan, A. (2010) Phosphorus dynamics in soils irrigated with reclaimed waste water or fresh water - A study using oxygen isotopic composition of phosphate. *Geoderma* 159(1-2), 109-121. Doi: 10.1016/j.geoderma.2010.07.002

## APPENDICES

### *Appendix 1: Sensors connected to the weather station.*

<b>Weather parameters</b>	<b>Sensor</b>	<b>Manufacturer</b>
Air temperature and relative humidity	CS 215-L temperature and relative humidity probes	Campbell Scientific Inc., Utah, USA
Barometric pressure	CS 100 barometric pressure sensor	Campbell Scientific Inc., Utah, USA
Evaporation	255-100 evaporation gauges	NovaLynx, USA
Plant canopy temperature	SI-111-PW infrared radiometers	Campbell Scientific Inc., Utah, USA
Precipitation	TE525WS-L rain gauge with 20 cm orifice	Texas Electronic Inc., Dallas, USA
<b>Soil:</b>		
Moisture content (volumetric)		
Electrical conductivity	CS 650 soil moisture reflectometers	Campbell Scientific Inc., Utah, USA
Temperature		
Solar radiation	CS 300-L pyranometer	Apogee Instruments, USA
Wind direction	024A-L wind direction sensor	Met One, USA
Wind speed	014A-1 3 wind sentry anemometer	Met One, USA

Appendix 2: Newlands-Mashu weather station information used to create the simulated weather station for the Soil Water Balance model.

**Edit** ✕

Station id	Description	Ref no		
<input type="text" value="337"/>	<input type="text" value="Newlands KwaMashu weather"/>	<input type="text"/>		
Latitude	Longitude	Altitude (m)	South/North	U height (m)
<input type="text" value="29.27"/>	<input type="text" value="30.95"/>	<input type="text" value="14"/>	<input type="text" value="North"/> ▾	<input type="text" value="2"/>
City	Region	Image id		
<input type="text" value="DURBAN NORTH"/> ▾	<input type="text" value="KWAZULU NATAL"/> ▾	<input type="text"/>		
Import ID				
<input type="text"/>				
<input type="button" value="Update"/>		<input type="button" value="Cancel"/>		

Daily weather data															
<span>+</span> <span>✎</span> <span>✖</span> <span>🖨</span> <span>🔍</span> <span>📊</span> <span>📁</span> <span>📤</span> <span>✓</span> <span>📈</span> <span>🔧</span> Insert Edit Delete Print Show all Calc Import Export Verify Graphs Generate															
Station	Newlands KwaMashu wea  From date 13/11/2013  To date 02/02/2017  Filter on notes <input type="checkbox"/>														
Station id	Date	Precip (mm)	T min (°C)	T max (°C)	Solar (MJ/m <sup>2</sup> )	U (m/s)	VP (kPa)	RH min (%)	RH max (%)	T dry (°C)	T wet (°C)	VPD (kPa)	ETo (mm)	DOY	Note
337	13.11.2013	0.3	17.3	29.0		0.6		59	98			0.8	2.3		
337	14.11.2013	0.0	19.9	30.3		0.7		56	97			1.0	2.1		
337	15.11.2013	2.3	20.9	32.5		0.8		55	98			1.1	2.4		

U is the wind speed; VP is the vapour pressure; RH is the relative humidity; T is the temperature, ETo is the reference evapotranspiration; DOY is the day of the year.

*Appendix 3: Banana crop specific parameters included in the SWB-Sci model based on measured and literature data.*

### Banana thermal time requirements

The growth model uses a thermal time approach (Monteith and Moss 1977) to determine crop growth and development stages. The growing degree days are calculated from the onset of crop growth and they are accumulated as the crop grows over time ( $\Delta t$ ) as calculated by Equation 3.11.

$$GDD_i = \sum (T_{avg} - T_{base}) * \Delta t \quad \text{Equation 3.11}$$

Where:  $GDD_i$  is the growing day degrees increment for the entire growing period;  $T_{avg}$  is the average daily temperature ( $^{\circ}C$ );  $T_{base}$  is the minimum temperature required for banana growth;

When  $T_{avg}$  is below the cut-off temperature, the  $GDD_i$  is set to zero.

### Dry weight ratio (DWR)

The relationship between transpiration limited growth and dry matter production can be calculated as the ratio of dry mass (DM in  $kg\ m^{-2}$ ) corrected for the vapour pressure deficit (VPD in Pa) (Sinclair et al. 1984) and transpiration. The DWR was therefore determined following Equation 3.13.

$$DWR = \frac{DM * VPD}{ET} \quad \text{Equation 3.13}$$

Where: ET is total evapotranspiration (mm).

Banana total dry mass ( $kg\ m^{-2}$ ) was measured after crop harvest. However, the dry mass partitioned to roots could not be accounted for since only above ground material was harvested. Therefore, total dry mass was estimated according to Nyombi et al. (2009) using Equation 3.14.

$$Y = ce^{ax} \quad \text{Equation 3.14}$$

Where: Y is total dry biomass ( $kg\ m^{-2}$ ) at harvest including root, stem, bunch and leaves; c (0.066) and a (0.085) are constants; e is the exponential function; x is the variable stem girth (cm). The variable stem girth must be expressed in centimetres as recommended by Nyombi et al. (2009).

The vapour pressure deficit (kPa) used to determine the DWR was calculated using the SWB-Sci weather unit (Equation 3.15) from the Food and Agriculture Organisation (Smith 1992).



$$VPD = \frac{[(e_{sTmax} + e_{sTmin})]}{2 - e_a} \quad \text{Equation 3.15}$$

Where:  $e_{sTmax}$  is the saturated vapour pressure (kPa) at maximum air temperature;  $e_{sTmin}$  is the saturated vapour pressure (kPa) at minimum temperature;  $e_a$  is the actual vapour pressure (kPa).

Water loss through soil evaporation cannot be related to crop physiology although dry mass is related to evapotranspiration (Jovanovic et al. 2000). Evapotranspiration (mm) was determined as a product of the reference evapotranspiration (ET<sub>o</sub>) and crop factors (FAO 2015).

#### Dry mass accumulation

Total dry matter for recalcitrant seed at emergence is equivalent to seed mass but in the present study banana plants were planted as suckers, hence sucker dry mass was measured. The root dry matter at emergence was estimated from Equation 3.16.

$$RDM = \frac{fr * TDM}{1 - fr} \quad \text{Equation 3.16}$$

Where:  $fr$  is the partitioning fraction to root biomass;  $RDM$  is the root dry mass (kg m<sup>-2</sup>).

#### Canopy extinction coefficient

The SWB-Sci can separate water loss through transpiration and evaporation. The transmission of light through the canopy follows Bouguer's law (Campbell and Van Evert 1994). Fractional interception of radiation through the canopy can be determined from Equations 3.17 and 3.18.

$$FI_{transpiration} = 1 - e^{(-K_{PAR} * LAI)} \quad \text{Equation 3.17}$$

$$FI_{transpiration} = 1 - e^{[-K_{PAR}(y LAI)]} \quad \text{Equation 3.18}$$

Where:  $K_{PAR}$  is the canopy solar extinction coefficient for photosynthetically active radiation;  $LAI$  is the leaf area index;  $y LAI$  is the leaf area index of the senesced leaves.

The  $LAI$  is the total area covered by leaves per unit area (m<sup>2</sup> leaf area m<sup>-2</sup> land area) and for the banana crop it was measured according to Equation 3.1

#### Dry matter accumulation under radiation limited conditions

Under radiation limited conditions dry matter increment (DM<sub>i</sub>) was calculated from Equation 3.18 according to Monteith and Moss (1977).

$$DM_i = E_c * T_f * FI_{transpiration} * R_s \quad \text{Equation 3.19}$$

Where:  $E_c$  is the radiation use efficiency ( $\text{kg MJ}^{-1}$ ). However, in this study it was measured using the total dry mass ( $\text{kg m}^{-2}$ ) per total solar radiation received as recorded by the on-site weather station. The  $R_s$  denotes solar radiation ( $\text{MJ m}^{-2}$ ) for a day and  $T_f$  is the temperature factor for radiation limited growth and was determined from Equation 3.20.

$$T_f = \frac{T_{av} - T_b}{T_{lo} - T_b} \quad \text{Equation 3.20}$$

Where:  $T_{av}$  is the average daily temperature ( $^{\circ}\text{C}$ );  $T_{lo}$  is the banana optimum temperature for light limited growth;  $T_b$  is the base temperature.

### Root growth rate

Root growth rate (RGR) was calculated from Equation 3.18. The maximum rooting depth (RD) was adopted from FAO (2015). Since banana was not destructively harvested the root dry mass (RDM) was derived from allometric equations given by Nyombi et al. (2009) (Equation 3.21).

$$RD = RGR * RDM^{0.5} \quad \text{Equation 3.21}$$

$$Y = c (x)^a \quad \text{Equation 3.22}$$

where: RDM is the root dry mass ( $\text{m}^2\text{kg}^{-0.5}$ ); Y is the RDM ( $\text{kg m}^{-2}$ ); c ( $1 * 10^{-4}$ ) and a (1.863) are constants; x is the variable banana stem girth (cm) at harvest. Nyombi et al. (2009) developed different equations for different parts of the banana plant at different growth stages hence Equation 3.22 differed from Equation 3.14.

Parameter	Value	Source
Canopy solar extinction coefficient for PAR		
( $K_{PAR}$ )	0.7	(Nyombi et al. 2009)
DWR (Pa)	2.1	Measured
Radiation use efficiency ( $kg MJ^{-1}$ )	0.0015	Measured
Base temperature ( $^{\circ}C$ )	12.5	(Chaves et al. 2009)
Optimum temperature ( $^{\circ}C$ )	25	(Chaves et al. 2009)
Cut off temperature ( $^{\circ}C$ )	38	(Chaves et al. 2009)
Emergence (day degrees)	0	Measured
Flowering (day degrees)	2568	Measured
Maturity (day degrees)	4950	Measured
Transition (day degrees)	260	Measured
Leaf senescence (day degrees)	3189	Measured
Maximum height (m)	2	Measured
Maximum root depth (m)	0.8	(FAO 2015)
Stem to grain translocation	0.5	Measured
Minimum leaf water potential (kPa)	-1 500	(Robinson and Bower 1988)
Maximum transpiration ( $mm day^{-1}$ )	6	(FAO 2015, Freitas et al. 2008)
Specific leaf area ( $m^2 kg^{-1}$ )	12	Measured
Leaf stem partitioning ( $m^2 kg^{-1}$ )	2	Measured
Total dry matter at emergence ( $kg m^{-2}$ )	0.0130	Estimated (Nyombi et al., 2009)
Root fraction	0.05	Estimated (Nyombi et al., 2009)
Root growth rate ( $m^2 / \sqrt{(kg)}$ )	3.1	Measured
Stress index	0.95	(Steduto et al. 2012)
Depletion allowed		
(Initial, Development, Mid-season, Late season)	35 %	(FAO 2015)

\* PAR is the, \*\*DWR is the

*Appendix 4: Nitrogen (N) and phosphorus (P) uptake crop parameters for banana.*

<b>Parameter</b>	<b>Value</b>	<b>Source</b>
N Fixation	No	
Grain N partitioning coefficient	0.4	(van Asten et al. 2003)
Photoperiod sensitivity	No	(Robinson and Saúco 2010)
Critical photoperiod	n/a	
Photoperiod parameter	n/a	
N: P ratio	5	
Root N concentration (kg N kg <sup>-1</sup> DM)	0.0108	(Ahumuza et al. 2015)
Maximum fruit N concentrations (kg N kg <sup>-1</sup> DM)	0.2075	(Ahumuza et al. 2015)
Slope	-0.405	
C3 or C4	C3	(Robinson and Alberts 1986)
Increased root active biomass (kg m <sup>-2</sup> )	0.05	(Nyombi et al. 2009)
Optimal P concentration (Emergence) (kg P kg <sup>-1</sup> DM)	0.00297	Measured
Optimal P concentration (Vegetative) (kg P kg <sup>-1</sup> DM)	0.003	Measured
Optimal P concentration (Reproductive) (kg P kg <sup>-1</sup> DM)	0.00245	Measured

DM is the dry mass.

Appendix 5: Soil physical properties used in the Soil Water Balance model.

Edit

Field: BANANA2014 Texture: Clay Loam

Runoff No: 100 Psi FC (kPa): -30 Psi PWP (kPa): -1500 Drain Factor: 0.50 Drain rate (mm/day): 19 Root depth limit (m): 1.00 Run off area: 0.00 Run on area: 0.00

Update Cancel

Soil profiles

Insert Edit Delete Find Print Copy Assign Texture Images N & P

Profile Detail

Field	Layer no	Z (m)	FC (m/m)	Initial WC (m/m)	PWP (m/m)	M-line (m/m)	BD (Mg/m <sup>3</sup> )
BANANA2014	1	0.085	0.402	0.402	0.286		1.348
BANANA2014	2	0.170	0.402	0.402	0.286		1.348
BANANA2014	3	0.255	0.402	0.402	0.286		1.348
BANANA2014	4	0.340	0.405	0.405	0.289		1.390
BANANA2014	5	0.500	0.405	0.405	0.289		1.390
BANANA2014	6	0.600	0.405	0.405	0.289		1.390
BANANA2014	7	0.700	0.428	0.428	0.313		1.350
BANANA2014	8	0.800	0.428	0.428	0.313		1.350
BANANA2014	9	0.900	0.428	0.428	0.313		1.350
BANANA2014	10	0.950	0.428	0.428	0.313		1.350
BANANA2014	11	1.000	0.428	0.428	0.313		1.350

FC is the field capacity, PWP is the permanent wilting point, BD is the bulk density, Z is the soil depth.

Appendix 6: Field management practices for the Soil Water Balance model.

Edit
✕

Field	<input type="text" value="BANANA2014"/>	Address ref no	<input type="text" value=""/>		
Sluice no	<input type="text" value=""/>	Water balance	<input type="text" value="Cascading"/>		
Field description	<input type="text" value="Sepane"/>				
Group	<input type="text" value="Group 3"/>	2D setup	<input type="text" value=""/>		
Schedule	<input type="text" value="Yes"/>	Irrigation system	<input type="text" value="Drip"/>		
Model	<input type="text" value="Growth"/>	Emitter delivery (l/h)	<input type="text" value="2.00"/>		
Crop	<input type="text" value="BANANA, I YEAR"/>	Lateral spacing (m)	<input type="text" value="3.00"/>		
Plant date	<input type="text" value="13/11/2013"/>	Emitter spacing (m)	<input type="text" value="1.50"/>		<span style="color: blue;">(DOY: 317)</span>
Start date	<input type="text" value="13/11/2013"/>	Wetted diameter (m)	<input type="text" value="0.40"/>		<span style="color: blue;">(DOY: 317)</span>
Field size (ha)	<input type="text" value="1.0"/>	Root fraction	<input type="text" value="1.00"/>		
Weather ID	<input type="text" value="Newlands mashu 2"/>	Irrigation capture	<input type="text" value="mm"/>		
Irrigation timing	<input type="text" value="Depletion (%)"/>	System efficiency (%)	<input type="text" value="95.0"/>		
Manage	<input type="text" value="Root zone"/>	Storage efficiency (%)	<input type="text" value="100.0"/>		

✓ Update

✕ Cancel

Appendix 7: Initial soil nitrogen (N) and phosphorus (P) parameters for the SWB-Sci model.

Parameter	Value	Source
Standing stubble mass (kg ha <sup>-1</sup> )	1	Measured
Surface mass (kg ha <sup>-1</sup> )	1	Measured
Bypass coefficient	0.6	Measured
Annual average air temp. (°C)	21.1	Measured
Half annual temperature amplitude (days)	170	Measured
Cultivation depth (m)	0	Measured
Soil group	Slightly weathered	
Soil P test type	Ambic	
Initial C fraction to microbial biomass (≤ 0.3 m)	0.03	Default
(> 0.3 m)	0.005	Default
Initial C fraction to active labile SOM* (≤ 0.3 m)	0.02	Default
(> 0.3 m)	0.000	Default
Initial C fraction to active metastable SOM (≤ 0.3 m)	0.450	Default
(> 0.3 m)	0.014	Default
Initial C fraction to passive SOM (≤ 0.3 m)	0.5	Default
(> 0.3 m)	0.985	Default

SOM-Soil organic matter

*Appendix 8: Land area calculations for three different soils*

Land area

$$A = \frac{P}{E_{t_{\text{crop}}}} \quad \text{Equation 3.23}$$

Whereby A = land area (m<sup>2</sup>); P = annual DEWATS effluent production (ML); E<sub>t<sub>crop</sub></sub> = Crop water requirements (ML m<sup>-2</sup> year<sup>-1</sup>).

Land area per household / per person

$$AH = \frac{A}{H} \quad \text{Equation 3.24}$$

$$AC = \frac{AH}{C} \quad \text{Equation 3.25}$$

Whereby AH = land area required per household (m<sup>2</sup>); H = number of households and there are 83 households; AC = land area required per person (m<sup>2</sup>); C = number of people per household.

Metric conversions

$$1 \text{ mm} = 1 \text{ L m}^{-2}$$

$$1 \text{ ML} = 1\,000 \text{ m}^3 = 1\,000\,000 \text{ L}$$

$$1 \text{ ha} = 10\,000 \text{ m}^2$$

Whereby L = litre; m<sup>3</sup> = cubic metre; ML = megalitre; ha = hectare; m<sup>2</sup> = square metre



*Appendix 9: Mean squares for inorganic N and P in perched water table and WFD samples collected during the field study period.*

<b>Source of variation</b>	<b>Degrees of freedom</b>	<b>Missing values</b>	<b>Total inorganic N (mg L<sup>-1</sup>)</b>	<b>NH<sub>4</sub><sup>+</sup>-N (mg L<sup>-1</sup>)</b>	<b>NO<sub>3</sub><sup>-</sup>-N (mg L<sup>-1</sup>)</b>		<b>PO<sub>4</sub><sup>3-</sup> (mg L<sup>-1</sup>)</b>
Treatment	4		3160	216	3125	**	114
Residual	84	-13	1800	101	847		57
Total	88	-13					

*Appendix 10: Irrigation data at Newlands-Mashu field experiment for the period June 2014 to July 2016.*

**Irrigation information for taro and banana**

<b>Month-year</b>	<b>Days irrigated</b>	<b>Irrigation per plant (L)</b>	<b>Taro irrigation (mm)</b>	<b>Banana irrigation (mm)</b>	<b>Banana / taro irrigation (mm)</b>
<b>Season 1</b>					
<b>Jun-14</b>	12	96	45	21	66
<b>Jul-14</b>	31	248	116	55	171
<b>Aug-14</b>	30	240	112	53	165
<b>Sep-14</b>	30	240	112	53	165
<b>Oct-14</b>	30	240	112	53	165
<b>Nov-14</b>	20	160	70	36	106
<b>Dec-14</b>	26	208	97	46	143
<b>Jan-15</b>	12	96	45	21	66
<b>Feb-15</b>	0	0	0	0	0
<b>Mar-15</b>	10	80	37	18	55
<b>Apr-15</b>	5	40	19	9	28
<b>Total</b>	206	1 648	765	365	1 130
<b>Season 2</b>					
<b>May-15</b>	0	0	0	0	0
<b>Jun-15</b>	0	0	0	0	0
<b>Jul-15</b>	10	80	37	18	55
<b>Aug-15</b>	18	144	67	32	99
<b>Sep-15</b>	16	128	60	28	88
<b>Oct-15</b>	12	96	45	21	66
<b>Nov-15</b>	13	104	49	23	72
<b>Dec-15</b>	10	80	37	18	55
<b>Jan-16</b>	0	0	0	0	0
<b>Feb-16</b>	10	19	9	4	13
<b>Mar-16</b>	23	88	41	23	64
<b>Apr-16</b>	24	103	48	23	71
<b>May-16</b>	25	105	49	23	72
<b>Jun-16</b>	30	1 073	501	239	740
<b>Jul-16</b>	17	358	167	80	247
<b>Total</b>	208	2 378	1 110	532	1 642

## Water balance data

<b>Month-Year</b>	<b>Et<sub>crop</sub> (mm)</b>	<b>Rainfall (mm)</b>	<b>Deficit (mm)</b>	<b>Irrigation applied (mm)</b>	<b>Surplus (mm)</b>
Jun-14	85.1	1.8	83.3	66.1	-17.1
Jul-14	99.8	2.5	97.2	170.8	73.6
Aug-14	131.9	13.2	118.7	165.3	46.7
Sep-14	177.1	25.7	151.4	165.3	13.9
Oct-14	173.5	77.7	95.8	165.3	69.6
Nov-14	177.9	46.0	132.0	110.2	-21.7
Dec-14	222.3	65.0	157.3	143.2	-14.0
Jan-15	240.6	74.7	166.0	66.1	-99.9
Feb-15	189.8	111.0	78.8	0	-78.8
Mar-15	182.8	76.2	106.6	55.1	-51.5
Apr-15	133.7	10.9	122.8	27.6	-95.2
May-15	135.6	0	135.6	0	-135.6
Jun-15	38.6	2.0	36.5	0	-36.5
Jul-15	42.7	85.6	-42.9	55.1	98.0
Aug-15	140.4	4.1	136.3	99.2	-37.1
Sep-15	135.1	35.1	100.0	88.2	-11.8
Oct-15	227.8	30.5	197.3	66.1	-131.2
Nov-15	214.9	96.2	118.6	71.6	-47.
Dec-15	238.8	110.7	128.0	55.1	-72.9
Jan-16	259.6	141.7	117.8	0	-117.8
Feb-16	219.5	58.4	161.0	13.1	-148.0
Mar-16	188.1	103.6	84.5	60.9	-23.6
Apr-16	136.2	11.7	124.5	70.8	-53.7
May-16	403.1	218.2	184.9	72.7	-112.3
Jun-16	93.7	4.6	89.1	739.8	650.7
Jul-16	99.3	267.5	-168.2	246.6	414.8

Appendix 11: Field studies raw data.

**AF effluent characteristics**

Date	NO <sub>3</sub> -N	NH <sub>4</sub> <sup>+</sup> -N	PO <sub>4</sub> <sup>3-</sup> -P	Mineral N	Total N		
					Sample 1	Sample 2	Sample 3
	(mg L <sup>-1</sup> )						
2-Oct-14	0.2	55.6	10.2	55.8			
15-Dec-14	3.1	50.3	7.9	53.4			
2-Feb-15	1.2	59.6	19.5	60.8			
28-Jul-15	3.6	56.9	7.2	60.5			
30-Sep-15	1.8	52.1	8.4	53.9			
31-Dec-15	2.6	59.9	15.8	62.5			
16-Mar-16	4.1	48.1	10.6	52.2	51.2	79.2	64.7
9-Sep-16	0.6	50.6	5.9	51.2	54.6	53.9	62.5
7-Mar-17	1.7	60.1	8.7	61.8	58.7	59.8	60.4

**Leachates**

Date	Days after planting	Block	Depth	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> <sup>+</sup> -N	Total N	PO <sub>4</sub> <sup>3-</sup> -P
2014/09/03	295	1	0.3 m	DEWATS	34.4	1.6	36.0	0.0
2014/09/03	295	2	0.3 m	DEWATS		1.6	1.6	0.0
2014/09/03	295	3	0.3 m	DEWATS	114.6	0.8	115.4	1.4
2014/09/23	315	1	0.3 m	DEWATS	21.9	0.9	22.8	0.0
2014/09/23	315	2	0.3 m	DEWATS	54.4	0.9	55.3	0.0
2014/09/23	315	3	0.3 m	DEWATS	6.3	1.1	7.4	0.0
2014/09/29	321	1	0.3 m	DEWATS	2.0	0.5	2.5	0.2
2014/09/29	321	2	0.3 m	DEWATS	47.4	0.6	48.0	0.0
2014/09/29	321	3	0.3 m	DEWATS	25.4	0.9	26.3	0.1
2014/10/02	324	1	0.3 m	DEWATS	11.7	1.4	13.1	1.3
2014/10/02	324	2	0.3 m	DEWATS	17.9	0.8	18.7	0.4
2014/10/02	324	3	0.3 m	DEWATS	7.8	0.7	8.5	1.0
2014/10/09	331	1	0.3 m	DEWATS	8.9	1.1	10.0	2.0
2014/10/09	331	2	0.3 m	DEWATS	1.8	1.3	3.1	0.1
2014/10/09	331	3	0.3 m	DEWATS	5.9	0.5	6.4	1.5
2014/10/27	349	1	0.3 m	DEWATS	8.4	0.7	9.1	4.6
2014/10/27	349	2	0.3 m	DEWATS	9.4	0.1	9.5	2.3
2014/10/27	349	3	0.3 m	DEWATS	0.6	0.2	0.8	3.1
2014/12/15	398	1	0.3 m	DEWATS	8.0	1.0	9.0	3.8
2014/12/15	398	2	0.3 m	DEWATS	1.7	1.3	3.0	2.2
2014/12/15	398	3	0.3 m	DEWATS	5.2	0.2	5.4	6.3
2014/12/31	414	1	0.3 m	DEWATS	1.5	0.3	1.8	
2014/12/31	414	2	0.3 m	DEWATS	1.3	0.1	1.4	9.0
2014/12/31	414	3	0.3 m	DEWATS	5.4	2.3	7.7	1.0
2015/02/02	447	1	0.3 m	DEWATS	6.8	5.2	12.0	2.8
2015/02/02	447	2	0.3 m	DEWATS				
2015/02/02	447	3	0.3 m	DEWATS	9.7	7.3	17.0	6.3
2015/10/15	702	1	0.3 m	DEWATS	9.0	1.8	10.8	14.8
2015/10/15	702	2	0.3 m	DEWATS	3.1	1.8	4.9	10.5
2015/10/15	702	3	0.3 m	DEWATS	5.6	1.8	7.4	13.5
2015/12/15	763	1	0.3 m	DEWATS	3.7	0.7	4.4	14.2
2015/12/15	763	2	0.3 m	DEWATS	4.6	1.2	5.8	22.4
2015/12/15	763	3	0.3 m	DEWATS	7.1	1.5	8.6	11.1
2016/03/14	853	1	0.3 m	DEWATS	13.5	5.4	18.9	7.4
2016/03/14	853	2	0.3 m	DEWATS	10.9	0.5	11.4	3.2
2016/03/14	853	3	0.3 m	DEWATS	11.9	0.5	12.4	6.5
2016/04/29	899	1	0.3 m	DEWATS				
2016/04/29	899	2	0.3 m	DEWATS	13.6	12.0	25.6	1.3
2016/04/29	899	3	0.3 m	DEWATS	24.2	11.0	35.2	2.7
2016/07/19	980	1	0.3 m	DEWATS	192.0	7.8	199.8	4.4
2016/07/19	980	2	0.3 m	DEWATS	12.0	2.7	14.7	2.0
2016/07/19	980	3	0.3 m	DEWATS	30.3	1.7	32.0	3.0
2016/08/08	992	1	0.3 m	DEWATS	478.5	0.1	478.6	2.4
2016/08/08	992	2	0.3 m	DEWATS	10.0	0.1	10.1	2.2
2016/08/08	992	3	0.3 m	DEWATS				
2014/09/03	295	1	0.5 m	DEWATS	18.7	1.6	20.3	0.1

2014/09/03	295	2	0.5 m	DEWATS	114.6	1.7	116.3	0.0
2014/09/03	295	3	0.5 m	DEWATS	114.6	1.4	116.0	0.1
2014/09/23	315	1	0.5 m	DEWATS	2.2	1.1	3.3	0.0
2014/09/23	315	2	0.5 m	DEWATS	33.0	1.1	34.1	0.0
2014/09/23	315	3	0.5 m	DEWATS	9.6	1.7	11.3	0.0
2014/09/29	321	1	0.5 m	DEWATS	1.6	0.9	2.5	0.0
2014/09/29	321	2	0.5 m	DEWATS	45.7	1.0	46.7	0.1
2014/09/29	321	3	0.5 m	DEWATS	5.3	0.7	6.0	0.0
2014/10/02	324	1	0.5 m	DEWATS	8.5	0.9	9.4	0.0
2014/10/02	324	2	0.5 m	DEWATS	3.2	0.8	4.0	0.0
2014/10/02	324	3	0.5 m	DEWATS				0.0
2014/10/09	331	1	0.5 m	DEWATS	5.3	0.9	6.2	0.0
2014/10/09	331	2	0.5 m	DEWATS	1.3	1.2	2.5	0.0
2014/10/09	331	3	0.5 m	DEWATS	2.2	0.4	2.6	0.0
2014/10/27	349	1	0.5 m	DEWATS	5.0	0.4	5.3	3.0
2014/10/27	349	2	0.5 m	DEWATS	3.1	1.0	4.0	5.4
2014/10/27	349	3	0.5 m	DEWATS	12.6	6.2	18.8	1.5
2014/12/15	398	1	0.5 m	DEWATS	1.9	0.1	2.0	2.0
2014/12/15	398	2	0.5 m	DEWATS	5.7	0.2	5.9	3.2
2014/12/15	398	3	0.5 m	DEWATS	8.5	0.1	8.6	1.2
2014/12/31	414	1	0.5 m	DEWATS	6.9	0.1	7.0	10.0
2014/12/31	414	2	0.5 m	DEWATS	5.0	0.1	5.1	
2014/12/31	414	3	0.5 m	DEWATS	6.0		6.0	
2015/02/02	447	1	0.5 m	DEWATS	2.2	3.9	6.1	2.5
2015/02/02	447	2	0.5 m	DEWATS	2.9	7.0	9.9	2.1
2015/02/02	447	3	0.5 m	DEWATS	2.1	5.8	7.9	12.9
2015/10/15	702	1	0.5 m	DEWATS	4.2	1.8	6.0	2.9
2015/10/15	702	2	0.5 m	DEWATS	1.8	1.8	3.6	13.5
2015/10/15	702	3	0.5 m	DEWATS	9.5	1.8	11.3	10.8
2015/12/15	763	1	0.5 m	DEWATS	3.6	0.9	4.5	7.9
2015/12/15	763	2	0.5 m	DEWATS	7.0	1.5	8.5	3.3
2015/12/15	763	3	0.5 m	DEWATS	4.4	0.8	5.2	16.0
2016/03/14	853	1	0.5 m	DEWATS	6.2	7.1	13.3	2.4
2016/03/14	853	2	0.5 m	DEWATS	13.5	0.2	13.7	4.3
2016/03/14	853	3	0.5 m	DEWATS	9.8	18.8	28.6	6.5
2016/04/29	899	1	0.5 m	DEWATS	5.5	32.0	37.5	0.6
2016/04/29	899	2	0.5 m	DEWATS	8.9	4.0	12.9	2.3
2016/04/29	899	3	0.5 m	DEWATS	10.4	1.0	11.4	1.4
2016/07/19	980	1	0.5 m	DEWATS	24.5	3.8	28.3	2.0
2016/07/19	980	2	0.5 m	DEWATS	8.4	4.3	12.7	2.9
2016/07/19	980	3	0.5 m	DEWATS	7.8	5.3	13.1	2.9
2016/08/08	992	1	0.5 m	DEWATS	15.0	0.8	15.8	1.9
2016/08/08	992	2	0.5 m	DEWATS	12.7	11.1	23.8	2.0
2016/08/08	992	3	0.5 m	DEWATS	12.5	7.7	20.2	2.7
2014/09/03	295	1	0.3 m	Tap water + fertiliser	4.5	1.3	5.8	0.0
2014/09/03	295	2	0.3 m	Tap water + fertiliser	100.3	6.4	106.7	0.0
2014/09/03	295	3	0.3 m	Tap water + fertiliser	11.1	1.1	12.2	0.0
2014/09/23	315	1	0.3 m	Tap water + fertiliser	3.2	1.5	4.7	0.1
2014/09/23	315	2	0.3 m	Tap water + fertiliser	99.2	0.4	99.6	0.1
2014/09/23	315	3	0.3 m	Tap water + fertiliser	110.9	1.1	112.0	0.6
2014/09/29	321	1	0.3 m	Tap water + fertiliser	58.7	0.7	59.4	0.1
2014/09/29	321	2	0.3 m	Tap water + fertiliser	1.2	0.9	2.1	0.1
2014/09/29	321	3	0.3 m	Tap water + fertiliser	25.8	0.6	26.4	0.1
2014/10/02	324	1	0.3 m	Tap water + fertiliser	3.4	0.8	4.2	1.2
2014/10/02	324	2	0.3 m	Tap water + fertiliser	1.7	1.3	3.0	0.0
2014/10/02	324	3	0.3 m	Tap water + fertiliser	5.9	0.7	6.6	0.4
2014/10/09	331	1	0.3 m	Tap water + fertiliser	24.9	0.9	25.8	0.0
2014/10/09	331	2	0.3 m	Tap water + fertiliser	18.1	0.9	19.0	0.4
2014/10/09	331	3	0.3 m	Tap water + fertiliser	1.6	1.1	2.7	0.7
2014/10/27	349	1	0.3 m	Tap water + fertiliser	7.0	0.1	7.1	2.1
2014/10/27	349	2	0.3 m	Tap water + fertiliser	3.3	0.1	3.4	3.1
2014/10/27	349	3	0.3 m	Tap water + fertiliser	2.4	0.8	3.2	1.4
2014/12/15	398	1	0.3 m	Tap water + fertiliser	3.3	0.1	3.4	4.0
2014/12/15	398	2	0.3 m	Tap water + fertiliser	1.8	0.5	2.3	1.2
2014/12/15	398	3	0.3 m	Tap water + fertiliser	1.8	0.8	2.6	1.1
2014/12/31	414	1	0.3 m	Tap water + fertiliser	1.0	2.3	3.3	16.0
2014/12/31	414	2	0.3 m	Tap water + fertiliser	3.1	0.7	3.8	
2014/12/31	414	3	0.3 m	Tap water + fertiliser	2.7	6.7	9.4	2.2
2015/02/02	447	1	0.3 m	Tap water + fertiliser	5.2	0.5	5.7	3.4
2015/02/02	447	2	0.3 m	Tap water + fertiliser	1.1	1.5	2.6	2.8
2015/02/02	447	3	0.3 m	Tap water + fertiliser	2.0	4.4	6.4	1.3
2015/10/15	702	1	0.3 m	Tap water + fertiliser	3.6	1.8	5.4	6.4
2015/10/15	702	2	0.3 m	Tap water + fertiliser	9.0	1.8	10.8	12.7
2015/10/15	702	3	0.3 m	Tap water + fertiliser	6.5	1.8	8.3	8.4
2015/12/15	763	1	0.3 m	Tap water + fertiliser	5.0	1.0	6.0	4.5
2015/12/15	763	2	0.3 m	Tap water + fertiliser	7.6	0.5	8.0	6.8
2015/12/15	763	3	0.3 m	Tap water + fertiliser	7.2	0.8	8.0	3.1
2016/03/14	853	1	0.3 m	Tap water + fertiliser	14.1	75.0	89.1	34.5
2016/03/14	853	2	0.3 m	Tap water + fertiliser	5.8	3.7	9.5	1.7
2016/03/14	853	3	0.3 m	Tap water + fertiliser	7.3	8.2	15.5	5.0

2016/04/29	899	1	0.3 m	Tap water + fertiliser	161.0		161.0	2.4
2016/04/29	899	2	0.3 m	Tap water + fertiliser	6.0	4.0	10.0	2.0
2016/04/29	899	3	0.3 m	Tap water + fertiliser	12.5	32.0	44.5	1.0
2016/07/19	980	1	0.3 m	Tap water + fertiliser				
2016/07/19	980	2	0.3 m	Tap water + fertiliser				
2016/07/19	980	3	0.3 m	Tap water + fertiliser				
2016/08/08	992	1	0.3 m	Tap water + fertiliser	12.1	0.1	12.2	3.4
2016/08/08	992	2	0.3 m	Tap water + fertiliser	6.8	0.1	6.9	1.7
2016/08/08	992	3	0.3 m	Tap water + fertiliser	4.8	8.4	13.2	4.8
2014/09/03	295	1	0.5 m	Tap water + fertiliser	5.9	1.2	7.1	0.0
2014/09/03	295	2	0.5 m	Tap water + fertiliser	37.6	5.1	42.7	0.1
2014/09/03	295	3	0.5 m	Tap water + fertiliser	73.9	1.9	75.8	0.0
2014/09/23	315	1	0.5 m	Tap water + fertiliser	2.7	0.8	3.5	0.0
2014/09/23	315	2	0.5 m	Tap water + fertiliser	90.0	0.9	90.9	0.0
2014/09/23	315	3	0.5 m	Tap water + fertiliser	15.2	0.9	16.1	0.0
2014/09/29	321	1	0.5 m	Tap water + fertiliser	1.0	1.3	2.3	0.3
2014/09/29	321	2	0.5 m	Tap water + fertiliser	26.9	1.2	28.1	0.0
2014/09/29	321	3	0.5 m	Tap water + fertiliser	11.9	0.9	12.8	0.0
2014/10/02	324	1	0.5 m	Tap water + fertiliser	3.5	0.4	3.9	0.0
2014/10/02	324	2	0.5 m	Tap water + fertiliser	36.7	0.6	37.3	0.0
2014/10/02	324	3	0.5 m	Tap water + fertiliser	25.5	1.7	27.2	0.4
2014/10/09	331	1	0.5 m	Tap water + fertiliser	3.0	0.6	3.6	1.1
2014/10/09	331	2	0.5 m	Tap water + fertiliser	18.9	0.4	19.3	0.2
2014/10/09	331	3	0.5 m	Tap water + fertiliser	63.8	1.8	65.6	0.4
2014/10/27	349	1	0.5 m	Tap water + fertiliser	2.4	0.4	2.8	1.7
2014/10/27	349	2	0.5 m	Tap water + fertiliser	0.5	0.1	0.6	0.6
2014/10/27	349	3	0.5 m	Tap water + fertiliser	10.4	0.1	10.4	2.8
2014/12/15	398	1	0.5 m	Tap water + fertiliser	1.2	0.1	1.3	1.4
2014/12/15	398	2	0.5 m	Tap water + fertiliser	1.7	0.1	1.8	1.6
2014/12/15	398	3	0.5 m	Tap water + fertiliser	1.8	0.6	2.4	2.0
2014/12/31	414	1	0.5 m	Tap water + fertiliser	2.2	5.8	8.0	6.2
2014/12/31	414	2	0.5 m	Tap water + fertiliser	4.5	1.3	5.8	1.8
2014/12/31	414	3	0.5 m	Tap water + fertiliser	5.4	0.6	6.0	7.3
2015/02/02	447	1	0.5 m	Tap water + fertiliser	0.4	1.5	1.9	0.8
2015/02/02	447	2	0.5 m	Tap water + fertiliser	2.6	2.3	4.9	1.3
2015/02/02	447	3	0.5 m	Tap water + fertiliser	3.8	2.9	6.7	2.1
2015/10/15	702	1	0.5 m	Tap water + fertiliser	4.8	1.8	6.6	15.0
2015/10/15	702	2	0.5 m	Tap water + fertiliser	6.4	1.8	8.2	3.8
2015/10/15	702	3	0.5 m	Tap water + fertiliser	3.7	1.8	5.5	7.3
2015/12/15	763	1	0.5 m	Tap water + fertiliser	10.6	2.2	12.8	14.2
2015/12/15	763	2	0.5 m	Tap water + fertiliser	8.0	0.8	8.8	5.1
2015/12/15	763	3	0.5 m	Tap water + fertiliser	8.3	7.3	15.6	3.9
2016/03/14	853	1	0.5 m	Tap water + fertiliser	2.8	16.4	19.2	28.3
2016/03/14	853	2	0.5 m	Tap water + fertiliser	3.3	5.5	8.8	2.0
2016/03/14	853	3	0.5 m	Tap water + fertiliser	6.0	6.7	12.7	2.2
2016/04/29	899	1	0.5 m	Tap water + fertiliser	2.9	21.0	23.9	1.2
2016/04/29	899	2	0.5 m	Tap water + fertiliser	5.0	4.0	9.0	2.3
2016/04/29	899	3	0.5 m	Tap water + fertiliser	13.8	141.0	154.8	0.8
2016/07/19	980	1	0.5 m	Tap water + fertiliser	3.8	2.8	6.6	2.2
2016/07/19	980	2	0.5 m	Tap water + fertiliser	4.3	2.8	7.1	1.3
2016/07/19	980	3	0.5 m	Tap water + fertiliser	8.1	4.0	12.1	1.3
2016/08/08	992	1	0.5 m	Tap water + fertiliser	7.3	0.1	7.4	1.1
2016/08/08	992	2	0.5 m	Tap water + fertiliser	7.3	0.1	7.4	1.3
2016/08/08	992	3	0.5 m	Tap water + fertiliser	4.7	0.8	5.5	2.7

## Groundwater quality

Date	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> <sup>+</sup> -N	Phosphate P
		mg L <sup>-1</sup>		
2014/10/27	P1			
2014/10/27	P2			
2014/10/27	P3	0.4	4.76	0.9
2014/10/27	P4	0.2	6.18	0.5
2014/10/27	P5	0.1	21.4	1.4
2014/10/27	P6			
2014/12/15	P1			
2014/12/15	P2	27.2	2.1	7.6
2014/12/15	P3	0.1	3.5	1.7
2014/12/15	P4	0.1	3.8	10.4
2014/12/15	P5	0.8	4.7	5.4
2014/12/15	P6			
2014/12/31	P1			
2014/12/31	P2	11.35	2.05	4.6
2014/12/31	P3	0.1	2.6	56
2014/12/31	P4	2.4	6.4	10.5
2014/12/31	P5	4.1	1.9	35
2014/12/31	P6			
2015/02/02	P1	8.1	3.4	2.5
2015/02/02	P2	5.1	1.6	2.8
2015/02/02	P3	2.9	3.2	1
2015/02/02	P4	6.2	4	1.5
2015/02/02	P5			
2015/02/02	P6			
2015/10/15	P1	0.2	2.6	3.6
2015/10/15	P2	0.6	75.5	5
2015/10/15	P3	5.6	16.9	3.9
2015/10/15	P4	4.5	5.9	2.9
2015/10/15	P5	7.4	8.3	2.2
2015/10/15	P6			
2015/12/15	P1	1.4	4.5	3.5
2015/12/15	P2	3.4	36.4	14.9
2015/12/15	P3	0.3	5.8	8.4
2015/12/15	P4	0.5	7.2	1.8
2015/12/15	P5	0.5	13.9	2.9
2015/12/15	P6			
2016/03/14	P1	2.1	5.1	4.5
2016/03/14	P2	2.1	7.3	10.9
2016/03/14	P3	1.8	8.9	2.9
2016/03/14	P4	1.5	3.8	21.4
2016/03/14	P5	0.5	11.9	2.4
2016/03/14	P6			

## Groundwater level

Date	Treatment	Water level (m below ground)
2015/12/15	P1	0.8
2015/12/15	P2	0.7
2015/12/15	P3	0.4
2015/12/15	P4	0.42
2015/12/15	P5	0.43
2015/12/15	P6	
2016/03/14	P1	0.8
2016/03/14	P2	0.7
2016/03/14	P3	0.4
2016/03/14	P4	0.42
2016/03/14	P5	0.43
2016/03/14	P6	
2016/07/19	P1	0.4
2016/07/19	P2	0.5
2016/07/19	P3	0.1
2016/07/19	P4	0.12
2016/07/19	P5	0.13
2016/07/19	P6	
2016/08/08	P1	0.81
2016/08/08	P2	0.44
2016/08/08	P3	0.49
2016/08/08	P4	0.53
2016/08/08	P5	0.46
2016/08/09	P6	

## Banana and taro nutrient uptake

Season	Block	Treatment	Crop	N (%)	P (%)
1	1	Tap water + fertiliser	Taro	1.99	0.54
1	2	Tap water + fertiliser	Taro	2.18	0.55
1	3	Tap water + fertiliser	Taro	2.08	0.54
1	1	DEWATS	Taro	2.02	0.54
1	2	DEWATS	Taro	2.35	0.54
1	3	DEWATS	Taro	2.96	0.53
1	1	Tap water + fertiliser	Banana	3.25	0.21
1	2	Tap water + fertiliser	Banana	3.29	0.21
1	3	Tap water + fertiliser	Banana	3.5	0.21
1	1	DEWATS	Banana	3.29	0.2
1	2	DEWATS	Banana	3.4	0.23
1	3	DEWATS	Banana	3.21	0.2
2	1	Tap water + fertiliser	Banana	2.97	0.2
2	2	Tap water + fertiliser	Banana	2.81	0.18
2	3	Tap water + fertiliser	Banana	3.06	0.18
2	1	DEWATS	Banana	3.12	0.17
2	2	DEWATS	Banana	3.7	0.24
2	3	DEWATS	Banana	3.27	0.22



## Soil chemical properties

Time	Block	Treatment	Depth	N (%)	P (mg kg <sup>-1</sup> )	pH (in KCl)	NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N (mg kg <sup>-1</sup> )	Total inorg. N (mg kg <sup>-1</sup> )	Organic C (mg kg <sup>-1</sup> )
Initial	1	Tap water + fertiliser	0.3 m	0.31	41.2	5.70	5.8	9.4	15.2	2.6
Initial	1	Tap water + fertiliser	0.6 m	0.3	18.6	5.40	4.2	12.3	16.5	2.7
Initial	2	Tap water + fertiliser	0.3 m	0.28	36.7	4.90	3.5	12.7	16.2	3.1
Initial	2	Tap water + fertiliser	0.6 m	0.23	7.5	5.20	4.3	7.9	12.2	3.2
Initial	3	Tap water + fertiliser	0.3 m	0.24	45.1	4.90	3.3	4.6	7.9	2.7
Initial	3	Tap water + fertiliser	0.6 m	0.21	9.7	4.70	2.1	6.3	8.4	2.5
Initial	1	DEWATS	0.3 m	0.31	34.2	5.10	6.7	10.7	17.4	2.7
Initial	1	DEWATS	0.6 m	0.29	2.8	5.60	2.6	14.2	16.8	2.5
Initial	2	DEWATS	0.3 m	0.31	38.7	5.40	5.8	13.8	19.6	3.2
Initial	2	DEWATS	0.6 m	0.27	17.8	4.90	5.7	8.9	14.6	2.9
Initial	3	DEWATS	0.3 m	0.29	40.1	5.20	2.1	6.7	8.8	2.8
Initial	3	DEWATS	0.6 m	0.26	15.0	4.80	1.8	7.5	9.3	2.4
504 DAP	1	Tap water + fertiliser	0.3 m	0.32	72.8	4.81	3.2	18.6	21.8	3.0
504 DAP	1	Tap water + fertiliser	0.6 m	0.32	4.3	5.44	2.4	25.0	27.4	2.7
504 DAP	2	Tap water + fertiliser	0.3 m	0.26	30.0	5.10	5.4	20.8	26.2	2.3
504 DAP	2	Tap water + fertiliser	0.6 m	0.31	5.9	5.01	3.2	23.5	26.7	2.8
504 DAP	3	Tap water + fertiliser	0.3 m	0.37	114.6	4.49	9.7	48.1	57.9	3.7
504 DAP	3	Tap water + fertiliser	0.6 m	0.32	5.6	5.00				2.9
504 DAP	1	DEWATS	0.3 m	0.34	52.9	5.39	4.1	21.2	25.2	3.4
504 DAP	1	DEWATS	0.6 m	0.31	3.7	6.14	2.0	29.1	31.1	2.3
504 DAP	2	DEWATS	0.3 m	0.32	55.2	6.29	3.7	24.7	28.4	2.9
504 DAP	2	DEWATS	0.6 m	0.28	6.4	5.35	0.5	36.0	36.5	2.6
504 DAP	3	DEWATS	0.3 m	0.36	48.5	5.09	6.9	16.6	23.4	3.6
504 DAP	3	DEWATS	0.6 m	0.32	5.4	6.12				2.1
992 DAP	1	Tap water + fertiliser	0.3 m	0.33	47.6	5.44	32.5	52.5	85.1	3.1
992 DAP	1	Tap water + fertiliser	0.6 m	0.22	1.8	5.48	15.3	34.4	49.7	2.3
992 DAP	2	Tap water + fertiliser	0.3 m	0.3	50.0	5.10	17.3	62.4	79.8	3.0
992 DAP	2	Tap water + fertiliser	0.6 m	0.2	1.8	5.26	5.2	34.8	39.9	2.3
992 DAP	3	Tap water + fertiliser	0.3 m	0.33	94.8	4.81	11.1	39.5	50.7	3.7
992 DAP	3	Tap water + fertiliser	0.6 m	0.29	1.9	5.00	7.2	33.7	40.9	3.1
992 DAP	1	DEWATS	0.3 m	0.25	16.7	5.25	50.8	53.5	104.2	2.6
992 DAP	1	DEWATS	0.6 m	0.23	1.8	6.32	19.1	24.2	43.3	2.2
992 DAP	2	DEWATS	0.3 m	0.28	66.0	6.02	39.6	58.2	97.7	2.7
992 DAP	2	DEWATS	0.6 m	0.28	23.6	5.22	26.6	45.6	72.2	2.7
992 DAP	3	DEWATS	0.3 m	0.35	93.3	5.27	8.8	60.4	69.2	3.6
992 DAP	3	DEWATS	0.6 m	0.29	4.7	5.13	21.6	56.0	77.6	3.1

Appendix 12: Tunnel raw data

**Plant growth**

Date	Rep	Soil	Treatment	Plant height (m)	Leaf length (m)	Leaf width (m)	Leaf number	Total leaf area (m)
30/09/2015	1	Cartref	DEWATS	0.40	0.36	0.06	5	0.02
30/09/2016	2	Cartref	DEWATS	0.87	0.94	0.41	5	0.32
30/09/2017	3	Cartref	DEWATS	0.60	0.50	0.10	4	0.04
30/09/2018	4	Cartref	DEWATS	0.70	0.70	0.32	5	0.19
30/09/2019	1	Sepane	DEWATS	0.70	0.77	0.27	10	0.17
30/09/2020	2	Sepane	DEWATS	0.60	0.55	0.24	7	0.11
30/09/2021	3	Sepane	DEWATS	0.38	0.40	0.27	5	0.09
30/09/2022	4	Sepane	DEWATS	0.80	0.9	0.32	11	0.24
30/09/2023	1	Inanda	DEWATS	0.55	0.52	0.17	9	0.07
30/09/2024	2	Inanda	DEWATS	0.66	0.75	0.28	8	0.17
30/09/2025	3	Inanda	DEWATS	0.54	0.69	0.26	8	0.15
30/09/2026	4	Inanda	DEWATS	0.58	0.65	0.24	8	0.13
30/09/2027	1	Cartref	Tap water + fertiliser	0.09	0.13	0.09	3	0.01
30/09/2028	2	Cartref	Tap water + fertiliser	0.10	0.24	0.10	3	0.02
30/09/2029	3	Cartref	Tap water + fertiliser	0.50	0.10	0.13	3	0.01
30/09/2030	4	Cartref	Tap water + fertiliser	0.23	0.16	0.11	3	0.01
30/09/2031	1	Sepane	Tap water + fertiliser	0.90	0.65	0.22	10	0.12
30/09/2032	2	Sepane	Tap water + fertiliser	0.70	0.63	0.22	8	0.12
30/09/2033	3	Sepane	Tap water + fertiliser	0.70	0.54	0.24	8	0.11
30/09/2034	4	Sepane	Tap water + fertiliser	0.77	0.61	0.23	9	0.11
30/09/2035	1	Inanda	Tap water + fertiliser	0.63	0.77	0.30	10	0.20
30/09/2036	2	Inanda	Tap water + fertiliser	0.60	0.67	0.31	2	0.17
30/09/2037	3	Inanda	Tap water + fertiliser	0.18	0.30	0.14	7	0.03
30/09/2038	4	Inanda	Tap water + fertiliser	0.74	0.91	0.35	10	0.26
31/12/2031	1	Cartref	DEWATS	0.60	0.70	0.30	9	0.17
31/12/2032	2	Cartref	DEWATS	1.13	0.90	0.34	9	0.25
31/12/2033	3	Cartref	DEWATS	0.93	0.93	0.31	9	0.24
31/12/2034	4	Cartref	DEWATS	0.94	0.90	0.33	10	0.25
31/12/2035	1	Sepane	DEWATS	1.14	1.02	0.44	14	0.37
31/12/2036	2	Sepane	DEWATS	1.16	1.11	0.49	11	0.45
31/12/2037	3	Sepane	DEWATS	1.07	1.09	0.49	11	0.44
31/12/2038	4	Sepane	DEWATS	1.20	1.17	0.49	11	0.48
31/12/2027	1	Inanda	DEWATS	0.85	0.90	0.44	8	0.33
31/12/2028	2	Inanda	DEWATS	0.85	0.90	0.44	8	0.33
31/12/2029	3	Inanda	DEWATS	0.90	0.94	0.41	7	0.32
31/12/2030	4	Inanda	DEWATS	0.80	0.93	0.46	6	0.36
31/12/2019	1	Cartref	Tap water + fertiliser	0.40	0.52	0.25	11	0.11
31/12/2020	2	Cartref	Tap water + fertiliser	0.64	0.85	0.37	9	0.26
31/12/2021	3	Cartref	Tap water + fertiliser	0.70	0.79	0.40	11	0.26
31/12/2022	4	Cartref	Tap water + fertiliser	0.58	0.65	0.24		0.13
31/12/2023	1	Sepane	Tap water + fertiliser	1.10	1.20	0.47	14	0.47
31/12/2024	2	Sepane	Tap water + fertiliser	1.10	1.10	0.48	12	0.44
31/12/2025	3	Sepane	Tap water + fertiliser	1.22	1.30	0.54	11	0.58
31/12/2026	4	Sepane	Tap water + fertiliser	1.14	1.20	0.50	12	0.50
31/12/2015	1	Inanda	Tap water + fertiliser	0.74	0.84	0.34	7	0.24
31/12/2016	2	Inanda	Tap water + fertiliser	0.50	0.45	0.21	5	0.08
31/12/2017	3	Inanda	Tap water + fertiliser	0.41	0.40	0.25	6	0.08
31/12/2018	4	Inanda	Tap water + fertiliser	0.97	1.15	0.44	7	0.42

Rep is the replication.

## Tunnel leachates data

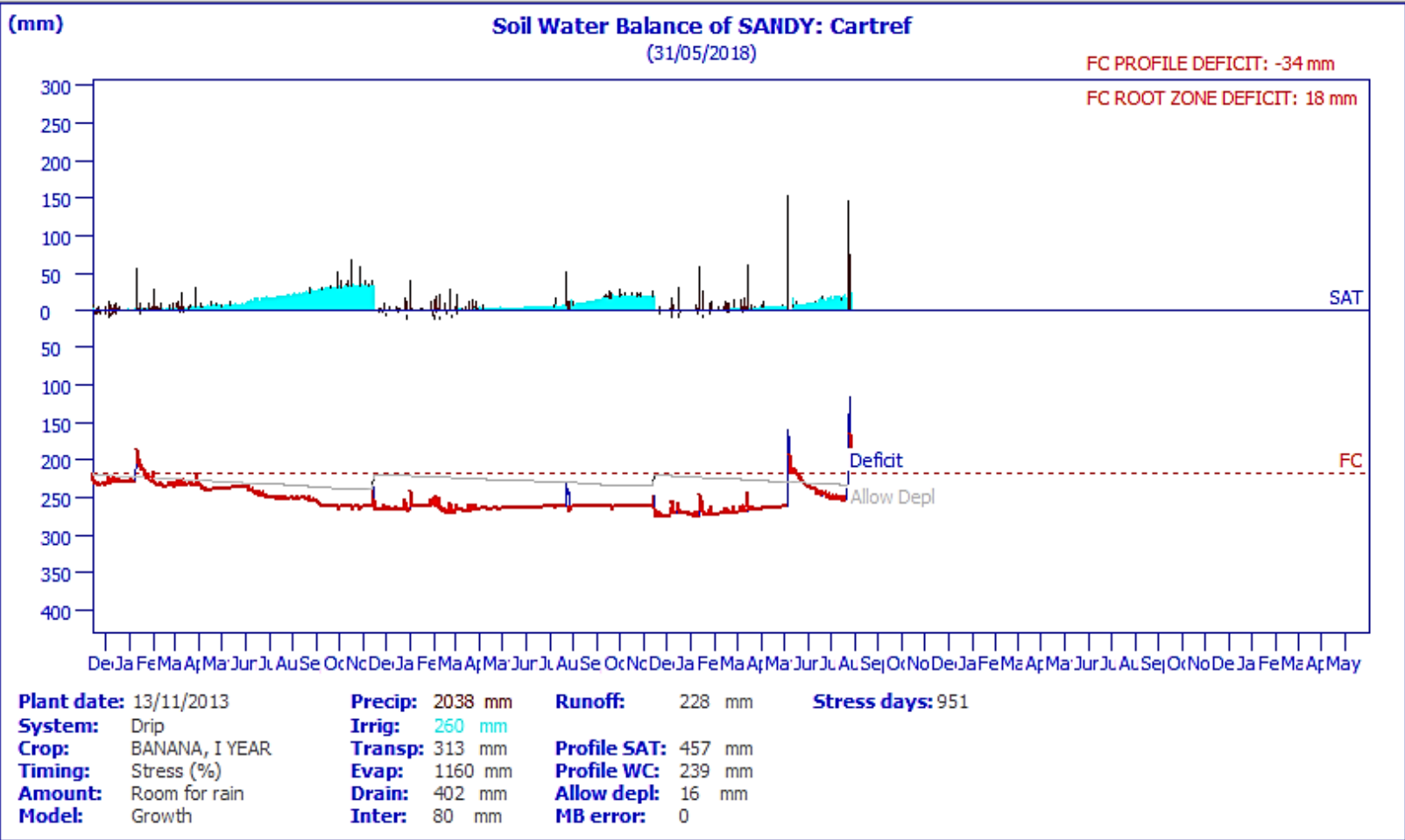
	Treatment	Soil	Rep.	NO <sub>3</sub> -N	NH <sub>4</sub> <sup>+</sup> -N	PO <sub>4</sub> <sup>3-</sup>	Total N	Volumes (L)
30/09/2015	DEWATS	Inanda	1	480	117	27	597	1.5
30/09/2015	DEWATS	Inanda	3	810	3	11.5	813	1.3
30/09/2015	DEWATS	Inanda	4	645	60	19.25	705	1.7
30/09/2015	DEWATS	Sepane	3	185.5	14	12	199.5	0.1
30/09/2015	DEWATS	Sepane	4	43	42	26.5	85	0.7
30/09/2015	DEWATS	Sepane	2	116.5	6	11.5	122.5	0.5
30/09/2015	DEWATS	Cartref	2	50	11	69	61	2.3
30/09/2015	DEWATS	Cartref	4	43.5	1.7	13	45.2	1.4
30/09/2015	DEWATS	Cartref	1	54.5	33	22	87.5	0.9
30/09/2015	Tap water + fertiliser	Inanda	4	1320	310	81.5	1630	0.4
30/09/2015	Tap water + fertiliser	Inanda	1	2185	560	42.5	2745	1.3
30/09/2015	Tap water + fertiliser	Inanda	3	1440	470	27.5	1910	1.1
30/09/2015	Tap water + fertiliser	Sepane	3	10150	28	26	10178	0.9
30/09/2015	Tap water + fertiliser	Sepane	2	6850	820	15.5	7670	0.4
30/09/2015	Tap water + fertiliser	Sepane	4	4350	210	197	4560	0.7
30/09/2015	Tap water + fertiliser	Cartref	3	115	195	30	310	1.9
30/09/2015	Tap water + fertiliser	Cartref	1	132	215	8	347	2.8
30/09/2015	Tap water + fertiliser	Cartref		123.5	205	19	328.5	2.35
31/12/2015	DEWATS	Inanda	4	13.5	4.5	5	18	1.1
31/12/2015	DEWATS	Inanda	3	23.2	2.3	3.6	25.5	0.8
31/12/2015	DEWATS	Inanda	1	43	0.4	45.1	43.4	0.6
31/12/2015	DEWATS	Sepane	1	45	2.9	13.9	47.9	0.1
31/12/2015	DEWATS	Sepane	3	34	0.5	10.1	34.5	0.2
31/12/2015	DEWATS	Sepane	4	24	0.3	11.1	24.3	0.6
31/12/2015	DEWATS	Cartref	4	29.7	0.5	8.8	30.2	2
31/12/2015	DEWATS	Cartref	1	23.6	4.4	7.2	28	1.6
31/12/2015	DEWATS	Cartref	3	12.1	0.8	12.8	12.9	0.5
31/12/2015	Tap water + fertiliser	Inanda	4	284	63.7	2.7	347.7	0.1
31/12/2015	Tap water + fertiliser	Inanda	3	181	35.8	1.9	216.8	1.7
31/12/2015	Tap water + fertiliser	Inanda	1	168	25	5.7	193	2.3
31/12/2015	Tap water + fertiliser	Sepane	3	21.7	61	6.2	82.7	0.3
31/12/2015	Tap water + fertiliser	Sepane	4	177	0.3	9.4	177.3	0.5
31/12/2015	Tap water + fertiliser	Sepane						
31/12/2015	Tap water + fertiliser	Cartref	1	18.4	0.6	3.7	19	2.5
31/12/2015	Tap water + fertiliser	Cartref	3	27	0.1	12.7	27.1	2
31/12/2015	Tap water + fertiliser	Cartref	2	107	54.6	10.5	161.6	1.5

## Pot irrigation data

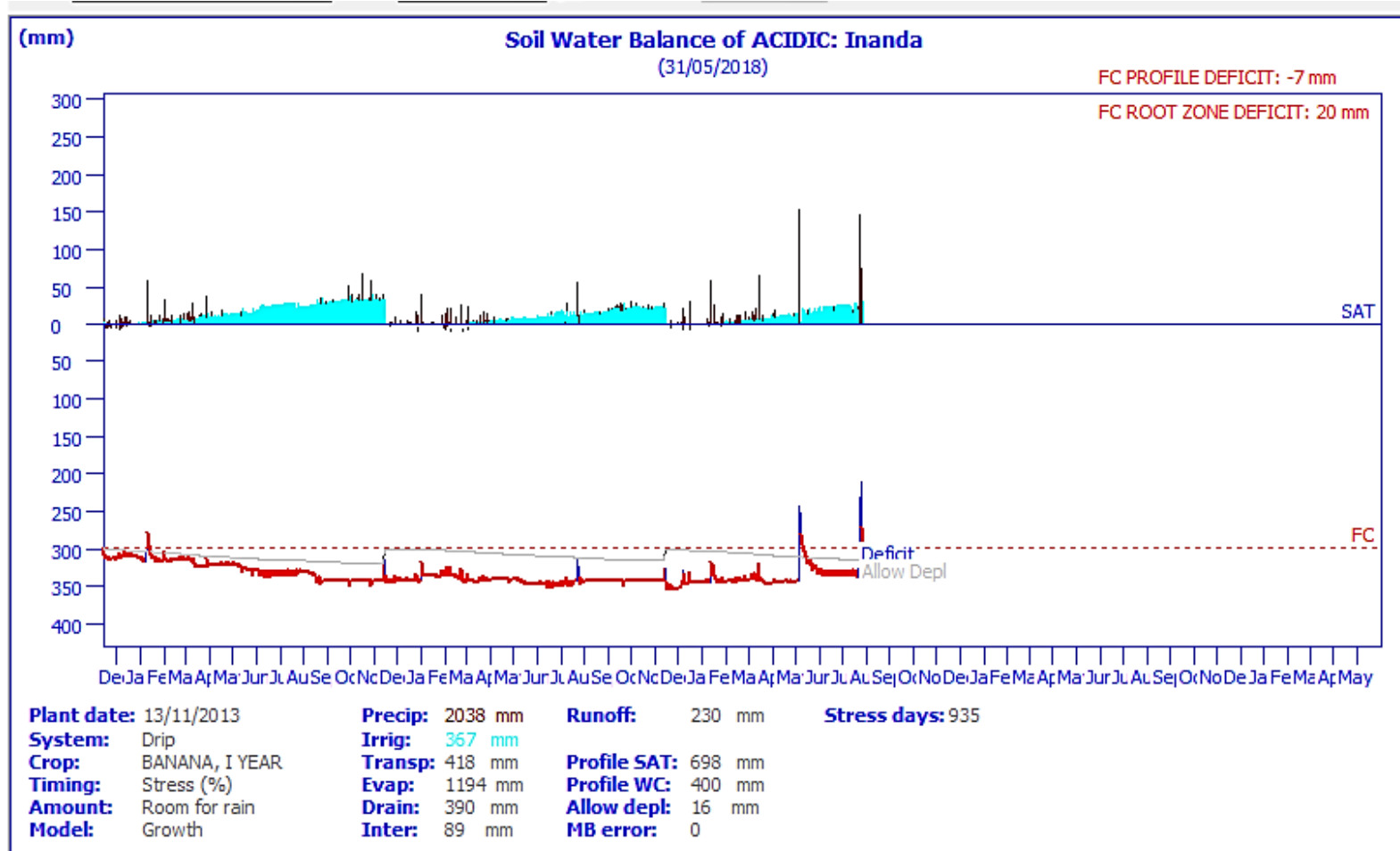
<b>Month-year</b>	<b>Irrigation volume</b> <b>(L pot<sup>-1</sup>)</b>
Apr-15	5
May-15	10
Jun-15	13
Jul-15	10
Aug-15	40
Sep-15	55
Oct-15	45
<b>Total</b>	<b>178</b>
Nov-15	60
Dec-15	60
Jan-16	75
Feb-16	40
Mar-16	60
Apr-16	60
May-16	60
Jun-16	0
Jul-16	60
Aug-16	60
Sep-16	60
Oct-16	60
Nov-16	40
Dec-16	50
Jan-17	40
Feb-17	40
<b>Total</b>	<b>825</b>
<b>Cumulative total</b>	<b>1003</b>

Appendix 13: Soil water mass balance for banana simulated by the SWB model over a period of 992 days at Newlands-Mashu.

Cartref soil



Inanda soil



Sepane soil

