Delft University of Technology

Improving water efficiency and crop yield on a sugarcane plantation in Xinavane, Mozambique

An analysis of irrigation practices, yield variability and the potential of a decision support system

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TU Delft

Abstract

This report contains the findings of a multidisciplinary project in Mozambique which ran from mid-November 2018 to mid-January 2019. This study is part of the IWACA-TECH project, which is an abbreviation for "Improved Water efficiency Control based on remote sensing TECHnologies. The goal is to increase water efficiency and crop yield without increasing the consumptive use of water, using remote sensing and Model Predictive Control (MPC). The structural water scarcity in the region points out the relevance of the IWACA-TECH project and with that this study. The research, carried out by students of Delft University of Technology, is of importance for both the company Tongaat Hulett and all inhabitants who are direct or indirect dependent on the water of the Incomati river. The study area on the plantation in Xinavane copes not only with inefficient irrigation water use but also suffers a sugarcane yield decline in recent years [12]. Therefore, the overall aim of this report is to improve water efficiency and crop yield within Tongaat Hulett. To achieve this from a multidisciplinary perspective several research questions have been formulated. Although they all contribute to the overall aim, they do so from different angles and in varying degrees. Therefore, to increase the readability of the report, the research questions have been divided into three sections: (1) Irrigation Practices, (2) Field Assessment on Yield Variability and (3) Decision Support System. Fieldwork was conducted over a five week period in order to gather data. Groundwater levels were measured, water quality of irrigation, ground- and precipitation water samples was analysed and soil moisture content was measured. This led to further research of soil types and quality. Soil profiles along the edges of both fields were made revealing a shallow aquifer in the bad-performing field. Irrigation water quality seems to form no hazard, but ground water quality analyses revealed significantly high electrical conductivity levels and a high sodium adsorption ratio in areas without growth. These findings, combined with an analysis of the digital elevation map and socio-technical data revealed that evaporation of irrigation water seems to be a large contributor to the impaired crop growth. When excess water cannot run off, puddles are formed. When these puddles evaporate, salts can be taken up by the soil once the thickened irrigation water infiltrates. This process is strengthened by the clay soil layer and the shallow aquifer, which prevent water from infiltrating deeper into the ground. Results concerning remote sensing prove the relationship between soil moisture content and precipitation for meteo-station XNA-20. Combining spatial and temporal variability of soil moisture content with remote sensing can play an essential role in managing irrigation practices. For the decision support system, and in specific the controller part of the system, measurements have been done. It can be concluded that storage area and delay times can be considered insignificant, and that canals do not have to be modelled. This makes the controller significantly easier and thus more time and effort can be spend on other aspects of the controller.

Keywords: *Sugarcane; water efficiency; over-irrigation; soil quality; remote sensing; Decision Support System.*

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Symbols

A	Area	m^2
c_p	Specific heat of air at constant pressure	$[Jkg^{-1}K^{-1}]$
e	Vapour pressure	$[kPa]$
e_s	Emissivity	$[-]$
ET	Evaporation from the soil surface	$[mm\,d^{-1}]$
f	Frequency	Hz
G	Soil heat flux density	$[Wm^{-2}]or[MJm^{-2}d^{-1}]$
g	Gravitation acceleration	ms^{-2}
h	Water depth	m
K	Hydraulic conductivity	md^{-1}
k	Time step	s
P	Pressure	Pa
p	Polarisation	Cm^{-2}
Q	Discharge	m^3s^-1
r_a	Aerodynamic resistance	$[sm^{-1}]$
r_s	Stomatal resistance	$[sm^{-1}]$
R	Net radiation at the crop surface	$[Wm^{-2}]$ or $[MJm^{-2}d^{-1}]$
T	(Physical) temperature	K
T_B	Brightness temperature	K
T_c	Canopy temperature	K
T_s	Sampling time	s
T_s	Soil temperature	K
γ	Psychrometric constant	$[kPa°C^{-1}]$
Δ	Slope of vapour pressure curve	$[kPa°C^{-1}]$
Λ	Transmissivity	$[-]$
λ	Latent heat of vaporisation of water	$[Jkg^{-1}]$
λ	Wavelength	m
ρ	Specific weight of air	$[kgm^{-3}]$
ω	Single scattering albedo	$[-]$

Definitions and abbreviations

Acidity	Ability of a substance to produce H+ ions
Active sensor	Radar instrument used for measuring signals transmitted by the sensor that were reflected, refracted or scattered by the Earth's surface or its atmosphere
Advance time	Number of hours needed for water to reach the lower end of a set
Albedo	Amount of solar radiation reflected from an object or surface
Alkalinity	Residual buffering capacity of water
Alternate furrow irrigation	Irrigating by applying water to every other furrow compared to irrigating every furrow
AM	Area Manager, manager of a specific area within Tongaat Hulett, in this case, the Xinavane area
Artesian water	Groundwater under hydrostatic pressure
API	Antecedent Precipitation Index, the weighted summation of daily precipitation amounts, used as an index of soil moisture
AMSL	Above mean sea level
Aquifer	An underground water saturated stratum of formation that can yield usable amounts of water to a well
Auger	Ground drill
Brightness temperature	Measurement of the radiance of the microwave radiation traveling upward to the satellite
CanePro	Software program used to plan and schedule irrigation
Carbonic acid	Carbon dioxide dissolving slightly in water to form a weak acid
Class A pan evaporation	Standard Bureau of Meteorology Class A type for manual measurement of evaporation
Conveyance	Efficiency of water transport in canals
Cut-off	Point within furrow where irrigation should be stopped to avoid over irrigation within a furrow
De-ionised water	Water of which the minerals and salts are removed
Dry-off	Period of no irrigation where sugarcane enters the final growth stage and forms sucrose
Delay times	Delay used to separate the occurrence of two events, especially in mechanical or electronic devices
DEM	Digital Elevation Model, grid size on the portrayal of the land surface and hydrologic simulations
Drainage	Artificial removal of excess water from land
DSS	Decision Support System, can serve the planning- and management levels of an organisation to make a decision about complex, rapidly changing problems
Earth feeder	Tertiary earthen canal
EC	Electrical conductivity as determined by the total amount of dissolved salts
E_o	Open water evaporation, evaporation that occurs from sources of open water
E_t	Transpiration, evaporation that occurs through plants
Field application efficiency	Efficiency of water application in the field
Float	Floating device used for water velocity measurements
Flocculation	The agglomeration of destabilized particles into microfloc and after into bulky floccules which can be settled called floc
Furrow	A long, narrow trench made in the ground by a plough, aimed towards planting seeds or irrigation
GW	Groundwater
Grouwndwater head	The height above a datum plane such as sea level of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system

Hardness	The amount of calcium, manganese and carbonic acid in water
Hydrostatic pressure	Static water column pressure
ID model	Integrator Delay model, a model based on a finite difference approximation of the linearized St. Venant equations
Infrared spectrum	The infrared region of the electromagnetic spectrum; electromagnetic wave frequencies below the visible range
IP	Irrigation Practices, the practice of irrigation including management, scheduling and irrigation itself
IWACA-TECH	Improved water efficiency control based on remote sensing technologies
Kc	Crop factor, describes crop characteristics
LAI	Leaf Area Index, dimensionless quantity that characterizes plant canopies
LPRM	Land Parameter Retrieval Model, model that converts brightness temperature into soil moisture, surface temperature and vegetation optical depth
Land preparation	Provision of the necessary soil conditions which will enhance the successful establishment of the young offshoots
Leaching factor	The ratio of the quantity of water draining past the root zone to that infiltrated into the soil's surface
Microwave spectrum	Electromagnetic radiation with wavelengths ranging from one meter to one millimeter
Modflow	Finite difference model for groundwater flow written and maintained by the U.S. Geological Survey
MPC	Model Predictive Control, an advanced method of process control that is used to control a process with multiple variables, while satisfying a set of constraints
Osmotic pressure/forces	The minimum pressure which needs to be applied to a solution to prevent the inward flow of its pure solvent across a semipermeable membrane
PA	Pump Attendant
Partial wetting	The concept of applying irrigation to field segments when considered necessary through visual observations
Passive sensor	Sensor that uses external energy sources to "observe" an object
Percolation	The process of a liquid slowly passing through a filter
Phreatic water	Groundwater under atmospheric pressure
Piezometer	Pipe used to measure groundwater levels
P & L	Profit & Loss, method that calculates moisture in the soil
Plopper	Measuring tape capped with a hollow weight, used to measure water depths in piezometers
Polarisation	The orientation of the electric field vector of the transmitted beam with respect to the horizontal direction
RAM	Readily Available Moisture, amount of water a plant can easily extract from the soil
Ratoon	A new shoot or sprout springing from the base of a crop plant, especially sugar cane, after cropping
Recession time	After water starts receding from the head end, it continues to the tail end. The time when water starts to disappear at the head end until it eventually recedes from the whole field is called the recession time.
Reclamation	Application of excess water until the soil salts are leached out of the intended root zone
Rootzone	Area of oxygen and soil surrounding the roots of a plant
Salinisation	Increasing salt content within soils
SAR	Sodium adsorption ratio, predicts the sodicity hazard of water and is determined by sodium, calcium and magnesium concentrations.
Semi-impervious layer	Layer where exchange can occur in both up- and downward direction
SI	Saturation Index, method of determining whether water will deposit calcium carbonate or maintain it in solution
Siphon	Pipe used to irrigate furrows
SM	Section Manager. One of the 2 managers in the Xinavane area who controls irrigation activities at the lower layers of hierarchy
SMC	Soil moisture content, quantity of water soil contains

SMP	Soil Moisture Probe, device which measures soil moisture at different depths within the soil profile
Socio-technical approach	Approach that recognises the inter-relatedness of social and technical aspects of an organisation
Sodification	The process by which the exchangeable sodium content of the soil is increased
Soil structure	Describes the arrangement of the solid parts of the soil and of the pore space located between them
Soil texture	Texture indicates the relative content of particles of various sizes, such as sand, silt and clay in the soil
Subsurface drainage	Removal of excess water from the surface of the land
TAM	Total Available Moisture, soil water availability which refers to the capacity of a soil to retain water available to plants
Transmissivity	Degree to which a medium allows electromagnetic radiation to pass through it
Turbidity	Measure of the degree to which the water loses its transparency due to the presence of suspended particulates
VanderSat product	Product made by different remote sensing observations to obtain the soil moisture content in the upper 10 cm of the soil
Water efficiency	Ratio between effective water use and actual water withdrawal. It characterises, in a specific process, how effective is the use of water. Furthermore, in addition to increasing the water efficiency this research focuses on increasing the crop yield while irrigating the same amount of water which indirectly increases water efficiency.
Waterlogging	Soil when it is saturated with water most of the time in a way that anaerobic conditions prevail
Wetted area	Area which is in contact with water in the irrigation canal

Contents

Conclusive summary

The overall aim of this report was to improve water efficiency and crop yield within Tongaat Hulett; To achieve this, several research questions were formulated. Although they all contribute to the overall aim, they do so from different angles and in varying degrees. The research questions were divided into three sections: 1. Irrigation Practices, 2. Field Assessment on Yield Variability and 3. Decision Support System (DSS). This chapter shows an overview of the research questions and main conclusions per section.

Irrigation practices
The following research question was formulated: What are the characteristics and specific problems of the current irrigation practices within Tongaat Hulett?

The hierarchy in Tongaat Hulett is an elaborate system with multiple layers yet efficient in reaching targets. However, this system can be slow in response time when issues occur and quick action is needed. Human interference is key within a socio-technical approach where the concrete civil engineers perspective links together with proper management. Human interference causes several interruptions within communication, maintenance and irrigation, related to scheduling and output in the field. Although this is inevitable in large companies like Tongaat Hulett it does show opportunities for improvement.

Field assessment of yield variability
The following research question was formulated: What processes cause the crop yield difference between field XND-21 and XNE-21 within the Xinavane area and how do these processes develop?

Regarding the yield difference between field XND-21 and XNE-21, different parts of the hierarchy provided contrasting possible causes, like poor drainage, over irrigation, slope, soil and salinity. When comparing the yield difference between XND-21 and XNE-21, this study shows that the irrigation water has low salinity and there is no indication to assume that it forms a direct hazard for the sugarcane. However, even high quality irrigation water can have detrimental effects on crop yield when not managed properly and enough time passes. This is seen on the no-growth spots in XND-21, where compaction, over irrigation, reversed slopes and poor drainage causes irrigation water to accumulate. When this water evaporates the quality of the water decreases and can disrupt the soil. Although it is risky to make assumptions on soil quality solely based on water measurements, both groundwater and puddle salinity/sodicity point in the soil direction. Groundwater salinity is most likely not a large contributor to the salinizsation within field XND-21. Rather, it is the presence of the shallow aquifer in field XND-21 causing waterlogging, that intensifies soil salinity in areas that are already more susceptible due to their low-lying nature, like spot X1 and spot X2. XNE-21 is less sensitive for over irrigation, since the field has a higher permeability due to the sandy composition of the soil. These are the main reasons for the yield difference between XND-21 and XNE-21.

DSS
The following research question was formulated for the model predictive control (MPC) part: To what extent does an accurate hydraulic model contribute to the possibility of implementing MPC at Tongaat Hulett?

For the DSS, and in specific the controller part of the DSS, it can be concluded that storage area and delay times are insignificant in comparison to the irrigation system components: water used and time per cycle. Therefore canals do not have to be modelled. This makes the controller significantly simpler to design and thus more time and effort can be spend on other aspects of the DSS. For the DSS to function optimally, hydraulic infrastructure should be repaired and maintained. We are one step closer to the final decision support system.

The following research question was formulated for the remote sensing part: What is the interchange between the water inlet and soil moisture content within the Tongaat Hulett area between 1 April 2017 and 31 March 2018?

Combining spatial and temporal variability of soil moisture content with remote sensing can play an essential role in managing irrigation practices. In this study the relationship between the SMC and the precipitation is proven for meteo-station XNA-20 and for all the meteo-stations combined for the rain event of 15-04-2017. With the help of predictive models, such as the controller used in this study's DSS, accurate and useful advice can be generated on whether or not to irrigate per specific field.

During this research many questions have been answered. However, many more have been discovered. Limitations within used methods were found and knowledge gaps stumbled upon. Both of these present opportunities for further research; this opens the door for many more projects within the field of water management and calls for cross-continental knowledge exchange.

Acknowledgements

We would like to thank all partners of the IWACA-TECH project for involving us in this beautiful project: Tongaat Hulett, VanderSat, Mobile Water Management, IHE Delft, Delft University of Technology, Universidade Eduardo Mondlane, ARA-Sul and Partners voor Water. We hope the results are beneficial to you.

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Xinavane,
May 15, 2019

David, Gijs, Jessie-Lynn, Judith, Kirsten, Sten

1
Introduction

This report contains the findings of a multidisciplinary project in Mozambique which ran from mid-November 2018 to mid-January 2019. During those two months the company of Tongaat Hulett hosted our team at their sugarcane plantation in Xinavane.

This study is part of the IWACA-TECH project [1], which is an abbreviation for “Improved water efficiency control based on remote sensing technologies. The IWACA-TECH project is funded by the Dutch Partners for Water program and brings together Dutch and Mozambican partners, satellite scientists, water experts, sugar producers and local operators. The goal is to increase water efficiency and crop yield without increasing the consumptive use of water, using remote sensing and Model Predictive Control (MPC). The IWACA-TECH partners are VanderSat, Tongaat Hulett, Mobile Water Management, IHE Delft, Delft University of Technology (TU Delft), Universidade Eduardo Mondlane, ARA-Sul and the Partners voor Water program of the Dutch Government. The Dutch students involved in this research all follow master programs at TU Delft. The specialisations involved are “Water Management”, “Environmental Engineering; technology” and “Geoscience and Remote Sensing”, and are all linked to the faculty of “Geosciences and Civil Engineering”. In the field there was a close cooperation between the TU Delft students, students from Eduardo Mondlane and employees of Tongaat Hulett, see Figure 1.1). The interaction between students and mentors from different backgrounds and universities was aimed to platform both academic and cultural knowledge exchange, enhancing cross-continental collaboration within the academics of water research.

Figure 1.1: The group including students from the Technical University of Delft, Universidade Eduardo Mondlane (Milton Paulao Acua, Frengue Baptista Junior, Yolanda Bila and Albino David Cossa) and employees (Nelson and Pietroc) from Tongaat Hulett.

1.1. General description of the area

The study area is located in Xinavane, in the province of Maputo in Mozambique. It is located approximately 140 km north of the capital of Mozambique; Maputo. Mozambique has a tropical savanna climate, 'Aw' in the climate classification by Köppen [2]. The wet season lasts from October until March, the dry season from April until September. The location of Xinavane can be seen in Figure 1.2.

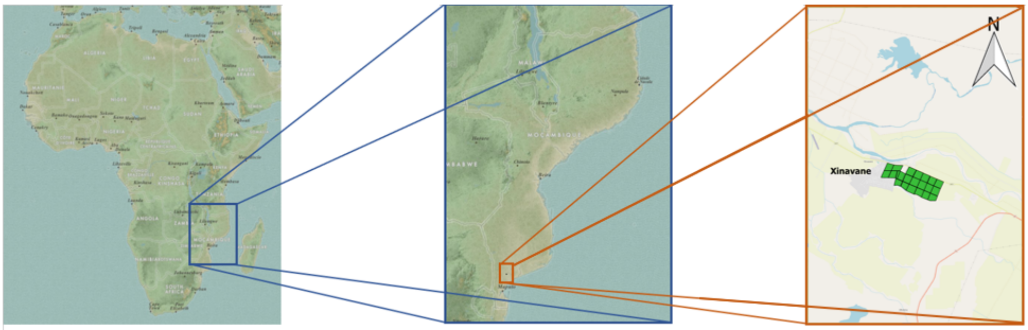


Figure 1.2: Map of research area. On the left is continent of Africa, on the right side is the zoom-in of the Xinavane area [5].

The town of Xinavane is surrounded by 18,000 hectares of sugarcane and characterised by a large factory near the city centre. The sugarcane fields are owned for 12 percent by the national government of Mozambique and for 88 percent by the company Tongaat Hulett, who also owns the factory and who are in charge of the complete production process [3]. Tongaat Hulett is a South African agriculture and agri-processing business that is located in Swaziland, Botswana, Namibia, Zimbabwe and Mozambique. Within Mozambique, there are two sugarcane plantations; one located in Mafambisse and one in Xinavane.

Sugarcane, see Figure 1.3, is a plant that originated in wet tropical regions such as Hawaii and Papua New Guinea [4]. It flourishes under long, warm growing seasons with high radiation. The crop needs adequate moisture throughout the maturing stages of the plant, followed by a dry but sunny ripening and harvesting period. Long growing seasons are essential to get high yields as normal growing periods vary between 9 to 16 months. A first crop is often followed by more ratoon [5] crops, each needing one year to mature. As it has a long growing period, crop water requirements are between 1500 and 2500 mm per season, making it a heavy water consumer [5]. Sugarcane will grow in direct proportion to the amount of water available, on the condition there is adequate sunlight and good temperature conditions. Irrigating sugarcane to increase its growth is a practice that has been recognised for over 100 years [4].

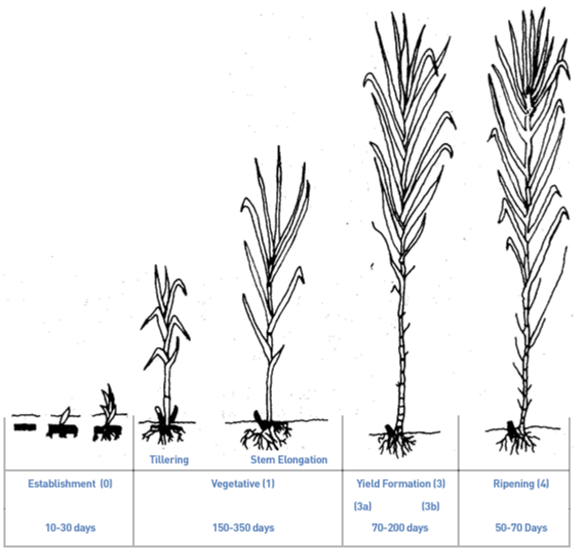


Figure 1.3: Sugarcane growth stages within Tongaat Hulett.

Within the 18,000 hectares of sugarcane around Xinavane, a subdivision is made in different areas, based on different irrigation systems. Each area uses their own technique, such as drip, sprinkler, pivot and furrow irrigation. Drip irrigation allows water drip slowly through to the roots. Sprinkler irrigation system distributes water through a system of pipes and is then sprayed into the air through sprinklers. Pivot irrigation consists of equipment which rotates around a pivot whereby crops are watered with sprinklers. Furrow irrigation applies water to the top end of a furrow [6] whereby water flows down the field under the influence of gravity [7]. One area applying the furrow technique, is the IWACA-tech research area. This is also the area on which this report is focused, see Figure 1.4; it consists of 25 different fields of approximately 20 to 25 hectares per field.

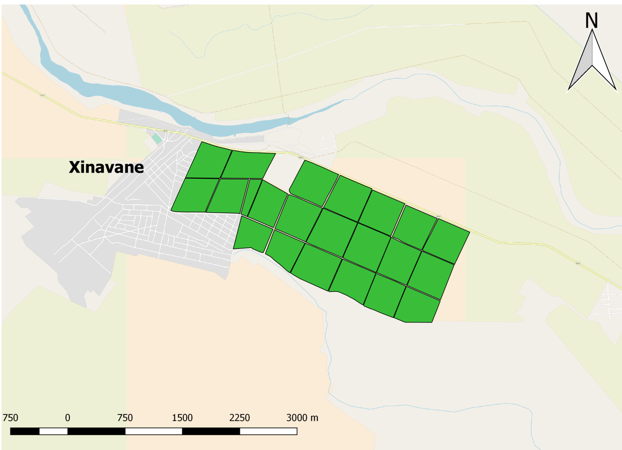


Figure 1.4: The IWACA-TECH research fields within the Xinavane area.

The irrigation water supply of the Tongaat Hulett sugarcane production area come from the Incomati river. Figure 1.5 shows a digital elevation map (DEM) [8] of the area and surroundings where the outline of the river is clearly visible and whereby it seems to be that the Xinavane area lies in between two branches of the river. However, the river located north of the area is the current river whereas the southern contours show the old river branch. Nowadays the southern part is cultivated and little of the surrounding implies that the river used to flow here. The Incomati is known to flood regularly and herewith depositing clay or silt over the more coarse material of the riverbed and –dunes. In short: the Xinavane area is formed by the Incomati river and therefore a riparian landscape.

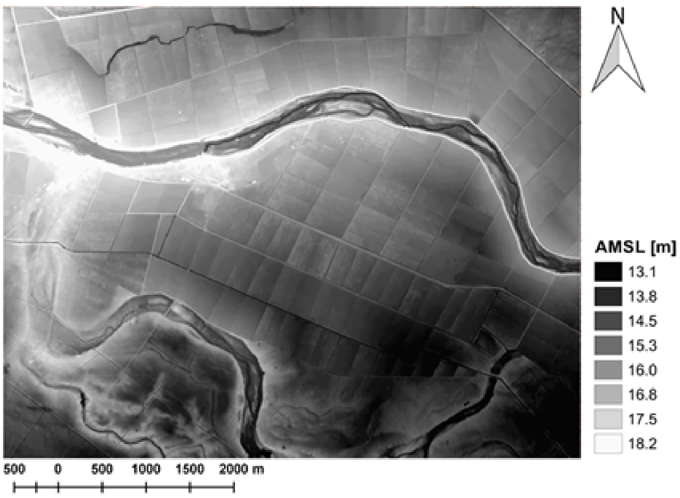


Figure 1.5: Digital elevation map of the Xinavane area.

1.2. Theoretical and practical relevance of the research

Many countries depend on their agricultural production to ensure food security and to contribute to economic development. Along with suitable land, availability of fresh water plays an important role in crop production. However, along with agriculture, there are many other sectors that impose demands on basin water resources. Declining water supplies and growing demand require better management decisions in water allocation. This water shortage is roughly caused by a precipitation deficit in the region and intensification of the water usage. A known Southern African example of intensification of water and is the water crisis in South Africa in 2018 were the city of Cape Town was on the verge of 'Day Zero' [9]. This water shortage is caused by a precipitation deficit in the region and intensification of the water usage. Within Mozambique, the Incomati basin has also been receiving less precipitation every year, resulting in a decrease of discharge and therefore less available water for irrigation each year [10]. Additionally, climate change in combination with the exponential population growth will further threaten food security, and economical growth.

The plantation, among others, has grown which also increases the demand for water. To contribute to solving the increasing competing demands for water in river basins it is necessary to focus on the largest water consumer: irrigation.

The volume of irrigation water that Tongaat Hulett uses is of vital importance for crop yield, and its expanding water requirements threaten the water availability for other users, including town and cities as well as ecosystems, and local fisheries. The ratio between how much water is added to and taken off the Incomati river has far-reaching consequences. In the weeks following the research the National Directorate of Water Supply and Sanitation announced the measure that the region of greater Maputo only got water from the tap every other day, due to shortages. The total water supply to the region was cut by 30 percent [11]. As goes for the plantation of Tongaat Hulett the water usage for irrigation was reduced to only 60 percent of the normal water usage. This highlights the importance of not only increasing the water efficiency directly, but also indirectly through increasing the crop yield while irrigating the same amount of water.

Against this background, the relevance of the IWACA-TECH project and with that this research, carried out by students of Delft University of Technology, is of importance for not only the company Tongaat Hulett, but also for all inhabitants who are direct or indirectly dependent on the water of the Incomati river.

1.3. Problem statement within study area

On the plantation of the study area in Xinavane, sugarcane yield decline is a major problem. In particular, there are local spots within some fields where sugarcane has stopped growing all together; these spots increase in size with time and result in significant yield differences between fields within the plantation. Opinions are divided within the plantation on the causes of this yield difference, but detailed research has yet to be performed.

Another issue within the plantation is the water efficiency of the irrigation practise [12]. This problem is double fold. Firstly, the main irrigation pump of the Xinavane area is not adjusted to meet the volumes required by the specific irrigation schemes: This could cause a higher or lower water uptake from the Incomati river than necessary. Even though the exact river water uptake volume is known, the distribution of this water among the sugarcane fields is not. This means irrigation water uptake does not match the water required on the fields. Secondly, once the irrigation water arrives at the field, water is believed to be lost by non-optimal execution of irrigation practices. Although execution and job tasks are clearly defined, it is unknown if the protocols are followed through and if Tongaat Hulett's hierarchy setup is contributing to maximising the irrigation system to its full potential.

1.4. Aim and research questions

The overall aim of this report is to improve water efficiency and crop yield within Tongaat Hulett; To achieve this from a multidisciplinary perspective several research questions have been formulated. Although they all contribute to the overall aim, they do so from different angles and in varying degrees. Therefore, to increase the readability of the report, the research questions have been divided into three sections: 1. Irrigation Practices, 2. Field Assessment on Yield Variability and 3. Decision Support System. This division is continued throughout the report; for a more detailed introduction, please refer to the chapters assigned to each specific section.

1.4.1. Part I. Irrigation Practices

Irrigation practice is the procedure of monitoring and managing the rate, volume, and timing of water application according to the crop needs. This section will focus on evaluating the current irrigation practices from a socio-technical approach [13] by answering the following research question:

What are the characteristics and specific problems of the current irrigation practices within Tongaat Hulett?

In order to assess this, interviews have been conducted and field observations have been made. The interviews were done with employees within each layer of the hierarchy of Tongaat Hulett, ranging from people working on the field to those that work in agricultural and operational management. The field observations were done to examine the biased answers from interviews and contribute to setting up an overview of what is supposed to be done versus what is actually done in the field. An examination of irrigation practices can give a pragmatic description of the status of the current furrow irrigation system and which aspects influence the state of it. This allows for the identification of actions that can be taken to improve irrigation practices which can ultimately contribute to increased water efficiency.

1.4.2. Part II. Yield Variability

This section will focus on assessing the issue of local yield depressions and crop death within Tongaat Hulett. In order to do so a comparative assessment has been made between two adjacent fields within the sugarcane plantation: field XND-21 and field XNE-21. These fields were selected because their annual yields have differed significantly over the last eight years; XND-21 performs under average, while XNE-21 is harvested with amounts that are above the average crop produce.
Although yield is different, they are comparable in other aspects; these aspects are addressed in table 1. The comparative assessment is made on the basis of the following research question:

What processes cause the crop yield difference between field XND-21 and XNE-21 within the Xinavane area and how do these processes develop?

By choosing fields with the same sugarcane variety, type of irrigation, land preparation [14], drainage system and precipitation levels several causes can already be excluded. However, a scala of processes remain that have the ability to influence sugarcane crop growth, among which management, salinisation, sodification, irrigation practices and water-soil interaction [15]. To find the processes that cause the difference in crop impairment several parameters have been analysed: groundwater table, groundwater quality, soil quality, soil type, vegetation, nutrients and fertiliser schemes, irrigation water quality and irrigation practices and their execution within fields XND-21 and XNE-21. Additionally, through interviews several layers within the hierarchy of Tongaat Hulett have been asked to verbalise their thoughts on what they think could possibly cause the dissimilarity in yield for these two fields. Determining the cause of the yield variability between both fields does not only aid the plantation into possibly increasing crop yield and/or improving management styles for field XND-21, it can also help to prevent yield depression in other areas of the plantation where similar issues might otherwise arise in the future.

1.4.3. Part III. Decision Support System

This section of the study will focus on the possibilities of implementing a Decision Support System (DSS) in the Xinavane area of Tongaat Hulett. A DSS can serve the planning- and management levels of an organisation to make a decision about complex, rapidly changing problems [17]. Additionally, by clarifying the problem and recommending the most advantageous decision, it is in the ability of a manager to oversee a larger area. For Tongaat Hulett, a DSS can be used to help managers decide on when to irrigate, when draining is desired, when the pump should be on and for how long. This would minimise the issues that are currently found with irrigation water uptake and water distribution. When timely decisions can be made, it is possible to prevent a field from flooding or becoming too dry, which in turn contributes to improving water efficiency and crop

Table 1.1: Overview of yield and similarities between field XND-21 and XNE-21. Yield, area, precipitation and sugarcane variety have been retrieved from CanePro data from Tongaat Hulett in October, 2018. Other characteristics have been retrieved through personal communication with Tongaat Hulett previous to the research. *The average yield at the plantation is 86 tonnes/hectare/annum. Both average and specific yields have been determined over the last eight years by Tongaat Hulett. ** Variety N25 produces on average a higher yield than N23 according to Tongaat Hulett.

	XND-21	XNE-21
Yield (tonnes/hec/y)*	70,7 (below average)	107,5 (over average)
Area (hec)	23,9	23,3
Precipitation (mm/y)	165	165
Age (y)	8	8
Irrigation type	Furrow	Furrow
Sugarcane variety	N25**	Mixed N23/N25, but mostly N25**
Land preparation	Shallow subsoiling	Shallow subsoiling
Subsurface drainage	Not present	Not present

yield. Additionally, human errors that can be made in decision-making can then be minimised. Overall, a DSS has the ability to improve both the water- and cost- efficiency of growing sugarcane.
To assess the potential of a DSS, several concepts can be applied: for this research a Model Predictive Control (MPC) is investigated. MPC was chosen for the DSS assessment, as MPC is the best option given the current hydraulic infrastructure at Tongaat Hulett; other concepts would e.g. require the installation of sensors, which would be both costly and at risk for theft.

Model Predictive Control Model Predictive Control is an advanced method of process control that is used to control a process with multiple variables, while satisfying a set of constraints. When making a decision, the current situation is optimised, while taking into account future developments. For a more detailed description of MPC systems, please refer to Chapter 15. Although MPC has been applied to irrigation schemes and water systems in general in the past [18], this project distinguishes itself by implementing MPC, while also actively involving remote sensing as input for the model predictive controller. The implementation of remote sensing within MPC will be addressed in the next chapter, this chapter focuses solely on the *hydraulic* element of the MPC, which in turn consists of four parts: canals, structures, disturbances and the controller. Accurately modeling these parts can be time-consuming and in some circumstances unattainable. Therefor, to find out if an MPC can be implemented for Tongaat Hulett, it is not only the feasibility of modeling the hydraulic system that must be explored, but also the essentially of modeling the hydraulic system in the first place. If an accurately defined hydraulic system does not contribute to the overall MPC, the time-consuming practice of achieving this accuracy might be avoided all together. This brings us to the following research question:

To what extent is an accurate hydraulic model feasible and how does it contribute to the possibility of implementing MPC at Tongaat Hulett?

In order to assess this each part of the model is investigated separately during the fieldwork period. This investigation will consist of visual inspections of the current hydraulic infrastructure, discharge measurements, flow delay tests and field observations.

Remote Sensing and MPC For a successful MPC that implements remote sensing; being able to establish the soil moisture content (SMC) with satellite-gathered data is necessary. One of the partners and initiators of the IWACA-TECH project, VanderSat, has developed an algorithm to do so. An in-depth explanation of this algorithm is described in Chapter 16. This algorithm has proven itself to produce accurate SMC values for several regions across the world [19]. For the region of Xinavane the SMC data is also available through Vandersat's algorithm. However, these values are yet to be verified for their reliability as Xinavane has a different climate than the regions where the algorithm has previously been successfully applied. In order to do this, water inlet events within the research area - which consists of irrigation and precipitation events - can be analysed for matches with changes in the satellite-gathered SMC values. This brings us to the following research question:

What is the interchange between the water inlet and soil moisture content within the Tongaat Hulett area between 1 April 2017 and 31 March 2018?

In order to assess the interchange between SMC and water inlet events, the fluctuations within the SMC data will be compared to historical irrigation data and precipitation measurements done in the meteorological stations located within Tongaat Hulett over the same time period. Determining this interchange will aid in determining if remote sensing can indeed be implemented within the MPC for Tongaat Hulett. The pioneering implementation as such does not only allow the MPC to cover a larger area as it would without remote sensing, it can also eliminate the necessity for time-consuming and often inaccurate field measuring devices, such as soil moisture probes.

1.5. Note from the writers

At first, it was attempted to write the report consisting of one big piece and one big research question. The reason for this simply was that MDP project's are usually set up as such. However, as the project went from preparation to execution, the six themes that made up the project initially, see Table 1.2, were split into three parts; current irrigation practices (part I), field comparison on yield variability (part II) and decision support system (part III). What all parts have in common is that they apply to the Xinavane area of Tongaat Hulett and that they aim to improve water efficiency and crop yield within Tongaat Hulett. Each part is designed to be read separately. However, in order to fully grasp the setting of part II and III, it is recommended to read part I too, as it describes the hierarchy and nuances within the plantation.

Table 1.2: Overview of initial structure of the report. Each theme was designed to fit the exact speciality of a specific TU Delft student.

Theme	Content	Part
1. Irrigation practices	Analysis of current irrigation practices	#1 Irrigation practices
2. Groundwater	Analysis of groundwater depths and heads	#2 Field assessment
3. Water quality	Analysis of irrigation water, groundwater	#2 Field assessment
4. Hydraulic infrastructure	Model Predictive Controller	#3 Decision Support System
5. Remote sensing	Soil Moisture Content vs rainfall analysis using remote sensing	#3 Decision Support System
6. Evaporation	Water balance and isotope analysis	Appendix

As the research progressed, some of the topics were discarded and some were supplemented. One of the largest subjects that was added during the research, was soil, as it proved itself to be essential in order to answer the research question of Part II. A discontinued topic was the isotope analysis, as sample retrieval was too challenging given the available equipment, mainly for gathering the xylem and soil pore water. Other challenges with equipment were found in the soil moisture probe. During this research the probe was used for two themes: remote sensing and irrigation practices. For remote sensing the probe was used with the aim to verify the remote sensing observations of the approximate soil moisture content. For irrigation practices it was used to try to determine the infiltration of water on field XND-21 and XNE-21. Unfortunately, data from the probe proved itself unreliable. Therefore, the part about the probe is omitted from the main text. More information on the probe can now be found in the appendix. The same holds for the water balance; it has been attempted to make a water balance of the fields but for several reasons this has not worked out. For this reason, the water balance and the causes for its disregard can be found in the appendix as well.

So, as of now, the report consists of three parts, with four research questions (as part III holds two). The first part is about current irrigation practices. Here it is analysed how and why Tongaat Hulett irrigates as it currently does. Part II covers the field comparison regarding water and soil quality, soil types and groundwater. Part III covers the DSS part; here it is investigated whether remote sensing combined with model predictive control could be successfully applied to Tongaat Hulett in the future. Part III consists of two sections. The first section investigates to what extent the hydraulics of the water system of Tongaat Hulett should be modelled. This is investigated as there always is a trade-off between invested effort to model the system and an increase in accuracy. The second section explores whether remote sensing can be used to approximate SMC and to what extent this related to water inlet. The two sections have in common that the second section is input for the first section. The report has five appendices: three appendices fore the three parts, where each part has its own appendix. The additional two appendices are for the soil moisture probe and for the water balance.

I

Irrigation Practices

2

Introduction

Within Tongaat Hulett, several irrigation methods are applied, among which furrow irrigation. Within sprinkler and pivot irrigation research has been done on within Tongaat Hulett; furrow irrigation has not yet been investigated [20]. Within furrow irrigation water application is done through siphons, see Figure 2.1, that are being inserted by the irrigators; this practice contains more manual work compared to sprinkler or overhead irrigation systems [21].

Figure 2.1: Irrigation with the use of siphons.

Therefore, it is essential that its execution is properly managed. This chapter focuses on the management and executions of irrigation practices and uses a socio-technical approach for evaluation. Taking both sides into consideration is important, as furrow irrigation entails working with people, but also requires observations in the field to look at how irrigation is done, for example by evaluating flows in the furrow [22]. In other words, the objective is to apply a socio-technical approach to evaluate the current irrigation system, which is crucial to identify how decision making is done within the irrigation practices [21] of Tongaat Hulett within Xinavane area. To analyse the decision making process, the following research question is formulated:

What are the characteristics and specific problems of the current irrigation practices within Tongaat Hulett?

3 Methodology

In this chapter the means and materials to obtain the required data to meet the objective of this research and to answer the research questions are presented.

3.1. Literature

Literature was used to get relevant information from different publications, internet and reports. Some important data obtained in literature are mentioned in the following three categories:

- General overview of irrigation practices
- Background information
- Evaluation on the distribution performance of the scheme.

3.2. Interviews

Semi (un)structured interviews were used to get full information. This kind of data collection was selected to allow the interviewees to have freedom to give information in their own words. Within Tongaat Hulett eighteen people were interviewed; a list is shown in Appendix A.1. In addition to this, it is important to say that interviews with the leaders of company and irrigation staff were done multiple times depending on the situation and state of irrigation system.

The interviews were done throughout the hierarchy of Tongaat Hulett, mainly focusing on the workers in the field. Individual interviews were done when anonymity was preferred; where needed a translator was used. The interviews were recorded and later on transcripted in a question and answer format, structured per interview. Highlights were made of important activities within this document and used for the following outcomes within this chapter.
The focus of the interviews was based on the following aspects:

- Management rules related to irrigation and water management
- Organisational structure of the company
- Irrigation practices from the persons perspective
- Difference between XND-21 and XNE-21

3.3. Uncertainties

This section aims to complement found results by discussing error possibilities or other possible information that should be kept in mind when consulting the data.

Socio-technical analysis such as interviews do not consist of numbers, or only partly at the least. That does not mean these analysis are free of errors. Cultural differences play a big role within any research consisting of members from different parts of the world. Mozambique and the Netherlands have different cultures. Much can be learned from these differences. Some of them however, should be kept in mind when looking at the results. Firstly, women in higher positions on the hierarchy ladder are uncommon at Tongaat Hulett. Only one position is occupied by a female. The result of this was that most employees were oriented towards males, which was first noticed during introductions, where communications were directed to the male members of the team. Interviews with employees were conducted by a female team member, however. Thus, due to the male-oriented culture, it could have been possible that certain questions were answered with more restraint or ambiguity than they would have been if the interview was done by a male.

Secondly, language formed a barrier. None of the project members speaks Portuguese. Most of the managers in Tongaat Hulett speak English, but explaining specific information in a second language can be troubling. Leading to information lost in translation. Irrigation workers and other employees on the lower end of the hierarchy ladder often barely spoke English, or not at all. Causing need for a translator, which was most of the time one of the students from Universidade Eduardo Mondlane. The second translation is more cause for possible missed information or miscommunication during an interview. The advantage of a translator is that interviewing all layers of workers becomes possible, resulting in more information.

Thirdly, hierarchy within the plantation is structured in such a way that pleasing answers occur more often than correct answer. Especially when higher layers of the hierarchy ladder are present. Through only meeting with a single person instead of multiple layers of the hierarchy at the same time the aspect of pleasing answers was tried to be avoided.

3.4. Field observations

Given that this research seeks to identify irrigation practices and the extent to which the irrigation rules are applied the observation, behavior is crucial. All these observations were important and served to examine the biased answers from interviews and helped to set up the plan versus reality overview. Therefore this kind of data gathering helped to gain a clear image of the daily irrigation practices in the scheme, the operation and the state of irrigation infrastructures.

3.5. Plan versus Reality

For the communication, irrigation and maintenance section an additional approach was used, based on determining 'chaos' within the system. “Chaos” exists when the reality in a project does not match with what project employees believe occurs [23]. Therefore, the employees were interviewed on what various operators do and how the water delivery is done within the main canal. Due to the ambiguous nature of the word 'chaos', this is further addressed as 'plan versus reality'. These actions are later compared against what was found in the field and analysed.

A division is made between three aspects of irrigation practices to structure the results namely: communication, irrigation and maintenance.

4 Results

Within this section several results are shown for communication, irrigation and maintenance aspects. When the 'plan versus reality' approach is applicable, first the plan is explained, followed by what happens in reality which is elaborated in the discussion.

4.1. Communication

As the agricultural business has expanded over multiple countries the hierarchy within Tongaat Hulett is substantial. This part elaborates on day to day interactions that occur when performing activities. These interactions will be placed in the context of the management structure in which they occur. Figure 4.1 shows an overview of the hierarchy including their roles and responsibilities within the company.

4.2. Irrigation

This section focuses on the irrigation chain, that can be subdivided into preparation, irrigation and check. A critical analysis of irrigation practices based on observations and interviews for evaluation input is done. The irrigation practice focuses on the amount of water applied to the soil and the rate at which it is removed [24]. For example, poor water management practices result in excess water being applied to the soil, or when machinery results in a soil with poor drainage [6] properties due to compaction [7]. This analysis shows the difficulties within both fields XND-21 and XNE-21, but mainly focuses on field XND-21 according to field observations and interviews done. Additionally, the decision making process in whether to irrigate or not is analysed.
Figure 4.2 shows the irrigation done according to plan which shows several steps and repetition to perform irrigation schedules.

4.2.1. Preparation

Annual irrigation targets are set per section based on total management allowed depletion and irrigation system (furrow, pivot, sprinkler or drip). The targets are then used to develop labour and electricity budgets and requirements. An irrigation plan of one week in advance is made using the Profit and Loss (P&L), which is explained further on, and evaporation. Information is recorded for each field at harvesting or planting: field number, hectares, irrigation system, Total Available Moisture (TAM), Readily Available Moisture (RAM), Maximum Allowable Deficit (MAD) and date of harvest/plant. [5]

4.2.2. Irrigation

The first irrigation restores the soil to field capacity which is TAM. Irrigation is afterwards scheduled with P&L. Daily rainfall is recorded and converted into effective rainfall which is 80% of the gross rainfall, see Appendix A.1. This amount is entered in P&L. If 20 mm or more rainfall has fallen irrigation is switched off, which is being reassessed the next day whether the cycle should continue or not. The net irrigation applied is entered into P&L on the first day of each irrigation cycle. To calculate the soil moisture balance daily Class A Pan Evaporation (E_o) [25] is recorded daily as well. The E_t, evaporation is then determined by multiplying E_o by given crop factors (Kc) (depending on month of harvest and cane age). [26]

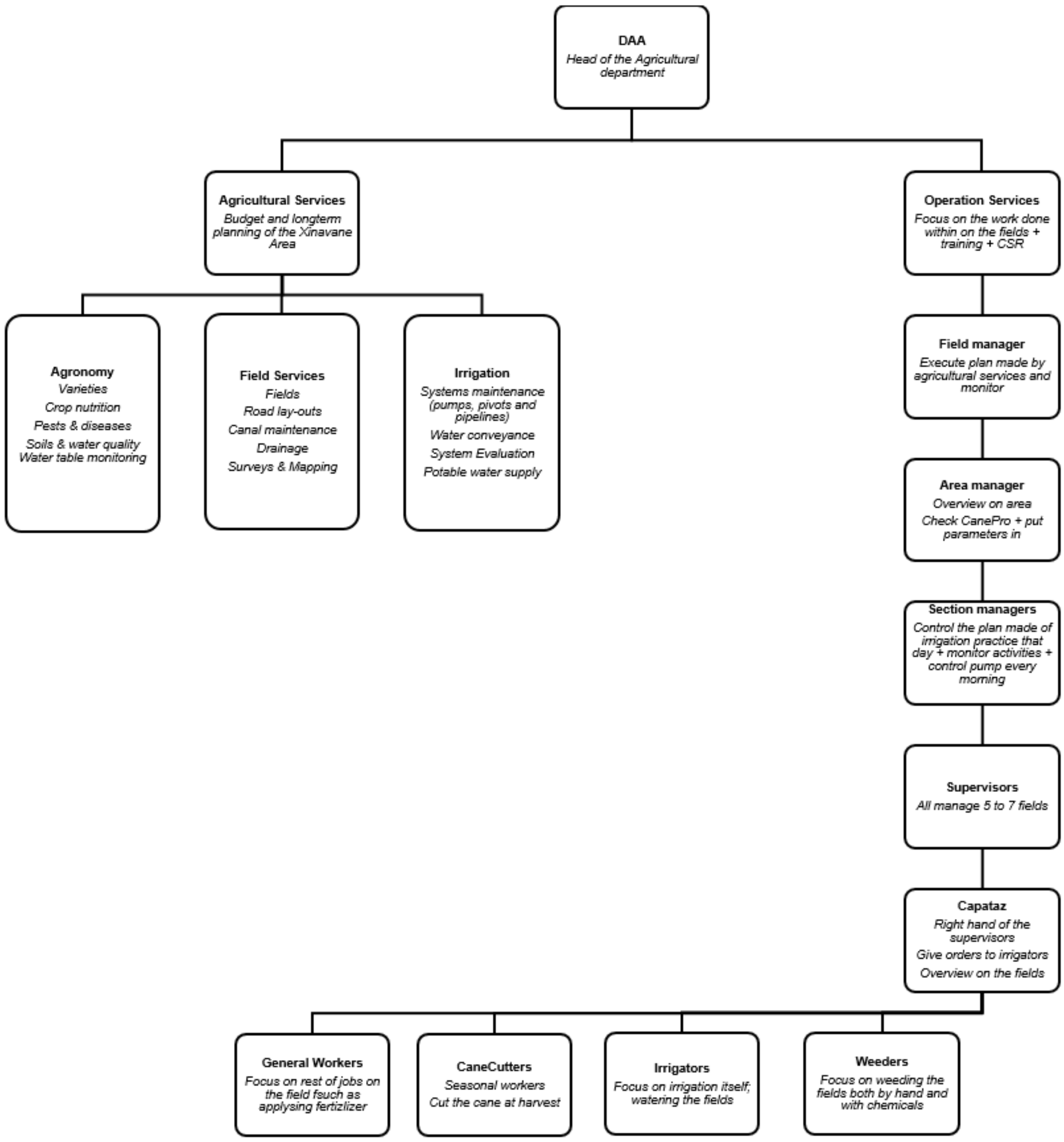


Figure 4.1: Hierarchy of Tongaat Hulett.

4.2.3. Check

Augering is done periodically and the 'feel method' is used to check P&L and correct where the two differ significantly (see Appendix A.2). The 'feel method' is elaborated further on.

4.2.4. Irrigation, yes or no?

For furrow irrigation, the decision making process whether to irrigate or not is based on three methods: P&L, the 'feel method' (see Appendix A.2) and Canepro.

4.2.5. CanePro

CanePro is a software program used to plan and schedule irrigation [27]. The program can replace the use of the P&L and improves the effectiveness of scheduling since it takes away human intervention and calculations done by hand. The planning, scheduling, controls and fertiliser for example can be done by CanePro as well. Within Tongaat Hulett the P&s is used more frequently especially within furrow systems as this type of irrigation requires more labour and human interference.

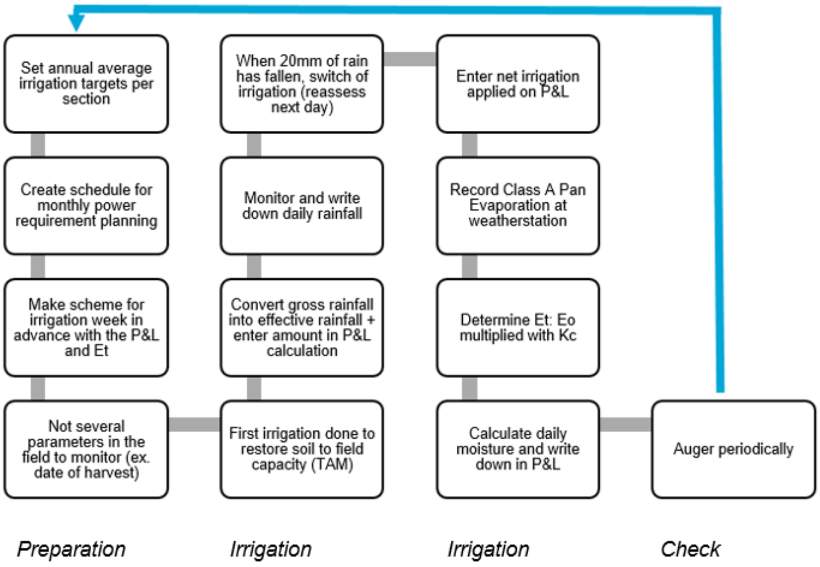


Figure 4.2: Irrigation Chain, based on Interviews (Appendix A.1).

4.2.6. Plan: the process of furrow irrigation

Firstly, the gates are opened from the main canal which lets the water flow into the earth feeder. According to the furrow evaluation team (Appendix A.1) the flow should reach 45 l/s. Based on which part needs to be irrigated the irrigators create a dam within the earth feeder to hold the water and create the water height and pressure needed to make use of the twenty siphons, which are the standard for the irrigation technique of Tongaat Hulett (Appendix A.1). By creating a vacuum with the hand of the irrigator the water is led into the furrows. At the cut-off point [28] the siphon has to be removed to avoid over-irrigation. For clayey fields the cut-off point is on two third of the furrow length, for sand this is almost at the end of the furrow [7]. Per day one irrigator needs to irrigate one hectare (Appendix A.1) which is set as target by from Tongaat Hulett. Per field two irrigators are trying to complete the cycle of irrigation as soon as possible. At the end of the day, the capataz collect all the numbers for all fields that were being irrigated that day and write down the lines irrigated and fill these in on one sheet, that is used every day for one month. After one month the sheets are collected and checked by the section managers and entered into CanePro.

4.2.7. Reality: the process of furrow irrigation

The following observations before irrigation within the field are shown in Table 4.1 and 4.2.

Table 4.1: Irrigation procedure; irrigation. All actions are performed by the section managers.

Action	When	Actually done
Prepare and submit water order	Weekly	Weekly
Begin irrigation on the day specified by irrigation schedule	During irrigation	During irrigation
Open secondary canal well in advance to avoid delays in irrigation.	Before irrigation	Before irrigatio
Establish cutoff and access points in the field to minimise runoff	During irrigation	Can be improved
Close all gates on the canal supply system at the end of each day's irrigation	During irrigation	Can be improved
Report all problems encountered during irrigation e.g. leaks, low spots etc	During irrigation	Can be improved
Calculate P&L	Daily	Weekly

Table 4.2: Observations in the field.

Aspect	Observations
Damage	Gates and weirs are broken/theft
Earth feeder	Dams created and not removed properly
Furrow	Irrigators create dams within furrows and not removed properly
Furrow	Ends of furrow are closed
Furrow	Excessive trash in furrow lines
Furrow	Excessive weeds in furrow lines
Furrow	Cut-off point not used
Technique	Different amount of siphons used
Technique	Traditional way of irrigation used (shovel)
Soil	Uneven slopes and puddles
Soil	Compacted soil
Augering	Only done in first twenty cm of soil
Augering	Only done at one spot in the field

Firstly, the establishments of cut-off points is seen to be different than planned, the cut-off points are misplaced or missing. When looking at the gates to the earth feeders observations show that multiple gates are still open although irrigation should not be done. Looking at the problems encountered during irrigation, this information is sometimes not passed onto the section manager and then higher levels for further actions (Appendix A.1). Lastly, the use of siphons is done inconsistently using both different amount of siphons or the traditional way of irrigation is used, which is explained in the efficiency section within this chapter. As the rest of these points also relate to the fieldwork part of this report, the rest of these points mentioned in the table above will be elaborated within the field chapter within interpretation of results.

4.2.8. Furrow Evaluation

To evaluate the flows onto the field furrow evaluations for field XND-21 and XNE-21 were done. The goal of furrow irrigation is to apply the right amount of water as uniformly as possible to meet the sugarcane crop needs. Irrigators need to pay attention to how much water is actually applied and where the water goes to infiltrate into the soil. The slope, surface roughness, and soil texture all influence how fast the water flows through the furrow, which is called the advance time [7]. If the advance time is long there may be an uneven distribution of water and thus uneven infiltration within the furrow. Shorter advance times show a more even infiltration profile. The water must reach the end of the fields to fill up the rootzone [5] within the ends of the furrow as well, this means that with a sloping furrow some run-off is needed. Another part in the furrow evaluation is the augering done to identify the soil moisture content at the day of evaluation, which is further elaborated in the next part.

After the water reaches the end of the furrow, FAO [7] states that furrow ends need to be open as excessive water needs to run to the drainage canal along the field. On fields XND-21 and XNE-21 this is not the case, but as XNE-21 consists mainly of sand, not opening up the furrows is a smaller problem here than in XND-21 (Appendix A.1). Based on multiple interviews with supervisors, capataz, irrigators and furrow evaluators opening up the furrow ends is not done because irrigation water can then flow into the next furrow to be irrigated, which is seen as a more efficient way of irrigating, nevertheless causes over-irrigation and restricts water to enter the drainage.

Related to the furrow evaluation, a side note is made; within the furrow evaluation the estimation of the soil moisture done by the team results in a wild guess of 50% soil moisture content everywhere applied within the furrow evaluation excel sheet.

4.2.9. Scheme irrigation efficiency

The scheme irrigation efficiency (e in %) is the part of the water diverted through the scheme which is used effectively by the plants. The scheme irrigation efficiency can be divided into:

- the conveyance efficiency (ec) [28] which represents the efficiency of water transport in canals
- the field application efficiency (ea) [28] which represents the efficiency of water application in the field.

The table in Appendix A.5 provides some indicative values of the conveyance efficiency, considering the length of the canals and the soil type in which the canals are dug. The level of maintenance is not taken into consideration: bad maintenance may lower the values of the table below by as much as 50%. [29] As maintenance is a point of improvement (Appendix A.1) unreliable values will otherwise be used to calculate the efficiency and thus only guidelines are give in the Appendix A.5.

Tongaat Hulett has been using siphons for just over a year to irrigate the furrow lines steadily applying two *l/s*. Workers often use the traditional way of irrigating. Using a shovel to open a furrow, and closing them after irrigation is done. As mentioned by the furrow evaluation team the change of technique, from traditional to the use of siphons, is a slow process whereby especially the elder women are having a harder time to use the siphon method (Appendix A.1). This results in a lower application efficiency of 40% (Appendix A.1), compared to the aimed 60% [92]. Also, siphon protocol is not always followed. Normally, two siphons should be used to transport water from the earth canal to one furrow. Field observations showed zero to three siphons per furrow during an irrigation event. Canal workers seemed to base these actions on the water level in the canal.

4.2.10. Maintenance

Attention is also given to various aspects of operation, maintenance, and process. According to protocol the canal state should be the same along the canal line (Appendix A.1). In reality there are significant differences in maintenance, slope, structures and obstacles along its length. By physically travelling along the canal from the pump to XND-21 and XNE-21, differences are seen. Table 4.3 shows what actions are required to maintain a good shape of the canals and what is actually done.

Table 4.3: Irrigation procedure; maintenance.

Action	Who	When	Actually done
Record any damage to structures.	SM	Daily	During Dry-Off
Inspect for leakages and silt build up.	SM	Daily	During Dry-off
Develop maintenance program for structures	SM	Annually	Annually
Keep canal clean	SM	When needed	Can be improved
Record pump station information	PA	Hourly	Daily/also online available

Appendix A.6 shows an overview, within three Figures, of spots along the lined canal towards XND-21 and XNE-21 where excessive weeds, leakages or other obstacles decrease or increase water flows along the canal.

5
Discussion

5.1. Communication

Recognisable was the difference between layers of the hierarchy of Tongaat Hulett. To begin with, it is said to be easier to deal with cultural differences at a higher level than in the field (Appendix A.1) because the needs of the company outbalances the cultural differences and thus conflicts in the fields and thus perception is different within each layer of the hierarchy. Also, information that is passed through the hierarchy has a risk of losing its content as it has many steps to go through. Information losses may happen both from bottom to top and vice versa. Especially when problems have to be elaborated on higher levels, response time could be too low for the quick response needed. Communication happens by telephone, email or personal interaction. Between capataz, supervisors and section managers telephones are used without issues. However, when problems need to surpass more layers within the hierarchy, for example when agricultural services need to be reached, it is more common to send emails. Communication trough mail can severely delay problems that need be addressed quickly (Appendix A.1).

Communication can be also be delayed due to lack or slower transportation. Transportation is done by bicycle, quadbike and car. As seen in the field the quadbikes or bicycle for example sometimes break down which makes the employee forced to either find other transport or arrange the activities from a distance resulting is a different outcome in the field as supervision is missing sometimes.

An interesting side note between 'communication' and 'irrigation' is that people get 50% extra salary when working overtime, as a results that working days are sometimes stretched and thus activities on the fields may be delayed. This results in uneven irrigation schedules and low work speed because of extra money that can be earned by these extra hours (Appendix A.1). At the same time, irrigation can be rushed, because you get paid the full eight hours regardless of finishing within eight or less. Overall motivation of Tongaat Hulett employees is strong, however for seasonal workers such as cane cutters motivation can be an issue. Motivation within Tongaat Hulett is well put by one of the employees from Tongaat Hulett (Appendix A.1) who says 'Everything is controlled by behaviour'.

At the end, the hierarchy within Tongaat Hulett is working: they have overview, reach targets and are efficient. However, when troubles occur the system is difficult to cope with and to react quickly, which can thus be stated as a fairly inflexible system.

5.2. Irrigation

As P&L and the 'feel method' are human induced, errors can be made within the determination to irrigate or not. The employee's expertise is trusted, as people are trained for at least two years within Tongaat Hulett (Appendix A.1). As experience comes with the years, expertise differs between people; Regardless of hierarchy, the knowledge of those that have worked for Tongaat Hulett longest is used for support within the decision making process. The profit and loss method calculates moisture in the soil by taking the previous day's moisture balance minus the E_t (crop water use) plus the effective rainfall and net irrigation. The effective rainfall is set to 80% of total rainfall (Appendix A.1). These calculations should be done daily, but are time consuming and thus often forwarded to later dates. A delay in calculations can cause unknown values throughout the day, which may lead to high or low soil moisture content within the field causing an undesirable situation where the best moment for irrigation may be misjudged (Appendix A.1). Also, within these everyday calculations mistakes are made easily, which may lead to different decisions in whether or not to irrigate.

The 'feel method' is based on observation, feeling and expertise. According to the section manager, deciding the soil moisture content per field is a source of human error. Those who are highly experienced in the field will likely be closer to the actual soil moisture content then employees with less expertise. The 'feel method' is not consistently done by one person, but by various people along the multiple layers of the hierarchy resulting in different outcomes. Another point of attention is the depth at which the sample is taken. Sampling should be done within the effective rooting depth, but this is done within the top layer of the soil (Table 4.2). Within the 'feel method', augering is done to determine the soil moisture content which is done by the supervisor, capataz or section manager. To get an accurate representation, soil moisture determination needs to be done at five different locations within the field, where the five auger holes form a Z along the edges according to protocol. In reality, however, only one point is taken per field to analyse its soil moisture. Additionally, the samples are taken in the first 20 *cm* of the soil, while this should be done within the rooting depth multiple times. As a consequence, the entire field is now represented by one measurement. Although the person in charge is often well experienced, it can still platform faulty conclusions about which part of the field must (not) be irrigated; possibly over-irrigating some regions and under-irrigating others. Even if their decision is supported by visual observations.

CanePro is used as a guideline for irrigation moments, but after irrigation, the irrigation date within CanePro is adjusted to either the right or wrong day that irrigation (should have) started. An adjustment causes changes in the irrigation schedule within CanePro that do not necessarily align with the field. This is one example of how field measurements are altered or incorrectly executed to get a specific result from CanePro, instead of allowing CanePro to advice based on correct measurements. It does not have to be a bad thing, especially with furrow irrigation, as the expertise of the decision maker could very well be advanced over the sugarcane software program. Opinions are divided on whether CanePro is a useful tool for future irrigation practices within Tongaat Hulett; The higher layers of the hierarchy advocate for CanePro's ability to exclude human interference and find that CanePro has not been exhausted to its full potential. Those who work in the field, however, stand by the hands-on approach of methods that are currently still most applied, such as FM and P&L (Appendix A.1).

As CanePro is currently only used for irrigation moments when it comes to furrow irrigation, further research on CanePro is excluded from the report.

Zooming into furrow irrigation itself; a point of attention is the cut-off point, which was not taken into account in both fields. Thus prolonging the advance time and eventually resulting in over-irrigation. As furrow lengths differ between both fields, cut-off points should also be different. The difference in soil type between the field strengthens this difference. However, these targets are not reached [16]. Instead, outcomes of the furrow evaluation are adjusted by the evaluation team during data-processing to result in better efficiencies, as extremely high amounts of water are applied onto the field. To get an idea about the cumulative infiltration, an infiltrometer would need to be used during furrow evaluation. However, the cumulative infiltration part of the evaluation was not prepared, thus missing infiltration rates and speeds. These infiltration tests have been conducted by the project team afterwards. Detailed explanation can be found in Section E.2. As data gathered through the use of the SMP showed to be unreliable, no quantitative conclusions could be based on these tests. Furrow evaluation proved to be insufficient for further use and are thus unfit for further calculations, for example efficiency and water balance aspects.

5.3. Maintenance

Maintenance is a point of attention as the irrigators are not allowed to stand in the canal (Appendix A.1) without boots but with high water this is not possible which delays the needed maintenance activities to the dry-off period [5] when the canals are empty. As mentioned by the furrow evaluation team the change of technique is a slow process whereby especially the elder women are having a harder time to use this method because of difficulties in mind-set to change compared to younger workers. Previously leaflets were used for irrigation but as theft is an issue in the area of Xinavane. Improvement is needed as theft is a problem which is difficult to tackle. (Appendix A.1) Within own field work theft was experienced as well as two of the installed piezometers were stolen. Besides theft, damage is another challenge in the area. An example of damages are the Neyrpic gates that are a useful resource to sell, when they are stolen they damage the infrastructure which also results in errors of Water transport between canal and field, because not all canal gates are closed properly. This again influences field application efficiency. Based on the interviews theft is most likely done by people from outside of Xinavane. Irrigators also damage the infrastructure but with the intention to elevate water levels.

6 Conclusion

The examination of irrigation practices gives a pragmatic description of the status of the current furrow irrigation system and which aspects influence the state of it. Relating to this statement the following research question is formulated:

What are the characteristics and specific problems of the current irrigation practices within Tongaat Hulett?

Firstly elaborating about 'communication'; overall, the hierarchy of Tongaat Hulett is a complex and big system with multiple layers but efficient in reaching targets. On the contrary, this system can be slow in response time when issues occur and quick response is needed. Human interference is key within a socio-technical approach where the concrete civil engineers perspective links together with proper management. Human interference causes several interruptions looking at the irrigation, both scheduling and output in the field, maintenance and communication. It is inevitable but does show opportunities for improvement.

Over-irrigation is a shown to be a problem when looking at irrigation. The overall procedure for irrigation is clear but the execution differs from its protocol.

Maintenance wise, the system lacks competence as maintenance is not executed to its maximum potential. Maintenance is shown to be of low priority when looking at the whole irrigation system.

7 Recommendations

7.1. Socio-technical systems

This research focused on two fields within the plantations. Meaning a limited amount of people more towards the field are interviewed. Conducting research which includes more parts of the plantation will result in a more general conclusion, directly applicable to the entire plantation. As Tongaat Hulett has a vertical hierarchical structure, most managers near the top of the structure have been spoken to. Further research should therefore be geared towards a broad analysis of people on the other end of the structure.
Adding to the previous point: if more socio-technical research is done, language barriers should be accounted for. Having interviews conducted by people who master both English and Portuguese is beneficial for the results. If Changane, the local language, is spoken, even more results could be achieved.

7.2. Education and management

Tongaat Hulett has a great program where people working for the company have a chance of educating themselves and learning more about agricultural practices. This way, employees can build a career within Tongaat Hulett. A win-win situation, resulting in knowledge and a good job for the employee, and well-educated people with relevant expertise for the employer. However, keeping these well-trained employees in the company is more difficult than expected. The Xinavane section of Tongaat Hulett is seen as a training hub. Well-educated employees are trained in Mozambique, and leave after training is complete. To Tongaat Hulett companies in other countries. Or, even worse, rivalling agricultural companies. Knowledge is a valuable product, and should be treated as such. Ensuring expert employees stay with Tongaat Hulett, and partly in Xinavane, is essential to the future of the company.
This problem can be found to a smaller degree when looking into seasonal workers. These are often hired for a one-year period and leave after the job is done ()Appendix A.1). Effort and money put into training these workers is thereby lost.
Another a social recommendation within Tongaat Hulett concerns the hierarchy structure. A vertical system has both up- and downsides. The main advantage is that a vertical hierarchy structure comes with overview, which results in achieving targets. However, the vertical structure works disadvantageous when responsibilities need to be taken. The many different positions cause escapism behavior on the address of accountability. By clearly addressing responsibilities of different positions, this escapism can be solved. Lastly, two piezometers were stolen during fieldwork. If further research is done, options to prevent this have to be considered. Section managers proposed stationing a guard near the fields, a simpler recommendation is to use cheap materials if possible and hide instruments from plain sight. Theft, and with it disruption of continuous measurements can be possibly prevented that way.

7.3. Irrigation

Over-irrigation has shown to be a problem based on interviews and own observations and thus two options to reduce over-irrigation are: alternate furrow irrigation [22] and partial wetting. These options are further elaborated in the Field assessment on yield variability chapter within 'Recommendations'.

7.4. Maintenance

Canal lining can reduce maintenance and seepage in the first place nonetheless, well maintained [23]. These topics have been discussed for years, big investments are dedicated to canal lining but have often not brought modernisation as a result [30]. This is because modernisation is not just a single action. A socio-technical approach is needed instead of a concrete civil engineers perspective only.

Furthermore, good maintenance is critical to maintain a constant flow through the canals and prevent clogging and thus floods. Therefore, the best option is to keep canals clean. This can be done in many ways which are described in the DSS chapter, recommendations.

II

Field assessment on yield variability

8

Introduction

As was mentioned in the overall introduction, this chapter aims to investigate variables and processes influencing the difference in sugarcane yield between low- and high-performing fields XND-21 and XNE-21, see Figure 8.1. While the fields are comparable in several aspects (See Table 1.1), crop production is lower than average for XND-21 and higher for XNE-21. In order to find possible causes, a comparative field assessment was made between XND-21 and XNE-21 on the basis of the following research question:

What processes cause the crop yield difference between field XND-21 and XNE-21 within the Xinavane area and how do these processes develop?

When excluding the similarities, several possible potential causes remain that have the ability to influence sugarcane crop growth, among which: groundwater, salinisation [31], sodification, fertilisers and execution of irrigation practices within the field [15]. In order to determine which play a role, the following aspects were researched in both fields: groundwater table, soil quality, soil type, vegetation, irrigation operations and quality of the irrigation and groundwater. For the water quality analysis, different parameters were researched for three types of water: irrigation, drainage and groundwater. These parameters are presented in Table 8.1.

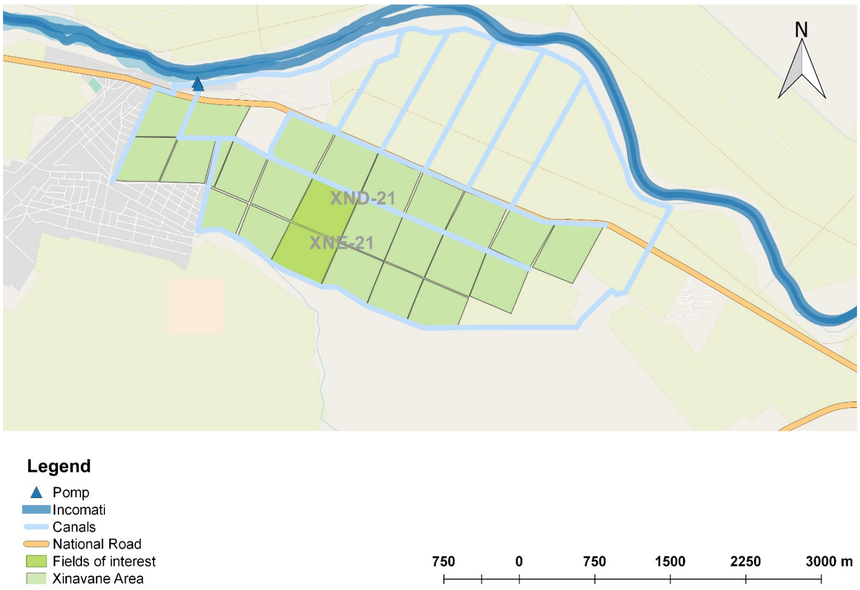


Figure 8.1: Field XND-21 and XNE-21.

Additionally, the quantitative field assessment will be compared to to what employees within different layers of the Tongaat Hulett hierarchy have stated to think the causes are of the yield variability between XND-21 and XNE-21. Overall, determining why there is a yield variability, and what the employees think to be the

Table 8.1: Overview of the parameters researched within the water quality analysis. Presented together with the processes and concepts for which these parameters are useful, often by determining an ongoing process or problem through quantification of an abundance or a deficiency in the parameter concentration.

Water quality parameter	Used for determination of
Electrical conductivity	*Salinity*
Sodium	*Sodicity*
Hardness	*Sodicity, Residual Alkalinity*
pH	*Acidity*
Alkalinity	*Alkalinity, Residual Alkalinity, Sodicity*
Phosphate	*Fertilisation*
Nitrate	*Fertilisation*
Ammonium	*Fertilisation*

cause, does not only aid the plantation with increasing crop production, it can also help to prevent similar issues on fields of the plantation where crop death issues might otherwise arise in the future. The processes, parameters and importance of groundwater, salinisation, sodification and fertilisers will now be addressed in the following sections of the introduction. For more background on the importance of the execution of irrigation practices, please refer to Part I.

8.1. Salinity and sodicity

Soil salinisation and sodification are of the main problems for land degredation in irrigated ares and has been reported to be an issue in Mozambique since the 1950s. Where primary salinisation is a consequence of long-term natural processes, secondary salinisation is human-induced and can be caused by irrigation water, mismanagement or by processes such as groundwater- and irrigation water evaporation [32].

8.1.1. Salinity

The salts determining the salinity of soil and water consist of ions like sulphate, sodium, chloride and magnesium [33] and are determined by measuring electrical conductivity (EC). High concentrations of these salts disrupt the water uptake capacity of the plant. In soils that are not affected by salinity the sugarcane can use the difference in osmotic pressure between the roots, which has higher sugar and nutrient concentrations, and the soil pressure to move fresh water from the soil into its roots. When this process is disrupted and the difference in osmotic forces [5] between roots and soil is altered, the uptake will decrease and can even reverse. This increase in salinity can cause water stress of which the symptoms are wilting to plant death [15]. In general, soils are considered saline when the soil EC [34] value exceeds 4 dS/m [33], although this can differ per soil type. When soils salinise, they do so in a non-uniform manner and salts will accumulate more readily in certain areas [35]. For furrow irrigation these areas are shown in Figure 8.2.

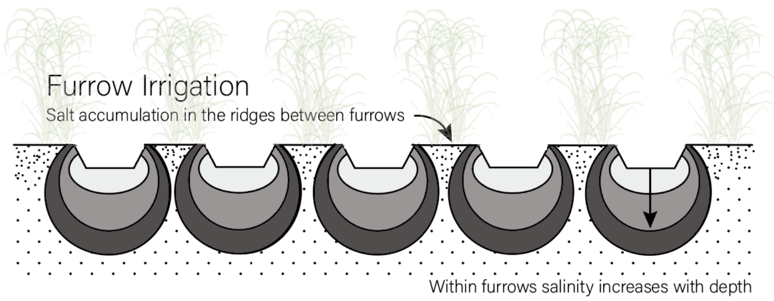


Figure 8.2: Locations of salt accumulation within the soil when furrow irrigation is applied and salts are not adequately leached. Salts will accumulate on the ridges between furrows as this is where the water is pulled towards by the roots of the sugarcane. Underneath the furrows salts will increase the deeper you go: The darker the color of the ring, the higher the salt concentration.

Conversely, while water with high EC causes salinisation issues for the crop, irrigating with water of low salinity can also create problems; this time with dispersion and water penetration. In other words, good quality (irrigation) water contains enough salts to prevent the breaking of soil aggregates, yet little enough salt to prevent salt accumulation in the rootzone [15]. Therefore, two classification systems are commonly used within salinisation analysis: one based on the EC of the water (EC*w*) threshold values (Table 8.2) and one based on EC infiltration risks as presented in Richards, 1954, see Figure 8.3.

Table 8.2: The ECw threshold values of irrigation and ground water are determined by the rootzone soil salinity (ECse) and soil type [36].

Soil type - yield loss	ECw sand - 10%	ECw clay - 10%	ECw sand - 25%	ECw clay - 25%
EC (dS/m)	1.7	0.6	5.9	1.9

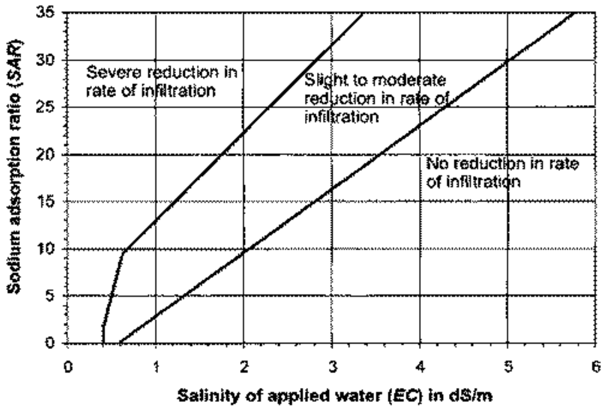


Figure 8.3: Infiltration risk assessment. As can be seen in the figure, there can be benefits of high saline water in heavy soils where the infiltration is low. The sodium adsorption ratio (explained in the 'Sodicity' section) also plays an important role in determining the infiltration reduction through its affect on the soil. [37]

A soil EC (EC*se*) value of 1.7 dS/m will cause a slight reduction in sugarcane yield, to a maximum of 10%, where an EC*se* of 5.9 dS/m causes a 25% yield loss. As well drained soils have a higher leaching fraction, the water that can be applied to the soil can be of higher salinity than a poorly drained soil. This means that the water EC (EC*w*) will differ from resulting EC*se*, depending on the texture if the soil. This water threshold is based on Equation 8.1, where the leaching factor (LF) for sand and clay are taken to be 0.45 and 0.15, respectively [36].

$$ECse = ECw \div (2. \cdot LF) \tag{8.1}$$

However, it has to be taken into account that other factors, besides soil texture [59], can influence the soil's capacity to withstand salinity. Circumstances like evaporation, moisture stresses, soil pH, stage of growth and waterlogging all play a role. The latter is a consequence of a higher water table that reduces the leaching fraction because water cannot leave the rootzone [36]. When there is adequate drainage, this can be beneficial for irrigation on heavy soils, because salinity helps to flocculate the particles. When there is no adequate drainage, like with waterlogging, it is a risky practice as there can be accumulation in the rootzone [15].

8.1.2. Sodicity

The sodicity of soil and/or water is determined by the amount of exchangeable Na^+ as opposed to the total amount of salts. Where a saline soil generally causes dehydration stress, sodic soils cause poor penetration, low readily-available water holding capacity, poor tillage and nutrient imbalances, see Figure8.3. To predict if irrigation water will cause a sodic soil, the sodium adsorption ratio (SAR) can be used, a ratio between the hardness (Mg^{2+} and Ca^{2+}) and sodium concentrations of the irrigation water. Over time, the sodicity of the soil will resemble the SAR of the irrigation water [15]. When sodic water passes through a soil its Na^+ cations may replace or exchange with the Mg^{2+} and Ca^{2+} cations that are attracted to and held to the negatively charged silt and clay particles [38]. Calcium and magnesium play a vital part in regulating ionic relations within the plant and has a good influence on the physical condition of the soil [39]. When they are replaced by sodium, the soil particles disperse or deflocculate, which results in a soil with small pores where water and air have difficulty to pass through [38]. An increase in soil sodium will also increase the soil pH. Although this does not have a direct affect on plant growth, it can limit the availability of essential nutrients [35]. The optimum sugarcane soil pH is around 6.5, but sugarcane grows well in soils with a pH in the range of 5 to 8.5

[5]. Another way to measure the sodicity hazard of irrigation water is through its residual alkalinity (RA) [40]. Here, alkalinity and hardness [41] concentrations are assumed to be an important indicator for the amount of sodium bicarbonate and sodium carbonate in the applied water [42]. As their presence influences the amount of Na^+ entering the soil, it can also increase the soil's sodicity [15].

It is actually possible to have sodic, saline or saline-sodic soils. While sodic soils are not necessarily saline; saline soils are usually also sodic [15], see Figure 8.4. Although it can be risky to make assumptions on soil, based solely on water quality measurements [31]. The SAR, together with EC, can be a good indicator for the infiltration and dispersion risk of water on soil, see Figure 8.3.

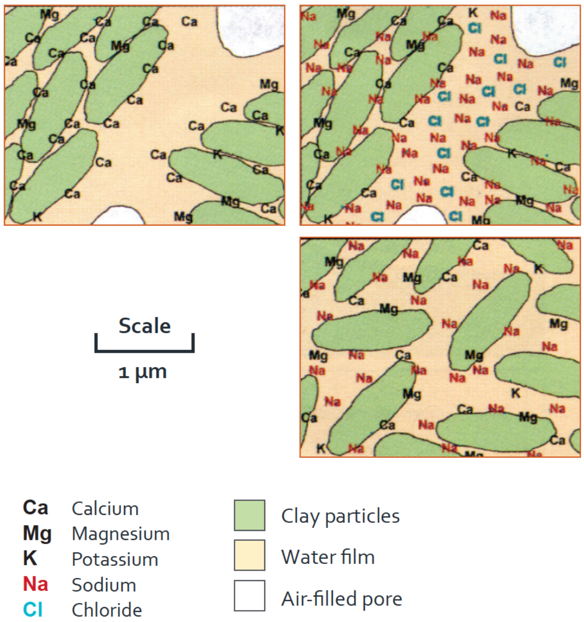


Figure 8.4: Different conditions of soil. The top left shows a non-saline, non-sodic soil: The clay is aggregated and there are pores filled with air. The top right shows a saline-sodic soil: There is a high salt content, a high sodium content and air-filled pores are present. The bottom right shows a non-saline, sodic soil: The clay is dispersed and there air-filled pores are not present [4].

8.2. Nutrients and fertilisation

Fertilisation is an essential part of providing nutrients for the sugarcane plant; a nutrient overload or deficiency can have an influence on the performance of the sugarcane crop. Nutrients researched within this report are: nitrate and phosphate. Ammonium was researched as it is a compound used in one of the stages of the conversion of nitrogen fertiliser (nitrogen > NH_4^+ > NO_2^- > NO_3^-). Even though potassium is a major essential nutrient, field quantification is often unreliable and therefore not included within this research. Nitrogen and phosphate are important as they drive photosynthesis and sugar production. The downside of N and P addition is that they can have a significant impact on water quality when they move away from the agricultural land into waterways [43]. Natural groundwater often doesn't exceed a concentration of 2 mg/L nitrate [44], the nitrate concentration that is deemed acceptable by the EU Directive 91/676/EEC for the run-off of agricultural areas is 50 mg/L [45].

Within Tongaat Hulett, each year soil samples of fields are sent to a lab in South Africa to analyse. Based on the soil analyses Tongaat Hulett gets a recommendation for fertilising. The fertiliser is applied once, in two runs. In the first run potassium and phosphate are applied, in the second run (three months later), nitrate is applied [3]. The fertilisation recommendation schemes for XND-21 and XNE-21 are presented in Table 8.3.

Table 8.3: Recommendation for fertiliser per field for 2017. For the fields two types of fertilisers are used: Urea and NPK (1-0-2). On XND-21 both NPK and Urea are applied, on XNE-21 only Urea. Units are in kg/kg [3].

	XND-21	XNE-21
Mg	0	0.16
N	121	150
P	0	0
K	150	0

8.3. Groundwater

The groundwater table depth is of interest for this study because of two reasons: sugarcane yield can be significantly affected by the depth of the water table [46] and there is generally room for improvement of the water efficiency in fields where shallow groundwater tables are present [47]. Research concerning the relation between the depth of the groundwater table and sugarcane yield shows that a maximum yield is obtained with a water table at 2 metres depth or below with a drastic reduction in yield when the water table rises above 2 metres. It was concluded that the crop growth and therefore the yield primarily depend on the conditions in the rootzone [46]. Additionally, the irrigation water volume is directly linked to the water table depth since a large proportion of the required water uptake can come from shallow groundwater [47]. Most interesting for this study is the fact that Tongaat Hulett does not consider groundwater uptake in their irrigation practice, more than that, they do not even measure the groundwater depth in most areas.

9
Methodology

9.1. Piezometers

In order to get a clear picture of the groundwater situation in both field XND-21 and XNE-21 ten piezometers were installed, five on each field, see Figure 9.1. Piezometer measurements were conducted each morning for a three week period. Using a plopper, the length from the top of the piezometer to the groundwater level in the piezometer was measured. Also, irrigation, drainage and other events that occured during the measuring period were noted. Detailed information on the making and installation of the piezometers can be found in Appendix B.1.

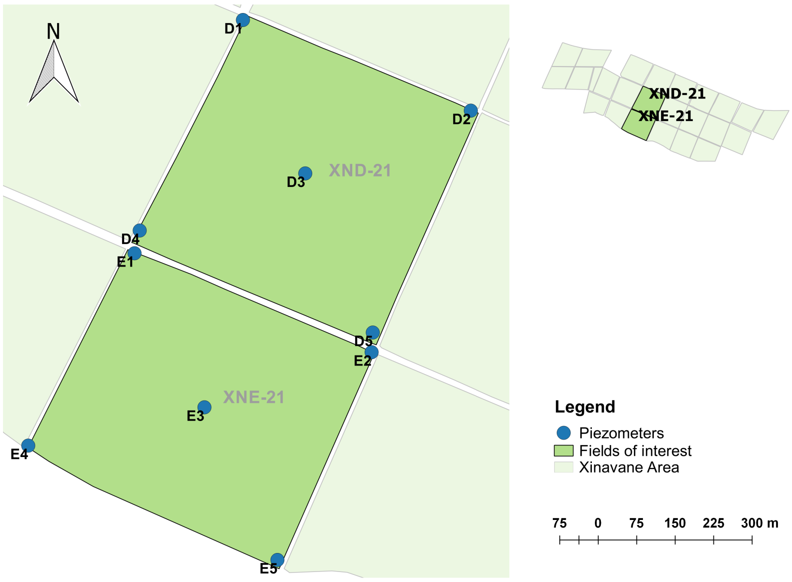


Figure 9.1: Piezometer codes and locations.

9.2. Groundwater model

The piezometer data was used to construct two separate groundwater models, one for each field. The groundwater depth was subtracted from the elevation above mean sea level (AMSL) in order to get head AMSL for each piezometer. The head data was processed in python using the Flopy package, this package creates a MODFLOW based model. MODFLOW is a finite difference model for groundwater flow written and maintained by the U.S. Geological Survey. The code is free and available from the USGS website [48] hence also accessible for specialists of Tongaat Hulett. The following parameters were used in the model: thickness of the aquifer, average hydraulic conductivity, average head values, depth of the aquifer, piezometer locations and field dimensions. Results are contour plots that show the groundwater depth in both fields and the head AMSL from which the flow direction was determined.

9.3. Slug tests

In each of the ten piezometers a slug test was conducted. This test was used to determine the hydraulic conductivity in saturated soils. Once the water inside the piezometer equaled the phreatic head, water was instantaneously extracted from the piezometer using a hand pump. The head difference and the time needed to restore the head were used to derive the hydraulic conductivity. The water level inside the piezometer was measured with a diver that measures the depth every five seconds. Detailed information about the slug test set-up and calculations can be found in Appendix B.1.

9.4. Rootzones

In order to determine the influence of groundwater on sugarcane, the extent of the rootzone was researched. This was done by digging a hole next to a sugarcane plant and visually inspecting to what depth the cane was rooted, see Figure 9.2. Seven sugarcane plants with different performance were researched, five of which were located in field XND-21 and two in XNE-21.

Figure 9.2: Inspection of the rootzone.

9.5. Water quality

Groundwater, irrigation water and drainage water were analysed for a period of 28 days on both field XND-21 and XNE-21 for the following parameters: electrical conductivity (EC), pH, sodium, total hardness, Ca-hardness, phosphate, ammonium, nitrate and alkalinity.

9.5.1. Groundwater quality

The sampled groundwater was divided into three groundwater groups depending on the location of sampling: *(i)* XND-21 (No Growth), *(ii)* XND-21 (Growth), all groundwater samples retrieved from high performing field XNE-21 were classified under *(iii)* XNE-21 (Growth), as the entire field consists of well-performing sugarcane. As this is not the case for XND-21 an additional visual distinction was made between *(i)* no growth areas and *(ii)* areas with reasonable to good growth. This brings each groundwater sample to be classified in one of the following three analysis groups:

- *(i)* XND-21 (No Growth) - Low yield field
- *(ii)* XND-21 (Growth) - Low yield field
- *(iii)* XNE-21 (Growth) - High yield field

The areas with no growth *(i)* have (close to) 100 percent yield loss and it is apparent sugarcane does not grow here (anymore). To retrieve samples Within region *(ii)* and *(iii)* five piezometers were installed, see Figure 9.1, from which water samples were taken and analysed twice a week for a period of 21 days, EC was measured in a more frequent manner, namely five times a week. Within the no-growth areas of group *(i)* no piezometers were installed, instead auger holes were drilled to retrieve groundwater. Field XND-21 consists of several spots with no growth, two of these no-growth spots were chosen to look at with more precision, namely:

- Spot X1 - part of *(i)* XND-21 (No Growth)
- Spot X2 - part of *(i)* XND-21 (No Growth)

The location of the two spots is shown in Figure 9.3. These no-growth spots were chosen because they didnt resemble each other visually and appeared to have different flora. Within these two spots five to seven auger holes were drilled along a line parallel to the field's northern edges, where each auger hole was two to five meters apart. Groundwater samples were retrieved and fully analysed. Additional holes were drilled at random throughout the spots to determine the average EC.

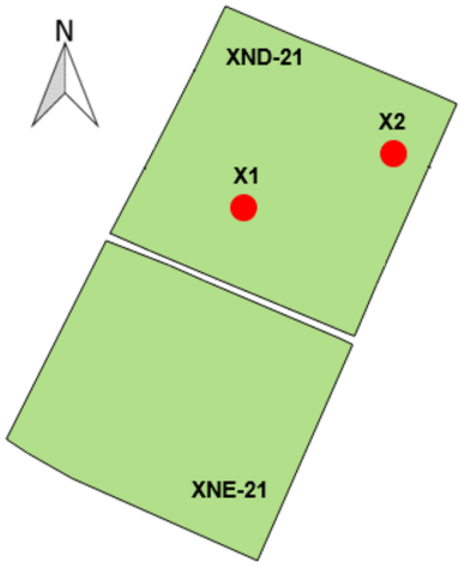


Figure 9.3: Spot X1 and spot X2.

9.5.2. Irrigation and drainage water quality

Irrigation water was collected along the irrigation channels, from the river pump to the concrete channels, earth channels and furrows reaching both fields. As both moving drainage and all irrigation water samples showed to have parameter values that didnt differ statistically, they were considered as one group for the quality analysis: *(iv)* Irrigation water. The slower running or still-standing puddles of irrigation water were taken as a separate analysis group due their alternate parameter values, resulting in two additional analyses groups:

- *(iv)* Irrigation water
- *(v)* XND-21 (Puddles)

9.5.3. Water collection and analysis

For both irrigation and groundwater samples EC, pH and Na^{+} were measured on site. Nitrate was measured directly in the field using strips, when there was an indication for presence of nitrate, further analysis was done at a later time. When immediate sample collection was not achievable, a hand pump was used for collection. For the remaining parameters a water sample of 250 mL was stored, sealed and cooled for further analysis within 48 hours according to the Drinking and Wastewater Quality Assurance Manual [49]. An overview of analysis material and their accuracy is presented in Appendix B.2.
Due to lack of availability in deionised water, *Montemor* mineral water was used with an EC of 76 $\mu S/cm$ when dilution of the water sample was necessary. The following values for calcium, magnesium and alkalinity were present within the mineral water: 1.0 mg/L as Ca^{2+}, 2.2 mg/L as Mg^{2+} and 13 mg/L as bicarbonate, respectively. Depending on the dilution ratio, the quantities were adjusted and subtracted from the measured

concentration. All samples were analysed twice and per sample the average was taken. For all water analysis groups *(i)-(v)* standard deviations were calculated with P-values. For all samples the Sodium Adsorption Ratio (SAR) was calculated and for group *(iv) and (v)* the residual alkalinity as well. Determining the statistical significance (P<0.05) was done for all measured parameters, including SAR and RA, with two sample t-tests and between each water group: *(i-ii), (i-iii), (ii-iii)*, etc. The saturation index (SI) was computed for each water analysis group using the averages for pH, temperature, alkalinity and Ca^{2+} concentrations and running them through the program PHREEQC. Due to time limitations, the mineral-saturation indices were based on the averages only, not on the entire data set.

9.5.4. Water quality material and accuracy

Material that was used per parameter is presented with its associated accuracy in Appendix B.2.

9.5.5. Water quality calculations

Sodium Adsorption Ratio

To indicate the level of water sodicity the water sodium adsorption ratio (SARw) was used, which was calculated as follows [42]:

$$SAR_w = \frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca^{2+}]+[Mg^{2+}])}} \tag{9.1}$$

When water or soil is considered to be sodic differs per country, which makes its classification somewhat inconsistent. In some countries the threshold value is 13, in many other countries the value is lower. An SAR of 6 is applied within this report, due to the thresholds often applied in research done by Mozambique's immediate neighbors [31].

Alkalinity

As samples measured fell between pH 6 and pH 10, the concentration of OH^- and H^+ are negligible [50]. Therefore, alkalinity was measured as:

$$Alk = [HCO_3^-] + 2[CO_3^{2-}] \tag{9.2}$$

Residual alkalinity

The residual alkalinity was calculated from the hardness and alkalinity values in units of *meq/L*. An RA of over 1.25 is considered to cause slight to moderate problems and an RA over 2.5 is a severe risk. A negative residual alkalinity will likely not cause any structural degradation to the soil [37].

$$RA = ([CO_3^{2-}] + [HCO_3^-]) - ([Ca^{2+}] + [Mg^{+2}]) \tag{9.3}$$

The calculations were only applied to irrigation *(iv)* and puddled water *(v)*, as this formula is based on assumptions that do not apply to groundwater.

9.6. Soil types

Auger holes were made to get a view of the different soil layers present in the field. Holes were drilled up to 2.25 *m*. Excavated soil was placed next to a measuring tape to indicate the thickness of different layers. When groundwater was found, a plopper was used to measure the depth of the groundwater and whether the water rises to the surface.
Initially, eight auger holes were made. One in each corner of both fields, corresponding with the piezometer locations. After these initial auger holes, four more holes were made halfway down the vertical axis of both fields, on both the eastern and the western side. Five more excavations were made in field XNE-21. Figure 9.4 below shows the locations of all the auger holes.
The collected soil type data was used to create two cross-sections showing different soil types. Both cross-sections were placed along vertical axis on the sides of the fields. The first cross-section includes piezometer locations D1, D4, E1 and E4. The second cross-section includes piezometer locations D2, D5, E2 and E5. Linear interpolation was used to assume soil types between auger holes.

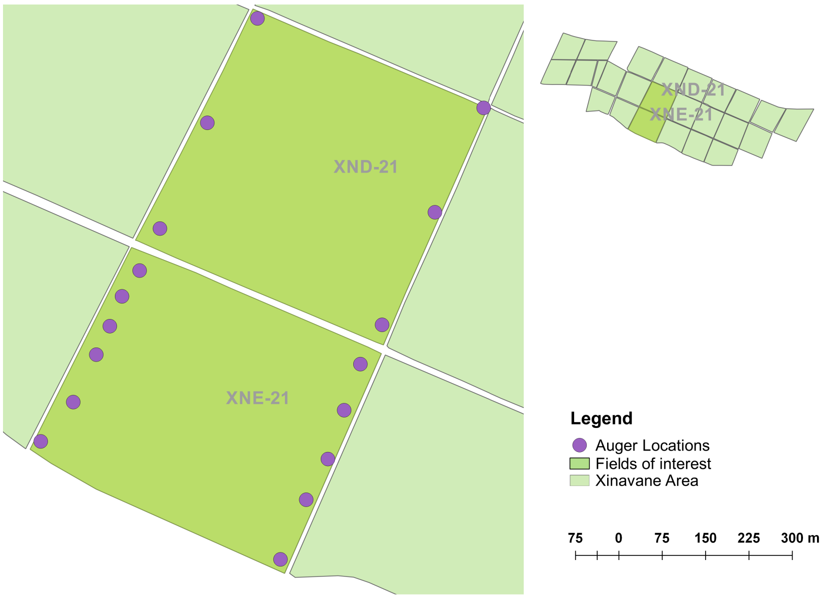


Figure 9.4: Location auger holes.

9.7. Soil quality

Along the two fields, eight indicative soil samples (of around 100 g) were taken and their pH and EC values were measured with a soil-water extract based on a fixed soil:solution, to see if there was an indication of a difference between soil salinity/sodicity within the regions of poor and good growth.

Table 9.1: Locations and depth of soil samples.

Sample #	Field	Location	Depth [cm]
S1	XND-21	X1	10
S2	XND-21	X1	60
S3	XND-21	D2	20
S4	XND-21	D2	70
S5	XNE-21	E3	18
S6	XNE-21	E3	66
S7	XNE-21	E5	9
S8	XNE-21	E5	68

After retrieval the samples were stored in plastic bags and transported to TU Delft, the Netherlands, where they were analysed in the Geosciences lab of the faculty of Civil Engineering. Here, the following procedure was followed: about 90-120 g of each sample was transferred into an aluminum tray and air-dried for several days in a climate room with a constant temperature of 20°C. 10.0 g of the air-dried sample was weighed in a plastic cup with cap. 25 mL of deionised water was added and the samples were shaken for one minute. After one hour the pH and EC of all suspensions were measured. The pH electrode was calibrated with buffer pH7 and pH4; because of low hydronium ion activity and low EC values, a more sensitive pH electrode for low ionic solutions was used. The EC electrode was calibrated with a 0.01 M KCl solution. All measurements were automatically corrected for temperature at 25°C. The 1:2.5 ratios were subsequently converted to 1:1 soil:water ratios, as this is a closer approximation of the soil EC. The values were subsequently classified in salinity degree according to the interpretation classification of soil water extracts as presented in [51].

9.8. Plant analysis

Within the no-growth spots X1 and X2 an additional plant analysis was done according to standard methods of Wageningen University [52] in order to find indirect clues on the state of the soil.

9.9. Irrigation practices on field XND-21 and XNE-21

Through interviews, several layers within the hierarchy of Tongaat Hulett were asked to verbalise their thoughts on what they think could possibly cause the dissimilarity in yield for these two fields. This was done as an additional question within the interviews that were conducted for the social analysis in Part II. On top of this, while the execution of irrigation protocol was analysed throughout Tongaat Hulett, special attention was paid to differences between field XND-21 and XNE-21. For the methodology on interviews and field evaluations, please refer to the methodology chapter of part I.

9.10. Uncertainties

9.10.1. Water quality

Besides material accuracy limitations (Appendix B.2), other steps within the analysis process could have sourced inadequate results. Firstly, due to the breakage of the initial pH meter, two pH devices were used separate from each other. Where the second device adjusted pH automatically (Palintest PT155), the initial pH meter (Greisinger G1500-GL) required for the temperature to be manually inserted in whole degrees.
Secondly, all water samples had to be diluted for hardness with mineral water in a 1:10 or 1:20 dilution ratio to get within range of the Lovibond MD610 measuring device. Alkalinity analysis also required 1:10 dilution, but not for the irrigation water samples. Puddled water had to be diluted 1:20 for all parameters, except for EC, Na^+, pH and nitrate. The dilution itself could have been performed inconsistently, as glass balloon pipets were used. On top of this, due to the absence of demi-water, mineral water was used that also contains alkalinity and hardness. There were times where Ca-hardness, which does not require dilution, had a higher concentration than total hardness, after the hardness result is corrected for.
An additional source of error is that not all groundwater samples could be analysed immediately, due to their high turbidity [53]. Sedimentation had to occur to clear out the water before chemical analysis could be performed. This was especially important for sodium and Lovibond MD610 measurements. For sodium, turbid water can clog the filter, while for the photospectrometry measurements presence of sediments can give an overestimation of parameter concentration.
In the absence of proper lab equipment, used drinking water bottles were used to store sample water. Even though bottles were rinsed with both mineral water and the sample before water was stored, contamination is still possible. With storing and sealing the groundwater samples for later analysis, there was not always enough available water to fill the entire bottle. This meant that, at times, a large oxygen:sample ratio could cause reactions within the groundwater altering its composition. Although all samples were analysed within 48 hours, some were analysed closer to retrieval than others.

9.10.2. Groundwater

First of all it is of importance to install the piezometers properly. The auger hole, which is slightly bigger than the piezometer pipes, should be filled with course sand around the filter but sealed of with clay on top in order to avoid irrigation water to infiltrate along the piezometer. If this seal is not applied properly the measured groundwater depth just after irrigation would be higher than the actual depth. Slug tests are conducted in the piezometers from which the hydraulic conductivity is concluded. However, a slug test is only applicable in a soil with a phreatic groundwater table and thus does not yield proper values in an artesian groundwater layer [54]. This conductivity in turn is used in the groundwater model. The model simplifies the actual groundwater flows and since the model produces a long term stationary output the obtained (higher) conductivity will not result in a significant difference.

9.10.3. Soil quality

As the samples were taken at alternating depths and not in bulk, their reliability to determine the sodicity and salinity levels of the soil is low. It is conventional to take samples at constant depths, as soil pH and Ec vary substantially with soil depth, and to take several sample points and bulk the soil to get a better average over the area. On top of this, it is common to do additional measurements besides EC and pH, such as the soil sodium adsorption ratio, exchangeable sodium percentage, soil texture and soil organic matter content: parameters that hold value in determining a soil's sodicity/salinity. Within the lab, the soil EC/pH are measured in a soil:water extract method, which is known to be a method that is less accurate than other soil determinations, such as the saturated paste method [55]. For all reasons mentioned above, the soil samples within this report were merely used as anecdotal evidence.

10

Results

10.1. Piezometers

Piezometers D1, D2, D3, were all in contact with a shallow aquifer, resulting in a difference between the measured head and the actual groundwater (GW) table. Piezometers D4 and D5 were in contact with a phreatic water table which means the hydrostatic pressure equals the pore pressure resulting in equal values for groundwater depth and head. The average groundwater depth in field XND-21 was 93 cm below ground level. The average standard deviation (σ) was 16 cm. The high σ values can be explained by the fact that some of the filter sand was not only applied around the filter but all the way to the ground level, see methodology.

Table 10.1: All values represent the distance below ground level in centimetres.

Piezometer	Water table	GW depth	Average head	Max. head	Min. head	σ
D1	Artesian	85	62	83	-1	20
D2	Artesian	65	22	27	14	4
D3	Artesian	55	11	42	-4	14
D4	Phreatic	-	180	204	125	25
D5	Phreatic	-	81	140	54	19
E1	Artesian	128	102	132	49	22
E2	Artesian	130	90	116	75	10
E3	Phreatic	-	78	119	18	28
E4	Phreatic	-	144	174	123	14
E5	Phreatic	-	179	186	161	7

In field XNE-21 piezometer E1 and E2 were located in the shallow aquifer, the water table at piezometer E3, E4 and E5 was phreatic. The average groundwater depth was 132 cm and the average σ was 16 cm. The deviation in the artesian layer is not significantly different from the σ of the phreatic water table. A comparison between the two fields shows a higher average groundwater table in field XND-21 and similar deviations.

10.2. Ground water model

Figure 10.1 indicates groundwater depths in fields XND-21 and XNE-21. In XND-21 the groundwater table was mostly defined by the depth of the semi-impervious layer on top of the aquifer. The depth of the aquifer seemed relatively stable throughout the field with exception of piezometer D4 where the layer drops to 170 cm below ground level. However, further soil research in the field did show a more variable aquifer depth, especially at bad spots X1 and X2.

Field XNE-21 showed more variation in the groundwater table. Figure 10.3 and 10.4 show that the aquifer is partly found in field XNE-21, starting at the drainage canal with an average depth of 130 cm and rising to 78 cm below ground level at D3. Approximately, the southern half of field XNE-21 contains a phreatic water table at a depth ranging from 78 cm at D3 to 178 cm at D5.

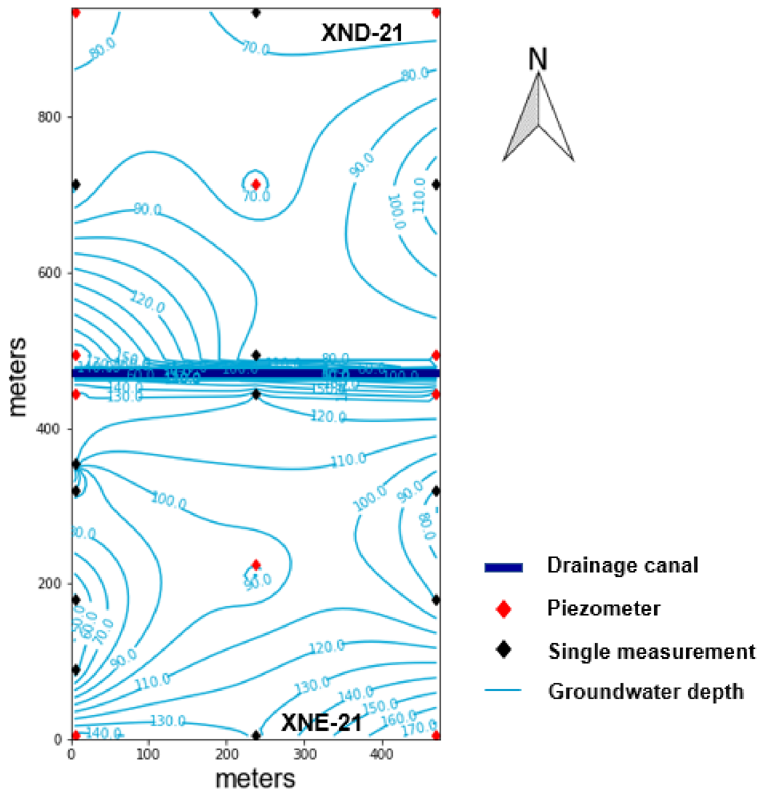


Figure 10.1: Contourmap of the groundwater depth in centimeters.

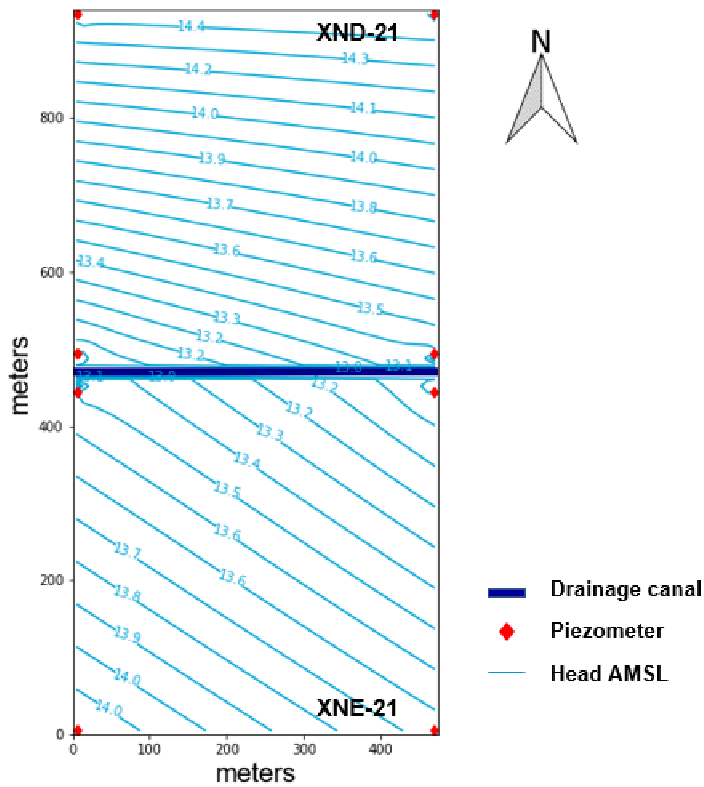


Figure 10.2: Contourmap of the head AMSL in metres.

Figure 10.2 shows the average head AMSL in field XND-21 and XNE-21. In case of groundwater flow, both maps show roughly the direction; north east - south west in field XND-21 and south west - north east in field XNE-21. In both fields low head values are found close to the drainage canal and higher values at more distance, suggesting a flow towards the drainage canal. The head AMSL in field XNE-21 follows, as one would expect, the ground level elevation, see Figure 1.5. In field XND-21, however, this is not exactly the case. The head AMSL is highest in the north east corner of the field although the slope of the field runs north west - south east, this is likely caused by the position of the artesian aquifer.

10.3. Slug tests

The hydraulic conductivity (K) values depicted in Table 10.2 show a distorted picture of the actual K values for the piezometers D1, D2, D3, D5, E1 and E2 since the water table in these piezometers was artesian not phreatic. The values of piezometer D4, E3, E4 and E5 approach K in a better fashion since the water table was phreatic. However, the distorted values still indicate the maximum velocity in the aquifer around the corresponding piezometer (assuming a constant head). Due to the artesian nature of the aquifer the K values resemble values for fine sand although the layer generally consist of a mixture of clay and fine sand. Soil material linked to K values can be found in Appendix B.1. The K values for the piezometers placed in a phreatic water show a lower velocity indicating very fine sand or silt as main soil type.

Table 10.2: Hydraulic conductivity values obtained with slug test data in md^{-1}.

Piezometer	K
D1	1.69
D2	1.78
D3	2.35
D4	0.02
D5	0.53
E1	0.56
E2	0.46
E3	0.01
E4	0.24
E5	0.02

10.4. Rootzone

In field XND-21 the main soil type was found to be clay and the sugarcane seemed to root generally with less depth, see Table 10.3. In bad spot X2 the rootzone of two plants, just five metres apart on the same furrow, were measured. The first plant was rooted in clay and performed relatively well. Although the soil type varies to sandy clay and the second plant roots deeper the performance of this plant is quite poor. The cane at location D5 preformed well, was rooted in a sandy soil and rooted all the way to the groundwater at 170 cm depth. A distinct relation between cane height and root depth cannot be formed with this small sample size. It should be mentioned that the cane, although cut each year in May and August for XND-21 and XNE-21 respectively, is over seven years old and therefore had enough time to form a considerable root system.

Table 10.3: Root depth of sugarcane with different performance in field XND-21 and XNE-21.

Location	Root depth [cm]	Cane height [cm]	Main soil type
D1	35	150	Clay
X1	35	40	Clay
X2	60	150	Clay
X2	80	50	Sandy clay
D5	60	170	Clay
E1	90	160	Clay
E5	170	190	Sand

10.5. Piezometer electrical conductivity

Table 10.4: Electrical conductivity of the groundwater measured in deciSiemens per metre.

Piezometer	Average EC	Max. EC	Min. EC	σ
D1	0.51	0.71	0.43	0.07
D2	0.56	1.13	0.49	0.18
D3	0.90	0.95	0.82	0.04
D4	1.30	1.44	1.00	0.14
D5	1.22	1.36	1.05	0.09
E1	1.15	1.20	1.07	0.04
E2	0.81	0.97	0.54	0.12
E3	0.87	0.95	0.83	0.03
E4	0.41	0.60	0.35	0.07
E5	0.59	0.65	0.45	0.05

Since all piezometers reached the aquifer (if present) Table 10.4 shows the EC of the groundwater at locations D1-D5 and E1-E5. The EC values in field XND-21 showed higher values closer to the drainage canal (south of the field). Piezometers D4 and D5 showed the highest average values of 1.30 and 1.22 dS/m, respectively. Field XNE-21 showed a similar pattern, the EC rose in the direction of the drainage canal, although the drainage canal lies north of field XNE-21. XNE-21 showed a slightly more stable EC value as the average standard deviation is 0.06 versus 0.10 for field XND-21. The σ values were small for both fields suggesting little groundwater flow.

10.6. Soil types

Figure 10.3 shows the cross-section between piezometers D1 and E4. The fields are separated by the drainage canal. The fields consist of different soil types. Field XND-21 has a clayey sand top layer. Followed by an aquifer, encased between two sandy clay layers, which limits the water from either rising or percolating. The aquifer consists of dark sand, which indicates that the aquifer is almost continuously submerged. In part of the field a clay layer is found underneath the sandy clay.

The first measurements in XNE-21 showed the same layering of soil types as in field XND-21. Further south XNE-21 however, soil layers start to change. The aquifer becomes thinner, and the aquifer material less dark. Sand is introduced as a soil layer, and takes over entirely at piezometer location E4. Looking at the Digital Elevation Model (DEM), it becomes apparent that the Incomati river used to flow just south of field XNE-21, see Figure 1.5.

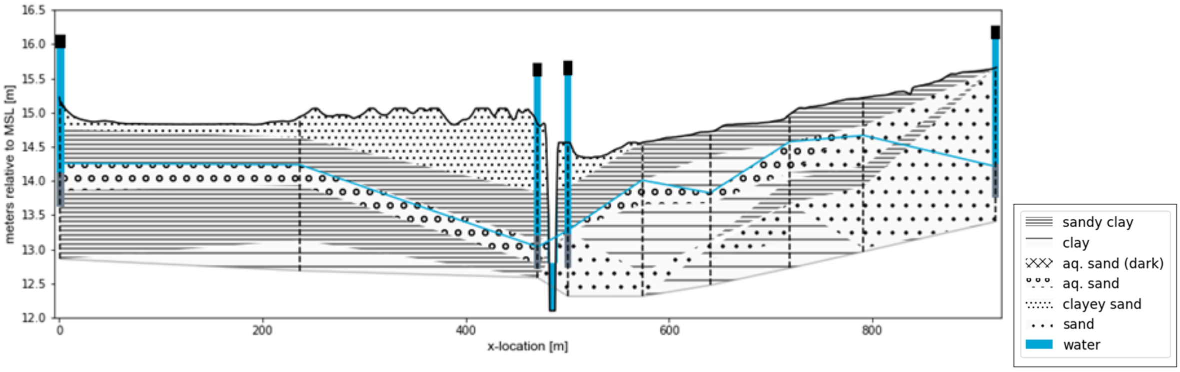


Figure 10.3: Soil types D1-E4

Figure 10.4 shows the cross-section of the Eastern side of the fields, between piezometers D2 and E5. A similar trend can be observed: in field XND-21, a sandy clay top layer is followed by an aquifer encased between two layers of clay. The aquifer material is dark. Moving to field XNE-21, the aquifer material becomes less dark. More south in field E, these layers disappear and sand becomes the major soil type. The top layer stays the same for all of the fields and reaches a depth of around 40 cm. An interview with the land preparation manager revealed that this is the same depth at which land preparation takes place (Appendix A.1).

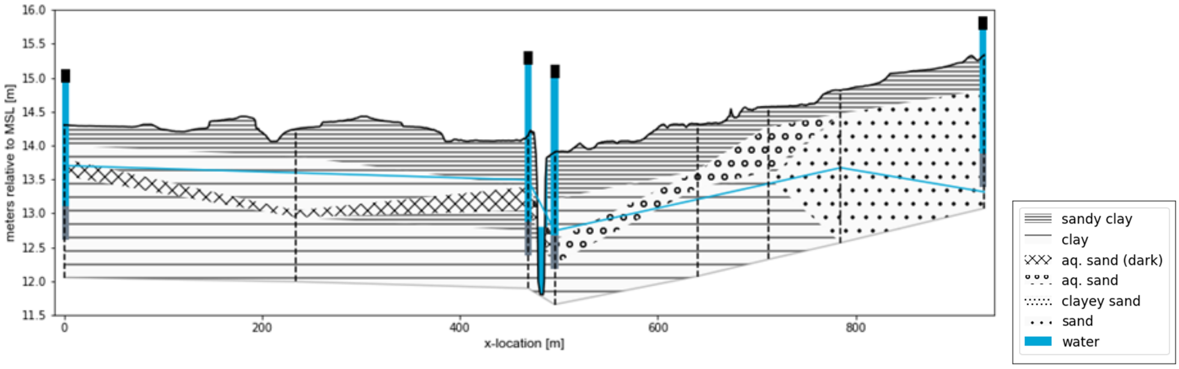


Figure 10.4: Soil types D2-E5

10.7. Soil quality

Table 10.5 shows the quality of the eight samples taken along field XND-21 and XNE-21.

Table 10.5: Indicative soil quality samples with locations and depth of sampling. All measurements were automatically corrected for temperature at 25°C. The EC*1:2.5* resembles the soil water extract EC measured in a 1:2.5 dilution of dried soil. The EC*1:1* stands for the EC if the soil:water ration would be 1:1. As was mentioned in the methodology, these results are to be considered anecdotal.

Sample #	Field	Location	Depth [cm]	Weight [g]	pH	EC*1:2.5* [dS/m]	EC*1:1* [dS/m]
S1	XND-21	X1	10	10.32	9.35	0.87	2,18
S2	XND-21	X1	60	10.28	9.17	0.51	1,28
S3	XND-21	D2	20	10.33	7.86	0.15	0,38
S4	XND-21	D2	70	10.37	6.37	0.06	0,15
S5	XNE-21	E3	18	10.28	7.26	0.01	0,03
S6	XNE-21	E3	66	10.37	7.53	0.08	0,20
S7	XNE-21	E5	9	10.40	6.80	0.15	0,38
S8	XNE-21	E5	68	10.37	7.70	0.06	0,15

It is apparent that both the EC and pH measured in no-growth Spot X1 (S1 and S2) are relatively higher than the areas where sugarcane does grow (S3-S8). Soil samples S1 and S2, who are located on the clayey soil, are alkaline and slightly saline. All other samples, S3/S8, are non-saline. Due to limitations in the sampling method, quantitative comparisons are not done and the soil quality results are considered to be anecdotal.

10.8. Water quality

The groundwater of spots that suffer severe growth reduction *(i)* and the puddled irrigation water *(v)* have higher EC and SAR values than the regions with reasonable to good crop productivity *(ii)-(iii)*, see Table 10.6, Table 10.7 and Figure 10.5. The increased SAR values are a direct result of the higher sodium concentrations found within the no-growth spots. Dark brown water puddles *(v)*, that are located on the unproductive and low-lying spots of XND-21, have the highest alkalinity values, followed by water group *(i)*. The highest sodium, EC and SAR are found for both water group *(i)* and *(v)*: this is the groundwater for XND-21's no-growth area (spot X1 and spot X2) and the puddled irrigation water. However, between *(i)* and *(v)* there is no significant difference for these parameters. The lowest concentrations of EC an sodium are found in the applied Incomati irrigation water *(iv)*. The regions with reasonable to good sugarcane growth *(ii)-(iii)* have groundwater values that are of similar quality to each other, with average EC values of 0.8-0.9 *dS/m* and do not differ from each other statistically, see Figure 10.5. The Residual Alkalinity (RA) hazard of irrigation water *(iv)* is not directly present, as the RA does not exceed 1.25. In terms of sodicity and salinity, the irrigation water *(iv)* can be considered non-saline and non-sodic with slight to moderate infiltration issues (Figure 10.6). The XND-21 puddles *(v)* show to have an average RA of 28, an EC of 2.6 and an SAR of 36 classifying it under water with severe infiltration problems and a large alkalinity, sodicity and salinity hazard.

The EC of irrigation water *(v)* remains under the clay yield loss threshold of 10%, as was shown in Figure 10.6. The groundwater values of the productive areas *(ii)-(iii)* cross the lower clay threshold value, but both remain under the 1,7 *dS/m* threshold. The groundwater SAR and EC of no-growth areas *(i)* cross both thresholds and show to be of saline, sodic and saline-sodic nature.
The pH and nutrient averages are shown in Table 10.7. Although the averages differ for ammonium, nitrate and phosphate, there is no significant difference between field XND-21 and XNE-21 or any of the measured water groups, see Figure 10.5. Nitrogen is hardly found, except in XND-21 where an occasional high value of NO_3^- is measured in between 25 and 50 *mg/L*. These higher values have occurred in 2% of the measurements and are singular events. Measurements taken at the same location, but at alternate times show that the nitrogen content has returned to the lower concentration between 0-1 *mg/L* NO_3^-. In terms of pH there are only small significant differences between some of the groups.

Table 10.6: Groundwater averages and STD of EC, Sodium, Alkalinity and Hardness, with SAR values of the five different groups: *(i)* XND-21 No growth (consisting of spot X1 and spot X2), *(ii)* XND-21 Growth, *(iii)* XNE-21, *(iv)* irrigation water and *(v)* puddle water. The unit for each parameters is: dS/m for EC, dimensionless for SAR, mg/L as Na+ for sodium, dimensionless for RA and mg/L as $CaCO_3$ for alkalinity and hardness.

		EC	SAR	Sodium	Alkalinity	Hardness	RA
(i)	XND-21 *No Growth*	**3.5** $\sigma = 0.9$, N = 24	**35** $\sigma = 29$, N = 10	**681** $\sigma = 418$, N = 10	**859** $\sigma = 194$, N = 10	**119** $\sigma = 65$, N = 10	NA
(ii)	XND-21 *Growth*	**0.9** $\sigma = 0.4$, N = 60	**4.9** $\sigma = 4.5$, N = 16	**120** $\sigma = 72$, N = 16	**168** $\sigma = 149$, N = 16	**85** $\sigma = 72$, N = 16	NA
(iii)	XNE-21 *Growth*	**0.8** $\sigma = 0.3$, N = 60	**4.7** $\sigma = 4.55$, N = 16	**136** $\sigma = 76$, N = 16	**187** $\sigma = 190$, N = 16	**87** $\sigma = 86$, N = 16	NA
(iv)	Irrigation water	**0.4** $\sigma = 0.05$, N = 42	**2.3** $\sigma = 1.5$, N = 8	**37** $\sigma = 3.4$, N = 8	**75** $\sigma = 44$, N = 8	**33** $\sigma = 26$, N = 8	**1.1** $\sigma = 0.4$, N = 8
(v)	XND-21 *Puddles*	**2.6** $\sigma = 1.7$, N = 3	**36** $\sigma = 32$, N = 3	**691** $\sigma = 609$, N = 3	**1403** $\sigma = 55$, N = 3	**94** $\sigma = 25$, N = 3	**28** $\sigma = 1$, N = 3

Table 10.7: Groundwater averages and STD of the nutrient analysis, with pH values of the five different analysis groups: *(i)* XND-21 No growth (Field X1 and Field X2), *(ii)* XND-21 Growth, *(iii)* XNE-21, *(iv)* irrigation water and *(v)* puddle water. The unit for each parameter is: mg/L as $PO^{3-}{}_4$ for phosphate, mg/L N for nitrate, mg/L as NH_4 for ammonium and dimensionless for saturation index (SI).

		Phosphate	Nitrate	Ammonium	pH	Saturation Index
(i)	XND-21 *No Growth*	**0.37** $\sigma= 0.54$, N = 10	**6.7** $\sigma = 10.8$, N = 12	**0.07** $\sigma = 0.03$, N = 10	**7.89** $\sigma = 0.38$, N = 10	0.55
(ii)	XND-21 *Growth*	**0.23** $\sigma = 0.35$, N = 16	**4.7** $\sigma = 12.7$, N = 16	**0.19** $\sigma = 0.14$, N = 16	**7.49** $\sigma = 0.71$, N = 6	0
(iii)	XNE-21 *Growth*	**0.21** $\sigma = 0.29$, N = 16	**1.0** $\sigma = 2.5$, N = 16	**0.18** $\sigma = 0.13$, N = 16	**7.28** $\sigma = 0.15$, N = 6	-0.26
(iv)	Irrigation water	**0.20** $\sigma = 0.14$, N = 8	**0.0** $\sigma = 0.0$, N = 18	**0.24** $\sigma = 0.13$, N = 8	**7.66** $\sigma = 0.24$, N = 24	-0.30
(v)	XND-21 *Puddles*	NA	**5** $\sigma = 5.0$, N = 3	**0.35** $\sigma =$ NA, N = 3	**8.57** $\sigma = 0.51$, N = 3	NA

[H]

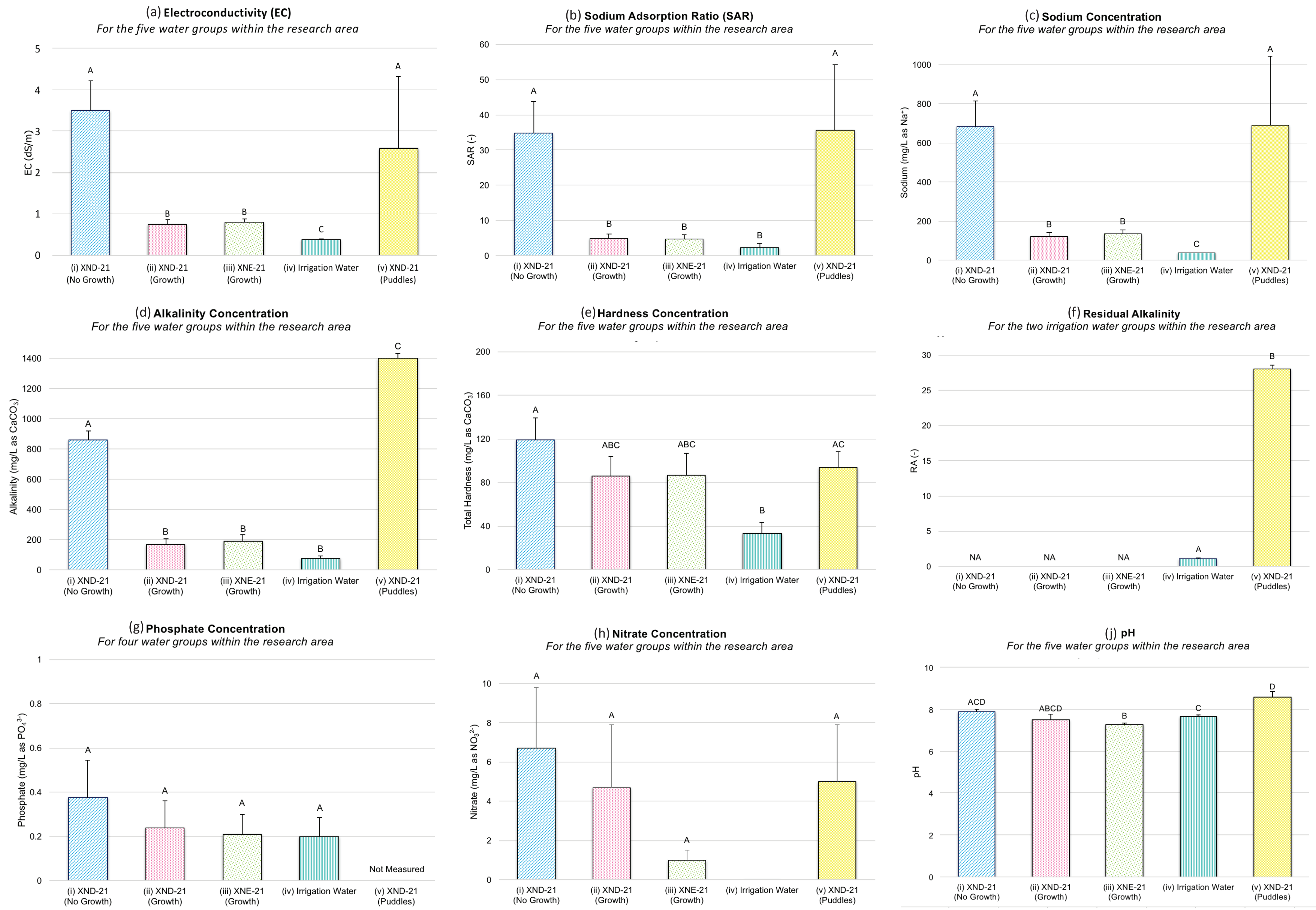


Figure 10.5: Parameter concentrations for the five water groups within the research area: (i) XND-21 No Growth, (ii) XND-21 Growth, (iii) XNE-21 Growth, (iv) Irrigation Water and (v) XND-21 Puddles. Bars show the standard error and letters shared in common indicate there is no significant difference (p>0.05) between the groups (two-sample t-test). For example, graph (e) for hardness shows that the following groups do significantly differ: (i)-(iv) and (iv)-(v). All other comparisons within graph (c): (i)-(ii), (ii)-(iii),(i-iii), etc. are of insignificant difference. For this report the means are not considered to be dissimilar when there is a higher than 5% likelihood the difference between means is due to chance.

When looking at the groundwater composition within areas of no productivity *(i)*, the chemical composition changes considerably over a relatively short distance. The largest jump in EC that is found in the field is 1 *dS/m* between two auger holes that are 0.45 *m* apart. This variability is also apparent in the cross-sections of spot X1 and X2 (Figure 10.7). Additionally, EC and SAR values are at their highest for the areas where there is no crop production, and lowest along the edges of each spot where sugarcane growth returns. At times there is reasonable EC, yet no growth (Spot X2). However, the hardness and sodium values in that same point result in groundwater with high SAR. Combined EC and SAR values that are both below the yield thresholds are for spots X1/X2 solely found along the edges where crop production has returned to reasonable yield.

10.9. Visual characterisation no-growth spots X1 and X2 (XND-21)

The plant analysis (see Appendix B.3.2) shows that the flora on spot X1 and X2 mainly consist of aquatic plants with reasonable to high salinity tolerance. Spot X2 platforms a larger quantity of plants and especially those that do well on soils that hold large amounts of water. Dried out regions, puddles, and soil crusting was found along spot X1, with white crystals deposited along the furrows. After irrigation the dry crust of X1 fell apart into a porridge-like composition. These symptoms are also found in other no-growth regions and are particularly noticeable at the lower ends of the field, close to where dark coloured irrigation puddles form. For pictures of both spot X1 and X2, please refer to Appendix B.3.

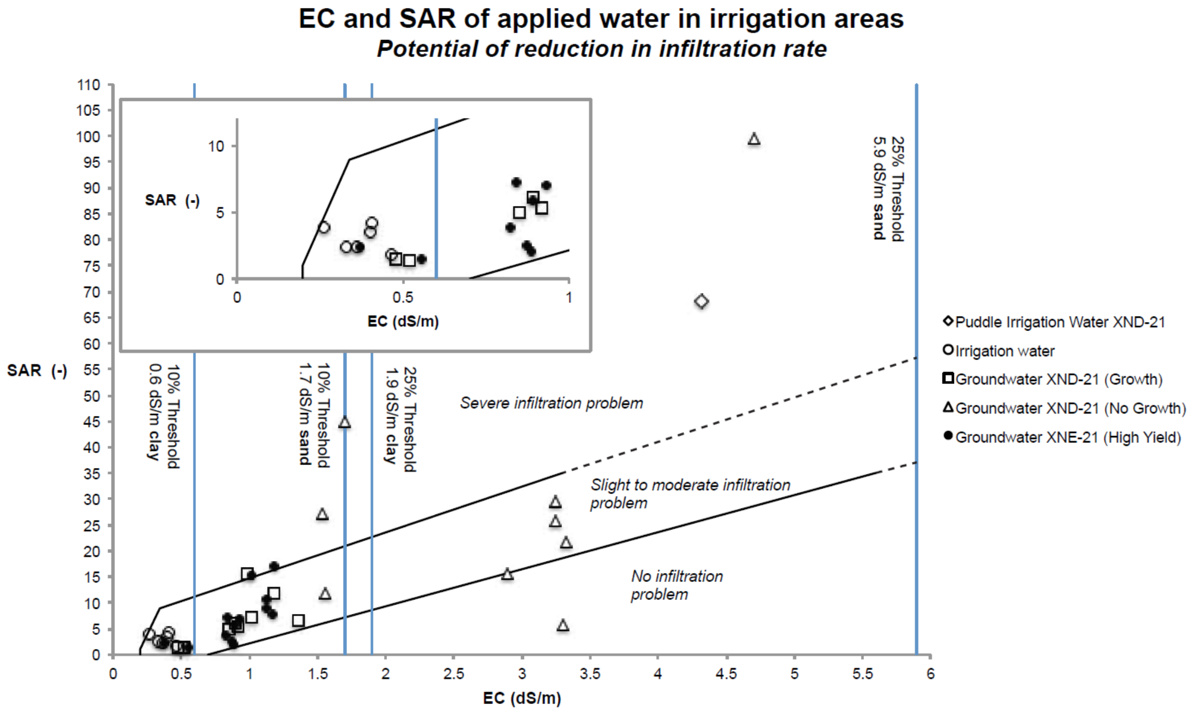


Figure 10.6: SAR and EC for all measured samples including ranges.

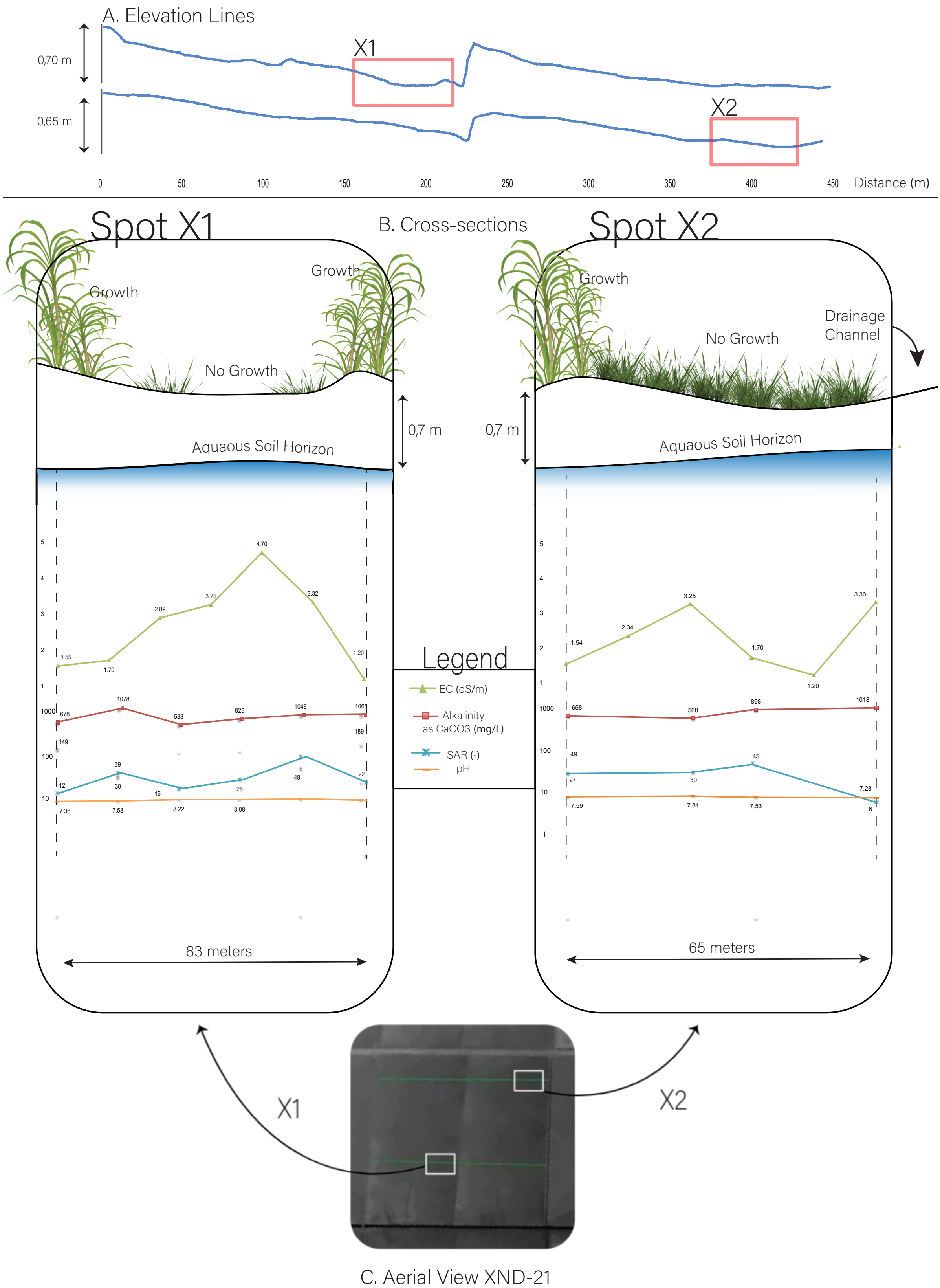


Figure 10.7: Visualisation of bad spots X1 and X2, showing the EC, sodium adsorption ratio, pH and alkalinity concentration of the grounwater.

10.10. Execution of irrigation practices - XND-21 vs XNE-21

Both in XND-21 and XNE-21 the irrigation procedure is executed in a similar manner and no considerable differences were observed, except one: The irrigators create dams on XND-21, which causes water to remain in one spot for longer periods of time and stops the flow through the furrows, within XNE-21 these dams are not observed . From field interviews, it has become apparent that this is done with the aim to increase infiltration (Appendix A.1) as XND-21 has a lower infiltration rate than XNE-21.

10.11. Tongaat Hulett's view on XND-21

Employees that work in different layers of Tongaat Hulett's hierarchy were interviewed on their thoughts about the problems within field XND-21. Figure 10.8 shows the outcome. For more information on the departments and levels within Tongaat Hierarchy, please refer to Part I, Figure 4.1. It can be seen that the following causes are shared among different departments: soil, over-irrigation, drainage and salinity, although no departments state the exact same combination of issues. The field employees are the only ones that mention slope as a possible explanation for XND-21's yield reduction.

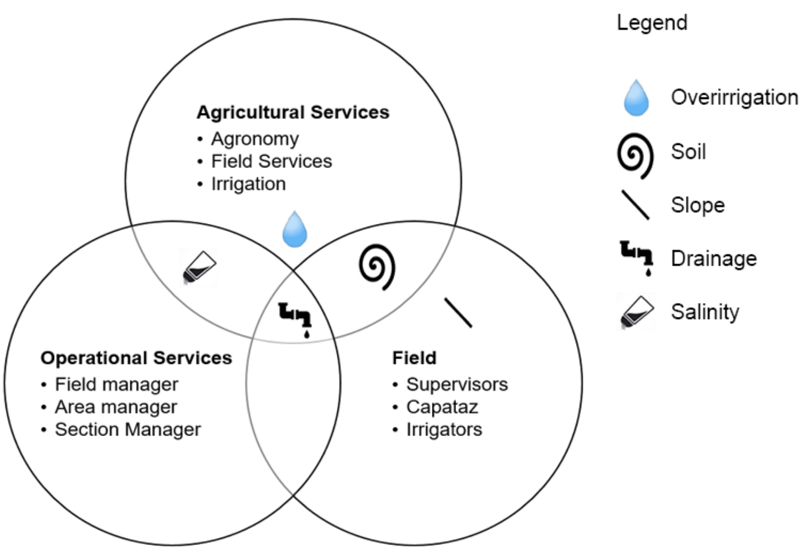


Figure 10.8: Concept Map. Based on the hierarchy tree shown in the chapter Irrigation Practices a division can be made between the agricultural services, operational services and people working directly in the field. When asked what they thought the cause of yield variability was between XND-21 and XNE-21, these were their answers.

11
Discussion

11.1. Groundwater flow

Table 10.1 shows that the groundwater table (the top of the aquifer in XND-21 and partly XNE-21) is mostly close to ground level and finds itself at depths of about $1m$. The same table shows that the head values differ within the fields, which indicates possible groundwater movement. It can be said, however, that the groundwater is not flowing near its maximum velocity based on present head, even though lateral groundwater flow is not researched. This is based on the fact that the head values in the piezometers do not deviate much on a daily base and EC values stay relatively constant. If flow would be present, it can be concluded from Figure 10.2 that the groundwater in field XND-21 would flow from NE to SW and in XNE-21 from SW to NE. Where the flow in XND-21 does not seem to follow the ground level elevation. XND-21's flow direction is most likely caused by the artesian aquifer. This layer is sealed on top by a semi-impervious layer and presumably fed by a distant water body; this semi-impervious layer causes an inability of the water table to balance out elevation differences and hence explains the difference between groundwater table and head.

11.2. Irrigation water and soil

The SAR, EC and RA of the irrigation water show that the Incomati river has low salinity and there is no indication to assume that the irrigation water forms a direct sodicity, alkalinity or salinity hazard for the fields (Figure 10.6). However, all irrigation water will add salt to the soil: Especially when the soil is heavy clay and when there is no adequate leaching, these salts will concentrate within the soil profile [15] contributing to human-induced salinisation [55]. The soil of XNE-21 is less prone to such accumulation, compared to field XND-21, due to the partial absence of the impervious layer and its generally more sandy soil (Figure 10.4). This distinction is caused by the free drainage that is possible through coarse sand and the fact that clay particles hold on to the water more strongly than sand particles do, meaning a clayey soil has more time to take up salts. Soils with higher clay content tend to have a higher cation exchange capacity, which is closely related to their water retention abilities [34].

11.3. Compaction

Besides salt accumulation, clay soils are also more susceptible to compaction. Although both fields have compacted soil, employee's state it is a more significant issue for XND-21 (Appendix A.1). Compaction is undesirable as it can influence furrow irrigation effectiveness, which can be caused by for example machines or by soil texture difference. Compaction causes alternate water advance rates between un-compacted (soft) and compacted (hard) rows. This can be seen in E.1, where XND-21's hard furrows have slower infiltration and faster advance rates than in XNE-21. Even if the flow in hard furrows is reduced to similar rates as a soft furrow, infiltration through hard rows may still be 50 to 100% less than in the soft furrows [21].

11.4. Irrigation water evaporation

An additional soil troublemaker is the presence of low elevation areas within XND-21's topography (Figure 1.5), this is an issue that has also been addressed by multiple people within Tongaat Hulett (Appendix A.1).

When there is insufficient slope to dispose of excess water, irrigation and rainwater can accumulate. This process is intensified by poor drainage, slow infiltration rates (see Appendix B.3) and compaction; all processes that occur more in XND-21 than in XNE-21. The accumulation process is also strengthened by over-irrigation. From interviews it has become apparent that this happens on both fields (Appendix A.1), yet it has stronger consequences on XND-21, due to the composition of the soil. Water accumulation causes salt concentrations in the irrigation water to increase by evaporation, before the water infiltrates in the soil. This shows that even high quality irrigation water can have detrimental effects on soil when enough time passes and when not managed properly [55]. The low quality water puddles that have been found on XND-21 confirm that this is indeed the case on no-growth spots, as seen in spot X1 and spot X2 (see Appendix B.3).

11.5. Irrigation practices

With the use of a shovel, irrigators build small dams in both earth feeders and furrows. This is done to stop and hold the water in place, with the intention to increase infiltration rates (A) and lower advance rates (Appendix A.1). This is a technique applied to field XND-21 as infiltration is visually poor and advance rates are high, due to the compacted furrows. Although the irrigators intuitively feel these dams will better the field (Appendix A.1), it will only add to puddle forming and irrigation water evaporation; especially when dams are not removed, which is often the case. Dams are also constructed right before the drainage channel (Appendix A.1). The reason for this is double-fold. Firstly, it prevents drainage water to enter the furrow lines in field XND-21, as in some parts the drainage channel is at higher elevation than the furrow. Secondly, it is done to manipulate the pathway of irrigation water in a way that will allow a 180-degree turn into the next furrow. Although this is not according to protocol, it is an effective way to reach daily targets within a shorter amount of time (Appendix A.1). These drainage dams are also frequently not removed, contributing to more puddle formation.

11.6. Soil and groundwater

Once the (more saline) irrigation water is infiltrated, sugarcane roots take up fresh water, until the osmotic water pressure reaches its threshold or water uptake is sufficient [56]. The residual soluble salts that are not taken up by the negatively charged clay soil then infiltrate further downwards. The groundwater SAR and EC values of the no-growth spots (Figure 10.7, and 10.6) surpass thresholds and confirm the presence of salinity and sodicity within the groundwater of Spot X1 and X2. This could mean that the soil present is also saline and sodic. Although it is risky to make assumptions on soil quality solely based on water measurements [55], several results do point into that direction. Firstly, the soil crusts and plants (B.3.2) indicate soil problems. Secondly, even the highest EC/SAR values that are found for groundwater (figure X), remain below values that would induce the 100% yield losses that are found on the bad spots within XND-21, making it likely that other factors, such as soil, play a role. The soil-groundwater interactions are still a point for discussion, but before drawing any further conclusions, the following summation has yet to be taken into account:

- There are areas where the groundwater is at similar depth as the no-growth spots, yet there is no groundwater salinity. This indicates that salinity does not originate from groundwater evaporation. Although groundwater evaporation can play a role in worsening areas that have already been affected, it is not interpreted as main cause.
- The high variability of quality parameters could be due to the in-homogeneity of the soil, and thus preferential flow paths within the soil, distributing the saline soil moisture in a non-uniform manner.
- Based on Figure 10.3 it is thought that when the irrigation water percolates downwards, infiltration will stop before it reaches the aquifer, due to pressure differences between the water in the aquifer and the infiltration water. This does not necessarily mean that soil moisture cannot salinise the groundwater.

11.7. Waterlogging and salinity

Due to the fact that water infiltration is limited because of the presence of the impervious layer other problems arise: like waterlogging. Soil is considered to be waterlogged when it is saturated with water most of the time in a way that anaerobic conditions prevail. Waterlogging causes an oxygen deficiency for plant roots due to excess water in the soil. Long exposure to waterlogging also causes a decrease of sugar content and can eventually lead to crop death. Waterlogging can be a consequence of soil impermeability, a high water table or the presence of an impervious layer [57]. The latter is most likely the cause of waterlogged areas within XNE-21 and XND-21 (Figure 10.7), as in both fields an aquifer was found, which is vertically sealed by a semi-impervious layer on both sides (Figure 10.4 and 10.3). The colour of this aquifer is blackish, which is likely caused by a long period of submergence, under which the soil undergoes reduction and turns dark [58].

It is only in the saline spots of XND-21, that waterlogging contributes to impaired crop growth. This occurrence is not uncommon, as waterlogging often goes hand in hand with soil salinity, due to the fact that waterlogged soils prevent leaching of salts [4]. This rings especially true for irrigational lands, and its effects can be found in spot X2 of field XND-21, where both groundwater quality (Table 10.6), plant analysis (Appendix B.3.2), root depth (Table 10.3) and soil colour (Section 10.6) confirm the presence of a waterlogged saline area. This strengthens the assumption that groundwater salinity and depth is not the primary cause of salinisation within field XND-21. Rather, it is the presence of waterlogging that intensifies soil salinity in areas that are already more susceptible due to their low-lying nature, like spot X1 and spot X2. Waterlogging can also be consequence of sodic soils, due to the swelling that can occur within dispersed particles [59]. This can create a positive feedback loop where sodicity and waterlogging enhance each other.

11.8. Groundwater alkalinity & pH

Waterlogged spots X1 and X2 have higher alkalinity (Table 10.6 and Figure 10.5) groundwater values than the other regions. The most common causes of alkaline ground waters are dissolved carbonate minerals and CO_2 present in the atmosphere or soil above the water table [60]. Waterlogging can cause growth-reducing gases (like CO_2) to accumulate in the rootzone [61], increasing the amount of carbon dioxide in the soil. This CO_2 can become hydrated to form carbonic acid, which then undergoes two stages of dissociation to form HCO_3^- and CO_3^{2-}. With an average groundwater pH of 7.84 (Table 10.7), HCO_3^- is the dominant carbonate species, which explains the higher values for total alkalinity within the waterlogged areas. Additionally, if the soil contains carbonate, the presence of CO^2 in the percolating water will allow for the carbonates to dissolve as shown in Equation 11.1:

$$\begin{aligned} CaCO_3 &\leftrightarrow Ca^{2+} + CO_3^{2-} \\ CO_3^{2-} + H_2O &\leftrightarrow OH^- + HCO_3^- \end{aligned} \tag{11.1}$$

Which will increase groundwater alkalinity even further.

11.9. Soil quality

The higher groundwater and soil pH of the no-growth spots (Table 10.5) could be a consequence of sodicity, due to alkalinisation caused by the hydrolysis of Na^+ ions or Na_2CO_3 within the soil, as shown in Equation 11.2 [106].

$$\begin{aligned} Na_2CO_3 + 2H_2O &\leftrightarrow 2Na^+ + 2OH^- + H_2CO_3 \\ Clay - Na^+ - Na^+ + H_2O &\leftrightarrow Clay - Na^+ - H^+ + Na^+ + OH^- \end{aligned} \tag{11.2}$$

The soil pH and presence of carbonate, however, cannot be determined solely based on groundwater measurements and anecdotal soil samples (Section 9.10.3). Even though the soil samples confirm the suspicion of a sodicity issue, it is highly recommended to research the soil with a more reliable method, a higher amount of samples, in bulk, and not just for the pH and EC, but also parameters like exchangeable sodium percentage that can help determine its true salinity and sodicity state.

11.10. Tongaat's view on XND-21

Most processes found to be causes of the yield difference between XND-21 and XNE-21 have been mentioned by employees of Tongaat Hulett, indicating that the awareness on the processes behind yield depression is high. Interestingly, the field employees were the only ones to mention slope as a possible cause; yet salinisation was not mentioned by this group. Conceivably, this matches the train of thought of the irrigators that building dams will aid in increasing infiltration, as opposed to reducing irrigation water and soil quality.

12
Conclusion

This part aimed to investigate variables and processes influencing the difference in sugarcane yield between low- and high-performing fields XND-21 and XNE-21 within Tongaat Hulett by answering the following research question:

What processes cause the crop yield difference between field XND-21 and XNE-21 within the Xinavane area and how do these processes develop?

It can be concluded that there are several significant differences between field XND-21 and XNE-21 resulting in the observed yield difference. The possible causes put forward by the employees of Tongaat Hulett; soil type, over-irrigation, drainage, salinity and slope all seem to be influencing factors, however not all are causes, some are effects. The main processes driving the yield difference appear to be salinisation and sodification. These processes are consequences of different aspects in field XND-21. The main soil type in field XND-21 is clay, where it is sandy clay in field XNE-21, the clay is more prone to processes such as compaction which generates a lower infiltration rate. This lower infiltration rate results in a higher advance rate to which the irrigators react by building small dams inducing over-irrigation and puddle forming in low elevation areas. These low laying areas are characterised by reverse slopes resulting in spots with standing water that cannot runoff neither infiltrate quickly. This water accumulation causes salt and sodium concentrations in the irrigation water to increase by evaporation eventually reducing the quality of the irrigation water. Likewise, the shallow aquifer found in field XND-21 contributes to the salinisation and sodification of the soil since water cannot percolate towards the groundwater in contrast of the mainly phreatic groundwater table found in field XNE-21. This shallow groundwater table appears to cause waterlogging at several locations within field XND-21. Both processes, salinisation and sodification, eventually result in no growth spots in field XND-21 with high EC, SAR, alkalinity and pH values. The high salt concentrations change the osmotic water pressure causing insufficient water uptake for the sugarcane. The high sodium concentrations are damaging the soil structure causing dispersion, swelling and compaction, reducing infiltration further. Overall, it can be concluded that the main processes causing the crop yield difference between field XND-21 and XNE-21 are salinisation and sodification which in turn are developed and enhanced by the differences in soil type, irrigation practice, slope, and groundwater table. However, to confirm this, a detailed soil analysis should be performed.

13

Recommendations

It became evident in chapter 1 that field XND-21 suffers different problems resulting in a reduced annual crop yield. Compaction, salinity, no growth spots and high sodium concentrations seem to be the biggest contributors to this yield reduction. In this section recommendations are discussed in order to regain a healthy and homogeneous soil.

First, the high salinity and sodicity could be reduced by leaching the soil. This technique entails the application of irrigation water in excess of the soil moisture depletion level. The excess water percolates through the rootzone dissolving the salt and sodium ions and carrying them towards the groundwater table. The total volume of this excess water over the total volume of irrigation water is known as the leaching fraction. Ensuring a large enough leaching fraction prevents most cations from accumulating in the rootzone.

There are roughly two types of leaching, maintenance leaching and reclamation leaching [4]. Since the soil in field XND-21 is already sodic/saline the required type will be reclamation leaching. The volume of excess water needed in reclamation leaching depends on the initial soil salinity, soil type, desired final soil salinity, the depth of the rootzone and the infiltration rate. Regarding field XND-21 the challenge will be increasing the infiltration rate. The current low infiltration rate restricts the volume of excess water in which the ions can dissolve making it difficult to reclaim the soil.

Second, improving the infiltration rate to make leaching possible. Improving the infiltration rate in XND-21 is somewhat complicated since the main driver of the poor infiltration is likely the high sodium concentration. Therefore the sodium should be leached, however the soil needs a high infiltration rate from the outset to do so. If the field can be ploughed to a depth of 1.20 metres and then tilled to mix the upper sandy clay layer, the underlying clay layer and the sandy aquifer layer, it could be possible to get a more homogeneous less compacted first meter of soil with an improved permeability. This higher permeability allows for more infiltration of the irrigation water in the first meter. However, when the artesian aquifer is reached with the plough the water table is likely to rise significantly at certain locations, resulting in a mud pool in which machinery cannot work, leaving the field unusable. It is therefore recommended to start ploughing at the end of the dry season.

A higher permeability that allows for leaching is a fine start in reclaiming field XND-21 however, there are complementary options like the use of calcium. Calcium can be used in the reclamation of sodic soils by adding it directly to the field or dissolving it in the irrigation water. The calcium ions will replace the exchangeable sodium ions in the soil, thereby reducing the dispersion and swelling of the soil and improving the permeability. The higher permeability allows for better infiltration, making sodium and salt leaching more effective. Several other types of compounds suitable for reclaiming sodic soils are: chloride, calcium nitrate, gypsum and dolomite [4].

Third, installing subsurface drainage. For effective leaching it is of importance to keep the groundwater table at depth so the water can percolate through the complete rootzone before it reaches the groundwater table. However, after ploughing the artesian nature of the groundwater causes the water table to rise significantly at several locations, making leaching impossible. By placing drainage pipes perpendicular to the furrows and sloping towards the drainage canal the water table could be kept at a fixed depth. The minimum gradient for a drainage pipe is 0.25 percent [62], this implies a drop of 1.19 metres since the field is 475 metres in length. Regarding the drainage canal (1.90 metres below ground level) the starting depth of the drainage pipe needs to be at 0.66 metre below ground level in the north. The water level at the drainage canal should then be kept below the elevation of the drainage pipes (1.85 metres below ground level) in order to make maximum use of the system. Compared to the current situation the depth of the groundwater table will not change significantly since the leaky layer keeps the groundwater currently at a depth of 0.75 metre in the North towards 1.80 at the drainage canal. Furthermore, the root water uptake will not change significant since the sugarcane does not seem to root more than 0.6 metres in the clayey soil of field XND-21. It should be noted that subsurface drainage has a downside, the cations that will be washed out will end up in the drainage water which is used by farmers downstream.

The fourth and final recommendation for reclaiming the soil of field XND-21 is levelling the field. This relatively simple and cheap technique should supplement the above mentioned measures. A smooth sloping surface without reverse slopes prevents ponding and enhances the effectiveness of the leaching as the infiltration volume will be more uniform.

13.1. Maintaining the obtained situation

Since the above mentioned measures should result in a field with lower salinity and sodicity concentrations and a higher permeability it is of vital importance to maintain the obtained situation. The following recommendations can prevent degradation once more.

Regarding the uniform distribution of the irrigation water. Shortening the advance time can be beneficial since a long advance time causes more water to infiltrate at the start of the furrow then at the end. The advance time is determined by the length, the gradient, the roughness and infiltration rate of the furrow. Therefore are shortening the furrows and maintaining a uniform smooth slope possible measures to keep the field in proper condition.

Over-irrigation has shown to be a difficulty as well and thus two options to reduce over-irrigation are: alternate furrow irrigation and partial wetting. Irrigating every other furrow supplies water to one side of each furrow ridge, but the wetting pattern is usually much more than that. This technique lets the irrigator apply water to more surface area in a given amount of time compared to irrigating every furrow. Research indicates that alternate furrow irrigation results in yields comparable to those achieved when every furrow is irrigated [6].
Using alternate furrow irrigation, see Figure 13.1, water applications may be reduced by 40 to 50% [6].

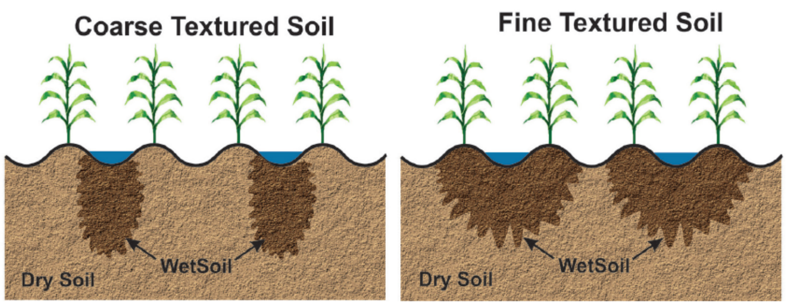


Figure 13.1: Alternate furrow irrigation.

Infiltration is not reduced by half because of increased lateral movement when watering alternate furrows. Lateral water movement in the field can be checked using a soil probe in the dry rows. Since data gathered with the SMP in this research has been proven unreliable, other methods can be used as well. For example the 'feel'-method already applied in the plantation. An added benefit of irrigating alternate furrows is that by applying less water when irrigating, more storage space is available for precipitation after an irrigation event. Alternate furrow irrigation is already being practised in times of drought to save water. It differs the irrigation pattern as lateral movement of water is possible on clayey soils like XND-21.

When applied correctly, and efficiently, alternate furrow irrigation (and normal furrow irrigation) is one of the most efficient irrigation techniques for clayey soils, both water- and cost wise (Appendix A.1).

Partial wetting is the concept of applying irrigation to field segments when considered necessary through visual observations. As this technique only irrigates parts of the field when necessary, it reduces over-irrigation and increases water efficiency [30]. However, this is a different technique, adding to the existing list of profits and loss, CanePro and "feel"-method currently used for decision making processes concerning irrigation. Another downside to partial wetting is that current irrigation structure in the field (i.e. furrows) is set up in lines. If the end of a furrow is in need of irrigation, the entire line needs to be used. Thus increasing irrigation amounts. Finally, in order to achieve equal partial wetting application over the entire plantation, field managers need to be trained when to apply partial wetting.
In conclusion concerning reducing over-irrigation, two viable options can be considered. This research did not examine the costs and benefits of all options listed above, so any conclusions on which option fits best cannot be made.

III

Decision Support System

14 Introduction

In this part the Decision Support System (DSS) will be discussed. As mentioned in the general introduction, two research questions will be answered here.

- To what extent is an accurate hydraulic model feasible and how does it contribute to the possibility of implementing MPC at Tongaat Hulett?
- What is the interchange between the water inlet and soil moisture content within the Tongaat Hulett area between 1 April 2017 and 31 March 2018?

A short introduction of two concepts, Model Predictive Control (MPC) and the desired DSS operation scheme, are given in order to explain the two following chapters. The first chapter of part III explains the MPC of the operation scheme in more detail. The second one discusses the remote sensing part.
The first concept to be introduced is MPC. One needs to be familiar with this concept in order to fully understand the second concept, which is application to scheduling irrigation events.

14.1. Model predictive control: an introduction

Model predictive control is an advanced method of process control. It is based on iterative, finite-horizon optimisation of a certain system or process, so a process that is constantly repeated and includes future predictions up to a certain point. The control method is also known as receding horizon control. The control method consists of the following components [63]:

- An internal model that is used to predict the future state of the system given a certain irrigation schedule up to a certain time horizon.
- All controllers optimise an objective function. An objective function indicates what the cost is of certain states and inputs of our system. In this case the objective is to minimise water stress, so to keep the soil moisture content (SMC) within a certain desired range.
- However, not all irrigation schedules are feasible. Constraints force controllers to only compute realistic control actions and that feasible system states will be achieved. To give an example, it prevents the flow of water from being larger than the pump capacity.
- When the optimal sequence of (future) control actions is determined by the controller, only the first (few) steps of the control action are executed. When new information becomes available the optimisation problem can be solved again to return a new irrigation schedule. This enables the controller to re-assess the situation one time step later, when actual measurements from the system are fed into the controller and new predictions are available.

Model predictive control has many practical advantages. It has a straightforward formulation, based on well understood concepts, it handles constraints and is based on a model [64].
To prevent any confusion, model predictive control is a method whereas a model predictive controller applies the concepts of the method in practice.
Model predictive control is the best option given the current infrastructure. Economically it is not feasible to make major alterations to the system or to place sensors. Using MPC, this is not necessary and only a minor investment has to be made for major improvements in water efficiency and possibly crop yield.

14.2. The decision support system scheme

Before the concept is explained, it is first motivated why a DSS is necessary. A DSS can increase crop yield as it enables managers to irrigate fields at the right time with the right magnitude. This prevents fields from being flooded or being too dry. It also enables managers to do so on a larger scale with relatively little effort. The DSS takes out possible human errors and present the irrigation advice in a clear manner, making it less labour intensive for the manager to make the right decisions. In the end, a DSS improves the cost-efficiency of growing sugarcane. Now it is clear why a DSS is necessary, the system will be explained. This explanation is done based on Figure 14.1, which shows a schematisation of the process involved.

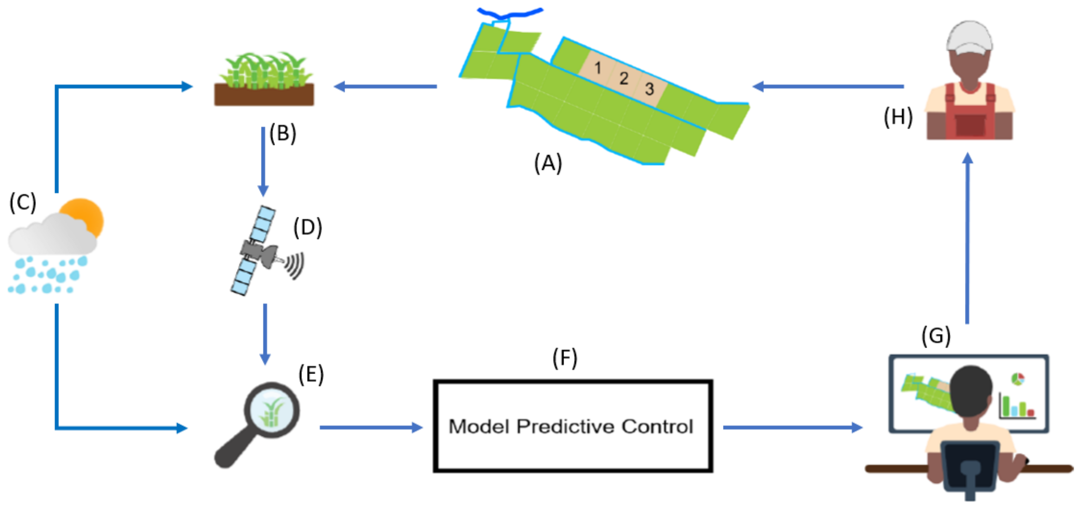


Figure 14.1: The DSS operation scheme.

Water is crucial for sugarcane to grow. Water required to grow is extracted from the soil by the roots. Water is supplied to the soil in two ways: by irrigation and precipitation *(element C)*. As it is hard to measure exactly how much water is available to the plant, soil moisture content (SMC) is used as the variable that indicates how much water is available for the crop, in the area of interest *(element A)*. SMC of the top ten centimetres of the soil layer can be measured using satellite data and an algorithm created by VanderSat *(element D)*. Other meteorological data, besides SMC, such as temperature, precipitation, growth stage of the sugarcane, are studied *(element E)* and also used in the internal model of the model-predictive controller. Based on these data and constraints, which will be elaborated on later, the controller *(element G)* gives an optimal irrigation advice to the area manager *(element H)*. This process is repeated when new information about, e.g. employee availability, weather or water availability becomes available. In short, with every iteration the DSS returns an optimal irrigation schedule to the manager based on the available information which the manager can then use to ensure the SMC stays within a desired range. This results in adequate water availability to the crops *(element B)*, i.e. no water stress. This, in turn, results in a higher yield.

15

Model predictive control

At the foundation of the model predictive controller is the internal model. As mentioned in Section 14.1 it consists of two linked models; a hydraulic model and a model that predicts the SMC. The latter one is not discussed in this report as only the hydraulic model has been researched in this project.
The hydraulic model investigated here consists of four parts: canals, structures, disturbances and the controller. By modelling these four parts of the water system a model predictive controller can predict the future water levels resulting of disturbances and control actions. A short description of each part is given first.

Canals Dynamic behaviour of flow can be accurately described by the non-linear Saint-Venant equations. However, due to the large computational burden simpler models are often used, such as the Integrator Delay (ID) model. For more information about the ID model and its assumptions, please refer to Schuurmans [18]. The model can be described by Equation 15.1 for the downstream water level:

$$h(k+1) = h(k) + \frac{T_s}{A_s} Q_{in}(k - k_{delay}) - \frac{T_s}{A_s} Q_{out}(k) + \frac{T_s}{A_s} Q_d(k) \tag{15.1}$$

where $h(k+1)$ is the water level in the reservoir at time step $k+1$, $h(k)$ the current water level, T_s the sampling time of the model, A_s the reservoir area, $Q_{in}(k - k_{delay})$ the delay flow to the reservoir, Q_{out} the flow out of the reservoir, and Q_d the disturbance inflow to the reservoir due to offtakes, rainfall, or evaporation to give some examples. A visualisation of the ID model can be seen in Figure 15.1.

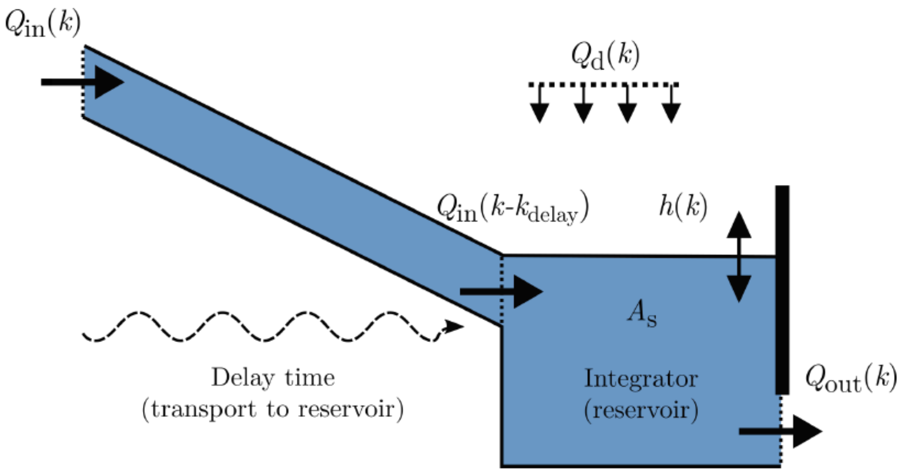


Figure 15.1: Integrator Delay model of a single canal reach [65].

Structures Modelling of hydraulic structures, gates and weirs to be more specific is not attempted except for one weir. There are only a couple of weirs intact whereas the major part is destroyed, see 15.4. Modelling these destroyed weirs is pointless as they change over time, e.g. a bag or vegetation gets stuck or gets free. During field work it was noticed that some weirs can change hourly. This alters the hydraulics of the structure, making it necessary to remeasure the structure again.

Disturbances Irrigation systems are influenced by disturbances such as rainfall, improper operation of gates, leakages and off-takes. However, rainfall predictions can be included and accounted for (given predictions are accurate). Improper operation of gates means inaccuracies in implementing control actions and/or at the wrong moment. Off-takes are generally accounted for as it is the water flowing out of the canal onto the field. Leakages are hard to account for because they are hard to detect, especially if it is leaking subsurface.

Controller The controller is not discussed in this report as only exploratory work has been done to investigate how sophisticated the model, and thus controller, should be. The controller will be designed later in the IWACA-TECH project.

15.1. Methodology

In order to answer the research question concerning MPC it is necessary to measure discharge, flow delay and discharge distribution at bifurcations, and to inspect the current state of the infrastructure. In this subsection it is explained which methods and materials are used to gather these data, and what the drawbacks of used methods are. For each of the parameters it is also explained why measuring it is necessary.

15.1.1. Discharge

Measuring discharge is essential for the hydraulic model. Discharge partitioning is based on it, as well as rating curves.
The velocity area method was used to obtain the discharge in the canals. The discharge Q of a stream is obtained by measuring velocities (u_i), representative for the part A_i of the area A, and then taking the sum of the product of velocity and area for each part i. The mathematical formula is given in Equation 15.2.

$$Q = \int^{A} u\, dA \approx \sum u_i \cdot \Delta A_i \tag{15.2}$$

However, as the canals were relatively small and only one velocity measurement was done for the entire cross-section the formula reduced to $Q = u \cdot A$. Velocity was measured using a float [114]. Similar floats have been used throughout the project, namely a 0.5 L bottle (because there were plenty of these available) filled half with sand (to make it partly submerged but not touching the bottom of the canal). Before the measurement a section of ten meters was marked next to the canal. Time needed for the float to travel the ten meters was recorded and each measurement was repeated three times and averaged. The cross-section of the canals was measured when there was no water flowing through the canal. Depth was measured using divers, these devices measure pressure every second. This pressure P, given in kPa, is then converted to water depth h, in meters, with the following formula:

$$\frac{P - P_{atm}}{g} + C = h \tag{15.3}$$

where P_{atm} is the average atmospheric pressure in kPa, g the gravitational constant which is 9.79 $kgms^{-2}$, and C is a correction factor because the diver is suspended slightly above the bottom. The factor depends on the suspension and is between 4.5 and 12.6 cm. Wetted area is then calculated using geometry, depending on the shape of the canal. The divers used, HOBO U20L-01, have a maximum error of 2 cm, but typically 1 cm. For more information, such as implicit assumptions, about the velocity area method, please refer to [66].

However, the velocity area method also has some flaws. As much of the results is based on discharge, they will be discusses here.
Firstly, only one velocity was taken for the entire cross-section. Velocity normally differs over channel width and depth. As the channel width is relatively small, using just one velocity seems reasonable. Especially given that due to the narrowness of the channel another trajectory cannot be followed using a float, at least not in a controlled manner, so for the width one measurement suffices. For the vertical velocity, however, floats measure surface velocity, not cross-sectional average velocity. Surface velocity is often higher than the average so the measured velocity should be multiplied by a factor. Normal values are between 0.85 and 0.95 [66].

Normally one would calibrate the float with another device. This was not done as the propeller current meter was not working properly.
A second reason why the measured velocity might deviate from the actual velocity is due to wind. During the flow delay test the float would sometimes move against the current due to heavy wind. Due to the same heavy wind, some measured velocities were significantly higher. Outliers have been removed but wind influenced the velocities to a certain extent still. This effect of wind on velocity depends on the orientation of the canal versus the wind, making it difficult to end up at the right correction factors.
Besides the inaccuracies when determining velocity, accurately measuring the effective cross-section is not as straightforward as one would hope for. Vegetation is present in all concrete canals, albeit in differing degrees. Aquatic plants make up part of the cross-section, in this part water cannot flow. Therefore, the effective surface area is less than the wet cross-section. On top of this, plants form another boundary layer, thereby increasing friction and thus decreasing average cross-sectional velocity [67]. This further increases the difference between surface velocity and cross-sectional average velocity. At some locations it was even impossible to measure velocity with the float method because aquatic plants would block the float.
Normally, one would increase the weight of float to make it submerged. This would solve the problems of surface velocity and of wind effects to a certain extent. Unfortunately, water depth was not always sufficiently deep to do so.

15.1.2. Inspection hydraulic infrastructure

It is necessary to inspect the current state of the hydraulic infrastructure for multiple reasons. To start with, it gives an idea whether maintenance is performed adequately. Secondly, it gives an indication of what has to be modelled, and whether it is possible. Thirdly, all locations of weirs, gates and bifurcation can be noted down. Canals, weirs and gates have been looked at. Canals have been inspected on cracks and vegetation, weirs on damage, type of weir and location, and gates on type and location. Finally, cross-sections of important canal sections have been measured.

15.1.3. Rating curve

A rating curve gives the relation between discharge and water depth [68]. They are useful because measuring discharge is cumbersome whereas measuring water depth is easier. Ratings curves are to be established at four locations, of which three at canal sections just after bifurcations, see Figure 15.2. One curve has been established at the main weir in order to estimate discharge entering the system. It is easy to establish a rating curve once the data has obtained. As discharge was measured using the velocity area method, both discharge and accompanying water depth are known. All one had to do was to repeat measuring at different water depths and discharges while remaining in the same location. Once sufficient measurements have been done, the more the better, discharge can be plotted against water depth. If all went correct a line can be fitted through the points. This line is known as the rating curve. The main pitfalls of creating a rating curve are overfitting and measurement errors. Overfitting can be prevented by keeping the model as simple as possible. Measurement errors are harder to prevent but can be easily seen on the graph and possibly removed as outliers.
Discharge uncertainty also affected the rating curves. Because velocities at the main weir were overestimated due to wind, the discharge wes too. This resulted in the rating curve overestimating the discharge for a given depth. The opposite was true for the upper canal. Velocities are underestimated, so were the discharges. Therefore, this rating curve underestimates discharge for a given depth.

15.1.4. Discharge distribution at bifurcations

The distribution of discharge across the three channels should be taken into account as only so much water is available, and this available water has to be distributed according to the controller over the three branches. There are two gates that can be operated to change the discharge partitioning, one at each bifurcations For a given discharge and gate opening, it can be predicted from the gathered data how the water will be distributed over the lower channel and main channel. The opening of the gate is defined as distance from the top as this is easier to measure when water is flowing. To get an accurate distribution function flow had to be measured at multiple water depths, and at each water depth at multiple gate openings. Pitfalls are measuring too quickly after changing the gate opening, as a steady flow is preferred. For each measurement, discharge has to be measured upstream of the bifurcation and either downstream of the bifurcation or in the side channel.

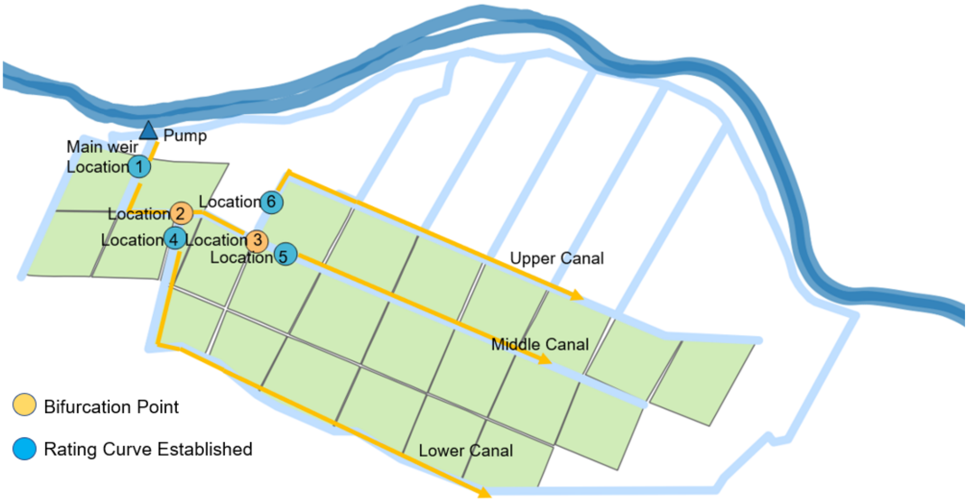


Figure 15.2: Locations of where delay time was measured.

15.1.5. Flow delay

In order to measure how long it takes for water to travel from the pump to a certain location two tests are held. One for dry conditions, so no water in the canals, and one for wet conditions, with water in the canals. For dry conditions, it was simply observed when water started flowing at a specific location. The time when the pump was switched on is noted, as well as when flow was observed at each location. For the wet conditions, divers were deployed at important locations. These locations were the main weir, the side channel at the first bifurcation ('Lower'), the side channel at the second bifurcation ('Upper') and the main canal ('Middle') after the second bifurcation, see Figure 15.2. The pump was switched on and off according to the schedule in Table 15.1. From the water depth data the delay time [63] was estimated.

Table 15.1: Time (minutes) passed between start of the pump test and activation of pumps.

Time	Big pump	Small pump
0	off	off
45	on	off
90	on	on

15.2. Results

15.2.1. Current infrastructure

The current infrastructure is not maintained well. There is vegetation growing in the canals nearly everywhere. At the end of the canals vegetation from outside enters the canals. In the northern section there are fish. This is due to the canal never being emptied, and sufficient protection from the plants. Practically all weirs are destroyed, some are replaced by sandbags. Some examples are shown in Figure 15.3.
Information regarding cross-sections of canals, coordinates and states of all weirs can be found in the attached data sheet.

15.2.2. Rating curves

Four ratings curves are established. One for the main weir and three for each side canal. The rating curve of the former one is shown in Figure 15.4. The fit, including outliers, is of good condition (R^2=0.89).
As can be seen in the figure, two points at approximately 0.78 m are well below the fitted line. This is likely to caused by the measurement method. Firstly, discharge was measured downstream of the weir where flow approximated steady-state. After the three measurements had been done, water depth was measured upstream of the weir were the flow approximated steady-state. The two points were taken when the big pump was turned on and flow increased fast. So a low average discharge was measured first and then a relatively high water depth.

(a) Example of destroyed concrete weir. (b) Example of a sandbag weir.

Figure 15.3: Two examples of damaged weirs.

A comment about the rating curve concerns the shape of the fit. The cross-section consists of two pieces; the bottom of the canal is trapezoidal, on top of the trapezoidal shape is a square shape. The increase of wet area given a small increase in water depth is different for the bottom section compared to the upper section. This means that the rating curve should consist of two lines that meet at the height where the sections change. This is not reflected in the rating curve as the difference is likely to be only minor, but it should have been done.

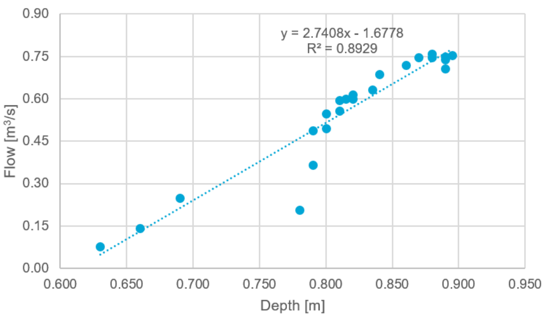


Figure 15.4: Rating curve of the main weir.

15.2.3. Discharge distribution at bifurcations

For a given discharge and gate opening, it can be predicted from the gathered data how the water will be distributed over the lower channel and main channel, see Figure 15.5. For example, if the discharge upstream of the bifurcation is 0.534 m^3/s and the gate is opened 0.30 m, the discharge in the lower channel will be 0.2 m^3/s and the discharge in the main channel will be 0.334 m^3/s. The opening of the gate is defined as distance from the top as this is easier to measure when water is flowing. Unfortunately no relation is yet found for the second bifurcation. This relation consists out of different regimes due to the presence of a punctured weir, gate and siphon at the bifurcation. The partitioning has to be measured at multiple discharges and the boundaries of each regime has to be found in order to establish a proper partitioning function.

15.2.4. Flow delay

The delay times for dry and wet conditions are given in Table 15.2 and 15.3, respectively. Two delay times could not be measured because the measurement device got turned over. These delay times can serve as input for k_{delay} in the ID-model.

15.2.5. Furrow evaluation

During a furrow evaluation, as described in Section 4.2.8, some discharges are measured. Among these are the flow per siphon and the flow from the lined canal into the earth feeder. The former one is 2.0 *L/s*, whereas the latter one varied between 20 and 30 *L/s*, based on two furrow evaluations. This variation is due to the different water depths at the gate, which are often Neyrpic gates. Neyrpic gates are standardised and the ones

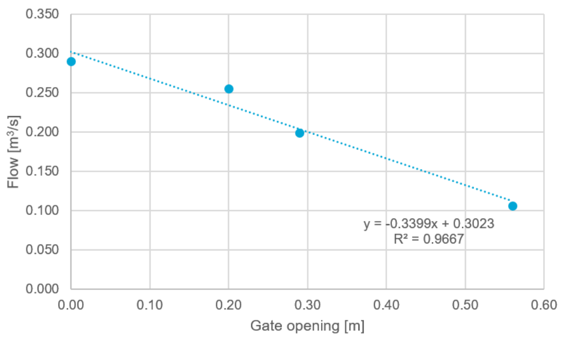


Figure 15.5: Relation between the discharge in side channel and the opening of the gate at the first bifurcation. Discharge before bifurcation is 0.534 m^3/s.

Table 15.2: Time (minutes:seconds) passed between start of the pump and water flowing at several locations.

Location	Time
1	03:32
2	23:51
3	52:36

in use here supply a discharge of 50 *L/s* given there is sufficient water depth at the gate. However, during evaluations done the water depth in the canal was not sufficiently high to reach the design discharge of the gate. There are weirs just behind each gate to raise water levels so that the design discharge is reached, but the majority of them is destroyed, see Chapter 2.

15.3. Optimisation problem formulation

As was mentioned in the introduction, part of the control method is the objective function that is optimised. For this project, the objective function is a mathematical description that penalises deviations from the desired SMC range. It also penalises use of water. i.e. if the pump has to be turned on. This objective function thus only irrigates when the bottom value of the desired SMC range is reached, because doing nothing while the SMC is within the desired range gives no pump penalty. The objective function also ensures that the upper boundary is not crossed. Crossing it gives two penalties; the pump has been on too long and the SMC is not within the desired range. This minimisation of penalties is done for each time step in the prediction horizon. The control option that has the lowest amount of penalties and fits all constraints is executed. A possible course is shown in Figure 15.6. Both a good and a bad controller are shown on the left and right, respectively.

15.4. Output to users

The output of the DSS is an optimal irrigation advice. This advice considers which pumps to turn on/off at what time, which fields to irrigate and when, and for that to happen how the opening of the gates at bifurcations should be set.

15.5. Interpretations for the hydraulic model

Given that it takes several days to irrigate an entire field, the delay times are insignificant when compared to an irrigation cycle. In addition, the storage volume (9,000 m^3)is rather small compared to the water that is used to irrigate daily (25,000 m^3). For the calculation, please see Appendix D.1. From the discussion above it follows that delay and storage volume can be ignored. Therefore, it can be said that the hydraulic model is partly superfluous, especially the ID model. Keeping the model simple, by excluding water routing from pump to plant, greatly reduces the efforts to be invested in the hydraulic model. Of course, accuracy of the model predictive controller will decrease but this seems to be a good trade-off to us. This saved effort can be invested in other parts of the project. For example, currently, the pump runs fourteen hours a day on maximum flow. Often, less water is needed for irrigation than what is coming into the system. Residual water is routed, through the earthen feeder of a dry-off field, directly to the drainage. Therefore, pump scheduling

Table 15.3: Time (minutes:seconds) delay after the both off, big pump on, and both pumps on.

Location	Both off	Big on	Both on
1	01:41	02:13	1:03
4	09:05	15:53	16:44
5	14:21	-	-
6	33:18	39:05	33:13

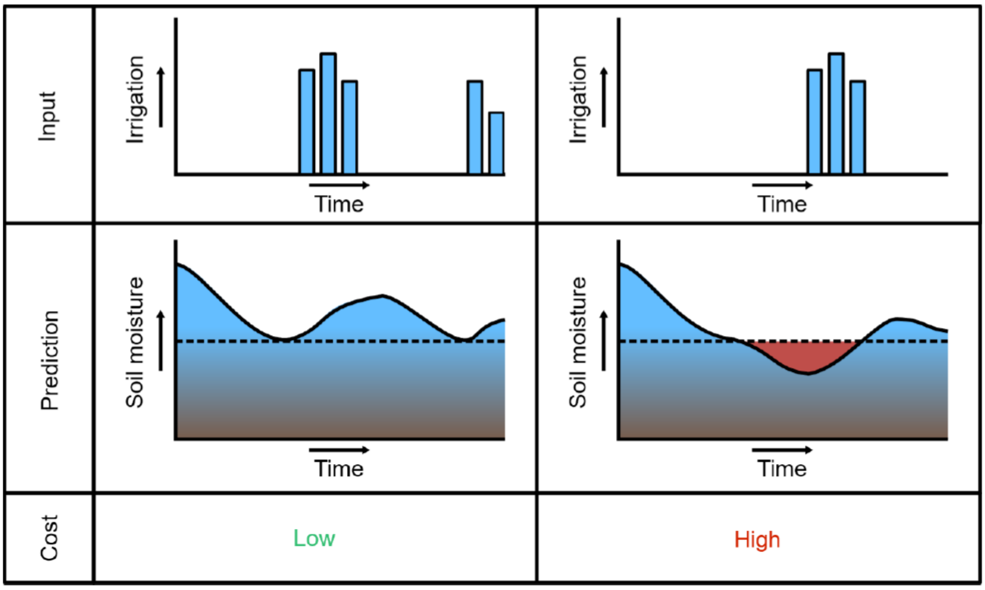


Figure 15.6: Visualisation of the objective function.

can be optimised in order to save water and energy. Another part of the project could be designing tools for operators to measure discharge in the canals. These tools can be used to get a more reliable estimate of the water efficiency and to assess whether the water is distributed correctly to the appropriate field.
Another option is to invest more effort in accurately predicting SMC. Closely related to this is the use of remote sensing. This will be discussed in the next chapter.

16 Remote Sensing

The innovative aspect of the MPC, that is being investigated by IWACA-TECH, is the input of the soil moisture content with remote sensing. A short introduction on remote sensing is given in the following paragraph, where the focus is on remote sensing in the microwave spectrum [69]. One of the partners of the IWACA-TECH project; VanderSat, has developed an algorithm that processes different measurements done by satellites into an approximation of the soil moisture content (SMC), this is further explained in Paragraph 'VanderSat product: soil moisture content'. The SMC data is made available for this study, yet has not been verified for reliability. In order to be able to carry out this verification, the effects of the SMC on a change in water quantity in the area can be examined, the different water quantity parameters are described in Paragraph "Rainfall data" and "Irrigation data". This chapter answers the following research question;

What is the interchange between the water inlet and soil moisture content within the Tongaat Hulett area between 1 April 2017 and 31 March 2018?

16.1. Remote Sensing: an introduction

Remote sensing is defined as; the process of detecting and monitoring physical characteristics of an area by measuring different kinds of radiation, from a significant distance [70]. Often remote sensing is used to measure, observe or identify objects or areas, without direct contact being possible [19]. It may be that the object or area is too far away to come into contact with, such as investigating the seabed, or the research area is too large which makes it too time consuming to investigate it close by.
Remote sensing can be applied along different frequencies and wavelengths of the electromagnetic spectrum [19]. An intuitive example is optical remote sensing; it is similar to taking a picture with a photo camera, a sensor captures electromagnetic radiation in the visible spectrum, allowing a surface to be identified as green, red or any other colour. While thermal remote sensing does observations in the infrared spectrum [71]; so that the temperature of an object can be determined. This research mainly uses passive remote sensing in the microwave spectrum. The microwave spectrum lays between the infrared and the radio spectrum, with frequencies roughly between 0.1 and 100 GHz and wavelengths between 100 and 0.1 cm respectively [70], this spectrum is shown in Figure 16.1. Because of this very low frequency in the microwave spectrum, the sensors are able to penetrate vegetation of any significant density. Longer wavelength microwave radiation can penetrate through clouds, storms, dust and all, except the heaviest rainfall, as the lower frequencies are not susceptible to atmospheric scattering. This allows detection of microwave energy under almost all weather conditions. Measurements can be taken during both day and night, resulting in a bigger data set [72].

There are two substantially different ways of data collection within remote sensing; passive- and active- remote sensing. In Figure 16.2 the differences between these two methods are explained. The frequency of microwaves is low, therefore the energy available is relatively small compared to optical wavelengths. Thus, the fields of view must be large to detect enough energy to record a signal. Most passive microwave sensors are therefore characterised by a low spatial resolution [74]. In summary it can be said that each spectrum that is measured by remote sensing displays different physical properties of the object or area. Measurements made is different spectra can also be combined to discover other physical characteristics, allowing remote sensing to be used for many purposes.

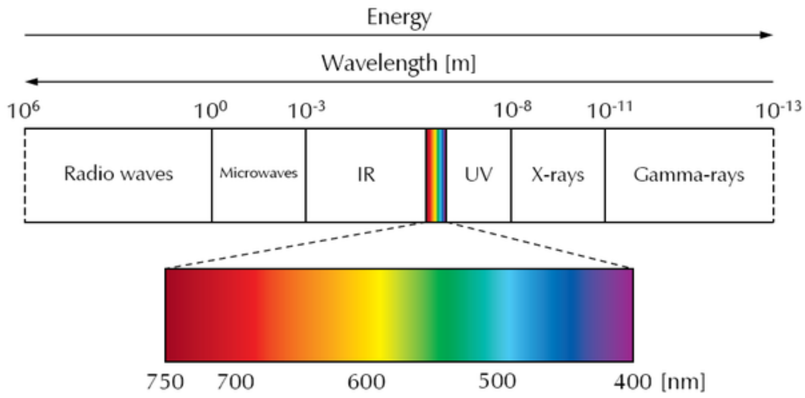
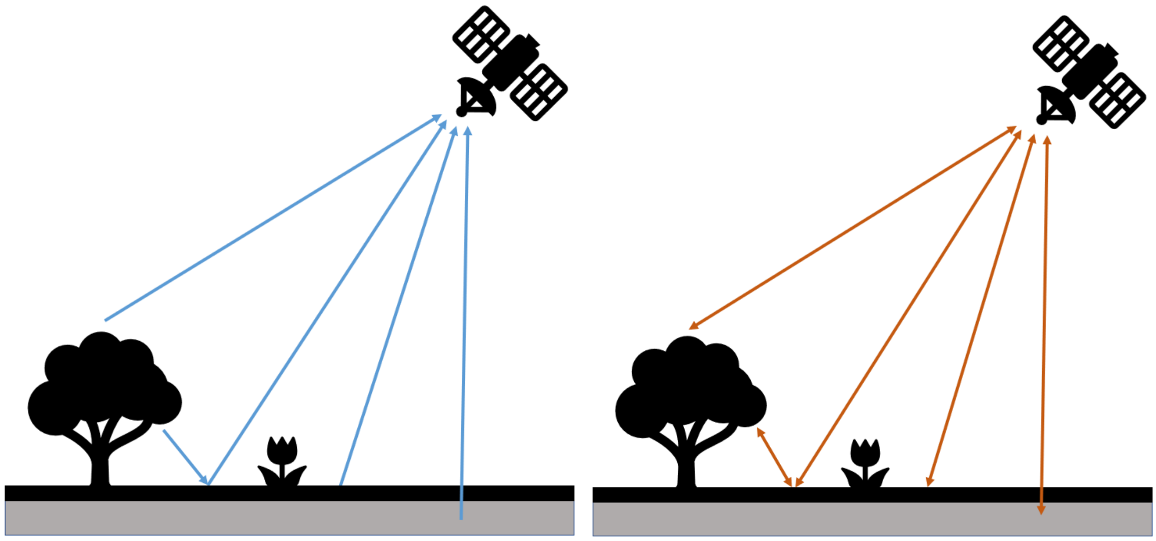


Figure 16.1: Electromagnetic spectrum [71].



(a) All objects on earth emit microwave energy of some magnitude. A passive microwave sensor, inside a satellite, detects the naturally emitted microwave energy within its field of view [70]. This emitted energy is related to the temperature and moisture properties of the object or surface. The microwave energy recorded by a passive sensor [120] can be emitted by the atmosphere, an object, the surface, or reflected by the surface, or transmitted from the subsurface [19]

(b) A active microwave sensor [73], inside a satellite, sends a radar pulse in the direction of the Earth. Thus the instruments provide their own energy (electromagnetic radiation) to illuminate the object or area they observe. The pulse can be scattered in all different directions, whereby a part is back scattered. The antenna inside the satellite measures the reflected radiation [70]. How exactly the physical properties of the object or area are determined is outside the scope of this research.

Figure 16.2: Difference between passive and active remote sensing.

16.2. Data sets used

16.2.1. VanderSat product: soil moisture content

VanderSat makes use of passive- and active microwave remote sensing, to obtain the SMC in the upper 10 *cm* of the soil. VanderSat downscales the raw brightness temperatures [75] to a resulting three-day product of 100x100m resolution.

In passive microwave remote sensing, microwave radiation is often represented by the surface brightness temperature (T_B), which is determined by the physical temperature (T) and the smooth-surface emissivity (e_s) of the object or area that is radiating [76]. The brightness temperature, at a given frequency (f), wavelength (λ) and polarisation (p) is defined as:

$$T_B = e_s * T \tag{16.1}$$

The brightness temperature from a soil is strongly dependent on the SMC. This is due to the fact that there is a direct relation between emissivity and the dielectric constant; the contrast in dielectric constant between dry soil (3) and water (80) is large [76]. Beside soil moisture, the brightness temperature of a surface is also affected by soil surface roughness, vegetation cover (influences the emissivity), surface cover (heterogeneity and texture) and the physical temperature of the soil and temperature [77]. For these effects a correction can be made; this can be done by using different frequencies and polarisations [78].
The brightness temperature needs to be converted into soil moisture, surface temperature and vegetation optical depth. To do so, the Land Parameter Retrieval Model (LPRM) was developed by researchers from the VU University Amsterdam, among others [77]. The microwave emission received by the satellite is influenced by the vegetation that may be present. This is represented in the more complicated equation of the brightness temperature, including the vegetation correction. The text written in the equation refers to the source of the microwave emission, as illustrated in Figure 16.3.

$$\begin{aligned} T_B &= \text{Direct from ground} + \text{Direct form vegetation} + \text{Indirect from vegetation} \\ &= T_S e_r \Gamma_p + (1-\omega_p) T_c (1-\Gamma_p) + (1-e_r)(1-\omega_p) T_C (1-\Gamma_p)\Gamma_p \end{aligned} \tag{16.2}$$

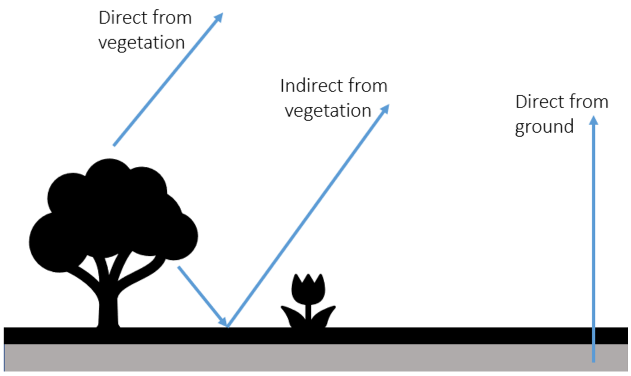


Figure 16.3: Schematic representation of the different microwave radiation. The brightness temperature is a summation microwave omission from *Direct from ground* ($T_S e_r \Gamma_p$), *Direct from vegetation*($(1-\omega_p)T_C(1-\Gamma_p)$) and Indirect from vegetation ($(1-e_r)(1-\omega_p)T_C(1-\Gamma_p)\Gamma_p$).

In which the T_b is the brightness temperature, T_S and T_C are the soil and canopy temperature respectively. The e_r is the emissivity of the rough surface, the ω the single scattering albedo [79] and Γ the transmissivity. Everything, except the T_S and T_C are at polarisation p [76–78]. How exactly this correction is done, is out of the scope of this research. The data that is used for the analysis is without correction for the vegetation.
When convergence between the modelled LPRM brightness temperature and the observed values by the satellite is reached, the soil moisture which results in the smallest residual between calculated and observed brightness temperature values is determined [78].

As described before, with passive microwave remote sensing the field of view is large, and there is often a low spatial resolution. To achieve the desired resolution of 100x100m, a down-scaling technique was used. By taking into account a Gaussian distribution inside the satellite footprint, it can be assumed that the centre of a single footprint contributes more to the observed brightness temperature signal than the edges of the footprint. For the different footprints, for the different microwave frequencies, a combination Gaussian distributions is made, after which the 100x100m resolution can be achieved [80]. This process is visualised in Figure 16.4
This process of data collection was done by VanderSat near the Xinavane sugarcane plantation, resulting in the SMC in the upper 10 *cm* of this surface.

16.2.2. Rainfall data

Tongaat Hulett has 44 meteorological stations under its management, 32 of which fall within the area that is being analysed for this study. These meteorological stations are spread over the entire plantation, distributed over both banks of the Incomati river. In Figure 16.5, the exact locations of the stations are shown. For reference, the location of the fields of interest are shown as well.

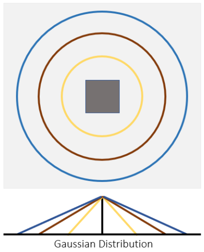


Figure 16.4: Schematic representation of the Gaussian Distributions per footprint (different colours of circles), resulting in the finer resolution of 100x100meter (dark grey box).

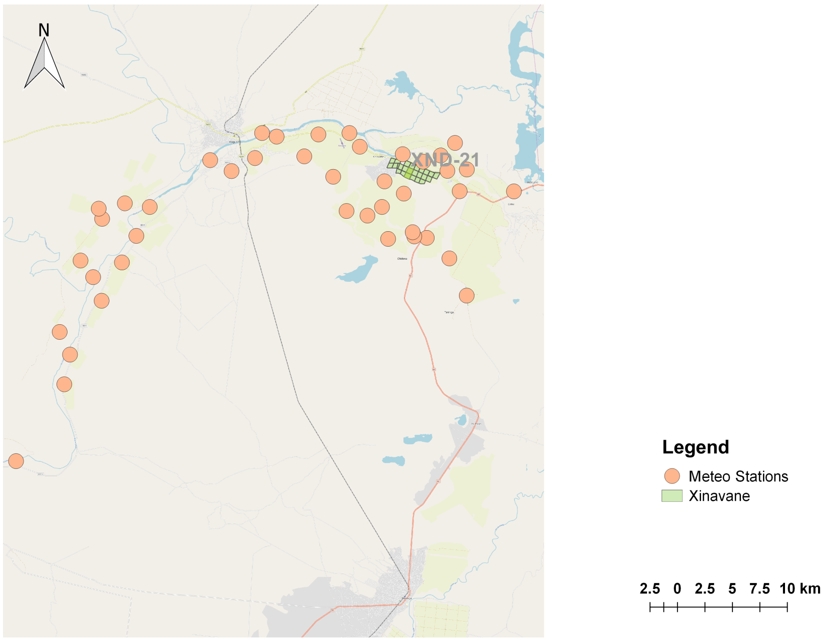


Figure 16.5: Location of the meteo-stations in the Xinavane plantation.

Each of these 32 meteorological stations measures the amount of rainfall per day, starting at midnight for 24 hours, measured in *mm*. The measured values -per meteo station- are put in an excel sheet, after which a monthly total and average precipitation is calculated. For this study, the precipitation data from 1 April 2017 to 31 March 2018 of the 32 stations in the area of interest is used. This period corresponds to the data for which the VanderSat product was made available, and the exact location of the meteorological stations is known. In previous years other meteorological stations were used, whose exact location is either unknown or unreliable.

16.2.3. Irrigation data

The aim is to determine the relationship between the water inlet on the soil and the SMC, within the Xinavane sugarcane plantation. The water inlet can be divided into two parts; precipitation, as previous described, and irrigation. In order to do a good analysis, a data set must meet certain conditions, one of which is reliability. The irrigation data obtained from Tongaat Hulett is -unfortunately- not reliable enough to do a well-founded analysis. The data obtained comes from the software CanePro. It consist of an overview per field, when and how much irrigation took place. However, when studying this data and the observations made in the field, several problems appear to arise, these problems that make the data set more unreliable are listed below.

- *Insufficient use of CanePro.* The irrigation moments are supposed to be inserted into CanePro correctly. However , this is not always the case. The period of irrigation is recorded as if it has taken place in one day, instead of over several days. Also, the amount of water that would have flowed into the field is chosen based on the desired values.
- *Unclear water flow quantities.* The purpose of using the CanePro software is to enter the irrigation

moments. It is expected that the concerned person indicates on which days there was an irrigation moment. However, this turned out not to be the case. The period of irrigation is recorded as if it happened on a singe day. While several observations in the field, and conversations with employees of Tongaat Hulett claim the opposite. Besides filling in the days on which the irrigation was carried out, it is also expected that the amount of irrigation water is recorded and entered in CanePro. Initially this data seemed correct, but observations in the field soon made it clear that the amount of water entering the field is not measured, and certainly not as accurately as in CanePro. An unclear water flow quantity makes the research into the interchange between the water inlet, including irrigation, and the SMC less reliable.

- *Uneven distribution of water within the fields.* The fields are all larger than the 100x100meter resolution of the previous described VanderSat product. To perform a good analysis, the distribution of the irrigation water over the fields is important. However, as mentioned earlier, there is no record of how much water goes to the field. Besides that, there is also nowhere recorded what the distribution of this water is over the fields.
- *Lack of sufficient field information.* For each sugarcane field the irrigation data is kept, however, for insufficient amount of these fields was the data released. Only the data that fell in the Xinavane area where obtained, to create a spatial distribution this is insufficient.

All the above phenomena together make the data too unreliable to use for a well-founded analysis. Therefore it has been decided, in consultation with the various partners involved in the IWACA-TECH project, not to use this data.

16.3. Methodology

The following section describes how the interchange between the water inlet and SMC within the Tongaat Hulett area was determined, between 1 April 2017 and 31 March 2018. The requested interchange consists of two different parts; the temporal variability and the spatial distribution.

16.3.1. Temporal variability

In order to perform the temporal variability analysis, the SMC is studied over time and compared with the rainfall in the same period. For the 32 meteorological stations used for this study an evaluation was performed. It was examined how much rain fell on which day, with the entire data-set running form 1 April 2017 to 31 March 2018. This gives the first results, which will be discussed in Section 16.4.

Not only the precipitation data should be studied, also the SMC data in the same period of time. To do this, the pixel belonging to the location of the meteo-station must be extracted and isolated from the VanderSat data set. The changes of the SMC over the period of interest can then be displayed in a graph; this is done for all 32 meteo-station. The results of this part of the research are also presented in Section 16.4, after that the results are also shown for a combination of SMC and precipitation.

For the comparison between the amount of water that enters the field and the amount that goes off the field, the run-off is also taken into account. The amount of run-off, after and during a rain event, is indirectly related to the moisture condition of the catchment at the start of a rain event. The Antecedent Precipitation Index (API) [81] is an empirical method to determine the soil wetness based on the rainfall that has occurred over preceding days. High values of API mean the upper layer of the soil is wet, so rain is more likely to run off, and vice versa. The formula for API is described in Equation 16.3.

$$\begin{aligned} API_n &= P_n && \text{for } n = 1 \\ API_n &= k * API_{n-1} + P_n && \text{for } n > 1 \end{aligned} \tag{16.3}$$

Whereby P the precipitation (mm) for day n is and the k an empirical decay factor. Without rain, the soil wetness (as measured by API) declines each day by the factor k. Any water inlet event causes the API to increase. The decay parameter k must be less than one and is usually between 0.85 and 0.98. The parameter is depended on seasonal influences. The constant, year round, value of 0.95 was recommended by [82]. If the SMC were to be plotted against the API, the graphs should be as similar as possible, where only the decay factor k can be changed manually. The k value was optimised, which showed that the difference between the SMC and the API was minimised at a k value of 0.94. With this decay factor is the API calculated for all the 32 meteo-stations in the Tongaat Hulett Area.

16.3.2. Spatial distribution

Spatial variability occurs when a quantity measured in different locations shows values that vary from location to location. In this research two different spatial dependent parameters are discussed; SMC and precipitation. To study what happens to the SMC after precipitation, one rain event has been selected to be analysed. This rain event must met three requirements in order to draw a well-founded conclusion. First, the day before the rain event the SMC must be known, as well as the day after the event. In addition, the rainfall must be substantial, and a minimum of 10 *cm* is required. One of the events that meets these requirements took place on 14 April 2017 (according to meteo-station XNA20 25 *mm* rain fell), which will be further analysed. The amount of rain is visualised using contour lines, which indicate in which area the amount of rain fell.

16.4. Results

In this section the results of the interchange analysis between the water inlet and the SMC are presented. In the same order as in Section 16.3, first the temporal variability is discussed followed by the spatial distribution.

16.4.1. Temporal variability

First the precipitation over the period of interest is plotted, this is done for all 32 meteo-stations.This results in 32 graphs, where on the x-axis the time course in days and on the y-axis the amount of precipitation that has fallen in *mm*. In Figure 16.6 the graph of meteo-station XNA20 is presented. This specific station is selected, as its rainfall measurements are used as CanePro input data by Tongaat Hulett for fields XND-21 and XNE-21. For the same locations and the same period of time, the SMC is plotted. On the x-axis is again the time course

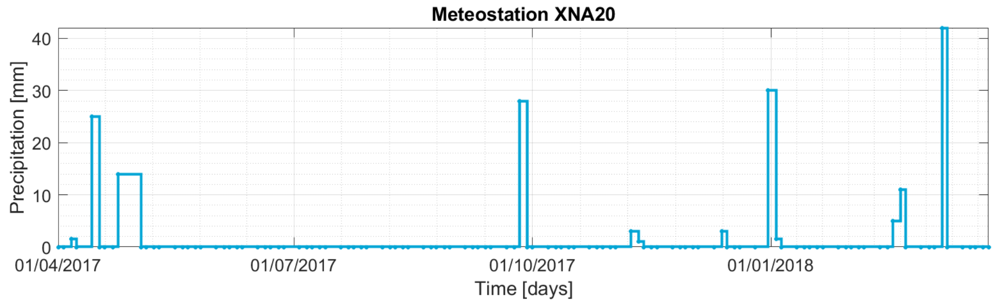


Figure 16.6: Precipitation at meteo-station XNA20 between 1 April 2017 and 31 March 2018.

in days, and on the y-axis the SMC, in $m^3 m^{-3}$. In Figure 16.7 the SMC for the area belonging to meteo-station XNA20 is presented. These two graphs are combined to determine the relationship, as shown in Figure 16.8.

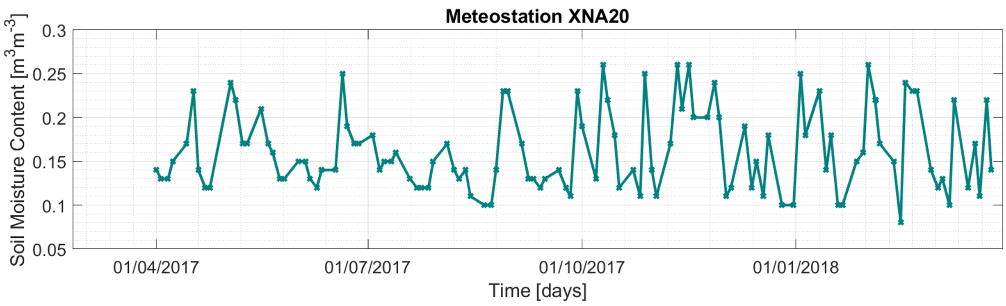


Figure 16.7: SMC at meteo-station XNA20 between 1 April 2017 and 31 March 2018.

On the x-axis is the time in days again, on the left y-axis the SMC and on the right y-axis the precipitation. After this the API is determined over time, and plotted in the graph. On the x-axis is still the time, on the left y-axis the SMC and on the right y-axis the precipitation and the API, as shown in Figure 16.9.

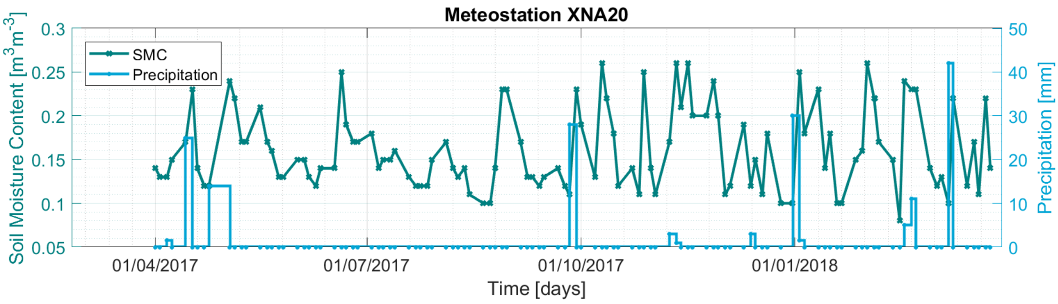


Figure 16.8: Precipitation and SMC at meteo-station XNA20 between 1 April 2017 and 31 March 2018.

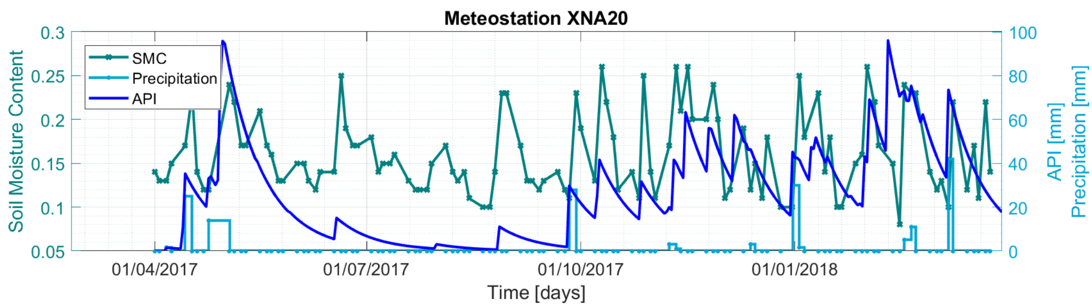


Figure 16.9: API, SMC and precipitation at meteo-station XNA20 between 1 April 2017 and 31 March 2018.

The last graphs shows the final result of the temporal variability analysis, showing only meteo-station XNA20. For the 31 other stations, the same analysis is done and the graphs are plotted, these are shown in Appendix D.3.

16.4.2. Spatial distribution

As already mentioned in the methodology, spatial distribution is studied using the rain event that took place on 14 April 2017. The spatial distribution of the SMC, in the upper 10 *cm* of the soil, before the rain event is illustrated in Figure 16.10

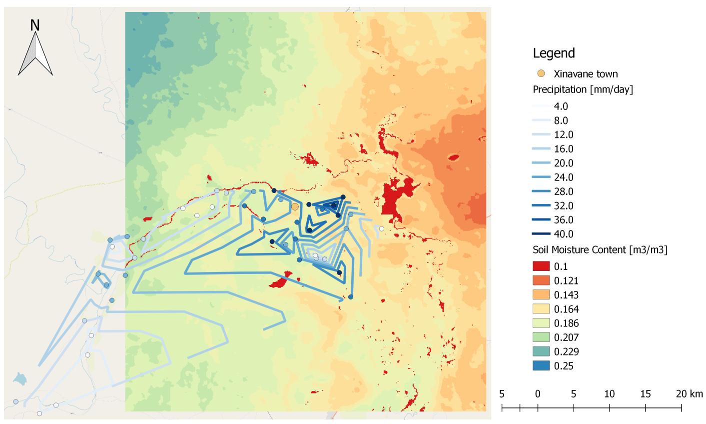


Figure 16.10: Spatial distribution of the SMC before the rain event of 14 April 2017.

This map shows that in the East, the SMC is around a value of 0.1 m^3m^{-3}. In the North-West, where the SMC is highest, the maximum value is 0.25 m^3m^{-3}. This difference of $0.15m^3m^{-3}$ is gradually changing from East to West.
After these observations have been collected, the rain event took place. The SMC was determined over exactly the same area and shown in Figure 16.11. At first sight it is already clear that the SMC is higher over the entire area. On 15 April the SMC is the highest in the North-East, with a maximum value of 0.25 m^3m^{-3}. In the

South-West the value of SMC is the lowest, a value of 0.18 $m^3 m^{-3}$. The difference between the maximum and minimum SMC is 0.7$m^3 m^{-3}$, and much smaller than before there was precipitation.

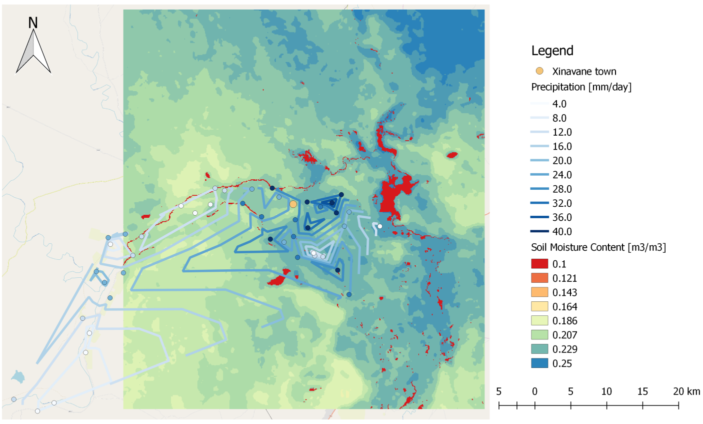


Figure 16.11: Spatial distribution of the SMC after the rain event of 14 April 2017.

The difference in SMC caused by the precipitation is shown in Figure 16.12. This map shows that on the western side there has been (nearly) no change in SMC. In the East, however, there is a change in SMC, with the largest change in the North-East with a value of 0.1$m^3 m^{-3}$. Between the East and the West, the SMC change is gradual. On this map, the amount of rain that has fallen is also shown. In the middle of the map, in other words in the East of the plantation, there has been more rain than in the West.

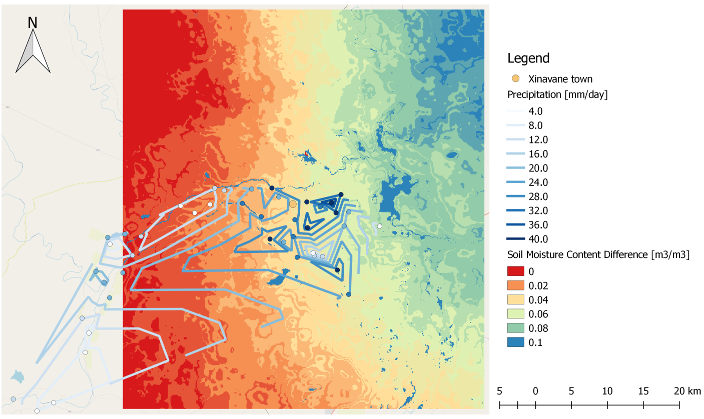


Figure 16.12: Spatial distribution of the SMC difference between for and after the rain event of 14 April 2017.

17
Discussion

In this chapter an interpretation of the results is given, followed by a discussion on the basis on these interpretations.
Hopefully it has become clear by now that the first idea of MPC is hard to implement. This is mainly due to the lack of maintenance. Also, it turned out that routing the water is not that important. A clear correlation between rainfall and soil moisture content measured using remote sensing has been found. Given this, the concept should be slightly changed while keeping the same objective in mind; increasing water productivity. This will be discussed in the recommendations.

One of the limitations encountered is accurately measuring discharge. It is hard, if not impossible, to remove the effect of wind using the simple float method. However, cleaning and maintaining the canals would greatly reduce the effect of vegetation on discharge inaccuracies, and improve measurements. Less inaccuracies in discharge means more accurate rating curves. As the hydraulic model is calibrated using rating curves it is crucial to have correct rating curves. And to keep them correct. If vegetation grows, the rating curve changes and has to be established again. Clean canals have more advantages besides a better functioning controller. It prevents flooding at clogged weirs, increases conveyance efficiency, prevents root damage, increases inspection capabilities, if vegetation cannot settle it is harder for sediment to accumulate and clean canals have more flow capacity to name some. The costs of cleaning and maintaining canals is less than the potential costs for flood damage, loss of project benefits, big repairs etc. [83, 84].
Besides the hydraulic model, measuring SMC using remote sensing data was explored. The remote sensing section was divided into two different aspects; the temporal variability and the spatial distribution. Both parts support the same interpretation of results; there is a direct relationship between the rainfall and the SMC. When looking at how the SMC around a meteorological station behaves over a period of one year, many fluctuations can be seen. If a rain event is measured at the meteo-station, the SMC rises in the pixel of the VanderSat product in which the meteo-station is located. If there has been no precipitation for a longer period of time, the SMC gradually decreases. If the graph of the SMC and the precipitation are examined carefully, it becomes clear that the SMC also increases when there was no precipitation. This could possibly be due to irrigation on the fields surrounding the meteo-station. If the SMC is not looked at over time, but over the entire area (spatial distribution), the same interpretation of results can be supported. Over the entire area an increase of the SMC can be seen, after rainfall. The argumentation is reinforced because the SMC increases more in areas where more rain has fallen. However, in order to draw a well-founded conclusion on the basis of these results, more rain events should be considered.
When doing field research there are also practical limitations, think of the insufficient work of measuring instrument; such as the soil moisture probe. This instrument could well be used as a verification of the SMC, determined by VanderSat. The SMC determined by satellite-gathered data can then be checked with data collected on the ground. This link was not possible because the soil moisture probe did not give reliable results and because the satellite data did not cover the same period of time. The period of fieldwork could be carried out, two months, is also not long enough to decide whether or not to implement a DSS. More measurements, in more different seasons, should be made. The influence of the weather is great on both the MPC research and the Remote Sensing part. The period that the field research now took place is not a representative for a whole year, or for several years. During the preparation it appeared that little literature

was available on implementing an MPC in comparable areas. The environment and the social aspects make the introduction of an MPC in the sugarcane plantation in Xinavane a big task. The literature available on introducing an MPC, in agriculture, describes situation where there are less challenging circumstances.
A great addition to this research would certainly have been if there had been access to decent internet. Besides looking up -new- literature, the processing of the data could have been much faster and more efficient with access to decent internet. During the research new aspects came to light, and these could not be searched sufficiently. Also the communication with the partners of IWACA-TECH for questions or additional information was a challenge.

18
Conclusion

In this study the possibility of implementing MPC was investigated. To this end, measuring SMC using remote sensing data was explored, and fieldwork was performed to find out how accurate the hydraulic model should be.

18.1. Implementation of hydraulic model

One of the research questions was; *´To what extent does an accurate hydraulic model contribute to the possibility of implementing MPC at Tongaat Hulett?´* In the current situation, a simple hydraulic model suffices. Reasons here for are that storage volume is negligible compared to the volume of water that is pumped into the system daily. Also, the delay times of about 50 minutes is insignificant compared to an irrigation cycle of about three days. As volume and delay times are ignored, canals do not have to be modelled. Likewise, most weirs are not modelled as they are prone to change temporally. Creating a rating curve for a changing weir is pointless as it has to be established time and time again. What is crucial, is establishing rating curves at essential points, such as after bifurcations to make sure discharge is distributed as planned. Simultaneously, an accurate function to predict discharge distribution over bifurcations is important to make sure enough water is supplied to each side channel. In our opinion, it is better to spend more time on other parts of the project than on the modelling routing from pump to crop.

18.2. Interchange water inlet and soil moisture content

As previously stated; the remote sensing section was divided into two different aspects; the temporal variability and the spatial distribution. Both parts support the same interpretation of results and therefore the same conclusion; there is a direct relationship between the rainfall and the SMC. When looking at how the SMC around a meteorological station behaves over a period of one year (temporal variability), many fluctuations can be seen. Some of these fluctuations can be explained on the basis of rainfall data; if there has been precipitation, the SMC increases. However, there are also several fluctuations that cannot be explained. If the SMC is not looked at over time, but over the entire area (spatial distribution), the same conclusion is supported. Over the entire area an increase of the SMC can be seen, after rainfall. The argumentation is reinforced because the SMC increases more in areas where more rain has fallen.

19 Recommendations

When zooming out to a bigger scale, the product of VanderSat comes to mind. It can be a great aid in increasing water efficiency. How this product can be used optimally in sub-tropical regions is an interesting subject for further research.
A combination of temporal variability and spatial distribution is desired. To achieve this there are several steps that need to be taken, the one that needs to be considered first is adding the irrigation data. When the obstacles that belong to the irrigation data, described in the section about the used data sets, have been overcome, the research can be done over a longer period of time. Spatial distribution is now based on a single rain event, while it is much more interesting to study the precipitation over the water inlet over a whole year. The dry periods and the rainy season are then included in the analysis. Another recommendation is not only to study the presence of a relationship between the SMC and the water inlet, but to try to make it quantifiable. Is the increase of the SMC proportional to the amount of water entering the fields? To expand and improve the research, the API can be included. In this way, the wetness of the catchment and the reaction of the SMC to the water inlet, and the consequences of the run-off, are taken into account. However, the formula of the API must be adjusted for this. The situation now is that the only parameter related to water inlet is the precipitation. The wetness of the soil is also influenced by irrigation water, so this should be included in the equation to determine the API.

Another recommendation is to further investigate a different application of the DSS. Initial findings in this report showed promising results for the application of a DSS for irrigation management within the plantation. However, more research is needed before a DSS can be implemented. If implemented correctly, a DSS can save significant amounts of water, time and money. Improving field production with similar, or even less amounts of water. Resulting in more crop per drop. For this to happen, recommendations are given below.

- Currently, the pump runs fourteen hours a day on maximum flow. Often, less water is needed for irrigation than what is coming into the system. Residual water is routed, through the earthen feeder of a dry-off field, directly to the drainage. Therefore, pump scheduling can be optimised in order to save water and energy.
- Tools for operators to measure discharge in the canals can be designed. These tools can be used to get a more reliable estimate of the water efficiency and to assess whether the water is distributed correctly to the appropriate field.
- Proper maintenance is critical for MPC. Rating curves are not constant, if the canals change (e.g. vegetation increase or decrease) the rating curve changes too and has to be established again. Therefore, the best option is to keep canals clean. This can be done by either excluding, or at least reducing, the sediment concentrations that enter the irrigation system or by removing excess sediment with an extractor [85]. Installing two or three screen filters with decreasing mesh size could be sufficient to reduce the majority of sediment, vegetation and seeds, if cleaned frequently. It is recommended to locate the filters as far upstream as possible, perhaps in the small reservoir where the pump pipes end up in. Installing two of each filter would be beneficial as one screen can be cleaned while the other screen still filters. If less sediment, vegetation and seeds enter the irrigation system, less effort is needed to clean and maintain canals. This saves manpower and thus expenses. Only one or two persons are needed to operate the filters, and a small investment. In long term we expect that it will save costs.

- Weirs are needed to increase water level just before the water flows from lined canal to feeder to achieve the 50 *L/s* at the Neyrpic gates. Therefore, it is recommended to rebuild the weirs.
- Train employees to understand the importance of weirs and to ensure that two siphons are used for each furrow. This way each furrow receives the same amount of water. Also, ensure that the furrows are opened at the end towards the drainage so that excess water is drained. This in order to prevent over-irrigation.
- Time that can be saved by keeping the hydraulic model simple can be invested in making the SMC model more accurate as predicting SMC is crucial to planning irrigation cycles.

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A

Appendix Irrigation practices

A.1. Interviews

Table A.1: List of interviewed people

Who	Function	When
Pitrosse	Section manager	14/11/2018
Nelson Matope	Section manager	16/11/2018
Elias	Section manager	21/11/2018
Felix Mabunda	Area manager	21/11/2018
Esperanca Muchanga	Pump operations	26/11/2018
Morgan Muleya	Irrigation services	28/11/2018
Dilenio	Irrigation services	29/11/2018
Cidonio	Section manager	30/11/2018
Pedro	Furrow evaluation team	2/12/2018
Sabatha Simelane	Field services	30/11/2018
Tivane	Supervisor	5/12/2018
Victoria	Supervisor	5/12/2018
Anonymous	Irrigators	6/12/2018
Micas Alfredo Soto	Land preparation manager	6/12/2018
Juliao	Capataz	11/12/2018
Miguel	Capataz	11/12/2018
Joao	Human resources	11/12/2018
Calvin Earnshaw	Agronomist	13/12/2018
Evaristo Mubaya	Manager	21/12/2018

Note of writers: full interviews are available on request to maintain anonymity as was requested by several employees.

A.2. The feel method

The table with the difference textures and the available soil moisture is shown in the table on the next page.

A.3. Furrow methodology

Materials needed for the furrow method:

- Parshall flume
- Small Parshall flume
- Timer
- Spade
- Level

Available soil moisture remaining (%)	Feel or appearance of the soil		
	Coarse Texture	Moderately Coarse	Fine Texture
0-25	Dry, loose, single grained, flows through fingers	Dry, loose, flows through fingers	Hard, baked, cracked sometimes has loose crumbs in the surface
25 – 50	Appears to be dry will not form a ball with pressure	Appears to be dry, will not form a ball	Somewhat pliable, will ball under pressure
50-75	Appears to be dry will not form a ball with pressure	Tends to ball under pressure but seldom holds together	Forms a ball, ribbons out between thumb and forefinger
75 – 100 (Field Capacity)	Tends to stick together slightly, sometimes forms a weak ball under pressure	Forms weak ball, is very pliable, sticks readily if relatively high in clay	Easily ribbons out between fingers, has slick feeling
At Field Capacity	Upon Squeezing no free water appears on the soil but wet outline of ball is left on hand	Upon Squeezing no free water appears on the soil but wet outline of ball is left on hand	Upon Squeezing no free water appears on the soil, but wet outline of ball is left on hand

- Float
- Infiltrometer

Together with the furrow evaluation team of Tongaat Hulett fields XND-21 and XNE-21 are analysed. Firstly the flow before and after the inlet of the earth feeder is measured using a float; this is done three times to reduce the error. Secondly the Parshall flumes are installed in earth feeder and in a randomly chosen furrow. Subsequently within the furrow every ten meters a knot was made in the sugarcane to follow the advance time over the length of the furrow. The flows through the Parshall flumes are written down and the advance and recession time are timed.

A.4. Profit and Loss

To calculate daily moisture balance the following three steps are taken:

- Previous day's moisture balance
- Minus Et (crop water use)
- Plus effective rainfall and net irrigation

A.5. Efficiency

The scheme irrigation efficiency (e) can be calculated, with
e = scheme irrigation efficiency (%)
ec = conveyance efficiency (%)
ea = field application efficiency (%)

A scheme irrigation efficiency of:

- 50-60% is good;
- 40% is reasonable, while a scheme irrigation efficiency of
- 20-30% is poor

	Earthen canals			Line canals
Canal length	Sand	Loam	Clay	
Long (>2000m)	60%	70%	80%	95%
Medium (200 - 2000m)	70%	75%	85%	95%
Short(<200m)	80%	85%	90%	95%

Irrigation methods	Field application efficiency
Surface irrigation	60%
Sprinkler irrigation	75%
Drip irrigation	90%

A.6. Map of maintenance issues

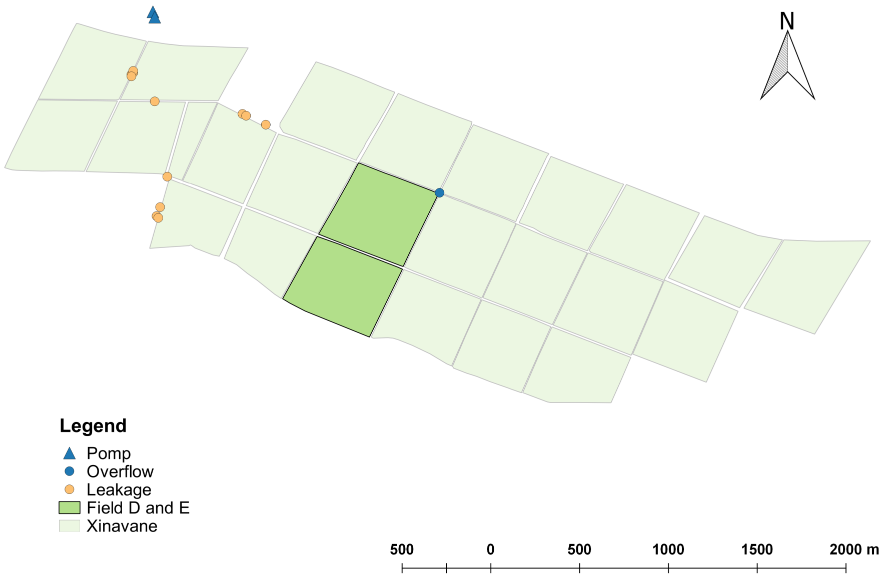


Figure A.1: Map of leakages.

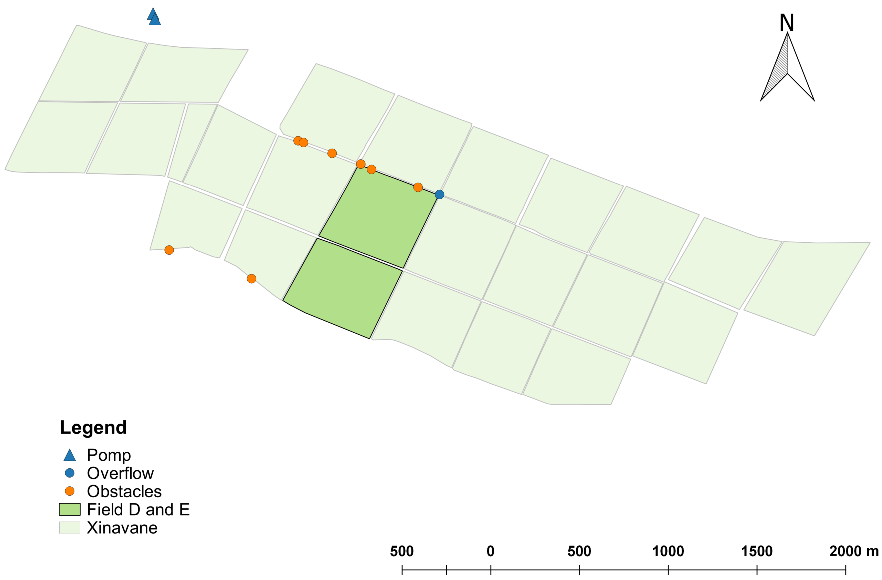


Figure A.2: Map of Obstacles.

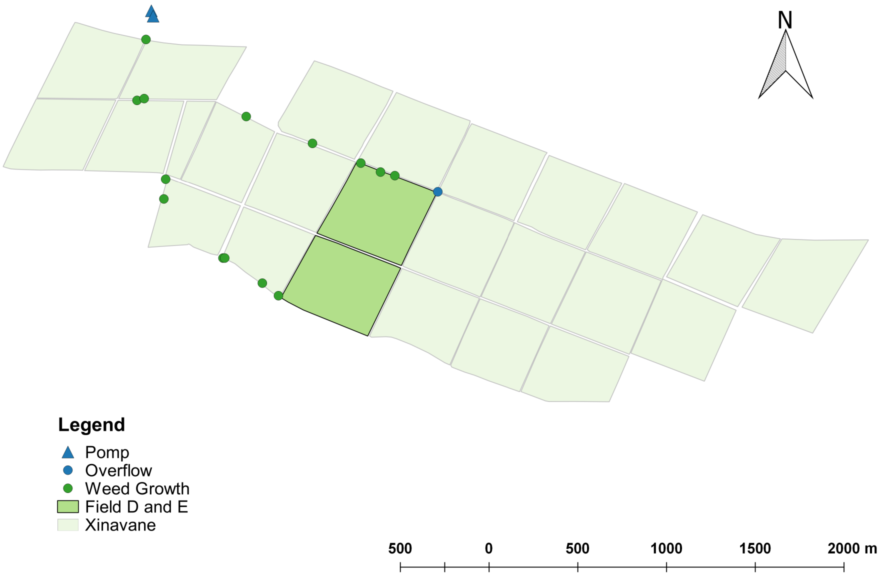


Figure A.3: Map of weed growth.

B

Appendix Field assessment on yield variability

B.1. Groundwater

B.1.1. Making piezometers

Piezometers were made using the following materials:

- PVC pipe
- Grinder
- End cap
- Filter stocking
- Cable binders
- Glue

PVC pipes are cut into segments with lengths of 2.5 or 3 metres. Slits are made on both sides of the bottom half metre of the pipe using a grinder, one centimetre apart. Filter stocking is put around these slits, secured by cable binders and glue. An end cap is placed on top of the pipe to avoid contamination. Finally, the length of the piezometer is noted down on the pipe.

B.1.2. Piezometer installation

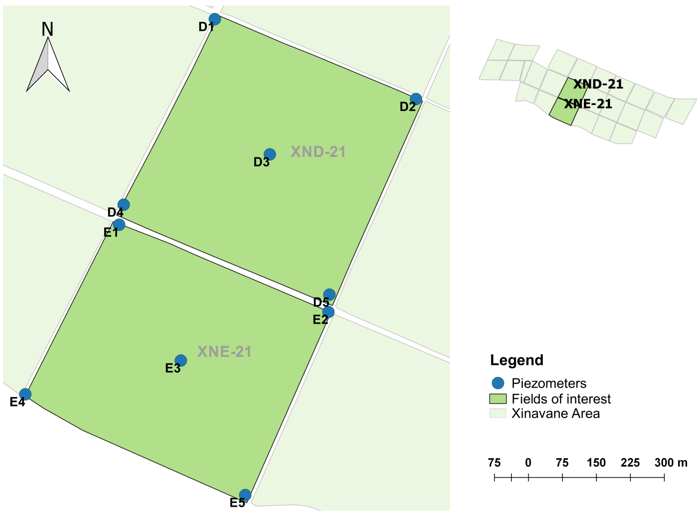


Figure B.1: Piezometer codes and locations.

Piezometers are installed in all four corners and the middle of both fields. Figure B.1 shows all piezometer locations, along with their respective code names. The following materials are used to install piezometers:

- Piezometer
- Auger
- Coarse sand
- Marker
- Water
- Plopper/measuring tape
- Hand pump, including Erlenmeyer and tubes
- GPS-tracker

A hole is drilled using the auger. Once the groundwater table is reached, indicated by saturated excavated soil, drilling continues for at least half a metre, preferably more. This way all the slits are placed below the groundwater table. Next, a piezometer is placed carefully in the hole to avoid tearing of the filter stocking. The empty space around the piezometer is filled with sand. Coarse sand is used because it has a relatively big grain size. This way the filter will not clog up with small clay particles and water flow is unrestricted. Water is used to flush the sand down to the bottom of the auger hole. After filling the hole with sand for at least one metre, the remainder of the hole is filled with excavated soil. The piezometer is drained using the hand-pump. GPS location of the piezometer is taken. Finally, the distance between the ground and the top of the piezometer is measured and written on the piezometer, along with its codename.

B.1.3. Slug tests

A slug test is conducted in each piezometer in order to determine the hydraulic conductivity. Once the water level inside the piezometer equals the phreatic head (thus indicating a stable situation), water is instantaneously extracted from the piezometer using a hand pump. The time needed to restore the head and the head difference are the measure to derive the hydraulic conductivity, see formula B.1.

$$K_{sat} = C\frac{\Delta h}{\Delta t} \tag{B.1}$$

With K_{sat} the saturated hydraulic conductivity in $[LT^{-1}]$, Δh the head difference in $[L]$ and $\Delta\, t$ the measuring time in $[T]$. Geometry factor C is computed using formula B.2.

$$C = \frac{4000}{(\frac{H}{r}+20)(2-\frac{h}{H})}\frac{r}{h} \tag{B.2}$$

Where H equals piezometer depth below the water table $[L]$, h equals the average draw down $[L]$ and r equals the radius of the piezometer $[L]$.

The water level inside the piezometer is measured using a diver that records the water level every 5 seconds. Figure B.2 shows a schematic overview of the measurement. The distance from the top of the piezometer to the diver, A in the figure, is measured. As total piezometer length and the length above ground are known, the water column underneath the diver can be computed.
The diver records total pressure. A barometer is used to record air pressure during the same time period. Subtracting air pressure from the total pressure results in water pressure, which can be converted to a water column above the diver. Adding the water column above and below the diver results in the total water level in the piezometer.

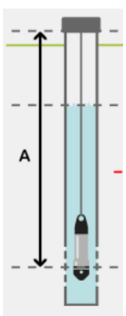
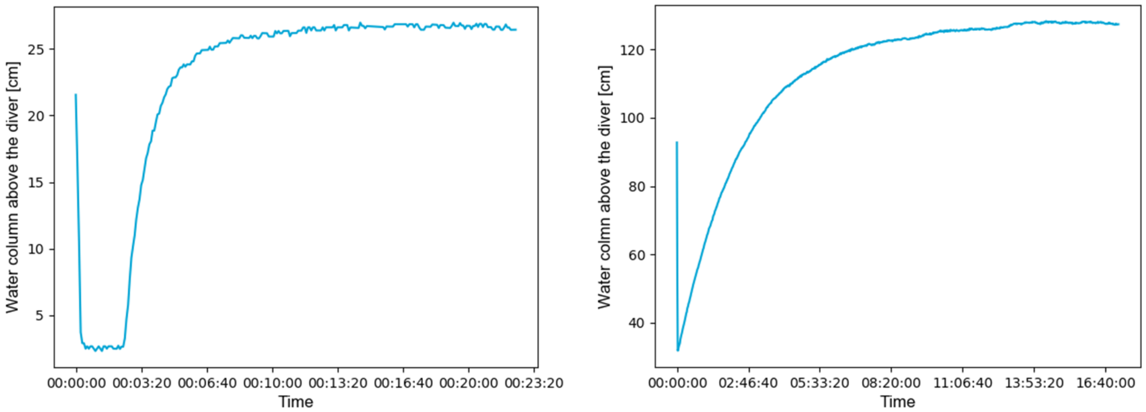


Figure B.2: Diver schematic.



(a) Pumptest D1.

(b) Pumptest E3.

Figure B.3: Diver data showing the head difference over time during the slug test.

Figure B.3 (a) shows diver data of the slug test conducted in piezometer D1. Piezometer D1 is located in the artesian aquifer found in field XND-21 meaning the water is pressurised which results in a distorted result for soil material. Table B.1 shows the different aquifer materials belonging to ranges of K values under phreatic conditions. According to Table B.1 the material of the aquifer should be fine sand since the K value is 1.69 [m/d] although the actual material is sandy clay.
Figure 6.2 (b) shows the diver data of the slug test conducted in piezometer E3. Piezometer E3 reaches a phreatic water table, this is clearly visible by the longer period it takes the water to restore to the normal level (more than half a day versus 15 minutes). The K value calculated with this data is 0.01, corresponding to silt.

Table B.1: Hydraulic conductivity ranges of different aquifer materials in md^{-1}.

Piezometer	K
Clay	<0.0001
Sandy clays	0.0001 - 0.001
Peat	0.0001 - 0.01
Silt	0.001 - 0.01
Very fine sands	0.1 - 1
Fine sands	1 - 10
Coarse sands	10 - 100
Sands with gravel	100 -1000
Gravels	>1000

B.2. Water quality material

Material per parameter is presented with associated accuracy in Table B.2.

B.3. Visual Observations

Within this Appendix the visual observations are shown of spot X1 and X2, within field XND-21. At first, the plant analysis is presented, followed by pictures taken of the two no-growth spots addressed within this research.

B.3.1. Images no-growth spots

In the no-growth spots of XND-21, shown in Figure B.4a and Figure B.4b.

Table B.2: Water quality parameters, material, range and accuracy.

Parameter	Analysis	Accuracy
EC	Greisinger GMH 3400 Series conductivity. Calibrated daily	± 0.5% for conductivity, ±0.2K for temperature (Greisinger Manual, 2014)
pH	Greisinger G 1500-GE pH meter & Palintest PT155. Calibrated bidaily.	±0.01 for pH (Greisinger Manual, 2014)
Na^+	Na^+ Horiba LAQUAtwin Na-11	10% (LAQUAtwin Manual, 2018
Phosphate	Lovibond MD-610 / Phosphate, T ortho LR tablets. Range: 0.05 - 4 mg PO4/L	Identical to precision specified in standard literature as American standards AWAA and ISO (Lovibond Manual, 2018)
Total Hardness	Lovibond MD-610 / Hardness, total T tablets. Range 2-50 mg/L CaCO3	idem
Ca-Hardness	Lovibond MD-610 / Hardness, Calcium 2 T tablets. Range 2-50 mg/L CaCO3	idem
Alkalinity	Lovibond MD-610 / Alka-M, total T tablets. Range 5-200 mg/L CaCO3	idem
Ammonium	Lovibond MD-610 / Ammonia T tablets. Range 0.02-1 mg/L CaCO3	idem
Nitrate	Aquacheck Field strips & ECO Visocolor Nitrate. Range: 0 -120 mg/L NO3-	Not able to measure NO3 <10 mg/L, 1±0% (Aquacheck manual, XXXX)

(a) Overview picture of spot X1 within XND-21.

(b) Overview picture of spot X2 within XND-21.

Figure B.4: Overview pictures of no-growth spots of XND-21.

In these two no-growth spots, the following observations were made: soil crusts and white coloured deposits. In Figure B.5a, B.5c, B.5b this phenomenon is shown.

(a) Both the white deposits on top of the soil and the soil itself tasted salty.

(b) Crusty top part of the soil is hard when the soil is dry.

(c) A dark peel-like soil top within spot X1.

Figure B.5: Soil crust spot X1. The crusty top part of the soil is hard when the soil is dry. Marker pen added for scale

In Figure B.6a and Figure B.6b the porridgy structure after wetting is shown.

(a) Wetted furrow after irrigation in spot X1, showing the porridge-like structure.

(b) Close-up of the wetted soil within the furrow after irrigation in spot X1.

Figure B.6: Porridgy structure after wetting.

In Figure B.7a and Figure B.7b, an example of puddles is shown.

(a) Puddle forming on spot X1 within the irrigation cycle.

(b) Puddles on spot X1 after the the irrigation cycle.

Figure B.7: Puddles.

In Figure B.8, two different aspect of poor water management are shown. In Figure B.8a, the dams are shown. These dams are built by the irrigators. In Figure B.8b the drainage problem is shown.

(a) Puddles that were formed due to the dams that were built by the irrigators and not removed after use.

(b) Poor drainage on low-lying spot X2. Water has been standing still and is not removed from the field.

Figure B.8: Two examples of poor water management.

B.3.2. Plants

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Phragmites Australis
	English name	Common reed
	Family	Poaceae
	User group	Perennial grasses
	Climatic zone	Wetlands & Tropical Regions, native from North America
	Botanic description	The leaf blade is flat; smooth; 1/2 to 2 inches wide; and 6 to 18 inches long. The seed head is an open panicle with a purplish or tawny and flaglike appearance after seed shatter. Common reed is readily identified by its height. It is the tallest grass in southern marshes and swamps.
	Notes	• Invasive status; out-competes native vegetation • lowers local plant biodiversity

Image source: http://sernecportal.org/portal/taxa/index.php?taxon=phragmites%20australis. Information source: Saltonstall, K. (2002). Cryptic invasion by a non-native genotype of the common reed, Phragmites australis, into North America. Proceedings of the National Academy of Sciences, 99(4), 2445-2449.

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Sesbania Sesbam
	English name	Common Sesban
	Family	Fabaceae
	Climatic zone	Wetlands & Tropical Regions, native from North America
	Botanic description	Leaves are long, narrow; leaflets in many pairs, rounded or oblong, usually asymmetric at the base. Flowers attractive, yellow, red, purplish, seldom white.
	Notes	• Ability to withstand waterlogging • Suited to flooded areas • Common along moist and inundated bottomlands • Shows tolerance to moisture stress and tolerates soil alkalinity and salinity

Image source: https://www.uniprot.org/taxonomy/76396. Information source: Source: Orwa C, A Mutua, Kindt R , Jamnadass R, S Anthony. 2009 Agroforestree Database:a tree reference and selection guide version 4.0 (http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp)

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Uruchloa Mosambicensis
	English name	Bushveld signal grass
	Family	Poaceae
	User group	Perennial grass
	Climatic zone	Tropics and Sub-tropics Native from KwaZulu-Natal northwards to east Africa
	Botanic description	A perennial 200-1500 mm high, stoloniferous, sometimes rooting and branching from lower nodes; Leaf blade 20-300 x 3-20 mm. Inflorescence made up of a number of spike-like racemes arranged alternately on a central axis.
	Notes	• It responds well to applied N • Environmental weed

Source: Chippindall, L.K.A., Crook, A.O. 1976. Grasses of southern Africa. Collins, Harare [Salisbury].

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Cynodon Dactlyon
	English name	Bermuda grass
	Family	Poaceae
	User group	Perennial grass
	Climatic zone	Widely distributed from Europe to in South Africa, and probably further south outside its native range.
	Botanic description	Growing to 0.3 m by 0.5 m at a medium rate. Conspicuous ring of white hairs of the ligule, the fringe of hairs on the keel of the lemma, and the gray-green appearance of the foliage.
	Notes	• Can grow in heavy clay and nutritionally poor soils • Prefers moist soils • Can grow in very acid, very alkaline and saline soils.

Source: Harlan, J. R., De Wet, J. M. J. (1969). Sources of variation in Cynodon dactylon (L). Pers. 1. Crop Science, 9(6), 774-778.

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Ipomoea aquatica
	English name	Bushveld signal grass
	Family	Convolvulaceae
	User group	Semi-aquatic perennial plant
	Climatic zone	Tropics, sub tropics. Native to central and south China
	Botanic description	Herbaceous trailing vine with milky sap. Stems hollow, rooting at nodes, floating in aquatic situations. Leaves are alternate, simple, with glabrous petioles 3–14 cm (1–6 in) long; blades generally arrowhead shaped but variable, glabrous or rarely pilose, to 17 cm (7 in) long, with tips pointed; blades held above water when stems floating.
	Notes	• Noxious weed • Grown in moist soils • Needs far more water than other vegetated crops.

Source: K.A. Langeland, H.M. Cherry, et al. University of Florida-IFAS Publication # SP 257. 2008

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Cyperus esculenso
	English name	Yellow nutsedge
	Family	Cyperaceae
	User group	Perennial sedge
	Climatic zone	Tropics to the Temperate zone. Eastern Hemisphere, including Southern Europe, Africa and Madagascar, as well as the Middle East and the Indian subcontinent
	Botanic description	Can be identified by the triangular shape of its stem. Leaves are arranged in groups of three (three-ranked), which also distinguishes it from grasses.
	Notes	• Muddy soil and shallow water • As a weed of cultivated ground • Difficult to control with non-chemical options.

Source: Rogers, H. H., Runion, G. B., Prior, S. A., Price, A. J., Torbert, H. A., Gjerstad, D. H. (2008). Effects of elevated atmospheric CO 2 on invasive plants: comparison of purple and yellow nutsedge (Cyperus rotundus L. and C. esculentus L.). Journal of environmental quality, 37(2), 395-400.

Plant analysis based on CSA 2014 Wageningen University	Scientific name	Cyperus Rotundo
	English name	Nut grass
	Family	Cyperaceae
	User group	Perennial grass
	Climatic zone	Native to Africa, southern and central Europe (north to France and Austria), and southern Asia
	Botanic description	Rhizomes are wiry, dark and persistent, connecting a network of daughter shoots and tubers. The tubers are dark brown to black, irregularly shaped and 1-2 cm (0.39 - 0.78 inch) long when fully grown. Each tuber has an apical bud and several lateral buds. Purplish-brown spikelets and leaf-tips coming to an abruptly acute tip.
	Notes	• Preference to wet, light soil • - Unfavourable effect on ecosystems by displacing native plants • Quickly form dense colonies.

Image source: cropscience.bayer.com Information source: Bayer Crop Science. (Year, month day). https://www.cropscience compendium/pests-diseases-weeds/weeds/cyperus-rotundus

C

Appendix Water balance

The water balance aims to illustrate incoming and outgoing water fluxes on a field scale. As illustrated in the previous chapter, many different water related fluxes influence a plethora of variables important to sugar cane growth. By mapping and measuring all inflow, outflow and storage of a field, relative contributions from different fluxes can be estimated.
A water balance holds true assuming that all in flowing fluxes in a time period are equal to all outgoing fluxes in the same period, as shown by Formula C.1.

$$Q_{in} - Q_{out} = 0 \tag{C.1}$$

Ingoing fluxes mainly consists of *precipitation (P) and irrigation (I)*. Precipitation consists of all rain (and theoretically also snow, hail and other forms of precipitation) falling onto the field. Irrigation is simply the amount of water artificially pumped onto the field. Furthermore, *groundwater (GW) and soil moisture (SM)* also influence the total inflow. This influence can be both positive and negative. Groundwater consists of only vertical groundwater movement was taken into account when constructing the balance. Soil moisture is the percentage of water of water in the soil of the field. Also see Formula C.2.

$$Q_{in} = I + P + GW + SM \tag{C.2}$$

Total outflow can be estimated by looking into *drainage (D), run-off (R) and evaporation (E)*. Drainage is the amount of water flowing out of the field through (sub-surface) drainage pipes. Run-off the amount of water flowing out of the field because the water is not infiltrated in the soil before reaching a drainage canal. Evaporation consists of three different fluxes: *transpiration* (E_t), *interception* (E_i) *and soil evaporation* (E_s). Transpiration is water that evaporates through the sugar cane, and possibly other vegetation if present. Interception is water that falls onto the plants and evaporates. Soil evaporation consists of the flux of water evaporating from the soil. Also see Formula C.3.

$$Q_{out} = E_t + E_s + E_i + D + R \tag{C.3}$$

Combining Formula C.1 with Formulas C.2 and C.3 leads to a complete water balance, see Formula C.4. Figure C.1 shows all variables in relation to the field.

$$I + P + GW + SM - E_t - E_s - E_i - D - R = 0 \tag{C.4}$$

C.0.1. Method

Precipitation (P)
Rain gauges were placed in the middle of each field, C.2. The gauge consists of a cone-shaped reservoir closed of by a lid with four small holes in the middle. Reservoirs were placed in a metal ring, 1.5 meters above the ground. Gauges were checked, and emptied if an event occurred, each morning on weekdays during a three week timespan.

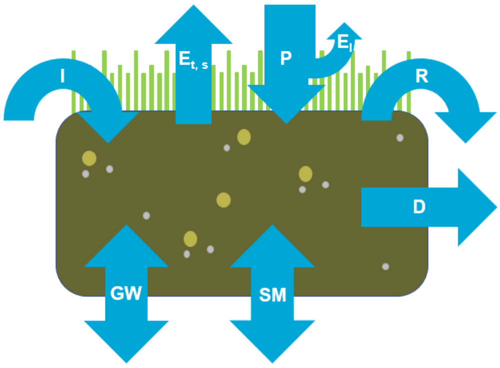


Figure C.1: Schematic overview water balance

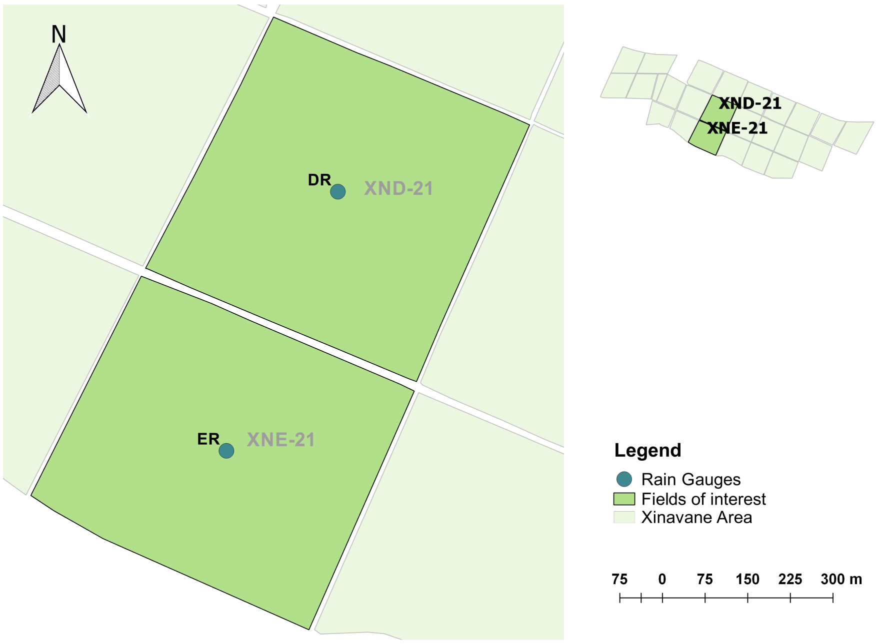


Figure C.2: Overview rain gauge locations

Irrigation (I)
Records of irrigation events were kept by area supervisors. The number of lines (furrows) irrigated was recorded. Protocol was two siphons per furrow. Furrow evaluations were conducted to estimate siphon discharge in each field. Multiplying these factors resulted in the amount of irrigation happening on an certain day, see Formula C.5.

$$I = 2 * n * Q_{siphon} \tag{C.5}$$

Where I is irrigation in L^3T^{-1}, n is the amount of lines irrigated in the field on a certain, protocol prescribes 2 furrows per line. Q_{siphon} is the amount of water coming through a siphon in L^3T^{-1}.

Groundwater (GW)
First, the root zone of multiple sugar cane plants was researched to determine whether groundwater should be included in the water balance. Next, groundwater depths were measured at five different locations: all four corners and the middle of the fields. Assuming a reference height of three meters below ground, four irregular triangular prisms can be made. The volume of each irregular triangular prism was computed. Next all four volumes were combined for a total volume. However, these numbers describe total soil volumes, not just groundwater volumes. Therefore, total soil volumes were adjusted for the porosity. The top layer of the soil consisted of a mixture of sand and clay, which have porosities of 0.36 and 0.44 respectively [86]. An average porosity of 0.40 has been used to adjust soil volumes to groundwater volumes. Comparing these volumes

day to day resulted in the groundwater change in $m^3 d^{-1}$.

Soil moisture (SM)
Soil moisture was calculated from daily soil moisture probe measurements. The probe measured soil moisture at 100, 200, 300, 400, 600 and 1000 millimeters below ground level. An average of these five measurements was used. The average of five measurements locations was used in the water balance, all four corners and the middle of the field. Details on soil moisture measurements methods can be found in Appendix E.2.

Run-off (R)
Infiltration tests were performed in both XND-21 and XNE-21. The results of these tests were used to calculate a run-off threshold. Detailed calculations on the run-off threshold value can be found in Appendix E.2.
When irrigation and precipitation combined exceeded the threshold value, excess water was considered run-off.

Drainage (D)
Inspection of the field and information from field managers confirmed the absence of drainage pipes in fields XND-21 and XNE-21. However, a drainage canal is present. This canal has a confusing name, as it drains run-off water. The drainage flux was not affected by this and was therefore assumed zero. Drainage is not included in the results.

Transpiration (E_t)
Evaporation values were based on CanePro data. These values were calculated using the Penman-Monteith equation, see formula C.6. Detailed information to determine evaporation was described by M.G. McGlinchley and N. G. Inman-Bamber [87]. Most input data for the Penman-Monteith equation was collected through the Chibanza Rancho weather station, located approximately 2 kilometres from both fields. The output determined by using the formula of Penman-Monteith in this way described transpiration by sugar cane.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho c_p \frac{e_a - e_d}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{C.6}$$

Interception (E_i)
CanePro used 20% of each precipitation event as an estimate as discussed in section 4.2.2. Research concerning rainfall partitioning in sugar cane plantations in Brazil concluded that 24% of precipitation is intercepted [88, 89]. CanePro's assumption of 20% was be used in this research.

Soil evaporation (E_s)
Soil evaporation was considered as an unknown. If all other parts of the water balance are known, Equation C.4 holds that the sum of all variables should result in the total soil evaporation.

C.0.2. Results

Data gathering went other than expected. The result of this is three different categories of data on fluxes. The first is fluxes where data-collection went successful and is reliable, resulting in useful data. The second category data-collection went successful, but due to a significant factor of unreliability data cannot be used in the water balance. The reasons behind the unreliability of the data differs and is explained for each flux respectively. Finally, data-gathering for some fluxes went completely wrong, resulting in no data.

Reliable data
Precipitation
From 26-11-2018 until 14-12-2018 rainfall gauges in both fields have been checked daily. Results can be found in table C.1, days without precipitation have been excluded from the table.
Precipitation data is minimal, only one rainfall event can be considered significant. This was also the only event big enough irrigation was not necessary. All other days, precipitation can be considered insignificant.
When considering possible errors in the dataset, sugar cane interference needs to be accounted for. Interference occurs when cane is tall enough that part of the precipitation is caught by the cane instead of the rain

gauge. The rain gauge in XND-21 is placed in a so-called bad spot. Where little to no sugar cane grows tall enough able to interfere with precipitation collection in the gauge. Field XNE-21 however, does not have a bad spot. At time of installation, sugar cane is too small to interfere. Near the end of the measurement period however, cane has grown and is now able to interfere part of the rain.
Only one significant rain event was recorded to verify possible interception. The difference between measurements in both fields on 09-12-2018 is considered too insignificant to adjust for interception. Many other reasons can be the cause of the small difference, with spatial variability as the most reasonable.

Table C.1: Precipitation in mmd^{-1} from 26-11-2018 until 14-12-2018, days without rainfall are excluded from the table.

Date	XND-21	XNE-21
29-11-2018	1.5	1.2
30-11-2018	1.8	0.2
09-12-2018	34.0	36.0
11-12-2018	0.9	0.4
12-12-2018	0.5	0.5

Interception
Data on evaporation through interception can be found in table C.2. Little rainfall occurred during the measurement period in order, which influences the quality of the dataset. Only one event can be considered significant. The other precipitation events are too small to consider possible partitioning. More likely is that the entire event is intercepted instead of absorbed by the soil.

Table C.2: Interception in mmd^{-1} from 26-11-2018 until 14-12-2018, days without rainfall are excluded from the table.

Date	XND-21	XNE-21
29-11-2018	0.30	0.24
30-11-2018	0.36	0.04
09-12-2018	6.80	7.20
11-12-2018	0.18	0.08
12-12-2018	0.10	0.10

Unreliable data
Irrigation
Results concerning irrigation data can be found in section 2. This data has been found too unreliable for further use and will therefore not be used in the water balance. Section **??** discusses unreliability of the irrigation data in detail.

Soil moisture
Data concerning soil moisture content (SMC) can not be used as values are unreliably high. Average measured values exceed expected porosities for a soil consisting of sand and clay. Section E.3 explains this in more detail. Section E.4 discusses SMP unreliability reasons. Gathered data is unfit to construct a water balance.

Run-off
In order to estimate a run-off boundary, infiltration tests have been conducted using an infiltrometer and soil moisture probe (SMP), the results of these tests can be found in E.3 However, SMC measurements have proven to be unreliable. Furthermore, average SMC does not change significantly over time. This is assumed to be due a compact clayey top layer, causing slow infiltration rates. Estimating a run-off boundary is therefore possible, but not advised as the boundary would hold no value. Instead, a theoretical explanation on how to calculate such a boundary using an infiltration test and SMC measurements is given in E.3.

Unknown data
Groundwater
Firstly, holes are dug next to plants in different conditions to expose root zones as explained in Chapter II.

Results can be found in Table 10.3. If the root zone reaches the groundwater table, groundwater should be considered in the water balance. In XND-21, where a high groundwater table is found, sugar cane roots reach depths up to 80 cm. If the groundwater table interferes at a more shallow depth, the root zone adjusts and is found closer to ground level as well. In XNE-21, the root zone reaches up to 170 cm below the ground, where groundwater is found. Root zone is connected to the groundwater table at all observations. Thus, groundwater can be considered a water source for sugar cane and should be included in the water balance.
Secondly, groundwater change was logged over a four week period through daily piezometer measurements. However, results concerning groundwater change measured by piezometer water levels are unreliable since an artesian aqueous soil layer was found entirely throughout XND-21 and partly in XNE-21. Groundwater is trapped within two semi-impervious layers and does not move phreatically. Instead, groundwater rises up and percolates down through the clay. These fluxes up and down are influenced by pressure on the artesian aqueous soil layer. However, simple water level measurements gathered from piezometers are too crude for any estimations about the quantity of these fluxes. They are based on a plethora of variables, the most important ones related to soil. Soil compactness, type and layering for example, are all important variables when considering rise and percolation of groundwater [90]. Since soil is extremely inhomogeneous in each of the fields, both laterally and vertically, more research should be done before making any assumptions on groundwater change.

Transpiration
Daily transpiration data was gathered for 2017. Estimated transpiration variations over the year can be found in Figure C.3, monthly statistics in table C.3. Evaporation follows seasonal variability with lower transpiration values in the dry season (May - July) and higher transpiration during the rain season (November - January) due to higher temperatures and precipitation events. The variability of rainfall events during the rain season also increases the variability of transpiration.
It should be noted that this data depicts transpiration over the year 2017. Other data is collected throughout November and December of 2018. This data is therefore not applicable to the water balance. However, transpiration data over 2017 seems likely given yearly weather characteristics. Meaning that weather station can be used for further possible water balances in the Xinavane area.
To do so the data should be accounted for different growth stages for different fields. Currently, data comes from the weather station directly and is not adjusted to field specifics, for example growth stage. Adjusting for growth stage results in a an accurate estimate for the transpiration flux.

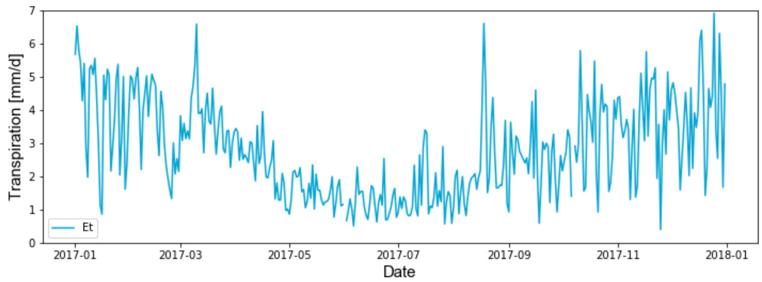


Figure C.3: Daily transpiration over 2017

Soil evaporation
Soil evaporation is considered as unknown in the balance. The sum of all other variables, if measured correctly, will result in an approximation of the soil evaporation. However, most other variables have been proven unreliable, incomplete or simply missing. An estimate on soil evaporation fluxes can therefore not be made.

C.0.3. Discussion

Precipitation
Using rainfall gauges to gather precipitation data is sufficient. Rainfall gauges worked as intended and daily rainfall data is gathered. However, sugar cane grew as data was collected. To the point that sugar cane in XNE-21 was tall enough to interfere with rainfall collection. Possible solutions for this problem are cutting the sugar cane around the gauge so it does not interfere. As a rule of thumb it can be said that no obstacles should be present nearer than five times the obstacle height [66].

Table C.3: Transpiration over 2017 in mmd^{-1}

Month	Avg.	Max.	Min.	St. dev.
January	4.1	6.5	0.9	1.5
February	3.6	5.3	1.3	1.2
March	3.7	6.6	2.3	2.8
April	2.4	3.9	1.0	1.7
May	1.5	2.3	0.8	0.4
June	1.2	1.5	0.5	0.5
July	1.5	3.4	0.6	0.8
August	2.3	6.6	0.8	1.3
September	2.5	4.6	0.6	0.9
October	3.2	5.8	0.9	1.2
November	3.5	5.7	0.4	1.3
December	3.9	6.9	1.4	1.4

Also, precipitation data should be gathered over a longer period of time. Preferably a year, through all seasons. The three week measurement period done in this research was short. As raining season in Mozambique starts in October [91], more rainfall events were expected. However, raining season started late and only one precipitation event is recorded. Longer measurement timespan helps this problem, and provide better datasets in general as variability has a smaller impact.
When measuring data throughout the entire year, or in general, multiple rain events within one day should be accounted for as this influences interception.

Irrigation
Irrigation data is based upon information from Tongaat Hulett in the from of irrigation sheets and furrow evaluations. The reliability of both can be disputed. Irrigation sheets are filled in after irrigation has taken place. Error checks are marginal and field workers do often not follow protocol. Meaning more siphons are used than intended, or even completely other irrigation methods. Furrow evaluations are performed by the evaluation team on the plantation. In the field, research seemed reliable. Processing gathered data however, led to an abundance of mistakes, as discussed in paragraph 4.2.8. Reliability of irrigation data can be improved if datasets are based on own measurements, not third-party datasets.
Lastly, irrigation data should also be gathered throughout the entire year. Sugar cane goes through different growth stages, and is irrigated accordingly. For example, water stress is imposed on the cane in the final stage in order to increase sucrose content [92]. Measuring irrigation throughout an entire year accounts for this growth process.

Groundwater
Data collection was started correctly. Unfortunately the discovery of an artesian aqueous soil layer turned data less useful. Adding to the previous discussion: the water balance only considers horizontal groundwater movement. Lateral movement is excluded from the balance. However, that does not mean lateral movement does not occur. Lateral groundwater movement could be a significant flux and should thus be taken into account. Modelling lateral groundwater movement is described by Tsubo M. & Ouk, M. [93].
Furthermore, capillary rise should be taken into account. This water balance assumed capillary rise to be a flux within the groundwater flux, and thus unnecessary to model as a stand-alone variable. However, capillary rise should be taken up in the water balance as well [94].

Soil moisture
Gathering and processing soil moisture data in a reliable manner turned out to be an Herculean task. Data gathered with the SMP was unreliable, and systematically exceeded soil porosity. More details on the discussion of the SMP can be found in section E.4. An interview with Diana Rietz, a soil moisture expert from South-Africa, revealed that SMP are the best way to measure SMC to date. There are no more sophisticated instruments [55].
If a SMP is used to gather SMC data, more measuring probes should be used. Fieldwork in this research had five measuring probes available. Since these are specific in shape and material, none extra could be made. When gathering data from big areas, more probes should be used in order to get comparable results.

One method to measure soil moisture more accurately is to consider the variable as an unknown in the water balance. If all other parts of the water balance are included and measured correctly, soil moisture can be computed as the missing variable. The downside of this method is that every single flux in and out of the field must be measured with great accuracy in order to get reliable results. As soil evaporation was considered unknown in this balance, soil moisture had to be measured in order to close the balance. Neither of these methods is easier or yields more accurate results per definition.
One possible way to measure SMC reliably is through satellite data. Remote sensing can be used to measure soil moisture data in the top 100 of the soil. This is the same depth infiltration was observed during tests (with the sidenote that infiltration rings did not reach past 100 mm below ground level). Resolutions of 100 meter by 100 meter result in 20-25 SMC measurements per field. Whether this is enough to account for in-field variability should be further examined. Other advantages of using satellite data include that ground sensors are unnecessary. Also: a well-written algorithm reduces the amount of human errors, thus increasing accuracy. Remote sensing can be used to measure large-scale areas and over longer time-spans. Meaning seasonal variability can be accounted for.

Run-off
The main concern using a general run-off threshold is that infiltration rates, and thus the threshold, are highly dependable on soil. Soil in the research area is extremely inhomogeneous. Thus, infiltration rates and run-off threshold values are inhomogeneous. A detailed soil profile helps this problem. In reality however, determining infiltration rates at different locations should reduce the problem as well.
Infiltration rates not only differ over location, they also change over time. As precipitation or irrigation events continue, and thus infiltration, soil becomes saturated and the infiltration rate decreases. Soil saturation can be measured with the soil moisture probe. When events are over, and no more water infiltrates, soil moisture content becomes lower and infiltration rates increase. These changes occur during and after events, within the time-scale of hours, minutes or even seconds. Making the run-off threshold value dependable on the SMC fixes part of the problem. Yet calculating the value over time seems difficult. Research on the influence of small-time variations on a daily scale should be done to see if it is significant.
Finally, run-off water does not always run off. Part of the water remains on the field, creating puddles. These puddles slowly evaporate, which is another flux of the water balance. Determining what part of the run-off evaporates needs further research.

Drainage
Drainage is a simple variable, as drainage pipes do not exist in either field and the outflow due to this flux is therefore equal to zero. Should drainage pipes exist in the research area, the flux can be estimated by observing what happens during irrigation and precipitation events.

Transpiration
Measuring evaporation and translating it to transpiration is either difficult or expensive. Using weather station data from the Chibanza Rancho is therefore a good solution. This comes with the problem that errors through the weather station are outside the reach of fixing. Furthermore, datasets are dependent on third-parties. In this case that resulted in no data from the current period of research. Though data quality was good, usage was minimal because the dataset describes a different timespan.
More importantly, only transpiration is measured. Meaning no flux accounts for soil evaporation. However, soil evaporation accounts for a significant part of the total evaporation [95] and should be accounted for when making a water balance.

Interception
Using a threshold value instead of a percentage in order to determine interception is an improvement. More improvements can be made however. Interception is based on sugar cane plant size. Bad spots in a field results in less interception. Taller cane on the other hand results in more interception. One way to model this is to make the threshold value dependable on the Leaf Area Index (LAI). That way the interception threshold becomes more accurate.
Furthermore, if multiple precipitation events occur shortly after each other, interception of the second event is decreased. This relationship should be examined in further research.
Fluxes More fluxes need to be mapped for a complete water balance, evaporation needs to be measured not only as transpiration, soil evaporation and interception, but also consists of soil evaporation and open water

evaporation from the puddles left by run-off water in low-elevated areas. As these puddles evaporate, salts in the water are left behind. This results in saline soil, unfit for sugar cane agriculture. Capillary rise should be further examined and taken into account for the water balance as well.

Timespan
This water balance is attempted over a three week timespan, measuring during weekdays only. This means data of just 15 days of measurements are gathered. From the results is concluded that such a timespan is not enough. Zero days with all variables gathered can be found for both XND-21 and XNE-21.
Besides the incomplete dataset, measuring over a short timespan comes with a second problem. Only part of the year, and thus weather variability, and part of the growth stage of sugar cane is accounted for. In reality, weather variability influences all variables. And as sugar cane matures, different irrigation amounts are used. Using a larger timespan, these variabilities can, and should be, accounted for. Then, a dynamic water balance can be made.
As discussed previously, remote sensing can be used to measure data over a longer timespan. Total evaporation can be measured using remote sensing data, as can soil moisture. The next chapter will discuss the usefulness of remote sensing through the introduction of a Decision Support System.

C.0.4. Conclusion

Results are not viable to make a feasible water balance. Collected data is either insufficient, unreliable or simply unavailable. Precipitation data is reliable, but too little rainfall occurred during the measuring period to make any conclusions on precipitation contribution. Irrigation data is unreliable. Groundwater is measured correctly, yet the presence of an artesian aqueous soil layer calls need for a different method. Soil moisture data proves to be unreliable as SMC exceeds porosity. Run-off data is based on SMP data, which is proven to unreliable. Drainage data is estimated correctly as drainage pipes are not installed and drainage simply equals zero. Evaporation results are correct in general but not field-specific and over the year 2017 instead of 2018. Finally, interception data is good. Yet, similar to precipitation, to little rain events occurred to base any conclusions off. Making a water balance out of these variables to base conclusions on would be unwise. A soil evaporation flux based on this dataset would hold no value. It can be concluded that making a water balance comes with many difficulties, which should be accounted for.
Another requirement for a conclusive water balance is that all data is measured during a similar timespan. A three week period in this research. In practice however, zero days are available with data about all fluxes. Limited availability of tools and unpredictable forces, for example precipitation, make it difficult to gather all variables on the same day in such a short time-span.

Instead of fabricating a balance with unreliable and inaccurate data, learning from made mistakes is the smarter option. This way, more reliable, and thus more useful, results in further research can be achieved. The discussions considers possible alternative methods for data collection.

D

Appendix Decision Support System

D.1. Hydraulic calculations

Field XND-21 is used as example. This field is 23.3 ha. The applied irrigation normally is 42 mm (according to CanePro), excluding 60% efficiency. The total water applied is thus:

$$(23.3 \cdot 100 \cdot 100 \cdot 0.042)/0.6 = 16310\ m^3 \tag{D.1}$$

The design discharge of the Neyrpic gate from the concrete canal into the earthen feeder is 50 L/s and on average three or four feeders are simultaneously used per field. This is because the protocol is to irrigate as shown in Figure D.1. For this example we use three feeders. The total irrigation time required can thus be calculated as

$$(16310/(50 \cdot 3))/3600 = 30\ hours \tag{D.2}$$

This makes sense as generally three days are used (ten hour a day) to irrigate one field.

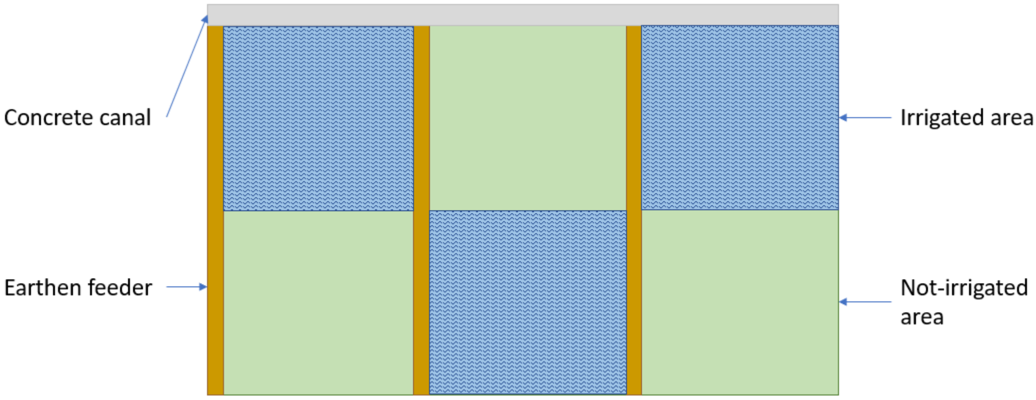


Figure D.1: Irrigation protocol.

Daily, the pump operates from 3 AM to 5 PM at an average flow of 500 L/s, which comes down to 25200 m^3/day.
Total canal length is 11.75 km and the average wetted area is 1.39 m^2 if all canals are filled to the top. This results in about 16300 m^3 of storage volume. However, water is stuck behind weirs and the even the main canal has not be seen completely filled, at most about 75 %. For the side canals the percentage is even lower, roughly estimated at 50%. Therefore, the actual storage volume used is about

$$2km \cdot 1.39m \cdot 0.75 + 9.75km \cdot 1.39 \cdot 0.5 = 8840\ m^3 \tag{D.3}$$

D.2. Rating curves

Established rating curves for three different locations can be seen in Figure D.2.

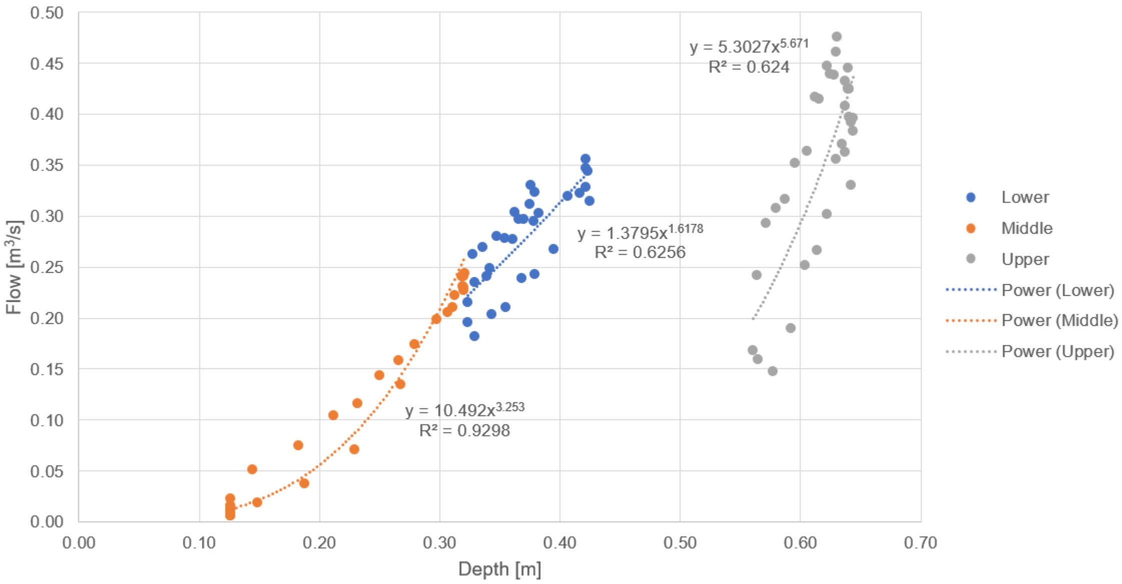
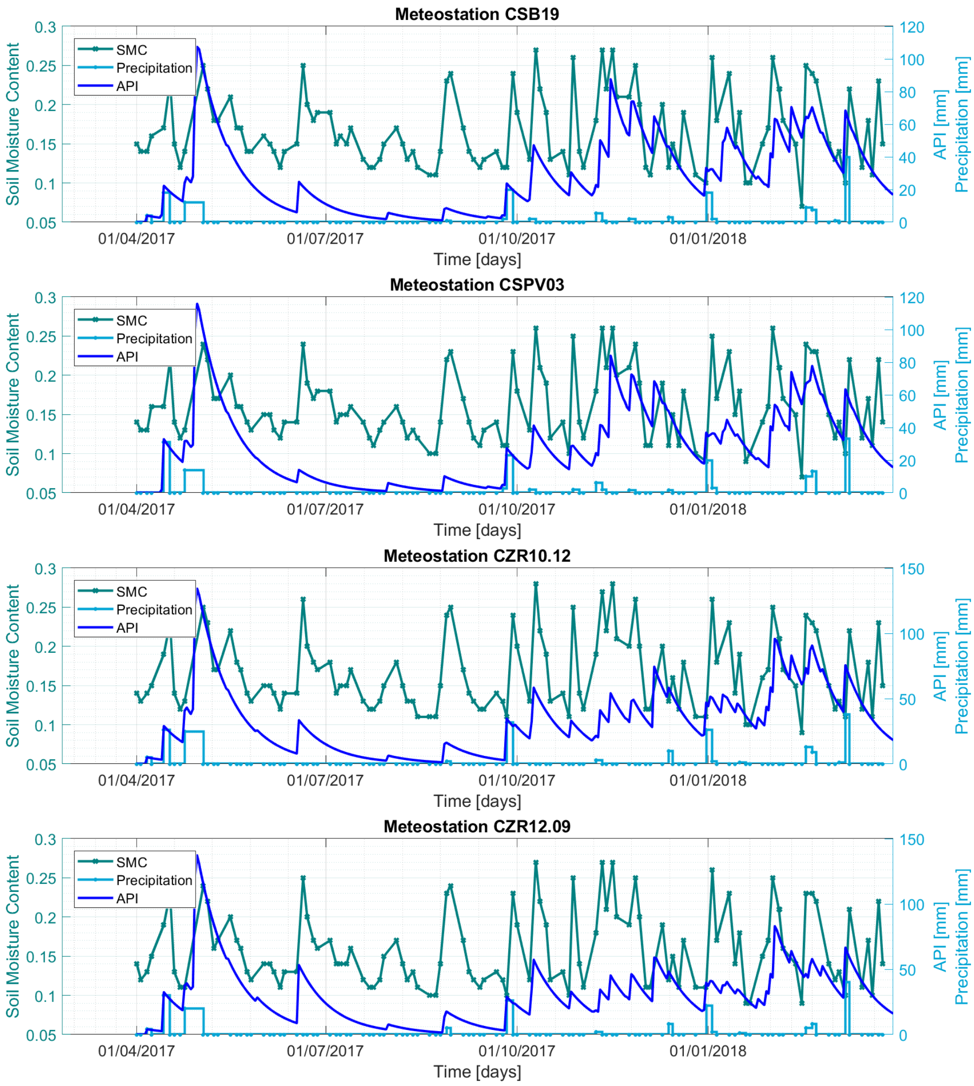
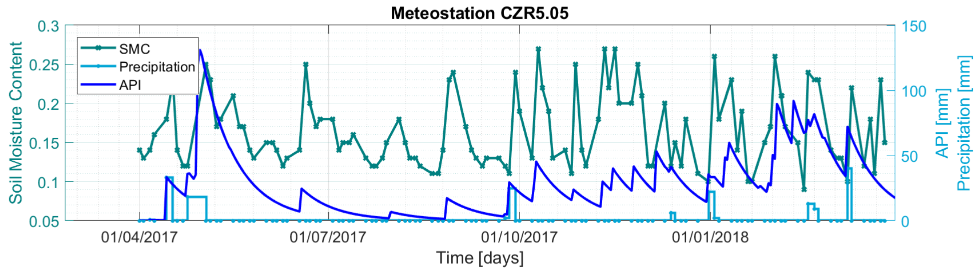


Figure D.2: Rating curves for three locations.

D.3. SMC, Rainfall and API over time per meteo-station

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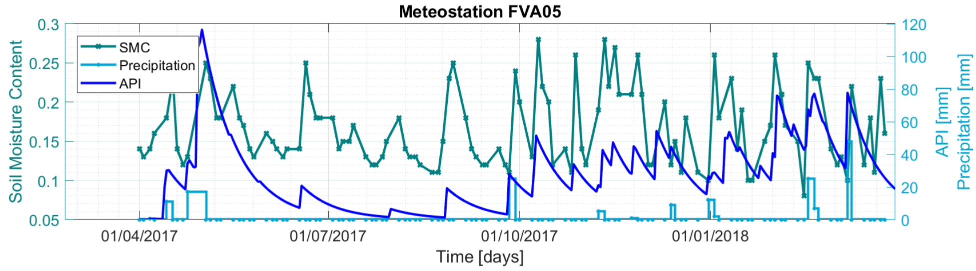
Time [days]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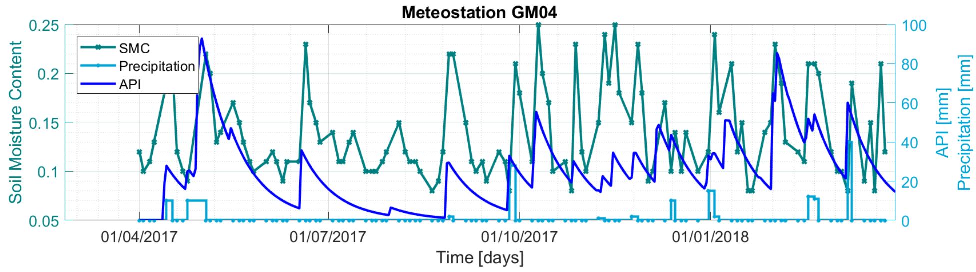
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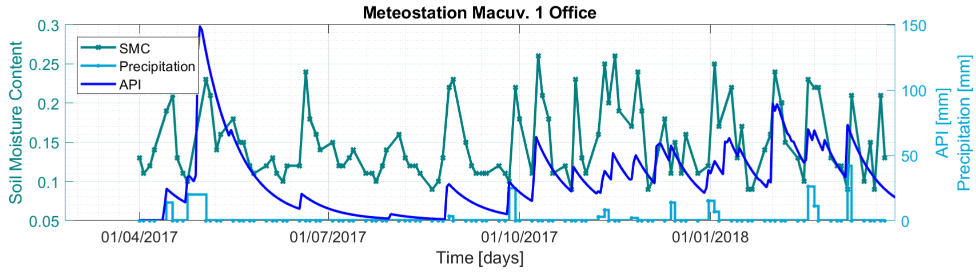
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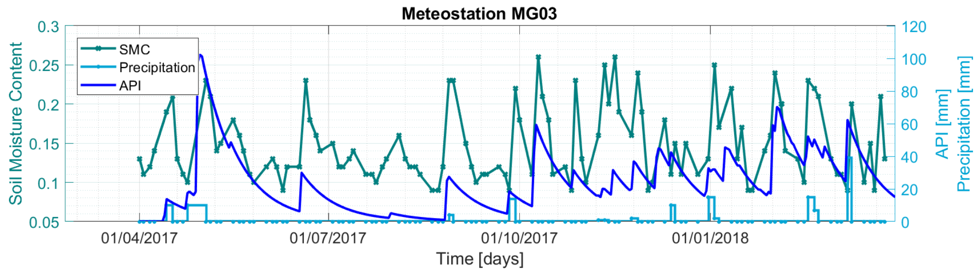
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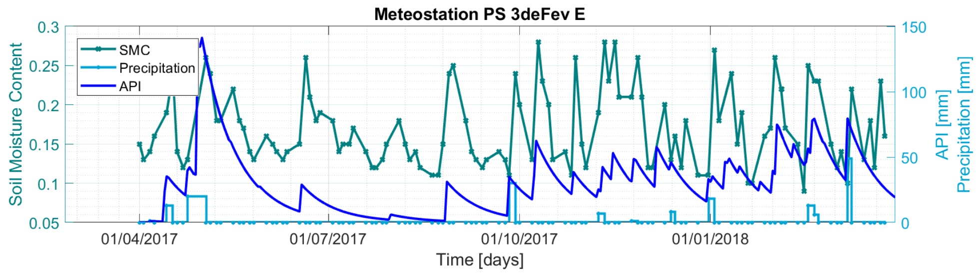
Time [days]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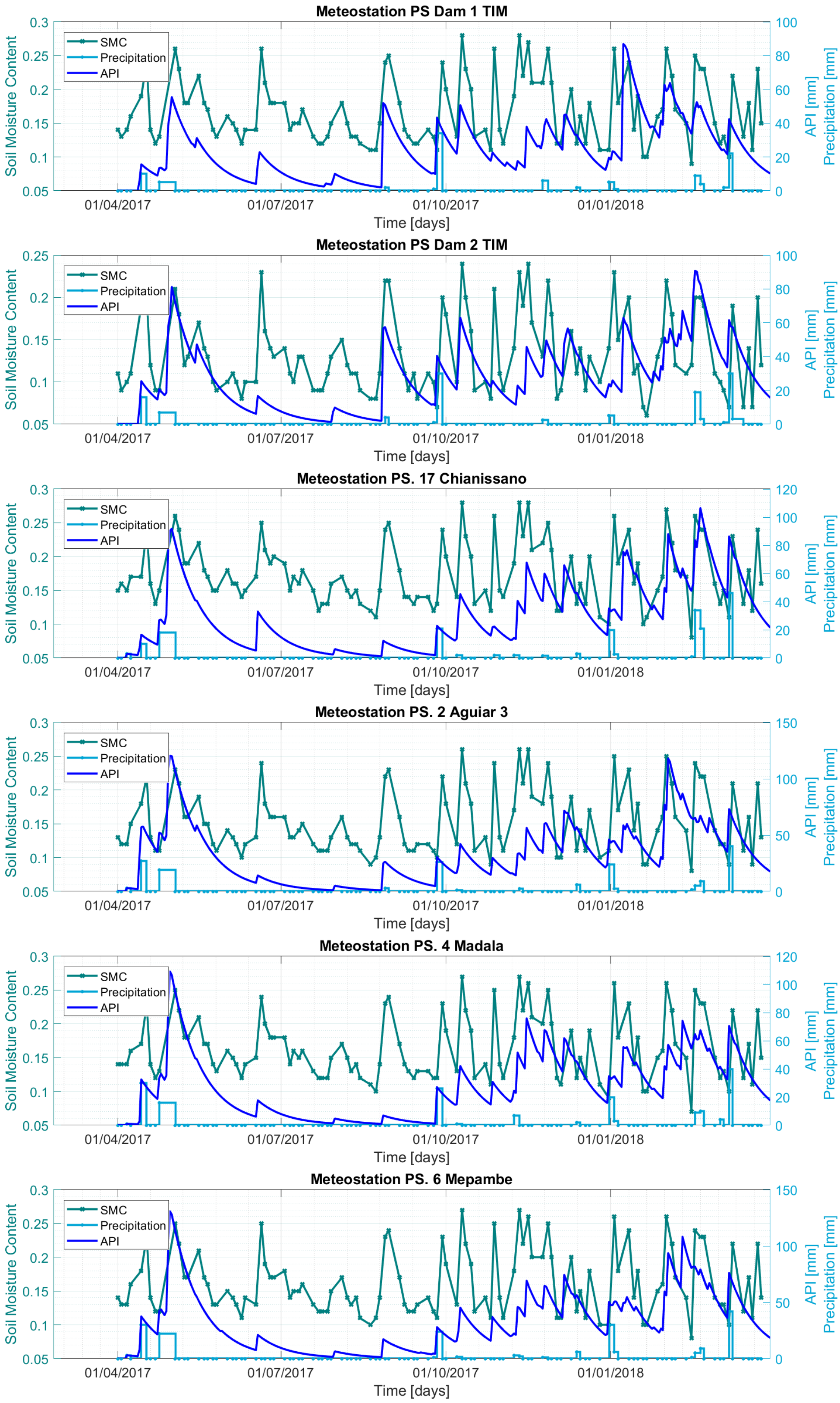
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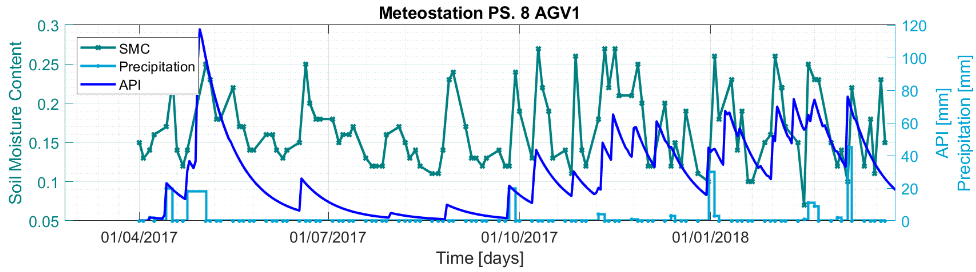
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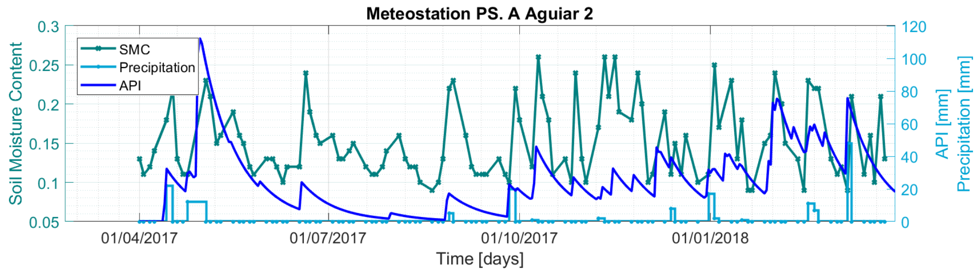
Time [days]


Meteostation PS. A Aguiar 2
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Soil Moisture Content
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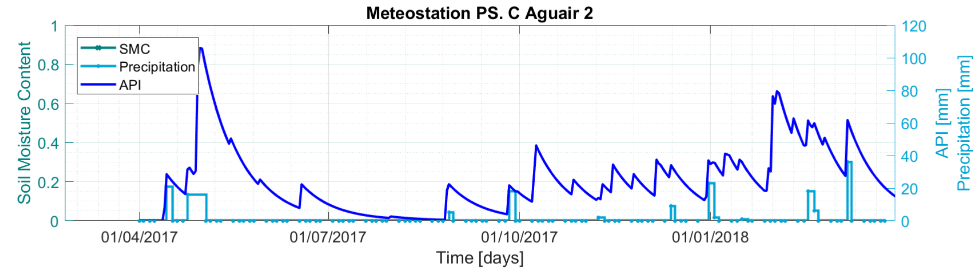
API [mm]
Precipitation [mm]
01/04/2017
01/07/2017
01/10/2017
01/01/2018
Time [days]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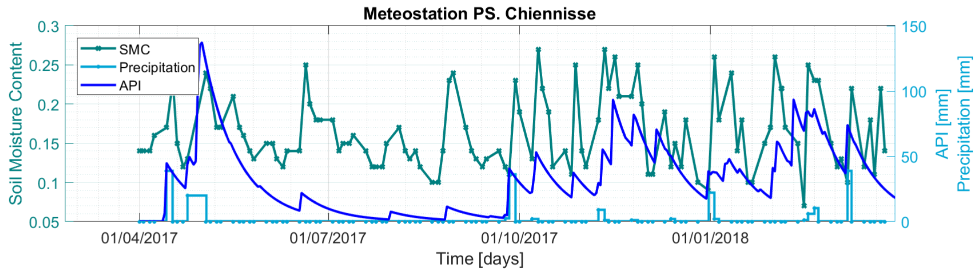
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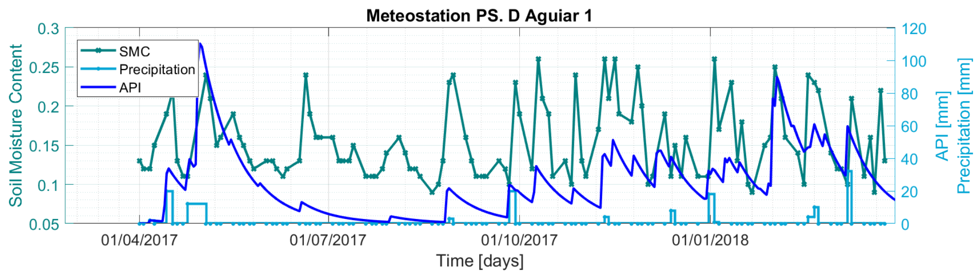
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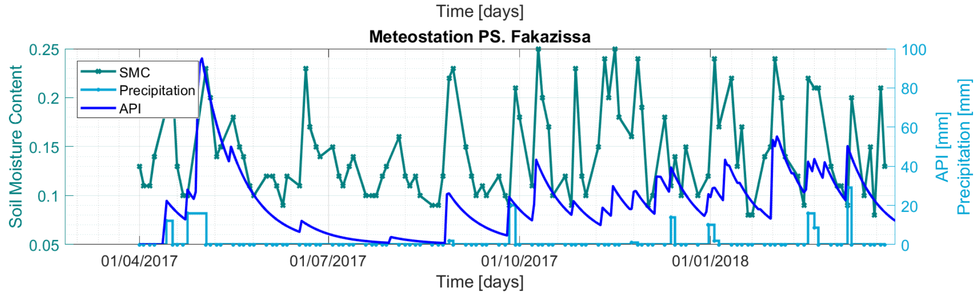
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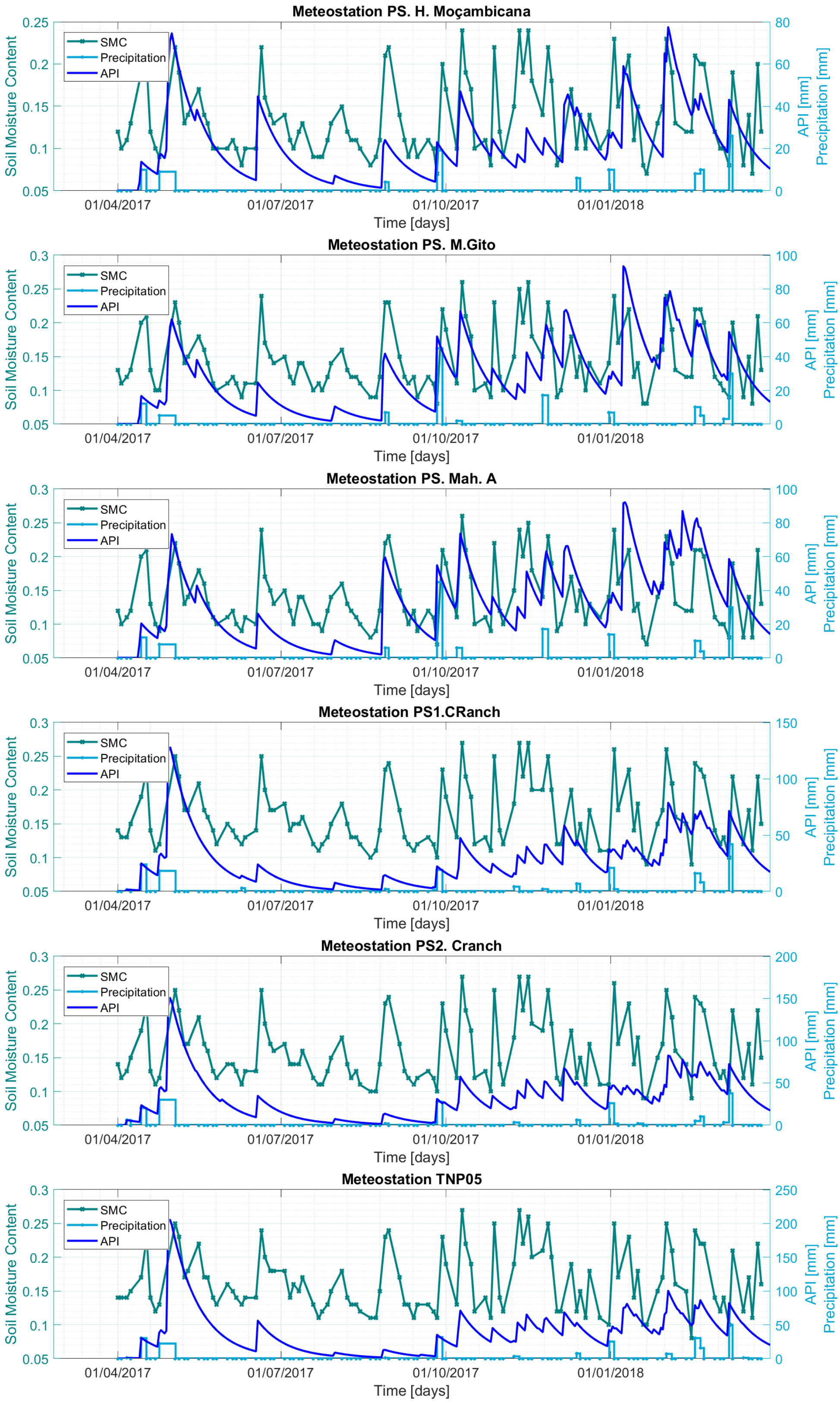
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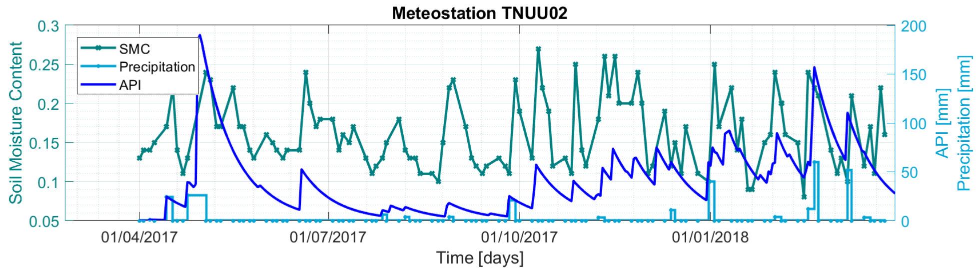

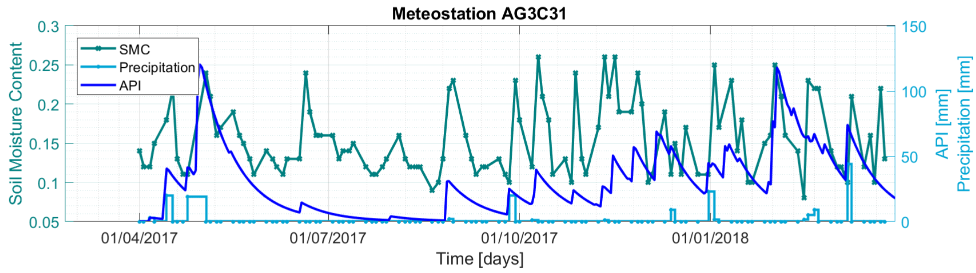

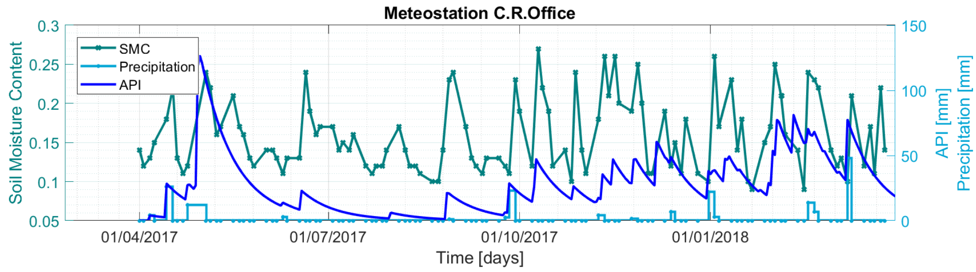

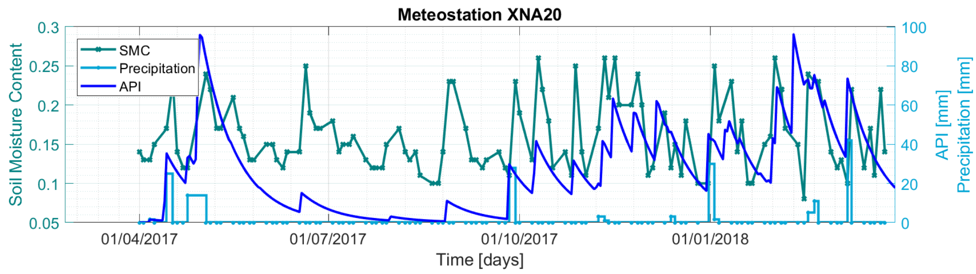

It is striking that meteo station *PS. A. Acuiar* does not show values for the SMC. This is because this meteo-station is placed very close to the Incomati river. The values shown by the VanderSat product correspond to what is measured in the river. Therefore they cannot be used, and this graph does not show SMC.

E

Soil Moisture Probe

E.1. Introduction

Soil moisture content (SMC) is an important variable in different parts of the conducted research. SMC is used directly as one of the variables in the water balance. Also, SMC is used indirectly to measure infiltration and thus a run-off boundary. Which is the value indicating the total water volume the soil can absorb. In order to measure SMC, a soil moisture probe (SMP) was used. The probe measures soil moisture at different depths within the soil profile. It consists of a sealed polycarbonate rod with electronic sensors arranged at fixed intervals along its length at 100, 200, 300, 400, 600 and 1000mm. Access tubes are installed in multiple locations in both fields. Daily SMC measurements are collected. An infiltration test is performed in both fields to estimate infiltration.

E.2. Method

E.2.1. Access tube installation

The following materials are used to install an access tube:

- Access tube
- Auger
- Bucket
- Water

An auger hole with a depth equal to the access tube length is made. Excavated soil is mixed with water. As the access tube is smaller than the auger hole, air surrounds the tube. This void is filled using the soil/water mixture. Air gaps in the soil around the probe interfere with the measurements and cause errors. Access tubes are installed at five locations in XND-21, all four corners and the middle of the field. Limited availability of access tube decreased the amount of locations in XNE-21 to two: the north-west and south-east corner of the field. After placing an access tube, a 72 hour waiting period should be followed before measurements can take place in order for the soil/water mixture to dry and resemble natural conditions.

E.2.2. Measuring soil moisture content

The following materials are used to gather SMC data:

- Installed access tube
- Soil moisture probe (PR 2, by Eijkelkamp)
- HH2 reader, including cables
- Pen and paper

Remove the end cap from the access tube. Make sure the access tube is completely dry. Remove the soil moisture probe from its protective case and place it in the access tube with a slight twist to ensure a lock. Attach the HH2 reader to the probe. Press ESC to activate the reader. Soil type needs to be selected. Moist soils can be characterised simply by choosing one of the two generalised calibrations, one for mineral soils (predominantly sand, silt or clay) and one for organic soils (with a very high organic matter content). As both fields consist have a clay/sand mixture as top layer, the mineral soil is chosen.

Once the correct soil is selected, reading can begin. Press READ and use the arrows to read SMC at different depths. Once all six depths are measured, press STORE to store results. Twist the probe 120 degrees and repeat twice clockwise and three times anti-clockwise.

E.2.3. Infiltration test

The following materials are used to perform an infiltration test:

- Access tube
- Auger
- Bucket
- Infiltrometer
- PVC pipe
- Hammer
- Soil Moisture Probe (PR2)
- HH2 reader, including cables
- 11.5 litres of water
- Pen and paper

An access tube is installed in a furrow using instructions above. Place a small piece of PVC pipe around the access tube to prevent water from contaminating the tube. The infiltrometer is placed around the tube using a hammer. Place the SMP in the access tube and start reading SMC according to instructions above. Next, water is applied to the soil. The water level should be above ground level to ensure maximum infiltration rate. Make sure not to flood the access tube, as this not only interferes with SMC measurements but also risks damaging the SMP. See Figure E.1 for the experiment setup.

In order to estimate infiltration rate, an infiltration test is conducted in both fields. Rainfall events are unpredictable. In order to get reliable results a rainfall event is simulated by applying 40mm, the same as a significant precipitation event, of water onto soil in an infiltrometer while SMC is measured over with fifteen minute increments. Keep measuring until SMC has both increased and decreased, indicating event results have ended.

Figure E.1: Infiltrometer.

E.3. Results

Table E.1 shows soil moisture content (SMC) during the measurement period. Limited availability of measuring probes resulted in no valid data for XNE-21. Measured values can be considered high. Soil porosity for sand and clay equal 0.36 and 0.44, respectively. As the top layer of the soil in both fields consists of a clay/sand mixture, soil porosity should fall within this range. Average SMC found in XND-21 falls between, or even slightly exceeds, the maximum values of these porosities. Meaning soil should be near complete saturation. As groundwater tables in field D start at 0.55 meters below ground surface at the minimum, this is not possible. Measured SMC is much higher compared to theoretically possible SMC and can not be included in the trusted.

Table E.1: Soil moisture in XND-21.

Date	XND-21 [%]	XND-21 m^3d^{-1}	Daily change m^3d^{-1}
26-11-2018	40.16	88,358	-
27-11-2018	40.60	89,319	961
28-11-2018	41.32	90,913	1,594
29-11-2018	38.78	85,319	-5,593
30-11-2018	44.00	96,789	11,470
03-12-2018	44.78	98,524	1,735
04-12-2018	43.32	95,295	-3,329

E.3.1. Infiltration tests

Figure E.2 shows the infiltration test conducted in the north-west corner of XND-21. Average SMC does not change over time. However, SMC at 100mm experiences a significant influx. SMC increases shortly after water is applied to the soil and keeps increasing for the next 7 hours. After seven hours the experiment had to be ended, thus the SMC decrease is not recorded. Quantitative results, for example a run-off boundary, can not be concluded from these results. The end of the increase in SMC, alias the decrease, needs to be recorded to deduct an infiltration rate over time.

Figure E.2 shows results from the infiltration test conducted in XNE-21. A similar pattern as in XND-21 can be seen. The average SMC does not vary significantly over the artificial precipitation event. SMC at 100mm however, is influenced by infiltration. A rise in SMC can be seen approximately during the first 1.5 hours after water was applied. This rise can be used to calculate a run-off boundary. However, since data is unreliable, a quantitative value will not be calculated since it holds no value. The fact that SMC only increases at 100mm below ground level is cause for doubt. Infiltrometer rings only reach the top 5 cm of the soil below ground level. Once water is past that point, lateral movement is possible. Since the soil consists of compact clay, horizontal and lateral movement have similar resistance and are approximately equally likely to happen. Once the infiltrometer rings stop limiting lateral movement, water spreads out in all directions, thereby nullifying horizontal SMC increase.

E.4. Discussion

- **Air gaps:** accuracy of SMP results is highly dependent on access tube installation. The hole created with an auger was wider compared to the access tube, resulting in air between tube and soil. Consultation with Eijkelkamp, the producer of the probe, resulted in fixing the problem by making mud from excavated soil and water. Using this mixture to fill the gap should fix the problem. However, since XND-21 mainly consisted of clay, the mud solution did not work. It did fill the gap, but the mixture did not resemble other soil in the field. According to the manual, this error could lead up to 10% [98].
- **Soil:** SMP measurements are most inaccurate when measured in a soil consisting of heavy clay [96]. If the soil cracks, which is the case in XND-21, readings from the probe can be more indicative of crack size instead of SMC. XND-21 has a clayey top layer throughout the entire field, XNE-21 throughout approximately half the field, making data gathered with the SMP even more unreliable.
- **Measurement radius:** soil is extremely inhomogeneous. Therefore, SMC varies greatly over small distances as well. The SMP measures SMC in within a 10 centimetre radius. This radius is too small for any conclusive results on a field scale. Furthermore, the radius made by the auger while installing acces tubes was already 2 centimetres. This means a significant portion of the soil measured by the probe is artificial, not natural.
- **Rotation:** measurements were taken six time per location. After the first measurement, the probe was rotated 120 degrees clockwise twice and anti-clockwise three times. Different angles of the probe in the ground yielded different results. A plethora of reasons could be the cause of this, the most likely being the high variability of soil moisture. However, this does cause another degree of unreliability in the dataset.

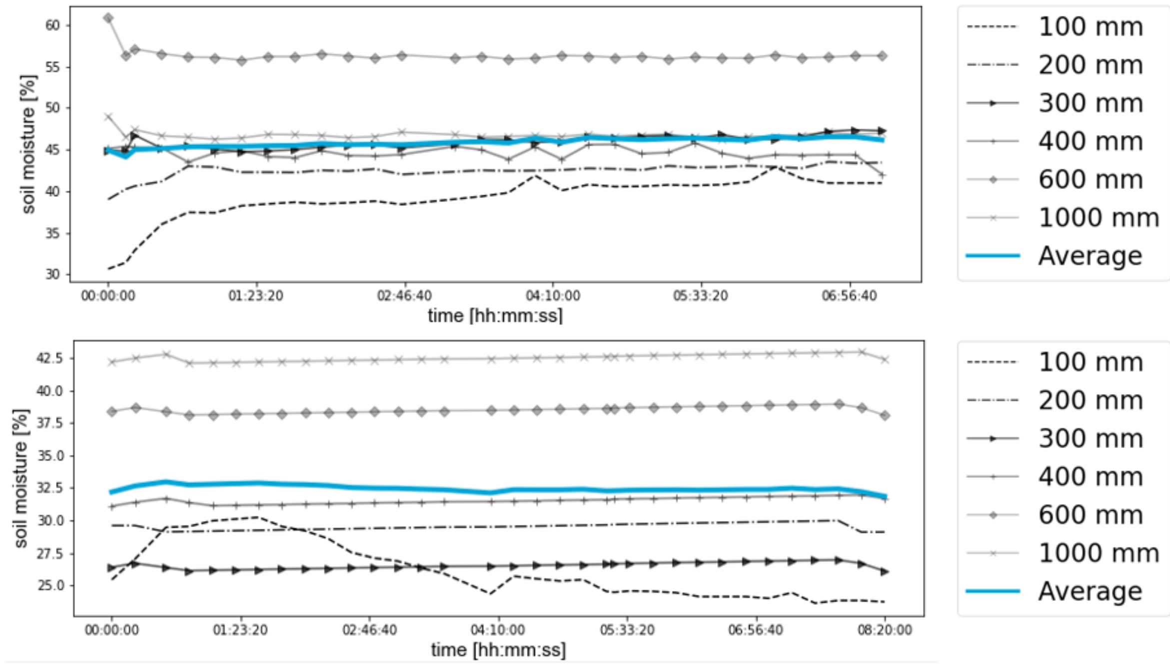

Figure E.2: Infiltration test results in XND-21 (up) and XNE-21 (down).

- **Outliers:** unusually high values were not uncommon within the dataset. Not only was the average SMC unusually high (averages above soil porosity), outliers could be as high as 80% SMC. These results can simply not be true, as 80% soil moisture would be observed by visual inspections. As stated before these outliers are not adjusted for as this would cause the false sense of reliability for the remainder of the SMP data.
- **Temperature:** measurements were conducted during summertime in Mozambique. Meaning temperatures often rose towards, or over, $40°C$. These high temperatures influence SMP measurements significantly, causing errors [97].
- **Missing instruments:** lastly, many parts needed to install access tubes correctly and transfer data were not present. Eijkelkamp did not provide all instruments needed to conduct proper research. The following tools were required, but not present: *cleaning rod, carrying rod, auger stabilisation pad, data logger, converters.* The missing converter resulted in the inability to connect the reader to the computer for the first five weeks. When, after extensive searching, a converter was found, provided software to read stored data did not work. Instead all measurements had to be written down by hand, increasing the possibility of errors due to human interference.

Based on the possible errors listed above, trusting any quantitative data gathered with the soil moisture probe would be unwise. Conclusions based on this quantitative data would hold no value. Much has been learned from fieldwork with the SMP, mainly that soil moisture is difficult to measure and that SMPs, even though they are currently the most sophisticated instruments available, should be avoided.

E.5. Conclusion

As stated in the discussion no quantitative conclusion can be made about the collected data. Some conclusions can be made however. The first is that infiltration in XND-21 occurs at a slower rate compared to XNE-21. Furthermore, water seems to infiltrate deeper in XNE-21, probably due to the difference in soil types. Where the infiltration test in XND-21 took place in clay, the location in XNE-21 was characterised by a sandy top layer.

The final conclusion about the SMP is that many factors influence the instrument, causing errors leading to an absurdly high degree of unreliability. The soil moisture probe is an unsuitable technique to collect SMC data in an area like Xinavane.