Improving water and nutrient use efficiency of *Phaseolus vulgaris* after flooded rice in Bwanje Valley irrigation scheme, Malawi.

by

Thandiwe Chinula

Mini-dissertation submitted in partial fulfilment of the requirements for the degree MSc Water Resources Management in the Department of Plant and Soil Sciences University of Pretoria

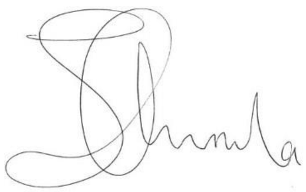
Supervisor: **Prof. J.G. Annandale**
Co-supervisors: **Prof. R.J. Stirzaker**
Dr. A.J. Sanewe

FEBRUARY, 2019

Declaration

I, Thandiwe Chinula, declare that this mini dissertation which I hereby submit for the degree of MSc Water Resources Management at the University of Pretoria, is my own work except where duly acknowledged and has not been submitted by me or another person for a degree at this or any other institution of higher learning.

SIGNATURE:



STUDENT NUMBER: U16223226

DATE: FEBRUARY, 2019

Acknowledgement

Thanks be to God for giving me sufficient grace to complete this research.

This material is based upon work supported by the United States Agency for International Development, as part of the Feed the Future Initiative, under the CGIAR.

Fund, award number BFS-G-11-00002, and the predecessor fund, the Food Security and Crisis Mitigation II grant, award number EEM-G-00-04-00013.

My sincere gratitude to the following people and organizations for their contribution to the successful completion of the study:

Prof J.G. Annandale, Prof R.J. Stirzaker, Dr A.J. Sanewe, and Dr I. Fandika for their consistent support, encouragement and expert guidance throughout the course of study.

The Ministry of Agriculture and Water Development, Malawi, for granting me study leave to undertake my studies.

The Administration and staff of Dedza Agriculture office, Malawi for their support throughout the data collection.

The VIA project for providing all the equipment's, inputs and protective wear.

Chitedze Agricultural Research station for helping me with laboratory analyses.

My colleagues, Nicholas Sichali and Trencio Kandinga for always being there for me.

Mr. T. Mpezeni, Mr. Chidani and Mr. Z. Gondwe for the encouragement and moral support.

Finally, my parents Mr.& Mrs. William Chinula, sisters Tasy, Pilirani and Melaie, brothers Kelson, Zebe, Prince and King George and my nieces Annie, Karen and Tazirwa for their love, prayers, encouragement and support throughout the study.

Table of contents

Declaration i

Acknowledgement ii

List of tables vi

List of figures vii

List of abbreviations ix

Abstract xi

Introduction 1

Bwanje Valley Irrigation Scheme (BVIS) 2

Problem statement and justification 4

Historical development of soil water monitoring devices 6

Gravimetric soil water content determination 7

Research questions 8

Research hypotheses 8

Research objectives 8

Chapter 1: Literature review 9

1.1 Soil water monitoring devices and methods 9

1.1.1 Tensiometer 9

1.1.2 Neutron Probe 11

1.2 Chameleon Sensors 12

1.3 Wetting Front Detectors 14

1.3.1 Limitations of the WFD 16

1.3.2 Relationship to other soil water measurement tools 16

1.4 Parshall Flume 16

1.5 Gravimetric method 18

1.6 Feel–and–Appearance method 18

1.7 Residual soil water 19

1.8 Surface Irrigation 19

1.8.1 Furrow Irrigation 20

1.8.2 Basin Irrigation 20

1.9 Sugar beans 20

Chapter 2: Materials and methods 22

2.1 Study site 22

2.2 Soil analysis 23

2.3 Experimental design and treatments 23

2.4 Field plot layout 24

2.5: Agronomic practices 26

2.5.1: Planting 26

2.5.2: Fertilization 26

2.5.3: Weed control 26

2.5.4 Harvesting 26

2.6: Installation of water monitoring tools 26

2.6.1: Wetting front detectors 26

2.6.2: Chameleon sensors 27

2.6.3: Parshall flume 28

2.7: Data collection 29

2.8 Statistical analysis 30

Chapter 3: The effect of irrigated water on soil nutrient levels available for dry bean 31

production. 31

3.1 Overview 31

3.2 Results 32

3.3 Discussion 38

Chapter 4: The effect of Chameleon sensor use on water management in bean production. 42

4.1 Overview 42

4.2 Results 43
4.3 Discussion 48
Chapter 5: Utilisation of residual soil water in relation to irrigated area. 53
5.1 Overview 53
5.2 Results 54
5.3 Discussion 61
General discussion 62
Conclusions and Recommendations 65
Recommendations 65
References 67
Appendices 71

List of tables

Table 1. 1: Advantages and Disadvantages of the main soil water monitoring tools 12
Table 1. 2: The colour used to denote wet, moist and dry soil, the typical ranges suggested for irrigation and associated vegetable crops 13
Table 1. 3: Parshall Flume Free Flow Discharge Values 17

Table 2. 1: Plot layout 25

Table 3. 1: Soil analysis results in the top and sub soil for BVIS 32
Table 3. 2: Yield of Beans (t ha^{-1}) 33
Table 3. 3: ANOVA: Differences between treatments 33
Table 3. 4: CV, SE and R^2 34
Table 3. 5: Least Significant Difference (LSD) Calculations for yield t ha^{-1} 34
Table 3. 6: Gross margin analysis 36

Table 4. 1: Water used if the profile ends dry 43
Table 4. 2: Amount of water available to each plot (mm) 43
Table 4. 3: ANOVA 44
Table 4. 4: Least Significant Difference (LSD) 44

Table 5. 1: Cropwat ET_o 54
Table 5. 2: Crop Water Requirement (CWR) from May to August 55
Table 5. 3: Crop Water Requirement (CWR) from August to November (late) 57

List of figures

Tensiometer (Charlesworth 2005) 10

Neutron Probe 11

Chameleon reader and sensor arrays (Via.farm 2015).................... 14

Wetting Front Detector (Via.farm 2015) 15

Figure 2. 1: Map showing the location of the study site 22

Figure 2. 2: Sign post placement.................... 25

Figure 2. 3: Nitrate test strip (Via.farm 2015) 27

Figure 2. 4: Wetting Front Detectors in the Field 27

Figure 2. 5: Placement of WFD and Chameleon sensors 28

Figure 2. 6: Parshall Flume dimensions (plan and side elevation view) (AR Robison 1957) 29

Figure 2. 7: Canopeo app screen (Patrignani and Ochsner 2015).................... 30

Figure 3. 1: Differences between treatment means 35

Figure 3. 2: Beans height vs Time 35

Figure 3. 3: Canopy cover (%) of beans vs Time 36

Figure 3. 4: Gross margin analysis.................... 37

Figure 3. 5: Farmers practice visualisations from Chameleon Sensor readings and WFD 39

Figure 3. 6: FILN visualisations from the Chameleon reader and WFD 39

Figure 3. 7: OILN visualisation from the Chameleon reader and WFD 40

Figure 3. 8: SILN visualisation from the Chameleon reader and WFD 40

Figure 4. 1: Availability of water in each treatment 45

Figure 4. 2: Visualisation of Chameleon patterns Source: (Via.farm 2017).................... 46

Figure 4. 3: Soil temperature visualisation (Via.farm 2017) 46

Figure 4. 4: FILN Chameleon pattern with crop growth stages.................... 47

Figure 4. 5: OILN Chameleon pattern with crop growth stages.................... 47

Figure 4. 6a and Figure 4.6b shows farmers' field while Figure 4.6c and Figure 4.6d show experimental plots.................... 49

Figure 4. 7: Visualization of the Chameleon pattern 50

Figure 5. 1: Crop water requirement and farmer irrigation for beans planted in May.........................56
Figure 5. 2 : Crop water use and available soil water depletion with days after planting 56
Figure 5. 3: Crop water requirement and farmer irrigation for beans planted in August 59
Figure 5. 4: Crop water use and available soil water against time...59

List of abbreviations

ANOVA: Analysis of Variance

ASARECA: Association for Strengthening Agricultural Research in Eastern and Central Africa

AWC: Available Water Capacity (mm/m)
BC: Branch Canal

BD: Bulk Density

BVIS: Bwanje Valley Irrigation Scheme

CSIRO: Commonwealth Scientific and Industrial Research Organization

CV: Coefficient of variation

CWR: Crop Water Requirement

DADO: District Agricultural Development Office

DARS: Department of Agricultural Research Services

EPA: Extension Planning Area

ETo: Reference Evapotranspiration (short grass mm d^{-1})

FILN: Farmer Irrigation and Luxury Nutrients

FP: Farmer Practice

GBI: Green Belt Initiative

MC: Main Canal

Mk: Malawi Kwacha

NP: Neutron Probe

OC: Organic Carbon

OILN: Optimum Irrigation and Luxury Nutrients

OM: Organic Matter

RCBD: Randomized Complete Block Design

SE:	Standard Error
SILN:	Strategic Irrigation and Luxury Nutrients
SWC:	Soil Water Content
TC:	Tertiary Canal
TDR:	Time Domain Reflectometry
VIA:	Virtual Irrigation Academy
WFD:	Wetting Front Detector
WUG:	Water User Group

Abstract

Phaseolus vulgaris is an essential legume crop for Bwanje people, because of its protein content for low-income population and good market availability. However, its yield is very low below pontential (2-3 t ha^{-1}). In terms of irrigation scheme utilisation, Bwanje irrigation scheme is heavily under-utilised in winter as only 145 ha is cultivated out of 800 ha. The Major factors contributing to all these problems are; inadequate nutrition, use of uncertified seed, poor water management and poor agronomic practices. The research was carried out to find the best way to use water and nutrients in order to improve the bean yields, and increase the irrigated area planted after flooded rice through use of residual soil water. The pontential yield could be achieved with appropriate balance of nutrients, water, good agronomic practices and timely use of residual soil water. The study looked at four different treatments replicated three times; Farmer Practice (FP), Farmer Irrigation and Luxury Nutrients (FILN), Optimum Irrigation and Luxury Nutrients (OILN), and Strategic Irrigation and Luxury Nutrients (SILN). Climatic database, Climwat and Cropwat were used to test the possibility of expanding irrigated area through better use of residual soil water by timely planting. FP received water as the farmer desired, OILN received water based on Chameleon sensors colours and SILN received water only when the crop showed stress signs. FP received 387 mm, FILN received 391 mm, OILN received 226 mm and SILN received 213 mm. OILN produced highest yield (2.75 t ha^{-1}), and FP produced lowest yield (2.1 t ha^{-1}). Farmer Irrigation leached most of the nutrients unlike in OILN and SILN where leaching was minimal. Through a desktop analysis the model indicated that in winter, an irrigated area could be increased by 78 ha. Therefore, Wetting Front Detectors and Chameleon Sensors could be used to minimise the loss of nutrients and improve water management through continuous monitoring thereby improve bean yield.

Key Words: Phaseolus vulgaris, water management, nutrients, Chameleon sensors, Wetting Front Detectors, residual soil water.

Introduction

The world's largest water consumer is agriculture, which uses about 70 % of the renewable water resource (WWAP 2014). Water scarcity is one of the major problems that has been experienced worldwide. According to the UNCTAD (2011), 1.4 billion people are living in water-stressed environments and this figure is expected to double by 2025. The world population keeps on rising and it is projected that by 2030 it may reach 9 billion. This growth in population will necessitate an increase in food production through rainfed or irrigated cropping (Jan Glazewski 2013, WWA 2012).

Malawi relies on rainfed agriculture to attain food security, improve earnings and sustain the development of the economy. The reliance on rainfed farming has contributed towards low yields and efficiency owing to adverse weather shocks and natural disasters. On the other hand, Malawi is gifted with very large water resources which cover around 30 percent of the country. Consequently, a well-developed water system is important for irrigation development and potable water accessibility (MGDS II 2016). Currently, the population is at 17 million and the total land area is 118484 km^2. The main food crop is maize and production is variable. Since 2001, population growth and mismanagement of food reserves have contributed to famines. Thus, irrigation development is considered vital and has been given high priority by the Malawi government in order to deal with food shortages (JICA 2005, Veldwisch et al. 2009). The government of Malawi views smallholder irrigation as a tool for increasing agricultural production for improved livelihoods and economic status of rural communities

Unlike rainfed agriculture, irrigated agriculture produces high yields and provides opportunities for multiple cropping (Moore 2012). Based on these advantages, irrigated areas have been expanding. It is projected that in developing countries, the total area under irrigation is expected to increase from 202 million hectares to 242 million hectares by 2030 (FAO 2002). However, this increase in area may not yield the expected increase in food production due to water scarcity. Furthermore, despite the fact that there are variations in the supply of fresh water, the competition for fresh water amongst agriculture, industries, households and the environment keep on rising (Rosegrant et al. 2002).

Water is directly linked to agriculture and a well-developed water system is important to the socio-economic development of the country. For instance, it has been argued that water development will also facilitate the Green Belt Initiative (GBI), a priority project by the Malawi government to increase agricultural production and productivity (MGDS II 2016). Thus, irrigation development is considered vital and has been given high priority by the Malawi government in order to deal with food shortages (JICA 2005, Veldwisch et al. 2009). Even though irrigation is considered vital its management through water and nutrients has been so poor in most the irrigation schemes leading to poor yields, hence use of simple tools to manage water and nutrients would be of great importance.

Bwanje Valley Irrigation Scheme (BVIS)

Bwanje Valley Irrigation Scheme (BVIS) is situated in Mtakataka Extension Planning Area (EPA), Dedza District, in the central region of Malawi. With an area of about 800 ha, it was built from 1997 to 1999 with funding support from the Government of Japan. The irrigation scheme started operating in the year 2000. The scheme consists of 1777 farmers cultivating 590 ha of paddy rice and 210 ha of dry bean, maize and other upland crops. Due to water shortages, only 145 ha is planted to dry bean, maize and other upland crops in the winter irrigation season. Bwanje irrigation scheme supports the production of flooded rice during the wet season and in winter they grow *Zea mays* (maize), *Vigna unguiculata* (cowpea) and dry beans (Chidanti-Malunga 2009, JICA 2005). This rice is harvested in April and the upland crops can be planted in May. Since rice is flooded, and cultivated in the wet period, soils are very wet at the beginning of the winter season. These soils hold a lot of water and naturally drain slowly. There is no scheme storage of water during times of water surplus, and river flow declines in the dry season. The possibility of expanding the limited area irrigated in winter by managing residual water as carefully as possible is worth investigating. Even if this is not possible, current yields are below what they should be, so productivity can likely be improved if limiting factors to production are addressed. This would enhance farmers' income, thereby improving their livelihoods. The research was conducted to improve dry bean production through improved water and nutrient management by using soil water and nutrient monitoring tools, and to ascertain if use of residual soil water could, in future, facilitate expansion of the area currently under irrigation.

The annually average temperature at BVIS is 25.1^oC and the monthly average temperature ranges from 21.7^oC in June to 28.2^oC in November. The maximum monthly average temperature exceeds 30.0^oC from September to December and the minimum average temperature drops to 16.0^o C from June to July. The average annual rainfall is 930 mm which falls from November up to April. Minimum total rainfall is 587 mm and the maximum is 1187 mm (JICA 2005). The Reference Evaporation (ET_o) varies from 4.18 mm day^{-1} in January, to 4.07 mm day^{-1} in May, 3.80 mm day^{-1} in July and 6.24 mm day^{-1} in October (Johnstone 2011). The scheme has three blocks which are named after Branch Canals (BC) that supply water to the blocks. Block 1 (BC1) is on the upper side of the scheme, Block 2 (BC 2) is in the middle of the scheme and Block 3 (BC 3) is on the lower side of the scheme. In summer, farmers use 0.45 ha while in winter, this is reduced to 0.09 ha. The scheme is managed by the Water User Group (WUG) which was formed by the farmers. The WUG is assisted by District Agricultural Development Office (DADO).

BVIS operates a surface irrigation system. In summer, they use basin irrigation, where the land is completely flooded and in winter, furrow irrigation is used where water is diverted into open channels. The source of water is the Namikokwe River which runs from the Dedza mountains to Lake Malawi. Water is supplied to the scheme through a diversion weir and open lined canals with earthen canals feeding the blocks. River discharge ranges from 0.15 m^3 s^{-1} in October to 5.04 m^3 s^{-1} in February, with an average of 2.25 m^3 s^{-1} (NKC 1997). The total discharge for the whole scheme is 1.42 l s^{-1} ha^{-1}. The headworks have an intake discharge of 1.14 m^3 s^{-1} .The Main Canal (MC) has a designed discharge of 0.385 – 1.14 m^3 s^{-1}, for Branch Canals (BC) 0.350-0.395 m^{3}s^{-1} and for Tertiary Canals (TC), 0.01-0.07 m 3s^{-1} (JICA 2005).

During summer, the scheme grows rice which is planted in January, or late planting occurs in February depending on the rainfall. The crop takes about 150 to 155 days to mature before it is cut down and dried in the sun, this crop is taken out of the field to dry. The fields are allowed to drain naturally before harvest. Harvesting occurs from end of April to May. The earliest upland crops are planted in May. After harvesting rice, residues are burnt on site which affects organic carbon levels of the soil, and nutrients such as N, P, K and S are lost. Microbes and fauna are also disturbed, and hence, their function in the soil is limited. After burning, soil aggregate stability is reduced and over time may result in soil acidity and erosion.

One of the crops grown in winter at BVIS is sugar bean. This crop does well in warm climates. They grow best at temperatures between 18^{o}C and 24^{o}C, with a maximum temperature of 30^{o}C. Any temperature below 20^{o}C will delay maturity and can cause empty or immature pods. Sugar bean can be planted in soils that are well-drained. Sandy loam, sandy clay loam or clay loam soils are ideal. Dry bean plants have a maximum rooting depth of 0.9 m and a maturity period of 115 days, depending on cultivar, weather conditions and soil type. Sugar bean is grown in winter at Bwanje due to its resistance to diseases, high yields and good prices on the market. The soils of BC1 where the experiment was conducted have a sandy clay loam texture. These soils have depths exceeding 150 cm, with a water holding capacity of 180 mm m^{-1} (DoI 2015) . Prior to the experiment the soils had pH levels in the range of 5.8 to 6.0, which is slightly acidic. They also had 0.21 % nitrogen (N) and phosphorus (P) levels of 74.9 mg/kg. Potassium (K) levels in these soils were 78 mg/ Kg.

Bwanje is one of the schemes being supported by the Virtual Irrigation Academy (VIA) project. The other two irrigation schemes in this project are Kasinthula and Nazolo. VIA was introduced in 2015 with the purpose of improving water use, fertilizer management, controlling salts and improving the return on investment from irrigation infrastructure. The project is currently being executed by the Department of Agricultural Research Services (DARS), in association with the Department of Irrigation (DoI). The Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA) coordinates and provides administrative support to the project within Tanzania and Malawi. VIA uses simple tools like Chameleon sensors to monitor soil water and Wetting Front Detectors to monitor soil nutrients (see chapter 1).

Problem statement and justification

Inadequate residual soil water utilisation soon after rice harvest is one of the challenges encountered at BVIS. Although it is a good agricultural practice to grow crops in fields where flooded rice has been harvested, as farmers can take advantage of large amounts of stored water in the soil, the practice is not implemented by most farmers. This was evident in research carried out by Humphreys et al. (2005). Their findings were that only a few farmers sowed wheat in fields that were previously grown to rice. In most cases, the fields are left fallow for several months after the rice harvest. This missed opportunity indicates that there may be some contributing factors that cause farmers not to explore this option. It was envisaged that after investigating these obstacles, practical strategies could be recommended that would make this practice attractive to farmers.

Another study, conducted in Bangladesh, showed that growing crops shortly after rice harvest can make better use of residual soil water, with minimal irrigation (M.N. Rahman et al. 2014). In India, it was observed that residual water present in the soil profile after rice cultivation can be used to grow crops with minimal irrigation. In the study in India, the factors that were investigated in residual soil water use were; 1) land preparation methods, where some fields were tilled while others had zero tillage; 2) time of planting after rice harvest, which focused on early and late planting and 3) method of planting (Kar and Kumar 2009). Since Bwanje farmers grow rice in summer and crops that require minimal irrigation in winter, a study was carried out on how best residual soil water can be utilized with minimal irrigation.

The yields at Bwanje for sugar bean (0.77 t ha^{-1}), are well below potential yields, as a result of inadequate water and/or inadequate nutrition, among other factors (Via.farm 2016). According to Seed Co (2010), the potential yield for sugar bean is 2-3 t ha^{-1} if the best management practices are followed, which is well above the 0.77 t ha^{-1} currently obtained. Bwanje is water limited in the dry season, and this is currently managed by reducing the cropping area from 800 ha to 145 ha. There is no storage of water during the surplus period, although the river declines during the winter season. All through the wet period, the supply of water surpasses demand, unlike in the dry season, where demand far surpasses supply. Water records are not kept at Bwanje, but a study conducted by Johnstone (2011) shows that a water gauge installed at the headworks assisted in recording water fluctuations. The water gauge has a scale of (0-9 m) and during the rainy season the water level rises from (5-6 m) and is reduced to (1.2 m) if rains are not available. When the rain period is over, and time has progressed, the water level declines lower on the datum (0 m). Farmers tend to irrigate the way they want and when they want without following the cropping calendar and good water management practices. The scheme does not have soil water monitoring devices to manage water and nutrients which could explain the poor water and nutrient management practices followed. It is anticipated that exploitation of residual soil water could provide opportunities to expand the area under production and rely on minimal irrigation. The use of simple soil water and nutrient monitoring tools could be beneficial in water and nutrient management.

It is important to indicate that farmers at Bwanje do not apply fertilizer to their dry bean crops because they fix nitrogen in the soil. However, whether this nitrogen is available in sufficient quantities for the crop is not known, since there are several factors that have an impact on nutrient uptake. It has been suggested that beans do respond to fertilizer application very well (Brown and Westermann 2000, FSSA 2007, SeedCo 2010) and this could boost its production at Bwanje. Beans may be fertilized using manure or low rates of 200 to 350 kg ha^{-1} of NPK. Applying nitrogen during planting time is important, especially after composted material has been incorporated into the soil before planting (DAFF 2010). Dry bean plants tend to nodulate late, towards flowering, are not efficient N fixers and hence need for starter nitrogen. Beans at BVIS are not inoculated.

Historical development of soil water monitoring devices

Richards and Neal (1937) suggested that utilisation of soil water recording devices would be important in understanding the impact of different irrigation treatments on evaporation, infiltration and water use. With increased water scarcity, more focus should be placed on devices that can help determine both when irrigation should occur and how much irrigation to apply (Peters et al. 2013).

In the 1930s the tensiometer was introduced as an instrument for soil water monitoring. The tensiometer comprises of a porous ceramic cup, sealed water-filled plastic tube and a vacuum gauge. The porous ceramic cup is buried in the soil and permits the movement of water in and out of the water-filled tensiometer and the soil. Pressure created during the movement of water is equal to soil suction and is recorded by the vacuum gauge. This can be used to determine when irrigation should occur (Charlesworth 2005).

The Neutron Probe (NP) was introduced in the 1950s (Evett and Steiner 1995). Unlike the tensiometer, it comprises of a nuclear source which is suspended from a cable and shielded by a housing when not in use. The Neutron Probe measures volumetric soil water content as the nuclear source is lowered down an installed access tube (Charlesworth 2005). It utilizes radioactive americium (an alpha particle emitter) to measure volumetric water content. Any country which uses Neutron Probes is obliged by law to obtain a license and provide training to users and adhere to safety regulations. This restrictive use of the Neutron Probe led to the development of devices that are non-nuclear (Evett 2000b) such as, Time Domain Reflectometry (TDR) and capacitance sensors, for example the Sentek Diviner 2000. These devices use the electromagnetic field that is generated to estimate the dielectric property of the soil which is translated into soil water content (Charlesworth 2005, Noborio 2001).

The Chameleon soil water monitoring tool is one of the tools that was developed to help in monitoring soil water. The tool turns from blue to green or red showing the depths where roots are mostly active. With the knowledge of the colour, a decision can be made when to irrigate.

The Wetting Front Detector (WFD) was developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, in response to low utilisation of existing irrigation tools. The aim was to achieve simplicity in irrigation scheduling and easy interpretation of the data. The WFD alerts the farmer to what is happening in the root zone following an irrigation or rainfall event. The tool can also be used to monitor nutrient loss and salt movement in the soil, as it is possible to extract a soil solution sample from a tripped detector (Stirzaker 2005).

The Parshall Flume was developed at the turn of 20^{th} century. It was known as the Improved Venturi, created by Dr. Robert L. Parshall. The flume developed was resistant to sedimentation and could operate submerged under free flow with less head loss compared to weirs. It can be created from wood, concrete or fibre glass (AR Robison 1957).

Gravimetric soil water content determination

The gravimetric method is the oldest quantitative method, adding to the earliest qualitative method of feeling the soil. It nonetheless, remains the most commonly used standard method for measuring soil water and for calibrating soil water sensors (Johnson 1962).

Research questions

1. What are the factors contributing to low yields in beans at BVIS?
2. Can the area at BVIS under winter crops be expanded through residual soil water utilisation?
3. If simple soil water and nutrient monitoring tools are used to manage soil water and nutrients, can yield be improved and irrigation minimized?

Research hypotheses

1. H_o: Under current farmer practice dry bean crops are nutrient limited.

   H_a: Beans are not affected by nutrient limitation under current farmer practice.

2. H_o: Under current farmer practice, beans are water limited.

   H_a: Beans are not water limited under current farmer practice.

3. H_o: Residual soil water utilisation has no effect on increasing winter irrigated area.

   $H_{a:}$ Utilisation of residual soil water will enable the winter irrigated area to expand.

Research objectives

Main objective:

The main aim was to explore how well dry bean can utilize residual soil water after flooded rice is harvested by improving irrigation water productivity and reducing nutrient leaching, without compromising the potential yield (2- 3 t ha^{-1}) of the crop.

Specific objectives:

- To determine if farmer irrigation scheduling leaches nutrients
- To determine if water management guided by Chameleon soil water sensors and Wetting Front Detectors could reduce irrigation and nutrient leaching.
- To ascertain if the area cropped in the dry winter season can be increased with better use of residual soil water after rice harvest**.**

Chapter 1: Literature review

1.1 Soil water monitoring devices and methods

Most farmers who practice irrigation struggle with effective and efficient water management. This has contributed to the creation of different equipment to measure soil water. It has been argued that farmers can ably manage water efficiently if they know how much water is available to the crop, and how much the crop requires (Charlesworth 2005). This suggests that continuous measurements and monitoring of soil water ought to be included in farm water management programmes. Charlesworth (2005) further suggests that when water is well managed, economic losses are reduced, and issues of over-irrigation or under-irrigation are avoided. In addition, the environment is conserved in such a way that water is not wasted, energy used is minimized, and chemicals or nutrients are prevented from leaching into the groundwater.

The success of water resource management depends on planning, monitoring and management. This would ensure that the crop would be serviced better by among other issues, providing the right quantity and quality of water whenever and wherever it is required (Jain and Singh 2003). Therefore, in order to plan for irrigation, soil water analysis and crop water requirement should be established. This entails an appropriate determination of the frequency of applying water and the duration of such applications to a particular crop at a certain stage of growth (irrigation scheduling) and the monitoring of the changes in soil water.

Discovering the appropriate technology to use is a difficult task, but also knowing how each soil water monitoring technology operates and is managed, becomes difficult for most farmers especially for smallholder farmers and old extension staff (Charlesworth 2005).

1.1.1 Tensiometer

The tensiometer measures the tension and suction that is applied by plant roots to take up water from the soil. Proper placement of the tensiometer is crucial. If the tensiometer is placed too deep in shallow rooted crops, results are that the crop will be irrigated late leading to water stress. On the other hand, if placed shallow in deep-rooted crops, this may result in overirrigation and deeper roots could be waterlogged. As a precaution against over-irrigation, a tensiometer ought to be placed at the bottom of the root zone to monitor subsoil water drainage.

The tensiometer has some advantages and disadvantages. The benefits are that it is less expensive than many other tools, can be easily understood by most farmers and no calibration is required (Stirzaker 2003).

Smajstrla and Locascio (1996), carried out a study using tensiometers on water use efficiency in tomatoes in Florida and found out that water use efficiency changes from 50% - 60% which was better since there was an improvement. Increase in tomato yields and reduction of nutrient leaching was realized in research carried out by Li et al. (1998).

On the other hand, tensiometers have some disadvantages. In Australia, tensiometers did not give the expected results due to the experiencing of very dry conditions (Charlesworth 2000). In another study conducted in citrus trees tensiometers provided unrealistic data due to the air that was entrapped in the device, and growing of the organics on the ceramic cup. Unless the tensiometer was recalibrated unrealistic data would be realized (Smajstrla and Koo 1986). Charlesworth noted that tensiometers cannot record soil water suction of more than 75 kPa which can damage the tensiometer due to the air that enters the ceramic tip (Charlesworth 2005). Figure 1.1 shows the tensiometer.

Figure 1. 1: Tensiometer (Charlesworth 2005)

1.1.2 Neutron Probe

One of the most accurate methods to measure soil water content is by using the Neutron Probe. Neutron Probes are usually bought by bigger organizations and small operations use experts to assist them in the operation of the device and with irrigation scheduling services.

The Neutron Probe was found to be precise and satisfactory and proved to be beneficial in soil water measurements (Evett and Steiner 1995). In another study, the Neutron Probe was able to determine soil water content with 80% accuracy. In the measurements of temporal change of volumetric water content, the Neutron Probe proved to be strong because it was not affected by the access air tube gap (Cayci et al. 2009, Grant et al. 2004).

The Neutron Probe has its limitations such as being restrictive in its utilisation due to a radioactive source. When soil water was measured close to the soil surface the Neutron Probe proved to be inaccurate due to neutrons escaping from the soil into the atmosphere without being detected, hence it was not recommended to estimate evapotranspiration, even if it is calibrated (Evett 2000a). The amount of water applied by farmers to crops mismatched that which is effectively and efficiently used (Stirzaker 2003). This is because farmers do not utilize the devices systematically (Stirzaker 1999). It was noted that most farmers are unable to install, calibrate and interpret data correctly from the device and for smallholder farmers it is cost prohibitive (Charlesworth 2005, Peters et al. 2013).
Figure 1.2 shows the neutron probe.

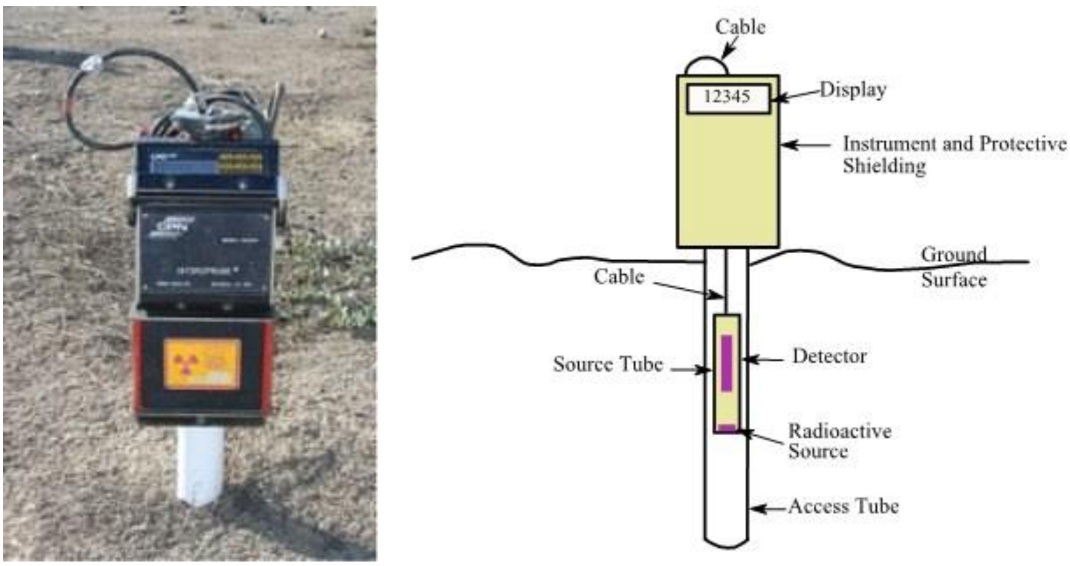


Figure 1. 2: Neutron Probe

Table 1. 1: Advantages and Disadvantages of the main soil water monitoring tools

	Sensor type	Advantages	Disadvantages
Soil water content	**Neutron probe**	Precise, Repeatable, Samples a quite large soil volume.	The government requires paper work and regulations, cannot be left in the field due to radiation issues.
	Time Domain Reflectometry	Less expensive, easy to log data.	Samples small area.
	Capacitance sensors (Sentek EnviroSCAN, Diviner 2000)	Easy to set up, to log or transmit data	Extremely affected by the soil condition next to the sensor, High variability, More expensive
Soil water tension	**Tensiometer**	Less expensive	Requires frequent maintenance, affected by freezing, works best only in coarse soils Can't measure tension greater than 80 kPa

Source: (Peters et al. 2013)

1.2 Chameleon Sensors

The Chameleon soil water monitoring tool determines the wetness or dryness of the soil. It consists of a reader which is connected to three porous sensors which are buried at different depths as well as a temperature sensor. The reader displays three colours; blue, green and red, depending on soil water tension in the sensors. The blue colour (0-20 kPa) shows the soil is wet, the green colour (20-50 kPa) shows the intermediate between wet and dry, and the red colour (> 50 kPa) indicates that the soil is dry and the plants may become water stressed (Stirzaker et al. 2014).

The Chameleon soil monitoring tool displays a pictorial description of soil wetness. The readings are time-stamped, geo-referenced and shown as patterns on the website with the help of Wi-Fi. Graphs can also be seen of how temperature in the soil is increasing or decreasing. The switch points between blue, green and red lights are based on extensive literature for avoiding crop water stress for most irrigated crops (Stirzaker et al. 2014).

Table 1. 2: The colour used to denote wet, moist and dry soil, the typical ranges suggested for irrigation and associated vegetable crops

Colour	**Water-Level (Meaning)**	**Switch points**	**Vegetable Crop**
Blue	Wet soil	20-30 kPa	Broccoli, Celery, Lettuce, Onion
Green	Moist soil	30 – 45 kPa	Dry Bean, Cabbage, Carrot, Capsicum, Corn, Tomato, Potato Cucumber, egg plant Melons
Red	Dry soil	>60 kPa	Beet, Peas, Sweet potato, Pumpkins

Challenges in the interpretation of data has been eliminated by the Chameleon sensors which measure soil tension and not soil water content. The problems of interpreting the units has been eliminated by the colour diodes (Blue, Green and Red) to show the available water in the soil. The use of visual data has made it easier to understand what is happening in the soil, unlike when data loggers are used due to their complexity (Stirzaker, 2014). Figure 1.3 show the Chameleon sensors and reader. The colours are really accurate in the sense that they really tell the condition of the soil whether dry or wet.

Figure 1. 3: Chameleon reader and sensor arrays (Via.farm 2015)

1.3 Wetting Front Detectors

The Full Stop Wetting Front Detector (WFD) consists of a shaped funnel, a filter and a float device. The funnel-shaped device is buried in the soil within the root zone depth of the plant. Once soil water reaches the buried funnel, water flow is focused (converges) so that the soil in the funnel becomes saturated as the cross-sectional area of the funnel become smaller. The saturated soil water at the base of the funnel trickles out of it and goes through a sieve and is intercepted in a reservoir. The intercepted soil water triggers a light weight float, which in turn activates an indicator flag above the soil surface. The Wetting Front Detector does not contain any battery, wires or electronics (Stirzaker et al. 2010). The collected sample of soil water is collected using a syringe and can then be analysed for its salt or nitrate concentration. The salts are measured by a simple field salinity meter and the presence of nitrates is measured with nitrate test strips which are dipped into the water sample and the colour of the strips is observed after a specific period of time. Then the colour on the test strip is compared to a standard colour chart provided by the manufacturer to check the nitrate levels in the soil.

Full Stop wetting front detectors are normally installed in pairs, one is placed about one-third in the operative root zone and the second at about two-thirds of the rooting depth. The placement of the WFD differs according to the irrigation system in operation. Whenever the shallow detector is hardly triggered, chances are high that the crop is under-irrigated. When the deep detector frequently pops up it shows that the crop could be over-irrigated. It is crucial that WFDs are placed at depths which are appropriate for the irrigation system and for the amount of water applied at one time (Stirzaker et al. 2004, Stirzaker et al. 2010). Figure 1.4 show the WFD.

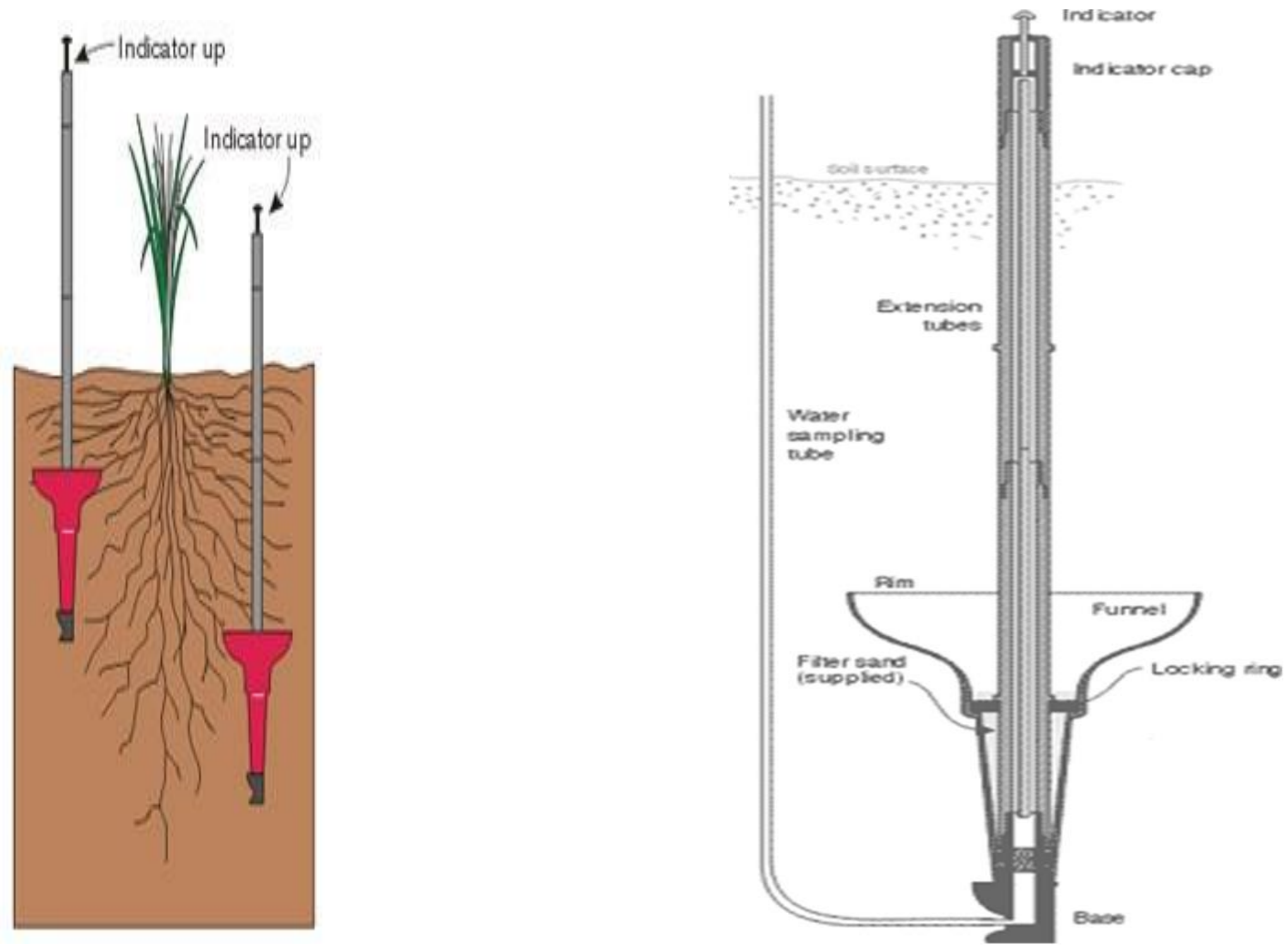


Figure 1. 4: Wetting Front Detector (Via.farm 2015)

1.3.1 Limitations of the WFD

The WFD informs the irrigator on the past irrigation but does not tell the farmer when the next irrigation should be (Stirzaker et al. 2004). This means that the farmer needs to decide when the next irrigation should be and how long it should last. The WFD does not detect fronts that are weaker than 2 to 3 kPa, which could lead to over irrigation, so some water could pass below the root system undetected.

Another limitation is that farmers experience difficulties with installation in terms of deciding on the right depth of placement and disturbance of the soil during installation (Stirzaker et al. 2004). The operation of WFDs was better in drip irrigation compared to centre pivot and furrow irrigation systems. Due to these limitations, a Chameleon sensor was developed to work together with the WFD. When these tools are used together, the WFD is mostly used for monitoring nutrients and the Chameleon for irrigation. Together they are better than either on their own.

1.3.2 Relationship to other soil water measurement tools

There are two types of soil water monitoring devices. One measures soil tension e.g. the tensiometer, which can be used without calibration, and others that determine the amount of water contained in the soil e.g. the Neutron Probe and capacitance probes.

A WFD is totally different from soil tension devices as well as devices that measure the amount of water in the soil. It simply shows the indicator up or down to indicate if a strong wetting front has gone past the depth at which the WFD is buried. There are no continuous readings from wet to dry (Stirzaker et al. 2010).

1.4 Parshall Flume

A Parshall Flume measures sub-critical flows of water in open channels. "Sub-critical flow is the flow where depth of the channel is greater than the critical depth, velocity of flow is less than the critical velocity and slope of the channel is also less than the critical slope. It has a Froude number of less than one" The critical flow is the transition or control flow that possesses the minimum possible energy for that flow rate and has a Froude number equal to 1.

The Parshall Flume has three sections, a convergence section, the throat section, and a divergence section. The flow comes through the convergence section and passes through the throat section where it is smaller. After the flow passes through the throat it enters the divergence section which allows water to flow freely from the flume. Sub- critical flumes similar to the Parshall Flume work by accelerating slow, sub-critical flow ($Fr < 1$) to a super

critical state (Fr > 1) by controlling the flow as it passes through the flume. The Fr is the Froude number. The Parshall Flume achieves this control by contracting the side walls and dropping the floor (AR Robison
1957). The equation $Q = KH_a^n$ is used where Q = Flee flow, K = Flume discharge constant (varies by flume size/units), Ha = depth at the point of measurement (meters). Table 3 indicates the values of Parshall Flume Free Flow Discharge which are used in the equation.

Table 1. 3: Parshall Flume Free Flow Discharge Values

Throat width (m)	**Throat width (cm)**	**K ($m^3 s^{-1}$)**	**N**
0.025	2.54	0.05	1.55
0.05	5.08	0.09	1.55
0.08	7.62	0.14	1.55
0.15	15.24	0.26	1.58
0.23	22.86	0.39	1.53
0.30	30.48	0.62	1.52
0.46	45.72	0.89	1.54
0.67	66.96	1.13	1.55
0.91	91.44	1.61	1.57
1.22	121.92	2.06	1.58
1.52	152.40	2.50	1.59
1.83	182.88	2.92	1.59
2.13	213.36	3.34	1.60
2.44	243.84	3.74	1.60
3.05	304.80	4.71	1.60
3.66	365.76	5.59	1.60
4.57	457.20	6.91	1.60
6.09	609.60	9.12	1.60
7.62	762.00	11.32	1.60
9.14	914.40	13.53	1.60
12.19	1219.20	17.35	1.60
15.24	1524.00	22.35	1.60

1.5 Gravimetric method

Gravimetric Soil Water Content (SWC) describes the amount of water in the soil on a mass basis. In this method, a small soil sample is taken, weighed and dried for a day in an oven, then weighed again. The mass difference is the water extracted from the sample through evaporation.

Its limitations are that the densities of various soils differ in such a way that a unit mass of soil might occupy a different volume. The delay in obtaining results is also at least 24 hours. It requires more time and physical effort in collecting and drying of samples and calculation of the moisture percentage. The sampling process can change the area where the research is carried out, owing to walking on the vegetation or by creating so many holes which require filling and packing (Johnson 1962, Reynolds 1970). To obtain the best results from samples, the soil should be similar, at least with water content to allow easy sampling, and samples should be free from roots, or organic matter and stones. Rarely are all these conditions met.

1.6 Feel–and–Appearance method

The feel- and-appearance method is a qualitative way of monitoring soil water to determine when and how much to irrigate in Bwanje. This method is simple and low cost and something that they really do. Before the collection of soil samples for estimation of soil water, one has to know the soil type, texture and available water holding capacity of each layer to be sampled. Soil texture relates to the amount of sand, silt and clay contained in the soil and helps in knowing the amount of water a soil will hold. The amount of water in the soil that can be readily absorbed by plant roots is known as available water capacity (mm/m) (AWC). The soil water conditions are estimated with low precision using the Feel– and-appearance method. Typically soil water is sampled at three or more sites per field. It is recommended to vary the number of samples sites and depths based on crop, field size, soil texture and soil stratification.

The feel- and-appearance method involves collecting the soil sample at a particular depth using a probe, auger or shovel. Then the sample is squeezed firmly in the hand for several times to form an irregularly shaped ball and then squeezing it out of the hand between thumb and forefinger to form a ribbon. Then observe the texture, ability to ribbon, firmness and surface roughness of the ball, water gleaming, soils not held together, soil water mark on fingers and soil colour. Finally, relate the results with photos and or diagrams to evaluate a percentage of soil water that is existing below field capacity. Field capacity is the amount of soil water a soil can hold, as by capillary action, before the water is drawn away by gravity. **(**Risinger et al. 1997).

1.7 Residual soil water

Residual soil water is the amount of water left in the profile after harvest. BVIS contains sufficient residual soil water in rice fallow in the post rainy season (November – April), which can be used to grow a second crop when timely planting is done (Kar and Kumar 2009). It is a good agricultural practice to grow crops in the fields where rice has been harvested as farmers take advantage of large amounts of stored water in the soil, however, the practice does not attract many farmers. This was evident from research carried out by (Humphreys et al. 2005). Their study revealed that only a few farmers sowed wheat in the field that was grown to rice after harvesting the latter. In most cases, the rice stubble is left in the field for some months after harvest. There may be contributing factors why farmers do not take advantage of this practice. It is envisaged that after exploring these obstacles, good strategies can be recommended to make this practice attractive to farmers (Humphreys et al. 2005).

Another study conducted in Bangladesh showed that growing crops shortly after rice harvest can better use the residual soil water, (M.N. Rahman et al. 2014). In India, it was observed that residual soil water present in the soil profile after rice cultivation can be used to grow crops with minimal irrigation. The factors that were investigated in this study that focused on the use of residual soil water were; land preparation methods, time of planting after rice harvest and method of planting (Kar and Kumar 2009). Growing crops soon after rice harvest offers some challenges. When the rice is harvested, soils are hard and compacted, resulting in poor drainage. The ability of a seed to grow and establish if the top soil is drying is a major limitation to crop production. Transformation from water-logged soil conditions to upland conditions results in substantial changes in soil reaction and nutrient availability particularly phosphate, hence fertilizer application is important for obtaining good yields of uplands crops.

1.8 Surface Irrigation

Surface irrigation is the application of water to the soil surface so that it gets wet partially or completely. In this system, water is carried from the source to the fields either in lined or unlined channels and low head pipelines. The system is suitable for soils that have low to moderate infiltration capacities and for terrain which is almost flat or levelled and has slopes less than 2-3%. The two methods of surface irrigation used at Bwanje are furrow irrigation in winter to grow crops like maize, cowpeas and beans, and basin irrigation in summer to grow rice.

1.8.1 Furrow Irrigation

In furrow irrigation longitudinal furrows and ridges are used. Water runs in small channels which are constructed across the slope of the field. Water is diverted into furrows from open ditches or pipes by use of syphon tubes. Water levels can be raised by the use of wood, check plates or canvas filled with sand. The head difference created is important for the absorption of water into the soil which spreads to wet areas between the furrows. In furrow irrigation systems, water is lost through deep percolation at the head of furrows and runoff dominates at the tail end. Example of crops grown under furrow irrigation are tomatoes, maize and beans.

1.8.2 Basin Irrigation

A basin irrigation system is flat land enclosed by earth bunds and that is completely flooded during irrigation. It is mostly utilised in rice cultivation but can also be used for cereal, fruit trees, and pastures. However, water logging of these crops should not last more than 24-48 hours. Water can be carried by syphon tubes, gated outlets from delivery channels into each basin. When designing a basin irrigation system, factors such as soil type, stream size, irrigation depth, land slope, field size and shape and farming practices need to be taken into consideration.

Basin irrigation is not recommended for crops that are sensitive to wet soil conditions, or on soils that crust badly after flooding. The main limitation of the basin is that the earth bunds interfere with the movement of farm equipment and reduce cropping area.

1.9 Sugar beans

The scientific name of beans is *Phaseolus vulgaris* and it belongs to the Fabaceae, (or Leguminosae) family. Dry beans originated in Central and South America and are used for both domestic consumption and commercial purposes**.** There are several bean seed types that vary in size, shape and colour. With each type, several varieties exist, with seeds slightly different from each other with differences in adaptability, growing habit, resistance to diseases and several other features (DAFF 2010).

Sugar beans have high protein content. They are grown by subsistence and commercial farmers because of their potential to achieve a high market price. Sugar beans have a high yield potential, can easily be stored and are resistant to some diseases. They can achieve yields that range from 2 to 3 t ha^{-1}.Time to harvest dry bean crops is influenced by where they are planted and planting time. The length of the growing season of sugar beans can be determinant or bush type

(type 1) indeterminate compact upright (type 2) and indeterminate runner type (type 3) (DAFF 2010). Beans can be planted shortly after rice harvest to use the residual soil water, but timely planting has to be taken into consideration before the residual soil water is naturally drained (Kar and Kumar 2009). The rooting depth is about 0.9 m and the crop water requirement are 300 – 500 mm per total growing period (Brouwer and Heibloem 1986). Planting should be done in soils with a pH of 5.2 and liming is crucial if the soils are acidic (DAFF 2010). The first half of the growth period of beans is vegetative growth and the last period is reproductive. Pods are green in the initial stage, then they change to yellow and light brown as they mature.

Normally the term sugar beans refer to speckled types e.g Cranberry and Pinto. It is very crucial to choose the right variety for the intended market, even though most consumers prefer the speckled type. Farmers in Malawi are advised to select cultivars that are resistant to diseases and are certified by agro-dealers e.g. SeedCo. Planting of sugar beans depends on the cultivar. Short determinate cultivars should be planted in 45 cm rows with 5 to 10 cm between plants, giving a population of 222222 plants per ha. Tall indeterminate varieties may be planted at wider spacings. Seed is planted 2 cm deep.

Literature suggests that certain crops can withstand periods of soil water stress, especially at particular physiological stages of development without compromising the potential yield mostly the indeterminate types. However, at other growth stages, even a small amount of water stress might result in a serious decrease in crop yield, and irrigation at such times would be very essential and profitable. Beans are easily affected by both too much water or too little. For example, there is a huge influence on the pod development and quality through vegetative growth and flowering if beans are water stressed (Saleh et al. 2018). Generally, flowering, pod development and pod filling stages are very critical and no water stress should be experienced if yields are to be improved. Most of the farmers in Malawi do not inoculate beans with rhizobia as it is the case with Bwanje farmers who don't inoculate but the practice is done by research institutions.

Chapter 2: Materials and methods

2.1 Study site

The research was conducted at Bwanje Valley Irrigation Scheme (BVIS) which is located in Dedza District, in the Central Region of Malawi, close to the town of Mtakataka, T/A Kachindamoto, from 24th July to 9th November 2017. The scheme is located at 14° 16 .415' S and 34° 33.503' E with an elevation of 524 m above sea level. The soils where the experiment was conducted are sandy clay loam and the water holding capacity, 180 mm m^{-1} (DoI 2015). Bwanje's main economic activity is the production of rice, maize, beans, and cowpeas.

Figure 2.1 shows the location of BVIS on a map of Malawi.

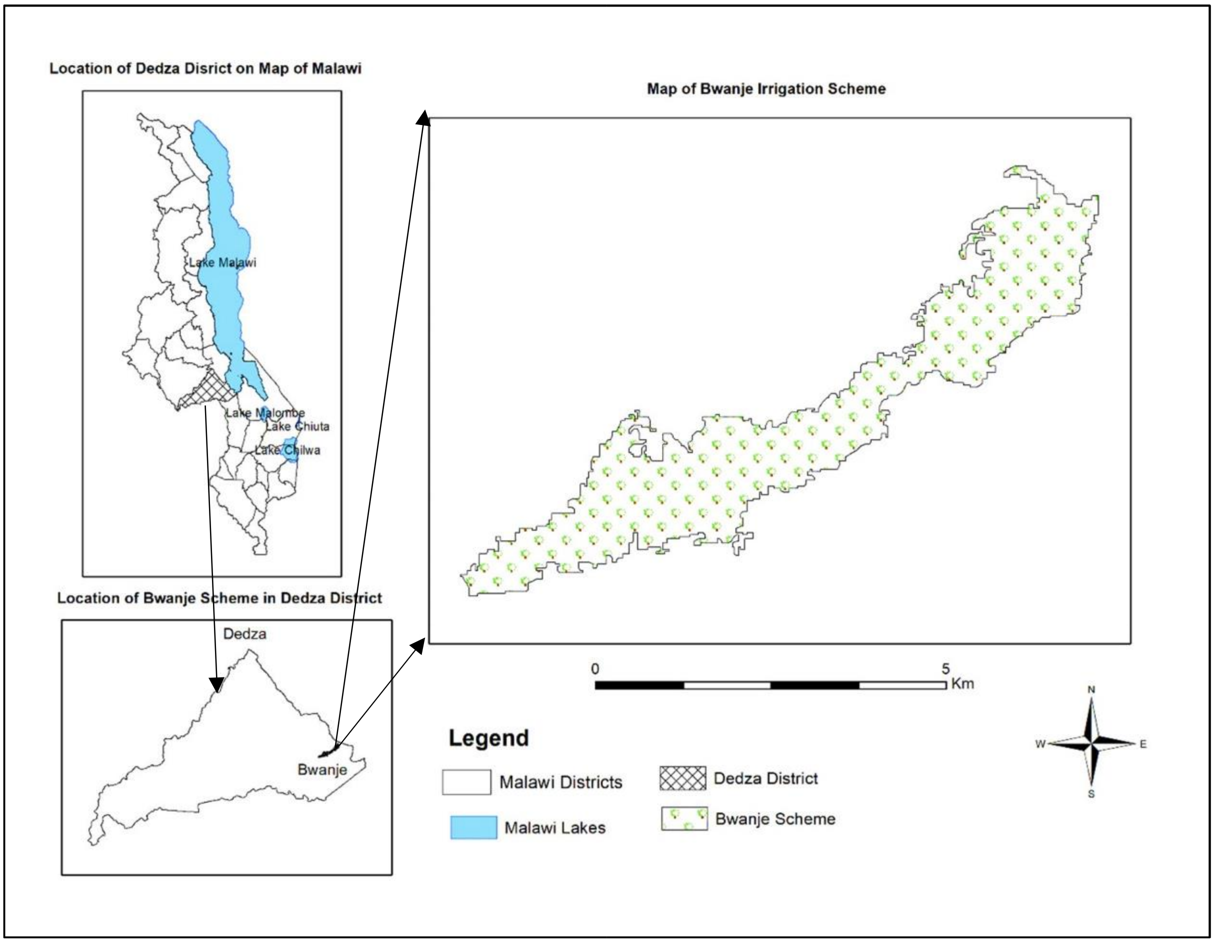


Figure 2. 1: Map showing the location of the study site

2.2 Soil analysis

This involved a set of various chemical procedures that determined the nutrient availability in the soil to the plant. Twenty-four samples were collected from all three blocks eight from each block using core samplers, with samples taken from the top soil (0-20 cm) and subsoil (20-60 cm). These samples were analysed at the Chitedze Research Station. The parameters which were analysed included pH, Organic Carbon (OC), Organic Matter (OM), Nitrogen (N), Phosphorus (P), Potassium (K) Bulk Density (BD), and soil texture.

2.3 Experimental design and treatments

The 72 m^2 (2.7 m x 27 m) plots were arranged in a randomized complete block design (RCBD) with three replicates. There were four treatments, each randomly assigned to plots within blocks, such that each treatment occurred the same number of times, once within each block. The total number of treatments was 12.

1. Farmers practice (FP): In this treatment, beans were planted with no fertilizer and irrigation commenced six weeks after planting. Irrigation was applied until the field was flooded. The water application was the same as that applied by farmers in the scheme.
2. Farmer Irrigation and Luxury Nutrients (FILN): This was done in the same way as the first treatment but the difference was the application of nutrients and 5000 kg ha^{-1} of calcitic agricultural lime. Nutrients added were 46 kg N ha^{-1}, 42 kg P ha^{-1}, 0 kg K ha^{-1} and 8 kg S ha^{-1}. The 0 K comes in because the fertilizer being used in Malawi comes with zero K component because the soils in Malawi were presumed to have adequate K for the crops, but the soil analysis indicated that K was insufficient. Even though the emphasis was on N and P, adding K could even be better based on the soil results.
3. Optimum Irrigation and Luxury Nutrients (OILN): In this treatment, nutrients were added and irrigation was only done based on the display of the colour on the Chameleon reader which was green or red at 20 and 40 cm depths. This treatment also received calcitic agricultural lime at 5000 kg ha^{-1}. Nutrients added were 46 kg N ha^{-1}, 42 kg P ha^{-1}, 0 kg K ha^{-1} and 8 kg S ha^{-1}. Water flowed in channels by means of gravity and infiltrated into the soil both sideways and downwards. The irrigation occurred until when the colour of the sensor indicated green which was followed by blue, of which this occurred when 40 mm of water was applied.
4. Strategic Irrigation and Luxury Nutrients (SILN): This treatment focused on the maximisation of residual soil water utilisation without affecting the potential yield and to save water for use in another area. Irrigation was only applied when the Chameleon

reader indicated green or red at 20 cm, 40 cm, and 60 cm depths. Water flowed in channels by use of gravity and infiltrated into the soil. The flow to each furrow was individually controlled. The nutrients were applied after the emergence the crop which was after 7days just like in treatment two and three. Top dressing did not occur because the crop did show any signs of purple colour of which if the purple colour was shown a top dressing would have followed. Calcitic agricultural lime was also applied as in the second and third treatments and incorporated into the soil using the hoe as the ridges were made. Nutrients added were 46 kg N ha^{-1}, 42 kg P ha^{-1}, 0 kg K ha^{-1} and 8 kg S ha^{1}. The beans at Bwanje are not inoculated with Rhizobia as a norm they do not apply fertilizer all to beans.

The experiment was supposed to be conducted soon after rice harvest in May so that residual soil water left after rice harvest could be utilised. Instead, it was conducted from the month of August due to the university calendar which did not permit commencement in May. In August the experiment was therefore started with a wetted-up profile to create similar conditions to what could be expected shortly after rice harvest. The water holding capacity of the soil is reported to be around 180 mm m^{-1} (DoI 2015). The conditions in May are different from August in such that in May more residual soil water is available and temperatures are cool unlike in August where soil water is less compared to May.

In order to control the amount of flood irrigation during the trials, proper time management was of paramount importance. In this way, the duration of water application to establish total water applied was timed and recorded. The source of N, P, and S was 23:21:0 + 4S. Treatments were chosen because no nutrients are applied to beans at Bwanje and low yields have been obtained. According to SeedCo (2010), beans may be fertilized with 200 to 350 kg ha^{-1} of NPK 23: 21 :0 +4S to obtain 2- 3 t ha^{-1}.

2.4 Field plot layout

In order to ensure a successful crop, the land was cleared by removing all the rice residues and burning them offsite, common practice in Bwanje. The field was then tilled to a depth of 20–30 cm using hoes and pick axes. The twelve treatments were randomly allocated to each plot soon after clearing. Sign posts were made with treatment names on them and were placed in respective plots as in figure 2.2. After plot allocation agricultural lime was applied through broadcasting on the surface of the soil and a hoe was used to mix lime with the soil during ridge making.

Figure 2. 2: Sign post placement

A length of string was stretched across the field at right angles to the slope and fixed in place at both ends using two pegs. Thereafter, 15–20 cm high ridges were made following the string. The pegs were moved and string pulled taught again until all the ridges were formed. The ridges were made to allow water to flow in the furrows. Table 2.1 show how the treatments were arranged. Where R1 represents rep 1, R 2, rep 2 and so on.

Table 2. 1: Plot layout

Block	Treatment	Description
Block 1	R1 FP	Farmers Practice
	R1 OILN	Optimum Irrigation and Luxury Nutrients
	R1 FILN	Farmer Irrigation and Luxury Nutrients
	R1 SILN	Strategic Irrigation and Luxury Nutrients
Block 2	R2 FILN	Farmer Irrigation and Luxury Nutrients
	R2 SILN	Strategic Irrigation and Luxury Nutrients
	R2 OILN	Optimum Irrigation and Luxury Nutrients
	R2 FP	Farmers Practice
Block 3	R3 SILN	Strategic Irrigation and Luxury Nutrients
	R3 FP	Farmer Practice
	R3 OILN	Optimum Irrigation and Luxury Nutrients
	R3 FILN	Farmers Irrigation and Luxury Nutrients

2.5: Agronomic practices

2.5.1: Planting

Kholophete, a certified sugar bean cultivar, was planted one seed per planting station, at a row width of 45 cm and 10 cm spacing within rows, giving a plant population of 222 222 ha^{-1}. Planting was done on 04^{th} August 2017. This cultivar growth habit is determinate which matures between 90 - 100 days.

2.5.2: Fertilization

Fertilizer application was done through basal dressing in all treatments, except for the Farmer Practice treatment**.** The amount applied was the same in all three treatments receiving nutrients. Fertilizer was mixed at the depth of (10-20 cm) and applied when the seed emerged that was after 7 days of planting but after the initial large irrigation applied to wet up the profile.

2.5.3: Weed control

Weeding was done three times using hand hoes in the 4^{th}, 7^{th} and 10^{th} weeks after planting. Emphasis was on early weed control, since root system development occurs at this stage and some weeds release chemical substances which prevent plants from growing. In the early stages, hand hoes were used, but when flowers emerged uprooting by hands was done to avoid shedding of flowers. The dominant weeds were tall grass.

2.5.4 Harvesting

Harvesting of sugar beans was done when all the pods were ripe and dry and it was done in the morning hours. The harvest area was 45 m^2 leaving 1 m lengthwise and 1.8 m width to avoid border effects. The plants were pulled out and beaten by hand with a stick in a sack after sun drying to allow easy breaking of the pods. Bean seeds were then separated from the chaff by wind winnowing, which separates grain from chaff by throwing the mixture into the air so that the wind blows the chaff away and allows the heavier grain to fall back down to the surface where it could be collected.

2.6: Installation of water monitoring tools

2.6.1: Wetting front detectors

Wetting Front Detectors were installed in all 12 plots at 20 cm (shallow) and 40 cm (deeper). They were installed at these depths because of the furrow system used. The detectors were installed using a hoe, pick and soil auger. When detectors tripped after irrigation, a sample was collected using a syringe to test for nitrates using nitrate test strips.

Figure 2.3 shows the sample in the syringe and nitrate test strips.

Figure 2. 3: Nitrate test strip (Via.farm 2015)

Figure 2.4 shows the WFD when placed in the field. In figure 2.4 all dimensions are in mm.

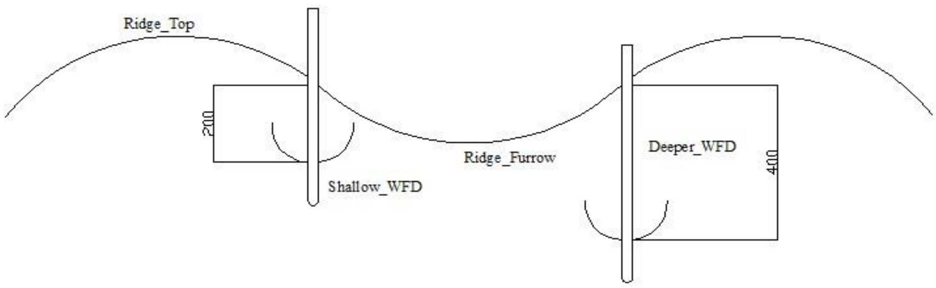


Figure 2. 4: Wetting Front Detectors in the Field

2.6.2: Chameleon sensors

Chameleon sensors were installed at different depths in a single hole. The hole was augured, and sensors placed at depths of 20 cm intervals from 20 cm down to 120 cm. The deepest sensor (120 cm) was placed first and soil above it compacted, followed by the 100 cm sensor up until the shallowest sensor at 20 cm. The temperature ID on each array of three sensors were placed either at a depth of 20 cm or 40 cm and 80 cm or 100 cm. Figure 2.5 shows the placement of Chameleon sensors and WFDs in the field. Black plastic was used to cover the wires of the Chameleon sensors to prevent vandalism by hiding them. The installation of Chameleon sensors should be in the following order: 1. Blue wire-shallowest, 2. White wire in the middle, 3. Red – deepest placement. The black cable which is the temperature ID must be placed either at the shallowest depth or middle sensor (Via.farm 2016). In the experiment Chameleon sensors were used to determine when to irrigate the Optimum and Strategic Irrigation treatments, while the Farmer Irrigation treatments were irrigated based on farmer observation, commencing about 6 or 7 weeks after planting.

Figure 2. 5: Placement of WFD and Chameleon sensors

2.6.3: Parshall flume

A Parshall flume was inserted at the inlet of each plot whenever irrigation was taking place to measure the amount of water that was flowing into the plot. After irrigation it was removed and kept in a safe place until it was used for the next irrigation. The Parshall flume was made of wood and painted. The point of measurement for upstream flows is H_a and for submerged conditions is H_b. Several water level depths measurements at point H_a were recorded and then averaged. This averaged value was then used in the equation, $Q = KH_a^n$ where K and n were obtained from the table at the throat width of 15.24 cm and then the volumetric flow (m^3) was converted to mm applied by dividing this volume by the area irrigated (AR Robison 1957).

Figure 2.6 shows the Parshall flume.

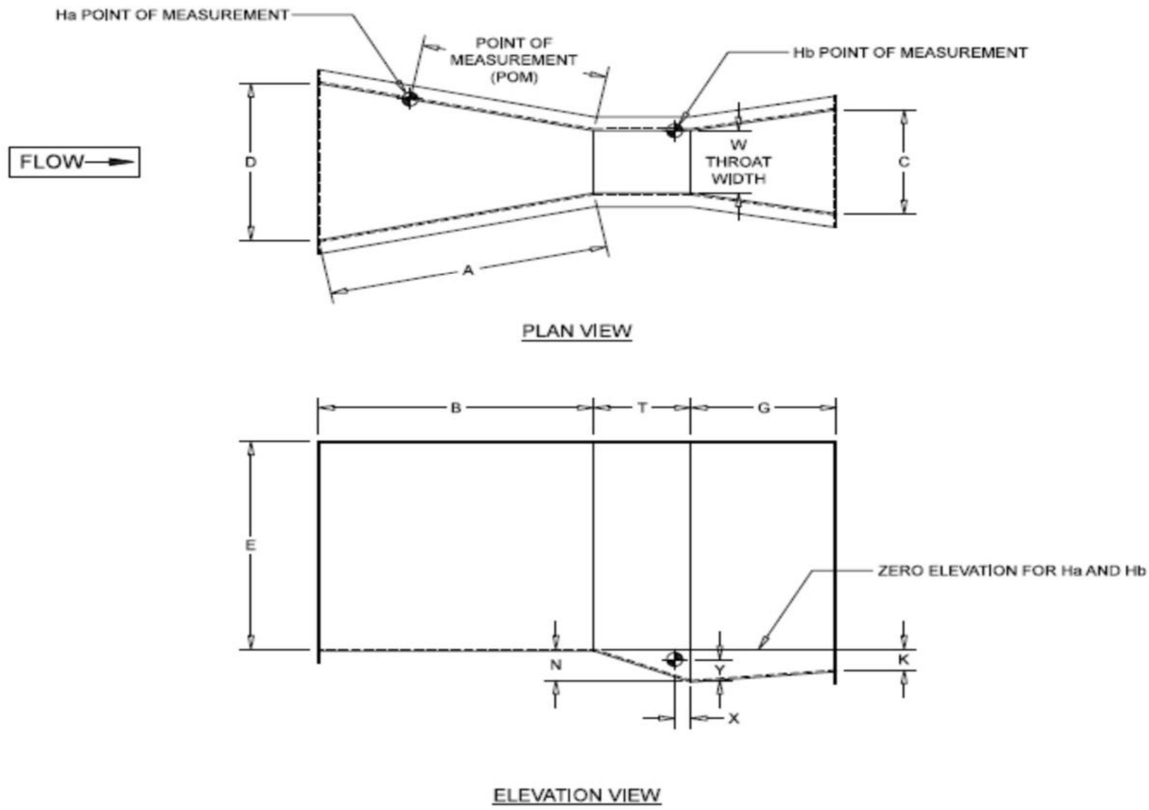


Figure 2. 6: Parshall Flume dimensions (plan and side elevation view) (AR Robison 1957)

2.7: Data collection

During the research period, data were collected at regular intervals thus after every one week. The data collected included crop height using a tape measure and recorded in units of cm. The plant height was measured from the base of the plant to the apical bud of the plant. Canopy cover percentage was captured using Canopeo. This was done using a phone app which was downloaded and installed on a smart phone. With the phone camera, videos or photos were taken above the canopy and processed to give percentage ground cover. This app can be used to measure the canopy cover percentage of any agricultural crop based on any downward facing photos taken by the mobile smart device. It can be downloaded from http://www.canopeoapp.com. Figure 2.7 shows the app screen.

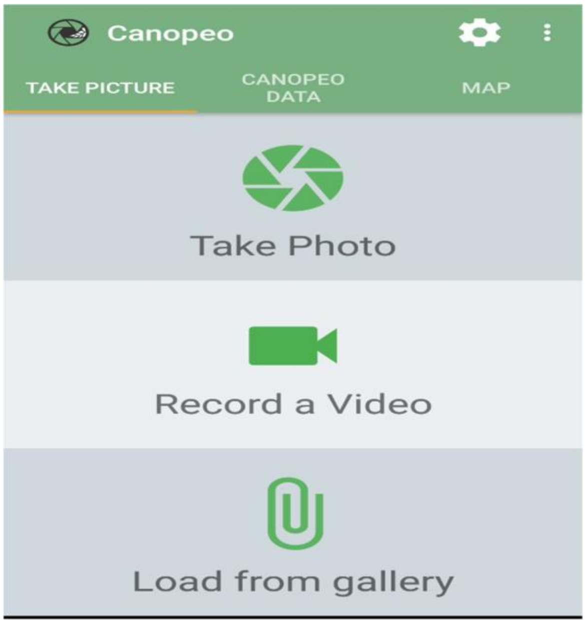


Figure 2. 7: Canopeo app screen (Patrignani and Ochsner 2015)

A Chameleon reader was used to monitor soil water in all plots. This was done by plugging the sensors into the reader which showed colours indicating water level in the soil. This data was stored and later uploaded to the VIA website (Via.farm 2016). Soil wetness patterns can be seen on the website.

A Parshall flume was used to record the amount of water that was irrigated. This was done by allowing water to pass through the flume and depths at point H_a were recorded and averaged. This averaged value was then used in the equation, $Q = KH_a^n$, to calculate discharge in $m^3 s^{-1}$. In the equation, Q is the free flow rate in $m^3 s^{-1}$, K is the flume discharge constant (varies with flume size), H_a is the depth at point of measurement in metres, and n is the discharge exponent (depends on flume size). K and n values were obtained from tables depending on the flume throat size. The amount of time taken to irrigate was recorded in seconds and was then multiplied with the calculated discharge Q in $m^3 s^{-1}$ to get the volume of water in m^3.

Gross margin data was collected that included inputs, water, plot fee and other costs like transport, planting, and calculated. Gross margin total sales revenue minus its costs of goods sold divided by total sales revenue, expressed as a percentage. The formula used was, GM = Total revenue – Total cost/Revenue

2.8 Statistical analysis

The data was analysed using the Statistical Package for the Social Sciences (SPSS) and R Statistical Software.

Chapter 3: The effect of irrigated water on soil nutrient levels available for dry bean production.

3.1 Overview

It has been traditional in Malawi, that smallholder farmers who believe that beans can access sufficient nutrients through the fixation of nitrogen in the soil do not apply fertilizer. However, whether this nitrogen is available in sufficient quantities to the crop is uncertain, since there are several factors that have an impact on nutrient uptake by the plant. These factors include soil temperatures, solar radiation, rainfall, weeds, diseases and pathogens.

It has been reported by Snapp (1998), that BVIS soils contain sufficient amounts of potassium (K), which means that no additional K is necessary. Crop production guidelines recommend that farmers should add N, P while K was deemed sufficient. However, the results from the soil analysis that was done at Chitedze Research Station for the soils of BVIS before conducting the experiment showed that all major nutrients are not sufficient for optimal bean growth as indicted in Table 3.1. Even though the emphasis was on N and P, adding K could even be better based on the soil results but was not done because the results became available after planting. After analysing the results top dressing of K could have been better but this was not the case since the crop did not show any signs of deficiency of the nutrient. BVIS farmers do not apply fertilizers to beans because of scarcity of funds to use in procurement of inputs, but according to FSSA (2007) and SeedCo (2010), beans do respond well to fertilizer and it can boost grain yield. The fertilizer manufactured in Malawi has components of 23%:21%:0% +4S% where 23% is N, 21% is P, 0% is K and 4% is S.

Currently, yields at Bwanje for sugar beans are 0.77 t ha^{-1} (Via.farm 2016), well below the reported potential of 2 to 3 t ha^{-1} (SeedCo 2010). This may be due to inadequate nutrition and poor water management. The potential yield for sugar beans may be obtained by the addition of fertilisers or manure. The soil contains most of the nutrients required and deficiencies of nutrients can be overcome by applying appropriate fertilizers.

Fertilizer consists of nutrients required by plants to grow and stay healthy. Fertilization methods in beans include basal dressing and fertigation depending on irrigation method. Basal dressing involves the placement of fertilizers in the soil at a specific position relative to the seed, while fertigation involves the combination of fertilizers and irrigation by injecting soil amendments into an irrigation system. In this experiment, fertilization was done by basal dressing, because the irrigation method practiced was furrow. The elements which were applied were Nitrogen (N), Phosphorus (P) and Sulphur (S).

The experiment conducted aimed to ascertain if nutrients are limiting in bean production under current farmer practice. The trial involved treatments with no application of fertilizers and treatments with the application of fertilizers. The results were subjected to analysis of variance (ANOVA) to determine if there were any significant differences between treatments and the error degrees of freedom was 8. A basal dressing was applied at planting with the aim of improving yield. To obtain the potential yield of 2 t ha^{-1}; 46 kg N ha^{-1}, 42 kg P ha^{-1}, 0 kg K ha^{-1}, and 8 kg S ha^{-1} were applied to all the three treatments except to the Farmer Practice treatment. Table 3.1 shows the soil analysis results collected at (0-20 cm) and (20-60cm).

3.2 Results

Table 3. 1: Soil analysis results in the top and sub soil for BVIS

Block and soil depth	**Soil characteristics**								
BC1	**pH**	**%OC**	**%OM**	**%N**	**P(mg/kg)**	**K(mg/kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.79	2.41	4.15	0.21	75.34	70.18	27.64	5.05	1.31
Sub	5.87	2.97	4.13	0.21	74.93	60.77	24.49	9.00	1.35
BC2	**pH**	**%OC**	**%OM**	**%N**	**P(mg/kg)**	**K(mg/kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.62	1.31	2.26	0.11	66.74	65.46	21.44	10.50	1.40
Sub	5.71	1.21	2.08	0.10	26.58	69.21	20.89	7.55	1.46
BC3	**pH**	**%OC**	**%OM**	**%N**	**P(mg/kg)**	**K(mg/kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.95	1.32	2.28	0.11	86.34	57.85	22.09	8.00	1.64
Sub	6.37	1.19	2.06	0.10	74.80	60.97	21.54	7.00	1.65

Table 3.2 shows the yield data for beans which was harvested on 9th November 2017. Field dry grain mass was weighed and recorded. Harvesting was done manually by field labourers and threshing was done by hand. A hanging weighing scale was used. Dry grain yield in tons ha^{-1} from three blocks was averaged and summarized for every treatment as shown in Table 3.2.

Table 3. 2: Yield of Beans (t ha^{-1})

		TREATMENTS			
		FP	FILN	OILN	SILN
BLOCKS	1	2.2	2.46	2.7	2.4
	2	2	2.5	2.76	2
	3	2.1	2.6	2.78	2.2

ANOVA analysis was done and table 3.3 shows the results of differences in between treatments with the R- squared and the adjusted R-squared

Table 3. 3: ANOVA: Differences between treatments

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	.793[a]	3	.264	18.569	.001
Intercept	68.641	1	68.641	4.823E3	.000
Treatment	.793	3	.264	18.569	.001
Error	.114	8	.014		
Total	69.548	12			
Corrected Total	.907	11			

a. R Squared = .874 (Adjusted R Squared = .827)

There was a highly significant difference between treatments means. The highest yield was obtained from the Optimum Irrigation and Luxury Nutrients treatment and the lowest yield was from the farmer practice treatment. Blocking had no effect in reducing the experimental error indicating that there was little or no variations in soil conditions within blocks. The coefficient of variation (CV) is within the acceptable range for the field experiment which is CV = standard deviation/mean x 100 = 12% and the Standard Error (SE) = ± 0.085 which is low indicating there was relatively precise estimation of the mean. In terms of Coefficient of determination (R^2), there was a strong positive correlation between the nutrients and yield since R^2 was 0.874 as indicated in Table 3.4.

Table 3. 4: CV, SE and R^2

Coefficient of Variation (CV)	Standard Error (SE)		Coefficient of determination (R^2)
12%	±0.085		0.874

After the Analysis of Variance was conducted, the data was further subjected to multiple comparisons where it was analysed to show differences between treatment means and the Least Significant Difference (LSD) was used, as shown in table 3.5 and figure 3.1, to show differences between treatment means results.

Table 3. 5: Least Significant Difference (LSD) Calculations for yield t ha^{-1}

(I) Treatment	(J) Treatment	Mean Difference (I-J)	Standard Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-.4200*	.09741	.003	-.6446	-.1954
	3	-.6467*	.09741	.000	-.8713	-.4220
	4	-.1000	.09741	.335	-.3246	.1246
2	1	.4200*	.09741	.003	.1954	.6446
	3	-.2267*	.09741	.048	-.4513	-.0020
	4	.3200*	.09741	.011	.0954	.5446
3	1	.6467*	.09741	.000	.4220	.8713
	2	.2267*	.09741	.048	.0020	.4513
	4	.5467*	.09741	.001	.3220	.7713
4	1	.1000	.09741	.335	-.1246	.3246
	2	-.3200*	.09741	.011	-.5446	-.0954
	3	-.5467*	.09741	.001	-.7713	-.3220

*The mean difference is significant at the 0.05 level.

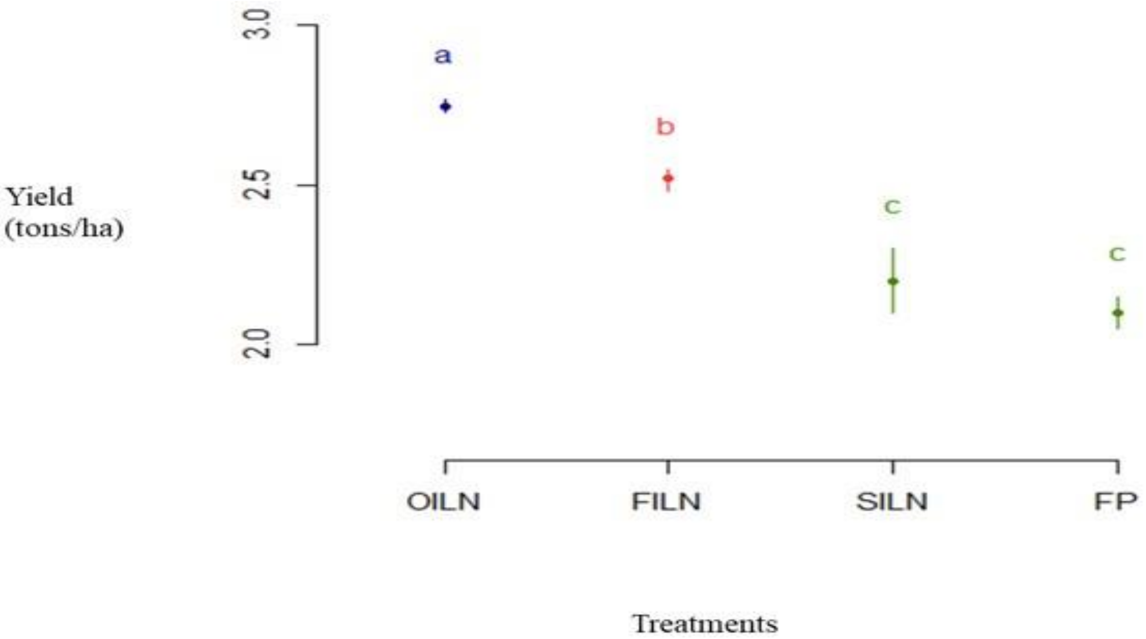


Figure 3. 1: Differences between treatment means

At the 0.05 significance level, the Optimum Irrigation and Luxury Nutrients treatment gave a significantly higher yield than all other treatments. The Farmer Irrigation and Luxury Nutrients treatment gave a significantly higher yield than the Strategic Irrigation with Luxury Nutrients and the Farmer Practice treatments. There was no significant difference in yield between SILN and FP.

Figure 3.2 shows the plant height during the growing season. The data used for plotting the graph is shown in appendix B.

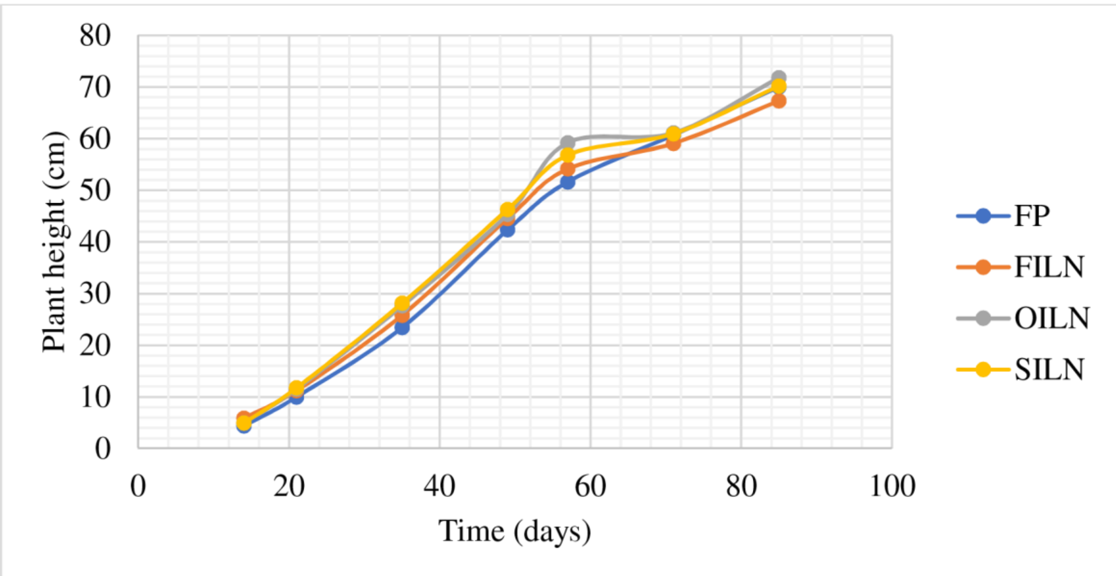


Figure 3. 2: Beans height vs Time

The growth in plant height shows that there was relatively uniform growth in all the treatments.

However, Optimum Irrigation and Luxury Nutrients exhibited the tallest growth response, and Farmer Practice growth was lower compared to the rest of the treatments but had no significant differences.

Figure 3.3 shows the canopy cover percentage measured during the growing season. The data used to plot the graph is shown in appendix B.

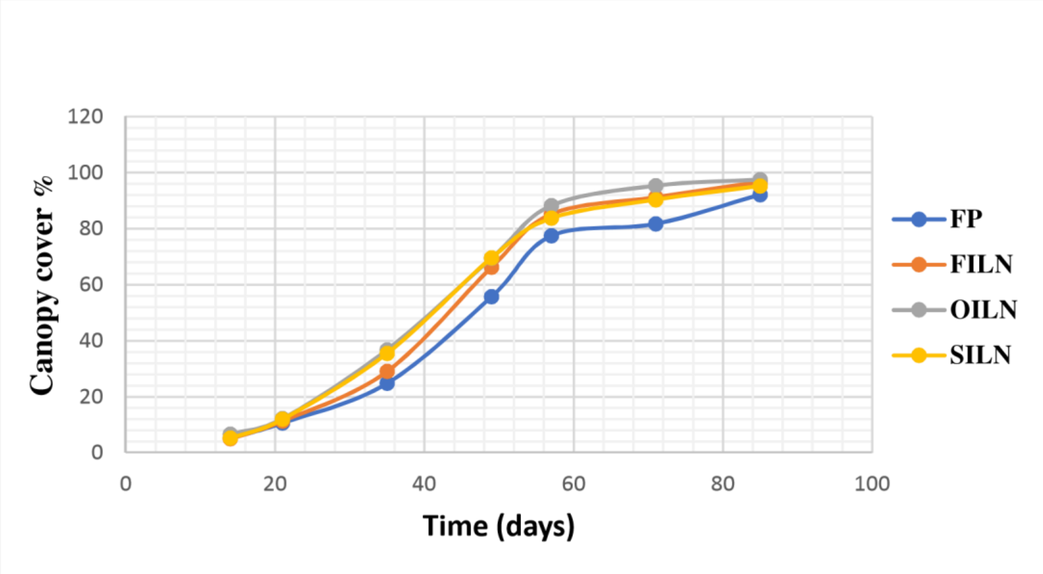


Figure 3. 3: Canopy cover (%) of beans vs Time

Canopy cover was lower with Farmer Practice, and higher with Optimum Irrigation and Luxury Nutrient treatments. While Farmer Irrigation with Luxury Nutrients treatment and Strategic Irrigation with Luxury Nutrients treatment were almost equal. As the growth continued the main difference was shown especially after Farmer management had received water which contributed to the lower canopy percentage.

Table 3. 6: Gross margin analysis

Treatment	**Water (Mk)**	**Plot fee (Mk)**	**Total Inputs used (kg ha^{-1}) fertilizer and seed (Mk)**	**Other cost (Mk)**	**Total Cost (Mk)**	**Total Cost (US$)**
FP	4000	5000	120000	72000	201000	276.86
FILN	4000	5000	170000	72000	251000	345.73
OILN	4000	5000	170000	72000	251000	345.73

SILN	4000	5000	170000	72000	251000	345.73
Revenue						
	Bean yield (kg ha^{-1})	**Selling price (Mk kg^{-1})**	**Total revenue (Mk)**	**Total revenue ($)**	**Profit (Mk)**	**Profit ($)**
FP	2100	400	840000	1157.02	639000	880.16
FILN	2520	400	1008000	1388.42	757000	1042.70
OILN	2750	400	1100000	1515.15	849000	1169.42
SILN	2200	400	880000	1212.12	629000	866.39

Note: The profit is per ha

Figure 3.4 shows the gross margin for different treatments

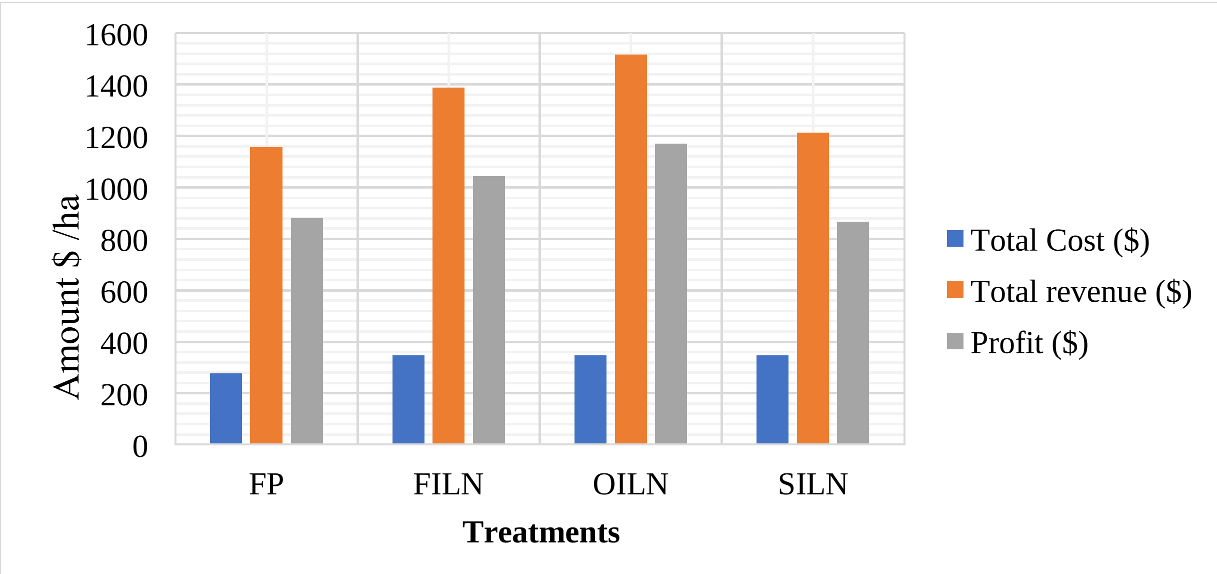


Figure 3. 4: Gross margin analysis

The gross margin analysis was calculated by computing the input cost divided into fertilizer and seed and other costs like planting, transport, weeding, and harvesting. The most profitable option for bean production in this research was the Optimum Irrigation with Luxury Nutrients treatment, followed by Farmer Irrigation with Luxury Nutrients treatment.

3.3 Discussion

Generally, plots which received 46 kg N ha^{-1}, 42 kg P ha^{-1}, 8 kg S ha^{-1} and 5000 kg ha^{-1} of Calcitic lime performed better compared to the ones that did not. Optimum Irrigation and Luxury Nutrients performed better than any other treatment. The results are different between Farmer Practice and Farmer Irrigation with Luxury Nutrients due to the differences in nutrient application. The Farmer Practice treatment received no fertilizer at all, yet it reached the potential yield of 2 t ha^{-1} unlike typical farmers' yields at Bwanje, of 0.77 t ha^{-1}. Just by practicing good crop husbandry, yields were increased. An example of an improved crop husbandry practice was the application of fertilizer to beans. The land was tilled and harrowed to ensure a fine tilth with no excessive clods that allowed proper root development, yet farmers only make a hole and plant the seed after rice harvest. Timely weeding was also done, especially in the early stages of growth, to eliminate the competition for nutrients, soil water and sunlight. Some weeds may provide shelter to insects and some may host pests and diseases. Chemical application was done to ensure that pests and diseases were controlled which farmers normally do not practice. The Farmer Irrigation with Luxury Nutrients treatment gave higher yields because of the additional nutrients which were applied, and it is clear that this is an affordable practice as gross margin was increased, provided other management aspects are also executed effectively.

The plant height and canopy cover performed much better in OILN compared to other treatments and FP treatment performed poorly contributing to the differences in yield.

The amount of irrigation to the Farmer Practice treatment and Farmer Irrigation with Luxury Nutrients treatment were almost the same. The soil water visualisations in Figure 3.5 and Figure 3.6 show that with Farmer Practice, the whole soil profile was wet when beans were still small, but when roots grew deeper they started utilising water deeper in the soil profile as indicated by the colour of the soil water patterns green and red. This was, however, not so evident in Farmer Irrigation and Luxury Nutrients treatment, where the soil profile remained blue throughout. When solute samples from Wetting Front Detectors were collected in Farmers Practice, it showed no leaching of nutrients as there was no application of fertilizers. The Farmer Irrigation and Luxury Nutrients treatment showed that nutrients were lost as indicated in Figure 3.6.

.

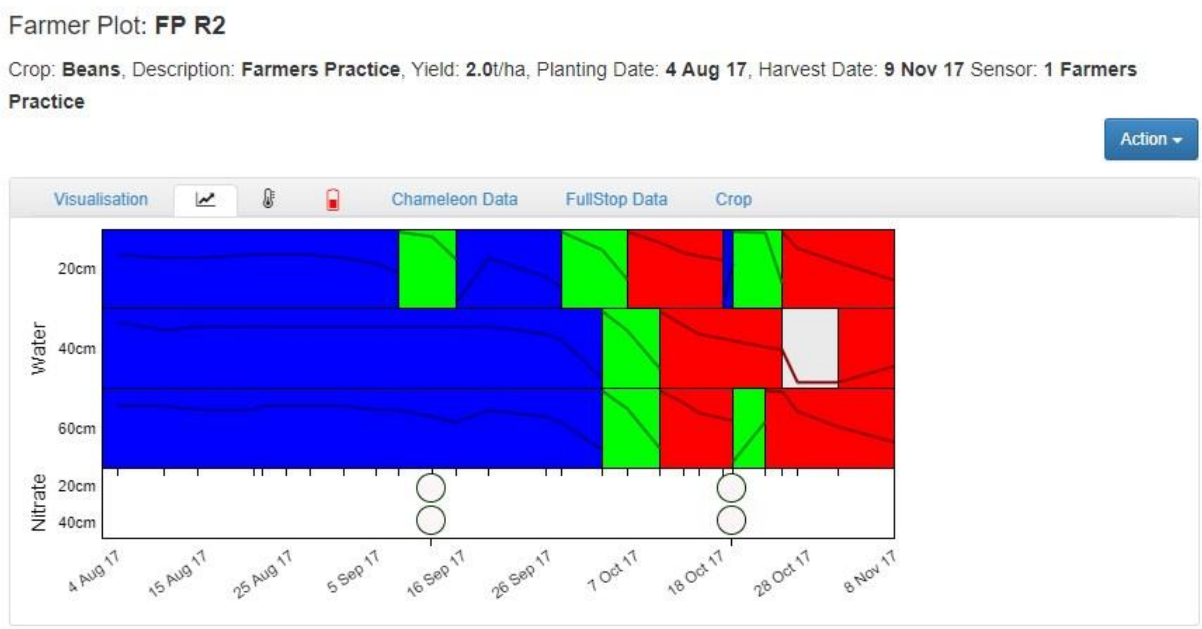


Figure 3. 5: Farmers practice visualisations from Chameleon Sensor readings and WFD

From 20th October, irrigation was stopped to allow the drying off period to take place. Late in the growing season, roots become more developed and spread further into the soil profile. And these roots were able to absorb soil water in the drying off period as shown in Figure 3.5.

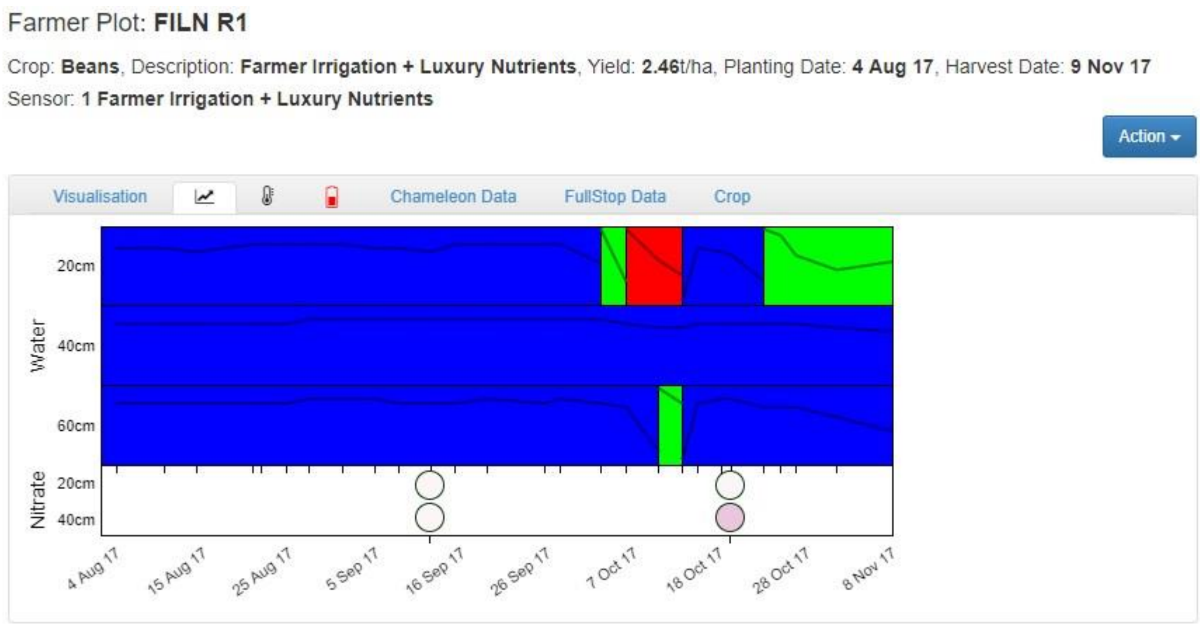


Figure 3. 6: FILN visualisations from the Chameleon reader and WFD

On the other hand, Optimum Irrigation and Luxury Nutrients and Strategic Irrigation and Luxury Nutrients treatments showed that low amounts of nitrates were lost due to control of water application using Chameleon sensors. Optimum Irrigation and Luxury Nutrients treatment obtained the highest yields of all treatments while Strategic Irrigation Luxury Nutrients managed to obtain marginally higher yields than Famer Practice despite its heavy reliance on residual water utilisation as shown in Figures 3.7 and 3.8. However, statistical analysis shows that there was no significant difference between SILN and FP.

Figure 3. 7: OILN visualisation from the Chameleon reader and WFD

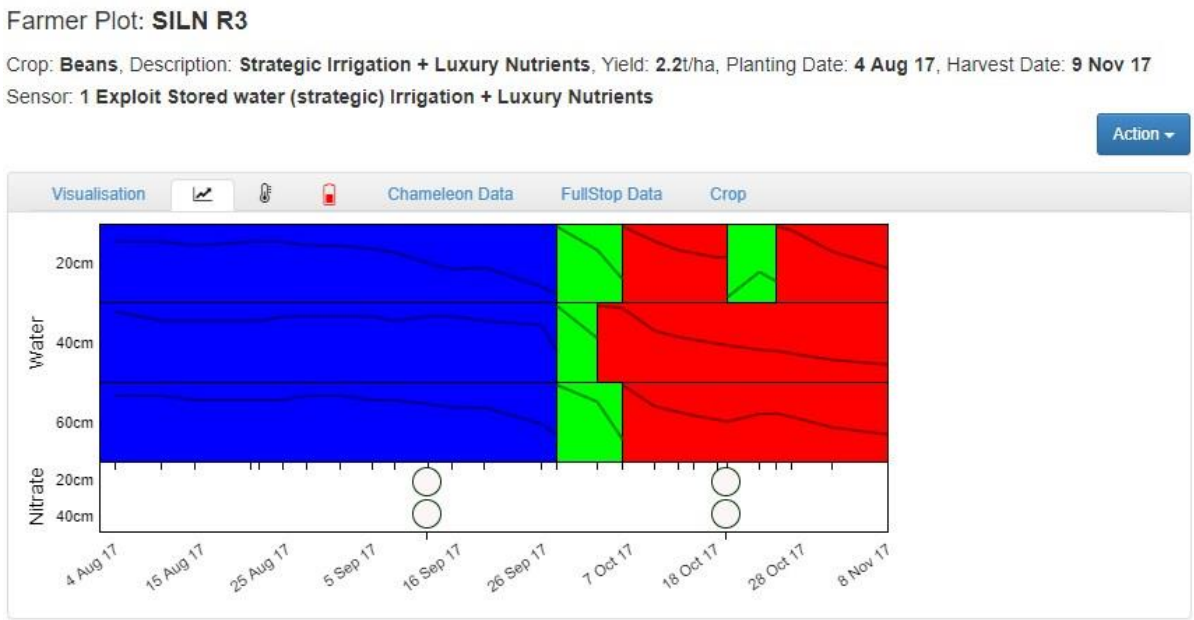


Figure 3. 8: SILN visualisation from the Chameleon reader and WFD

Nutrient limitation had an impact on the Farmer Practice treatment even though potential yield was obtained. This was due to implementation of good crop husbandry practices. Farmers Irrigation and Luxury Nutrients performed better than Farmer Practice alone due to nutrient availability. The possibility of over irrigation would be a contributing factor to low yields in

Farmers Practice and minimal irrigation in Strategic Irrigation and Luxury Nutrients also contributed to low yields. However, Optimum Irrigation and Luxury Nutrients performed well due to wise water applications and nutrient supply which was managed with the help of WFDs and Chameleon sensors. These tools helped in determining whether irrigation water was moving below the root zone and leaching nitrogen that would then no longer be available for crop uptake.

The yields for Strategic Irrigation and Luxury Nutrients achieved the potential yield even though the crop relied on the utilisation of residual soil water, with minimal irrigation. In this treatment, nutrients also played a role as they were added. Using the Wetting Front Detector to evaluate nutrient leaching, it was evident that less nitrates were being lost and were mostly used by the plant. SILN received almost the same amount of water, nutrients and lime with OILN but differed in yield.

Chapter 4: The effect of Chameleon sensor use on water management in bean production.

4.1 Overview

Irrigation development has great potential to boost the agricultural sector and economy of the country. However, most of the irrigation schemes developed in Malawi are poorly managed or have completely failed. Reasons for this include low water availability and poor management of this limited supply. This leads to great losses at local and national levels. Schemes generally do not have access to soil water monitoring tools, and even where such tools are available, few farmers are able to understand how they operate or interpret the data.

Despite the fact that there is variation in the supply of the fresh water, competition for this scarce resource between agriculture, industry, households and the environment is increasing (Rosegrant et al. 2002). These developments have forced water planners into a continuous decision making process regarding water resource availability under different conditions and for different users (Mahmoud et al. 2011). One of the options that has been explored in order to address the problem is construction of storage reservoirs and use of water saving technologies. Agriculture is reported to be the biggest global water consumer at about 70 % of total fresh water usage (Saleh et al. 2018).

BVIS experiences shortages of water in the dry season and this is managed by restricting the cropping area from 800 ha to 145 ha. The scarcity of water in the dry season and poor water management leaves the farmers with low yields. The development of a simple soil water monitoring tool, known as the Chameleon sensor, shows promise in helping farmers to improve their crop water management. This tool was used in this experiment to guide irrigation management in furrow irrigated beans. One of the purposes of this experiment was to determine the benefit of using Chameleon sensors in monitoring soil water and managing irrigation. Table 4.1 below indicates how the amounts of water applied to different experimental plots were obtained.

4.2 Results

The amount of water supplied to each plot using a Parshall Flume throat size 15.24 cm, with K value of 0.264 and n value of 1.58 is indicated in table 4.1.

Table 4. 1: Water used if the profile ends dry

Treatment	**Ha (averaged depth at point of measurement in m)**	**Time (S)**	**Q(m^3/s) (Q=KHa^n)**	**Water supplied (m^3) = Q (m^3/s) x time (s)**	**Water supplied to each plot (mm)**
R1 T1	0.129	1620	0.01	16.82	207
R1 T3	0.06	1155	0.003	3.58	44
R1 T2	0.126	1800	0.01	18.007	222
R1 T4	0.05	1168	0.002	2.713	33
R2 T2	0.127	1680	0.01	17.019	210
R2 T4	0.05	1155	0.002	2.683	33
R2 T3	0.06	1160	0.003	3.593	44
R2 T1	0.126	1620	0.01	16.207	200
R3 T4	0.05	1156	0.002	2.684	33
R3 T1	0.129	1680	0.01	17.443	215
R3 T3	0.065	1165	0.003	4.095	50
R3 T2	0.127	1620	0.01	16.41	202

The summary of water in Table 4.2 includes the water used in each treatment plus the residual water of 180 mm.

Table 4. 2: Amount of water available to each plot (mm)

	Rep 1	**Rep 2**	**Rep 3**
FP	387	380	395
FILN	402	390	382
OILN	224	224	230
SILN	213	213	213

Table 4. 3: ANOVA

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	86856.901[a]	3	28952.300	682.825	.000
Intercept	1114531.701	1	1114531.701	2.629E4	.000
TRT	86856.901	3	28952.300	682.825	.000
Error	339.206	8	42.401		
Total	1201727.808	12			
Corrected Total	87196.107	11			

Table 4. 4: Least Significant Difference (LSD)

(I) Treatment					Lower Bound	Upper Bound
1	2	-3.9700	5.31669	.477	-16.2303	8.2903
	3	161.1833*	5.31669	.000	148.9230	173.4436
	4	174.5800*	5.31669	.000	162.3197	186.8403
2	1	3.9700	5.31669	.477	-8.2903	16.2303
	3	165.1533*	5.31669	.000	152.8930	177.4136
	4	178.5500*	5.31669	.000	166.2897	190.8103
3	1	-161.1833*	5.31669	.000	-173.4436	-148.9230
	2	-165.1533*	5.31669	.000	-177.4136	-152.8930
	4	13.3967*	5.31669	.036	1.1364	25.6570
4	1	-174.5800*	5.31669	.000	-186.8403	-162.3197
	2	-178.5500*	5.31669	.000	-190.8103	-166.2897
	3	-13.3967*	5.31669	.036	-25.6570	-1.1364

*. The mean difference is significant at the 0.05 level.

At 0.05 significance level there was no significant difference in water usage between the Farmer Practice treatment and the Farmer Irrigation with Luxury Nutrients treatment, but there was a highly significant difference in water usage between Optimum Irrigation with Luxury Nutrients and Strategic Irrigation with Luxury Nutrients, compared to Farmer irrigation management.

The amount of water which was available in different treatments is shown in figure 4.1

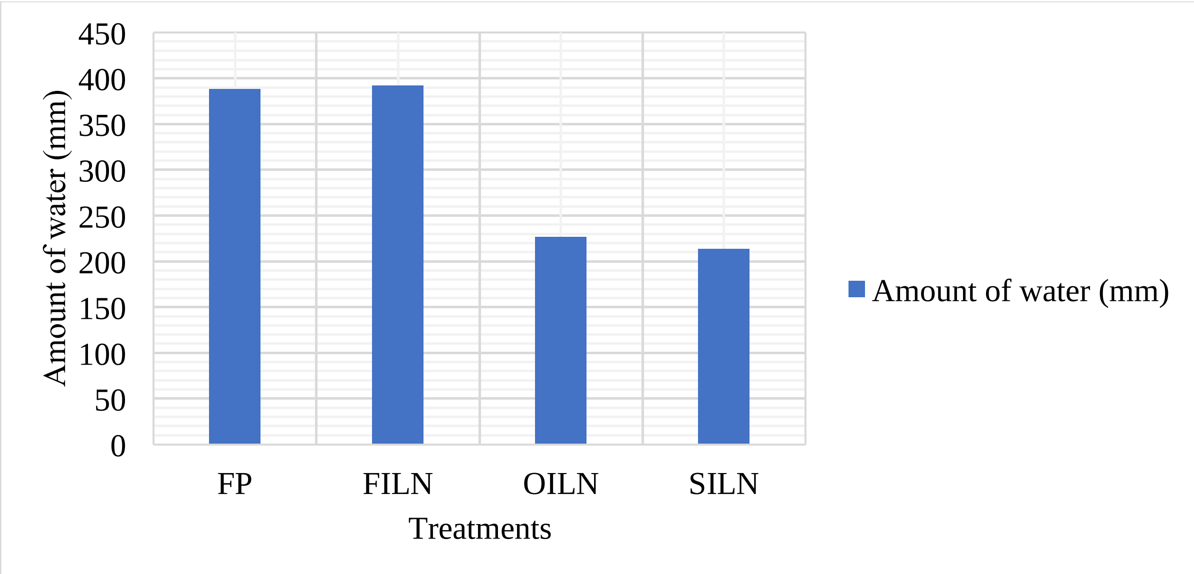


Figure 4. 1: Availability of water in each treatment

Figure 4.1 show the average amounts of water available to the different treatments. For Farmer Practice and Farmer Irrigation with Luxury Nutrients, the amount of water supplied was similar. Farmer management had more water compared to Optimum Irrigation and Luxury Nutrients and Strategic Irrigation and Luxury Nutrients. This difference in water availability had an impact on crop yield.

There was no rainfall during the period of study which meant that the experiment relied fully on residual soil water and irrigation. The mean temperature (28.5^{o}C) and sunshine hours (10.4) increased and were very high in the month of October which led to an increasing loss of water through evapotranspiration this was during flowering stage. However, the Chameleon readers were blue for almost the whole growing period, which means that the soil profile was very wet as shown in Figure 4.2.

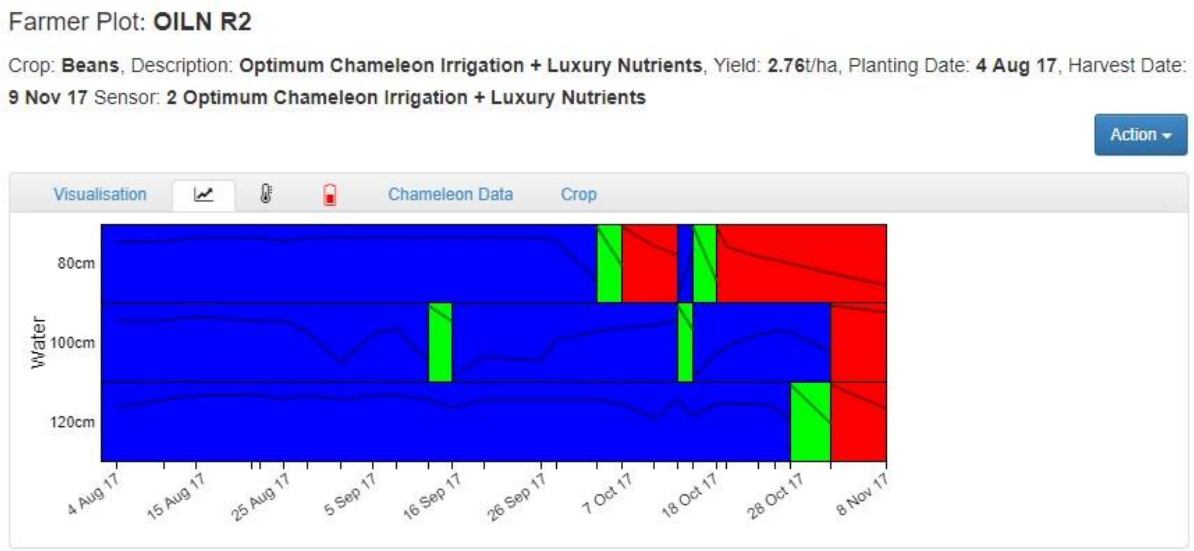


Figure 4. 2: Visualisation of Chameleon patterns Source: (Via.farm 2017)

Figure 4.3 shows the soil temperature trend, which was low in the beginning and increased as the season progressed.

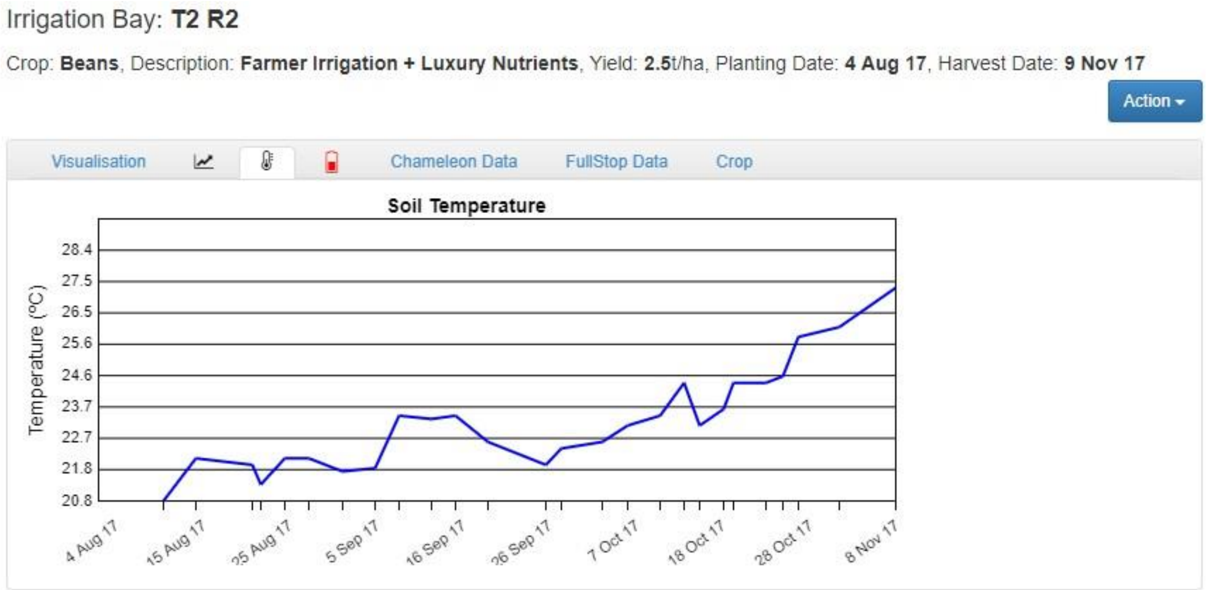


Figure 4. 3: Soil temperature visualisation (Via.farm 2017)

Irrigation scheduling is very crucial in using water efficiently, as excessive water reduces yields while inadequate irrigation causes water stress and reduces yield as well. Overwatering by irrigation or rainfall results in loss of plant nutrients through leaching. Figure 4.4 show the sensitive growth stages of beans and how they coincide with the Chameleon pattern in the Farmer management treatment. The same is shown in figure 4.5 for Optimum Irrigation and Luxury Nutrients.

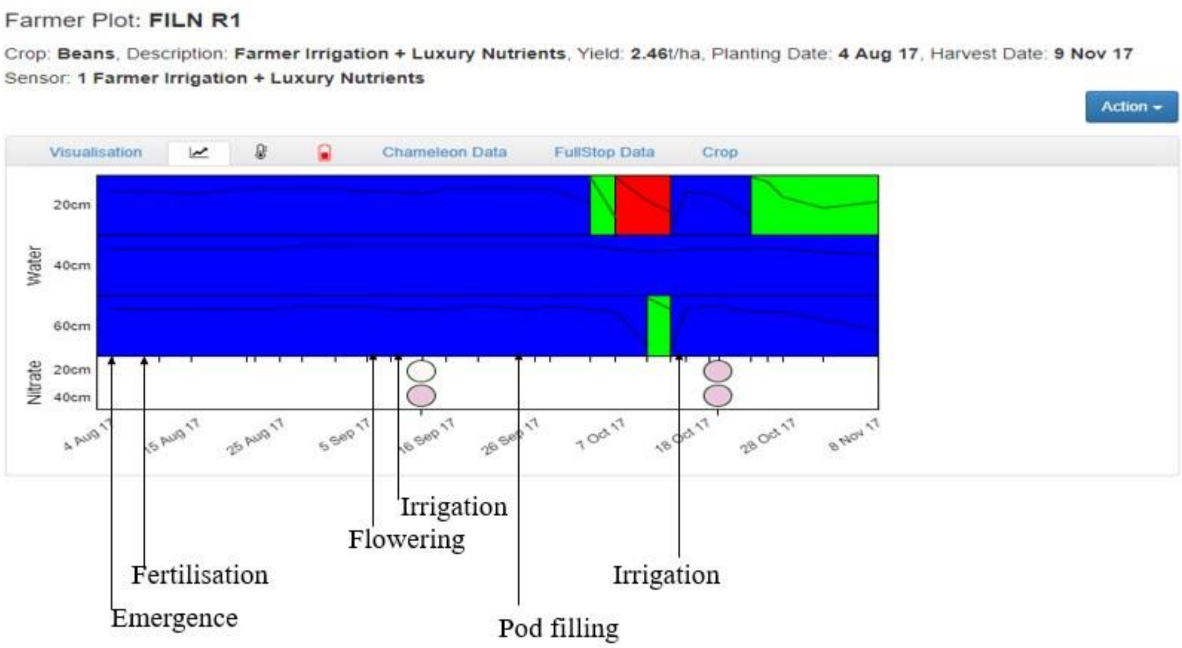


Figure 4. 4: FILN Chameleon pattern with crop growth stages

Figure 4.4 shows that Farmer managed irrigation lead to leaching of nutrients, while figure 4.5 show how the pattern of Optimum irrigation coincides with sensitive growth stages.

The purple colour represents the amount of nutrients that were leached after irrigation and the stages of growth stages were compared to see if the crop experienced water stress of which figure 4.4 indicates that there was no water stress in Farmer management treatment but leaching of nutrients occurred.

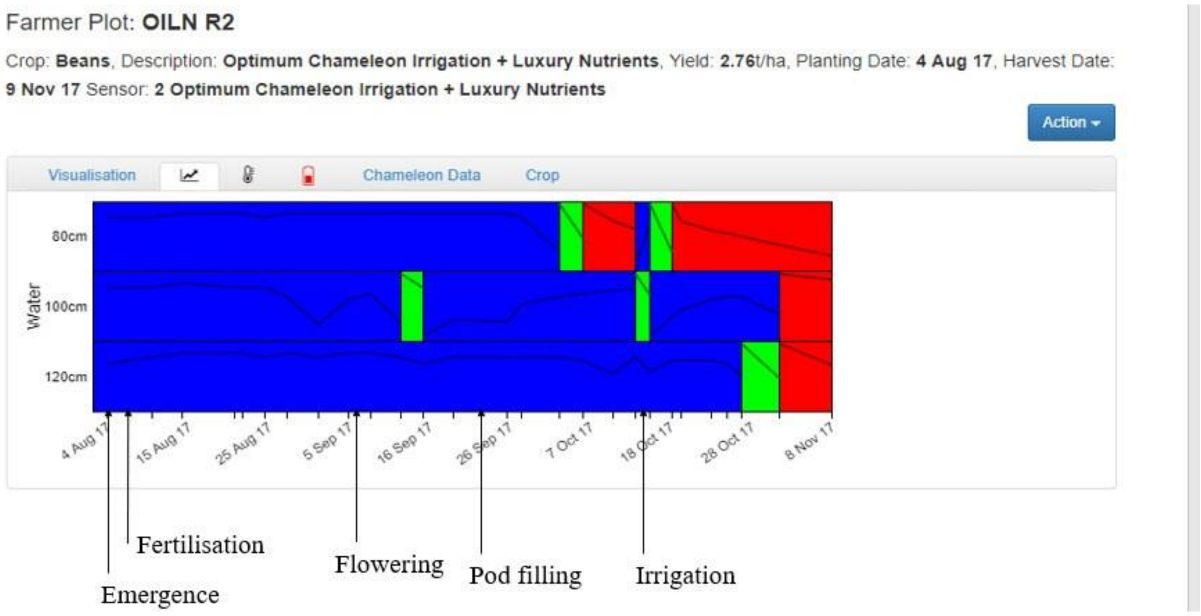


Figure 4. 5: OILN Chameleon pattern with crop growth stages

The emergence period had adequate water to sustain the germinating seed and this water availability was maintained throughout to flowering and pod filling, indicating that the crop had no water stress during sensitive growth stages as is evident from the Chameleon pattern.

Although an irrigation calendar is available indicating who should irrigate and when, this calendar is not followed and water is managed and used poorly. Farmers tend to steal water overnight or any time that they get a chance, others irrigate whenever they feel like irrigating. This shows that farmers do not understand how water should be used and managed properly in the scheme, leading to over irrigation or under-irrigation. With the use of the colour from the Chameleon it could help farmers decide when to irrigate, so that high yields can be realised and proper nutrient management achieved.

4.3 Discussion

When the treatments were compared it was observed that Optimum Irrigation and Luxury Nutrients produced better yields than Strategic Irrigation and Luxury Nutrients which received the lowest amount of water. Although Strategic Irrigation and Luxury Nutrients produced lower yields, it still managed to achieve the potential yield. If the Strategic Irrigation and Luxury Nutrients approach could be embraced, the area under irrigation can be increased, whilst still enabling farmers to produce better yields than currently achieved.

Farmer Practice in the experiment produced higher yields than what the actual farmers in the scheme usually get. The lower yields obtained by farmers would be due to water stress or excessive water application as was observed. Water stress has an effect on the development of the plant causing a decrease in growth, leaf area development and photosynthetic capacity. Irrigation aims to provide sufficient water to replenish soil water in time to prevent physiological water stress.

However, too much water could also decrease production, as excessive soil water levels can result in oxygen deficiency in the root zone. Figures 4.6a and 4.6b show the bean crop in the farmers plots in the scheme (with Farmer Irrigation) while Figures 4.6c and 4.6d show the crop during the field trial emulating the Farmers Practice. From the two figures it is evident that farmers stressed the crop such that the development of pods was poor and leaves were few while in the field trial the pods and leaves were well developed. Figures 4.6a and 4.6b experienced rapid phenological development where fast growth took place, few numbers of seeds were produced before the soil water was depleted. This does not consider this plant to have any special morphological, physiological or biochemical adaptations for it to grow fast.

The amount of water applied by farmers was not enough hence the rapid development to escape drought.

Figures 4.6a and 4.6b show how beans were both nutrient and water limited.

Figure 4. 6a and Figure 4.6b shows farmers' field while Figure 4.6c and Figure 4.6d show experimental plots

Figure 4.7 shows that roots were able to absorb water from a depth of 120 cm.

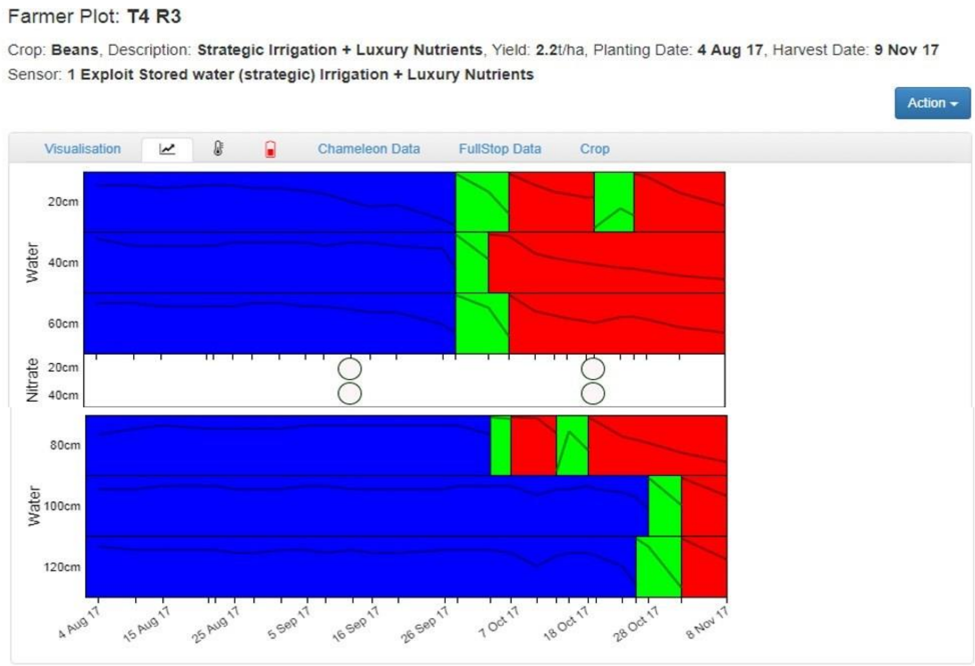


Figure 4. 7: Visualization of the Chameleon pattern

The figure 4.7 shows that during the early stage of crop growth, the root system was not fully developed, and hence there was little utilisation of water by the crop and the Chameleon pattern constantly showed blue. In the mid-season stage, the root system had fully developed and water uptake was evident by the green colour at 60 cm. Much water was used at this stage because of flowering, pod development and filling. In the late stage, the root system was able to absorb water up to a depth of 120 cm as indicated by red at this depth. At the same time, high temperatures led to high rates of photosynthesis and evapotranspiration, leading to even more water loss from the soil of which if planted in May this loss could be avoided.

It is worth noting that Bwanje uses no tools to monitor soil water, which is one of the contributing factors to over and under irrigation. The only method that they use is the feel - and - appearance method, which is not accurate and they tend to look at the crop to decide as to when they should irrigate. They also rely on the local knowledge and experience to help them irrigate. Even though the extension workers give advice most of them do not adhere to the advice. These farmers lack funds to purchase any soil water monitoring tools.

Another contributing factor why farmers experience water management problems is the lack of capacity building in smallholder farmers. These farmers lack knowledge on when, how much and how often irrigation should be done. This has led to over irrigation or under irrigation which results in poor yields and contributes to the reduction of land productivity and inefficient use of water. With a lack of knowledge on how much water a crop should receive, everybody tries to take as much water as possible for their plots. Farmers at BVIS are disorganized with regard to water use management, hence most of them operate the way they want without following guidelines. The trainings are mostly offered to the committees with the aim that they will teach others but that is not the case and it is the mixture of youths and old people who cultivate at BVIS.

There is no proper synchronized irrigation management at Bwanje because some farmers do not follow the agronomic practices which are formulated by the management committee pertaining to what crop should be grown in a particular season or when weeding should be done. This results in the supply of water to different seasonal crops which require different amounts of water. The different crops grown in the same season within adjacent fields have different water requirements which can easily impact on other crops. This results in farmers having different water interests. If a farmer does not follow the rules and regulation, little or no water is allocated to them resulting in theft of water. Much as the WUG tries to address these problems there has been little improvement.

Preparation of seed beds, especially ploughing and making raised ridges have an impact on the crop. This preparation is not followed by all farmers in Bwanje, instead many of them make direct holes in the ground and plant their seeds. The making of holes in the field is mostly done sometime after rice harvest but it is advisable that it should not be too soon. This could lead to soils being poorly aerated and cause the roots to have some difficulties in penetrating into the soil due to compaction that has not been alleviated, resulting in poor utilisation of nutrients and water. In addition, there could be heavy runoff after each irrigation event due to low water infiltration that could affect yields.

From interactions with a small number of farmers who had hands on experience on the tools in the previous season (2016), they were able to tell that conflicts over irrigation water have completely decreased and that they do not apply the same amount of water as they did without the tools. This shows that the amount of water not used can be used for other purposes. Hence availability of monitoring tools is very crucial in water management. Furthermore, farmer trainings on water management should be provided so that they understand the importance of water use efficiency. Any farmer who wishes to learn more about the tools can consult the extension staff. It would be ideal if equipment to monitor soil water and nutrients should be available to as many farmers as possible to avoid over irrigation and loss of nutrients. On vandalism security measures by WUG needs to be put in place since most of the farmers are willing to use these tools.

Chapter 5: Utilisation of residual soil water in relation to irrigated area.

5.1 Overview

More than 80 % of the land at Bwanje is not being used during the dry season due to inadequate availability of water, and this is managed by restricting the cropping area from 800 ha to 145 ha. The situation is worsened when areas which are irrigated experience crop failure due to drying up of the river in the months of October to November. If the bean crop is planted in May or June the drying up would not be a problem since there could be much water until maturity.

Most of the farmers at Bwanje hardly ever strategically utilise residual soil water during the dry periods, due to the fact that they are unfamiliar with the practice and are not sure as to whether or not the available soil water after rice harvest, with the addition of a strategic irrigation or two if water is available, can sustain their crops throughout the growing period. Generally, farmers leave their lands fallow after the rice harvest. However, efficient use of this available residual soil water for production of crops is an alternative practice that should be considered, and the reduced area currently being cropped in winter could possibly be increased.

The question of whether or not residual soil water at BVIS could be used to save irrigation water and if the saved water could be used to irrigate and expanded area was investigated in this study. Chameleon soil water sensors were installed and used to know when irrigation should occur. A desktop analysis was done using the Climwat model with data from Cropwat to answer this question, and the results from the model on crop water requirement were compared to the actual amount of water irrigated by farmers. The assessment required the crop water needs under early and late sowing conditions, to determine the impact of planting date on the possibility to expand the current irrigated area.

In the absence of actual experimental data, a projection was made on the effect of planting date. Climwat data from the nearest meteorological station which has similar climatic conditions to the study area was used to run Cropwat to determine crop water requirements. The station used was Salima which is 40 km away from Bwanje and lies in the same agroecological zone.

5.2 **Results**

5..2.1 Climwat and Cropwat

The climatic data that was used in Climwat from Cropwat in the months of January to December is shown in table 5.1 indicating the estimation of monthly reference evapotranspiration ET_O.

Table 5. 1: Cropwat ET_o

Month	**Min Temp °C**	**Max Temp °C**	**Humidity %**	**Wind km/day**	**Sunshine hours**	**Radiation MJ/m²/day**	**ETo mm/day**
January	21.4	29.4	80	147	5.9	19.5	4.18
February	21.3	29	82	147	6.2	19.8	4.1
March	21.4	29.5	77	181	7.4	20.8	4.42
April	20.7	28.9	73	216	8.7	20.8	4.45
May	17.9	27.8	68	207	9.5	19.7	4.07
June	15.9	26.2	63	225	9.3	18.2	3.8
July	15.8	25.9	61	225	8.9	18.2	3.85
August	16.9	27.8	57	216	9.7	21.2	4.56
September	18.7	30.6	55	207	10	23.9	5.4
October	21.3	32.5	54	225	10	25.4	6.24
November	22.3	32.2	61	216	9	24.3	5.96
December	22.2	30.3	75	173	6.7	20.7	4.68
Average	**19.6**	**29.2**	**67**	**199**	**8.4**	**21**	**4.64**

The crop factors and growth stages used were default values from the CROPWAT model which represented similar conditions present at Bwanje irrigation scheme. The model indicated that if the crop is planted early less water will be required to be supplemented while if planted late the crop would require more water to reach maturity. As this was evidenced in the actual experiment where the crop was planted late in August and much water was required since temperatures were high and there was evapotranspiration and less water availability in the stream. And also, in the Climwat data which indicated an average temperature of 32 ^{O}C. Since rice is harvested in April end the next crop can be planted in May end to allow the soil water to drain.

Table 5.2 shows the Crop Water Requirement if the bean crop is planted in May (early).

Table 5. 2: Crop Water Requirement (CWR) from May to August

Month	**Decile**	**Stage**	**Kc coeff**	**ETc mm/day**	**ETc mm/dec**	**Eff rain mm/dec**	**Irr. Req. mm/dec**
May	1	Init	0.4	1.68	16.8	9.2	7.6
May	2	Init	0.4	1.63	16.3	0.7	15.6
May	3	Dev	0.55	2.18	24	0.7	23.3
Jun	1	Dev	0.81	3.15	31.5	1.4	30.1
Jun	2	Mid	1.06	4.01	40.1	0.4	39.7
Jun	3	Mid	1.14	4.37	43.7	0.3	43.4
Jul	1	Mid	1.14	4.38	43.8	0.3	43.6
Jul	2	Mid	1.14	4.4	44	0.1	43.9
Jul	3	Late	1.13	4.63	50.9	0.1	50.8
Aug	1	Late	0.85	3.66	36.6	0.1	36.5
Aug	2	Late	0.49	2.23	17.8	0.1	17.7
				TOTAL	**365.5**	**13.4**	**352**

The total amount of water required by beans to mature if planted in May is 365 mm and the irrigation requirement is 352 mm including effective rainfall.

Figure 5.1 show the amount of water required by the crop and what farmer management typically applies when the crop is planted in May.

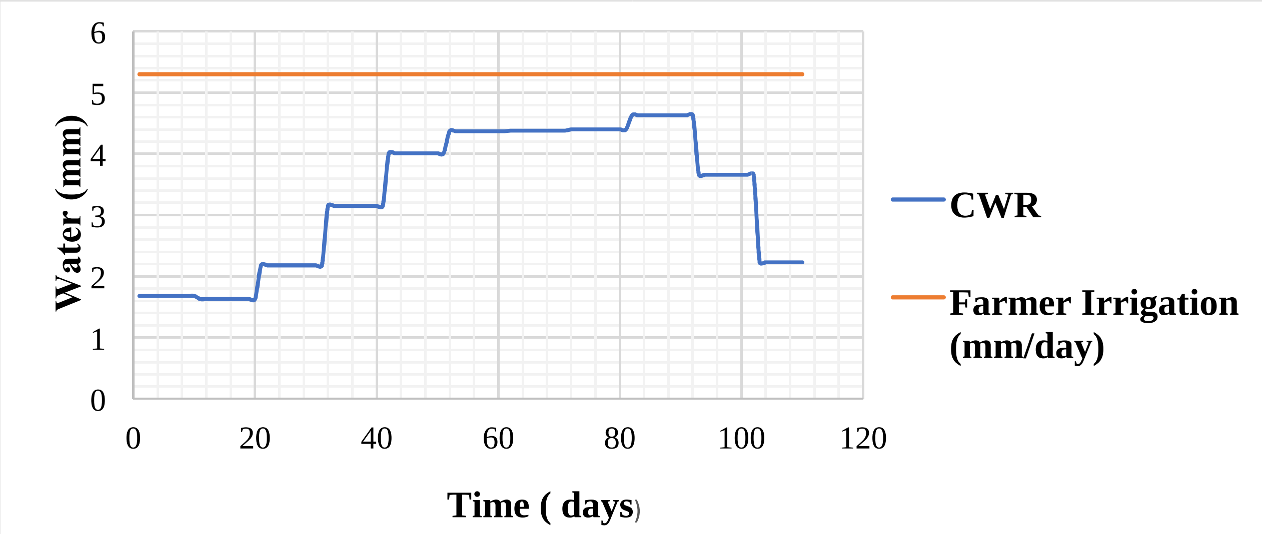


Figure 5. 1: Crop water requirement and farmer irrigation for beans planted in May

Figure 5.1, clearly shows that farmers apply too much water to the crop compared to the actual amount required by the crop if planted in May. The difference between the area under the Farmer Practice and that of CWR is the overirrigation. With the use of residual soil water, the crop can mature with very little addition of irrigation as was evident from the Chameleon patterns presented in the previous chapter 4.

The figure below indicates available soil water depletion as the season progresses and the demand for crop water by beans increases.

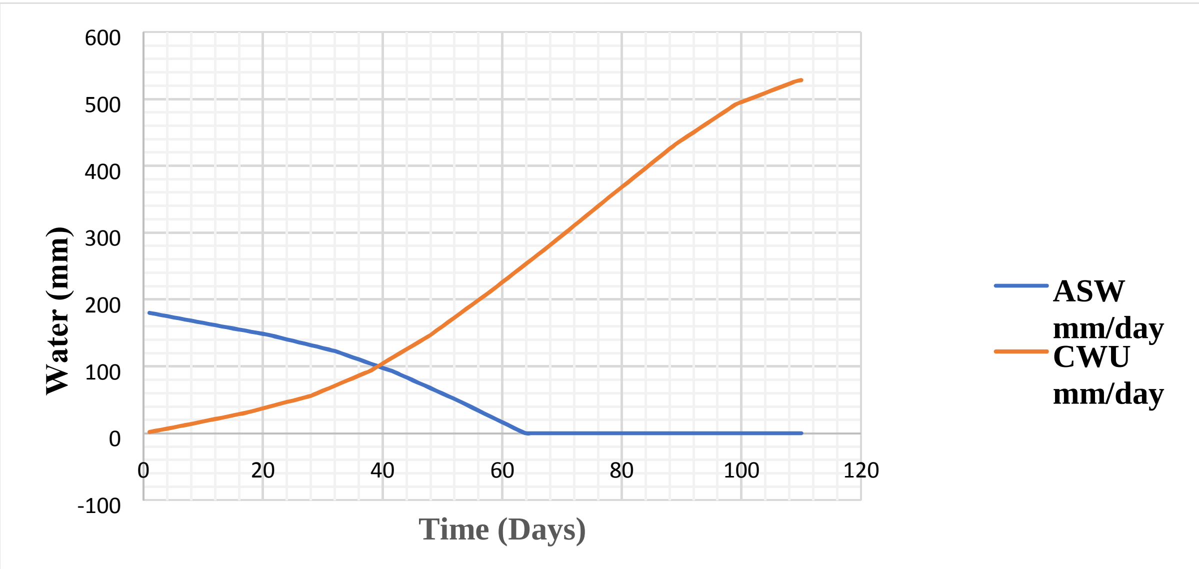


Figure 5. 2 : Crop water use and available soil water depletion with days after planting

Figure 5.2 shows that the available soil water would be depleted on day 63 after planting, which means for two months the crop will not require some additional water from day 64 there is an irrigation requirement. Under normal circumstance one needs to irrigate to meet evaporation and Crop Water Requirement, but farmers tend to irrigate the way they like without any consideration. The amount of water which could have been used to irrigate for these two months could instead be used to irrigate another area. Below are some calculations if the crop is planted in May.

Amount of water in the soil, Available soil water (ASW) = 180 mm

Amount of water irrigated by farmers (FI) = 402 mm

Irrigation requirement (IR) = 352 mm or 0.352 m

Plot size of each farmer (Area) = 900 m^2

Total number of farmers = 1777

The amount of water that can be saved = IR - ASW

= 352 – 180 mm

= 172 mm or 0.172 m

Amount of water saved in cubic meters = 0.172m × 900 m^2

= 154.8 m3

The area that can be added using saved water = 154.8 m^3 / 0.352 m

= 439.77 m^2 / 10000

= 0.043977 ha by each farmer

Therefore, the whole scheme, the area that be added = 0.043977ha × 1777

= 78 ha

So, 78 ha can be added to 145 ha if planted in May. This is just an estimation from the model.

Table 5. 3: Crop Water Requirement (CWR) from August to November (late)

Month	Decile	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Aug	1	Init	0.4	1.73	12.1	0.1	12
Aug	2	Init	0.4	1.82	18.2	0.1	18.1
Aug	3	Deve	0.48	2.33	25.6	0.1	25.5
Sep	1	Deve	0.74	3.77	37.7	0.1	37.6
Sep	2	Deve	0.99	5.32	53.2	0	53.2
Sep	3	Mid	1.15	6.51	65.1	0.4	64.7
Oct	1	Mid	1.15	6.92	69.2	0.6	68.6
Oct	2	Mid	1.15	7.28	72.8	0.8	72
Oct	3	Mid	1.15	7.13	78.5	5	73.4
Nov	1	Late	0.97	5.93	59.3	7.4	51.9
Nov	2	Late	0.57	3.45	34.5	10	24.5
Nov	3	Late	0.35	1.96	2	2.3	2
					528.1	**26.8**	**503.6**

Figure 5.3 indicates the status of water applied by farmers against what the crop requires for the whole season if beans are planted in August (late).

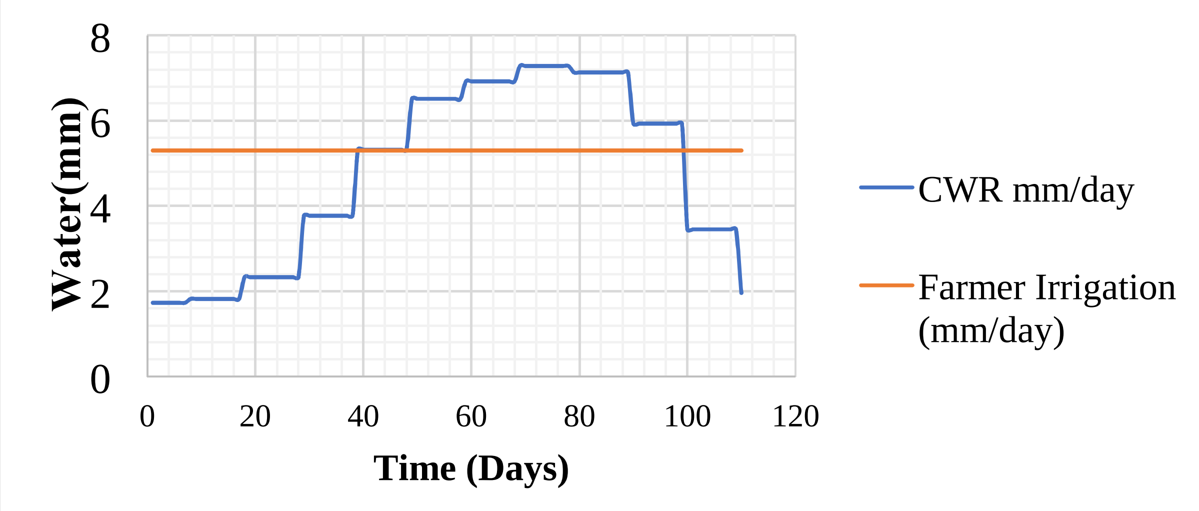


Figure 5. 3: Crop water requirement and farmer irrigation for beans planted in August

Figure 5.3 shows that if beans are planted August more water application will be required but in actual sense farmers do apply little amount of water compared to what the crop requires. The difference in area between the area under CWR and Farmer Practice straight line is the irrigation requirement. This also indicates that the actual land to be cultivated would be reduced since more water will applied on small area. Figure 5.5 show the crop water use and available soil water plotted against time.

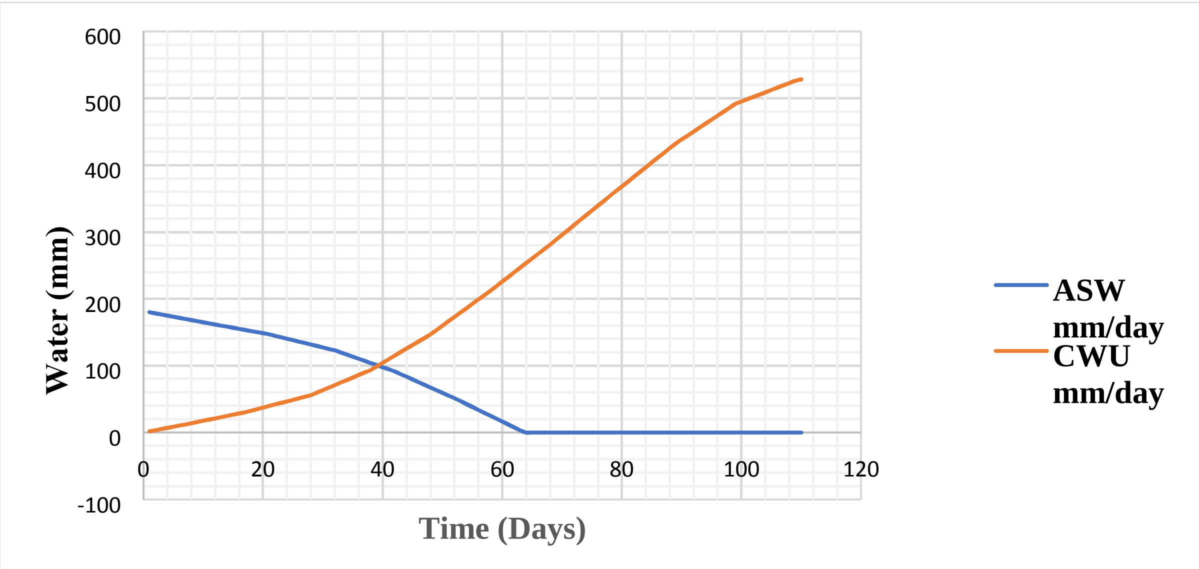


Figure 5. 4: Crop water use and available soil water against time.

Below are some calculations if beans are planted in August.

Amount of water in the soil, Available soil water (ASW) = 180 mm

Amount of water irrigated by farmers (FI) = 402 mm

Irrigation Requirement = 503.6 mm or 0.5036 m

Plot size of each farmer (Area) = 900 m^2

Total number of farmers = 1777

The amount of water that can be saved = IR – ASW

= 503.6 – 180 mm

= 323.6 mm or 0.3236 m

Amount of water required in cubic meters = 0.3236 m × 900 m^2

= 291.24 m^3

The area that can be reduced =291.24m^3 / 0.5036 m

= 578.32 m^2 / 10000

= 0.05783-0.0181 ha by each farmer

Therefore, the whole scheme, the area that be reduced = 0.05783 ha × 1777

= 102.77 ha

When the crop is planted early in May the amount of water that is required to irrigate is 172 mm but famers do apply around 400 mm which is a waste of water and over irrigation takes place. On the other hand, when the crop is planted in August the amount of water required to irrigate the crop is 326 mm which is almost double the irrigation requirement in May. The problem is it is getting warmer, so the crop needs more water to mature, and the profile would have drained more, so we have a smaller initial reservoir, and the river flow is declining so not easy to estimate the available water.

5.3 Discussion

From the tables it can be seen that crops planted early (May) require less irrigation water due to the strategic utilisation of residual water in the soil. However, when planted late in August the crops require more water since much of the residual water could have been evaporated or lost to the rivers and the ET_o is usually high. Mostly, early planting uses most of the residual soil water unlike late planting where irrigation has to start even before planting the seed so that soil water can be available to the seed.

Early planting of sugar beans can result in significantly higher yields than for later planted crops. This results through the maximization of available soil water by the crop since temperatures are low resulting in low evaporation and transpiration. This is the opposite when planted late, where temperatures are high and high evaporation and transpiration take place making the crop to use most of the available soil water very quickly. High temperatures of more than 30^{o}C during flowering may result in abscission of flowers and low pod set resulting in depressed yields. Stressing the crop during critical periods of development has a great impact on yield since it leads to poor development of flowers and pods.

Even though figures 5.2 and 5.4 indicate that the residual soil water would run out after day 60, the reality is that the soil still had water after day 60 as evidenced from the chameleon patterns. The chameleon pattern showed that water would still be available and only little irrigation would be added

Early planting contributes to canopy growth which increases radiation interception that increases assimilate production, resulting in improved utilisation of water and nutrients and improved soil cover that reduces evaporation. Planting early may reduce weed competition early in the season and could prevent weeds that emerge later from becoming a problem. Planting early would also limit the likelihood of the river drying up before the crop reaches maturity and could possibly eliminate one or two irrigations so more farmers could benefit from an expanded cropped area.

Late planting of beans would likely encounter much higher temperatures and a reduction in the flow of the river which end up in completely drying up of the river before the crop reaches maturity, which would negatively affect growth, development and yield. More water would be required to meet the crop water demand which might not be available, and this may lead to reducing the actual area of production.

General discussion

BVIS experiences low yields of beans due to poor water management, poor crop husbandry agronomic practices and inadequate nutrition. During the dry season there is a shortage of water due to drying up of the river and the absence of storage. This drying up of the river is due to poor management of the catchment where people tend to cut trees despite their importance by improving the water cycle, reducing runoff and resultant siltation?, replenishing of the water table and controlling floods. Farmers who cultivate along the river banks also contribute to the river running dry. Much as there are regulations to control this but farmers do not implement it. There is poor communication between upstream and downstream users, which has contributed to poor water management. At scheme level, a lack of a sense of collective responsibility was observed as one of the factors leading to poor water management. The WUG had problems in both ensuring equitable access to water and resolving conflicts among farmers. The government and other stake holders try to provide trainings to minimize the present-day problems but after the training only few farmers follow the right procedures.

Water is a fluid resource which requires having administration boundaries. Irrigation management should take into consideration the management of water across administrative boundaries and good coordination at catchment level should be put in place. For smallholder farmers a committee is formed that looks into the administration of the boundaries and management of the catchment e.g Ntchenachena irrigation scheme and Lumbwezi in Rumphi district.

Once the catchment is properly managed, improving water use efficiency should be at the centre of efforts. This can be done through the provision of soil water monitoring tools which could help in determining when to irrigate. With the use of Chameleon sensors, irrigation events could be minimized and reduced in magnitude, and the saved water could be used to irrigate other areas which are currently not irrigated. In so doing, the area could be expanded and more farmers could benefit in terms of food security and household income. As observed with the Farmer Practice and Farmer Irrigation with Luxury Nutrients treatments, much of the water was used of which it could be used for other purposes like irrigating another area or domestic purposes. Water development could help in facilitating the Green Belt Initiative project to increase agricultural production and productivity in Malawi. When the Chameleon soil water monitoring tool was used to determine when to irrigate for the Optimum Irrigation with Luxury Nutrients and the Strategic Irrigation with Luxury Nutrients treatments, the former treatment performed better. The OILN treatment had received irrigation based on the colours of the

Chameleon sensors without stressing the crop compared to the SILN treatment which was stressed. If Bwanje farmers or any other farmer in the country can irrigate based on Chameleon sensor colours, unnecessary irrigation could be avoided.

There was a highly significant difference in yield in the treatments which received nutrients compared to the ones that did not. Optimum Irrigation and Luxury Nutrients yielded higher than any other treatment, with Farmer Practice having the lowest yield. This shows that nutrient addition to the bean crop is essential to improve yield and this could result in improved food security of Bwanje farmers. Economically this was not viable considering that Farmer Practice obtained the pontential yield by following good agronomic practices. If surplus production can be sold at a good price, it will also assist in lifting farmers out of poverty. Low yields are achieved by inadequate nutrition, whereby nutrients are never applied to the bean crop based on the fact that beans fix nitrogen into the soil. Farmers need to be trained on nutrient application in beans since the soil does not contain all the nutrients in sufficient quantities for the crop. Soil nutrient monitoring tools such as Wetting Front Detector should be provided to farmers to better understand the concept of nutrient leaching after heavy irrigation or rainfall. Once WFDs are available to farmers, training on how to operate them and to interpret data is essential. The Optimum Irrigation and Luxury Nutrients and Strategic Irrigation and Luxury Nutrients showed that with the use of Wetting Front Detector most of the nutrients were monitored and were within the root zone depth which gave the chance to the roots to absorb them instead of being leached.

Farmers should be linked to markets and information to ensure that their products earn cash income which can help lift them out of poverty. Revision of pricing policies should be conducted to make farmers more productive in light of the need to make products more valuable. If prices are reviewed it could contribute to economic value of the country. Generally, smallholder farmers sell their produce from rainfed agriculture as their main source of income and use the irrigation produce for consumption.

Most farmers tend to ignore good crop agronomic practices because it is labour intensive to carry out the activities. As a result, they tend to lose out on yield. In Farmer management treatment, much as irrigation was based on how the farmers do in the scheme, potential yield of 2 t ha^{-1} was achieved. This was due to following the good crop husbandry practices such as timely weeding and tilling the land before planting.

The Strategic Irrigation and Luxury Nutrients treatment was stressed because it achieved the potential yield. This is because SILN used much of the residual soil water and required minimal irrigation.

Traditionally, Bwanje farmers plant one rainfed crop, which is rice and it is always flooded, and after harvest the fields are left fallow and rice straw is burnt. After rice harvest there is a lot of residual soil water which could be sufficient for short-duration crops like beans. Timely planting could be very beneficial, such that most of the residual soil water can be used. Residual soil water utilisation could ensure that more land is cultivated and higher yields could be realised. With high yields being achieved, farmers can sell surplus grain and extra returns could possibly contribute towards operation and maintenance of the scheme. Farmers need to be aware that use of residual soil water can help in minimization of water conflicts and that the residual water in the soil can sustain crops. This can be done through training and demonstrations in their fields. With the drying of the river in the dry season, beans could be ideal to be cultivated using residual soil water since they are short season crops and require less water and from the experiment the crop showed that it had deep root system which allowed waster absorption by the roots. Residual soil water management reduces the likelihood of leaching and makes farmers less reliant on irrigation when the river discharge is low. Since residual soil water use was analysed using a model, an actual planting date and residual water use experiment needs to be carried out at Bwanje to confirm results and better evaluate the opportunity available. And use of early maturing variety of dry bean could be beneficial. The farmers comments on the performance of the trial versus their crops were much amazed to see how the dry beans trial performed compared to their crops. Few of the farmers who came to appreciate indicated that they emulate what happened in the trial.

Conclusions and Recommendations

Conclusions

Wetting Front Detectors helped in the management of nutrients as was evident with the colours in Optimum Irrigation and Luxury Nutrients and Strategic Irrigation and Luxury Nutrient treatments, where minimal amounts of nitrogen were leached. In Farmer Irrigation the colour pattern shows that leaching of nutrients really occurred. Therefore, we accept the null hypothesis that under current farmer practice dry bean crops are nutrient limited and reject the alternative hypothesis.

Chameleon sensors gave satisfactory results in monitoring and managing soil water as the colour patterns helped to show when to irrigate. The number of irrigations was minimized in OILN and SILN unlike in Farmer Irrigation where multiple irrigations occurred. It can therefore be seen as a useful tool in irrigation water management through continuous soil water monitoring. However, care should be taken during installation of the sensors. Therefore, we reject the null hypothesis that under current Farmer Practice beans are water limited and accept the alternative hypothesis.

Climwat and Cropwat calculations confirm that with residual soil water utilization the area of cultivation could be increased if the crop is planted on time. Timely planting could indeed use much of the residual soil water unlike when planted late where more water could be required. Therefore, we accept the alternative hypothesis that utilisation of residual soil water could enable the winter irrigated area to expand and reject the null hypothesis.

Recommendations

- Farmers should be sensitized on the potentials of timely use of residual soil water after rice harvest and an actual experiment on the effect of early and late planting should be conducted.
- Agricultural Research Institutions are advised to intensify efforts in conducting experiments on the reliability and sustainability of residual soil water use in order to support a second cropping season and to boost annual food production.
- Agricultural extension services need to improve their technical back-up to farmers with regards to crop irrigation and catchment management.
- There should be the provision of soil water monitoring tools and nutrient management tools in the scheme and their use and benefits should be well highlighted.

- There should be more awareness on the importance of nutrient application to legume crops since nitrogen fixation alone may not be adequate for beans, and requisite water management to avoid nutrient leaching.

References

AR Robison. 1957. Parshall measuring flumes of small sizes.

Brouwer C, Heibloem M. 1986. Irrigation water management: irrigation water needs. *Training manual,* 3.

Brown B, Westermann D. 2000. Soil Fertility and Bean Production. In: Singh SP editor. *Bean Research, Production, and Utilization*: University of Idaho. p. 63-71.

Cayci G, Heng L, Öztürk H, Sürek D, Kütük C, Sağlam M. 2009. Crop yield and water use efficiency in semi-arid region of Turkey. *Soil and Tillage Research*, 103: 65-72.

Charlesworth P. 2000. *Soil water monitoring*. Land & Water Australia.

Charlesworth P. 2005. *Irrigation Insights No. 1- Soil Water Monitoring 2nd edition. National Program for Irrigation Research and Development. CSIRO Publishing, Melbourne, Australia.*

Chidanti-Malunga J. 2009. When government acts against the will of the people: the case of Bwanje Valley Irrigation Scheme in Malawi. *Journal of Applied Sciences Research*: 323-328.

DAFF. 2010. Dry Beans Production Guideline, Department of Agriculture, Forestry and Fisheries.

DoI. 2015. Irrigation and Development, National Irrigation Master Plan and Investment Framework, Appendix 3. Lilongwe: Government of Malawi.

Evett S. 2000a. Some aspects of time domain reflectometry, neutron scattering and capacitance methods for soil water content measurement. *FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. Comparison of Soil Water Measurement using the Neutron Scattering, Time Domain Reflectometry, and Capacitance Methods. IAEA-TECDOC-1137*: 5-49.

Evett S. 2000b. Some aspects of time domain reflectometry, neutron scattering, and capacitance methods for soil water content measurement. *FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. Comparison of Soil Water Measurement using the Neutron Scattering, Time Domain Reflectometry, and Capacitance Methods. IAEA-TECDOC-1137*: 5-49.

Evett S, Steiner J. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. *Soil Science Society of America Journal*, 59: 961-968.

FAO. 2002. World Agriculture towards 2015/2030, Summary report. Rome.

FSSA 2007. Fertilizer handbook, Fertilizer Society of South Africa. Fertilizer Society of South Africa Pretoria.

Grant L, Seyfried M, McNamara J. 2004. Spatial variation and temporal stability of soil water in a snow-dominated, mountain catchment. *Hydrological Processes*, 18: 3493-3511.

Humphreys E, Smith D, Fattore A, Bhuiyan A, Fawcett B. 2005. *Quantifying and maximising the benefits of crops after rice. CSIRO land and water.*

Jain SK, Singh VP. 2003. *Water resources systems planning and management* (1st ed. edn). Boston: Elsevier.

Jan Glazewski LdT. 2013. *Environmental Law in South Africa*. *Butterworth Publishers (Pty.) Ltd, South Africa.*

JICA. 2005. Basic design study report on the project for the rehabilitation of the Bwanje Valley Irrigation System in the republic of Malawi. Government of Malawi.

Johnson AI. 1962. Methods of Measuring Soil Moisture in the Field. Geological survey water-supply paper 1619-U. US Government Printing Office

Johnstone J. 2011. Vulnerability of a Run-of-River Irrigation Scheme to Extreme Hydrological Conditions-A Case Study of the Bwanje Valley Irrigation Scheme, Malawi.

Kar G, Kumar A. 2009. Evaluation of post-rainy season crops with residual soil moisture and different tillage methods in rice fallow of eastern India. *Agricultural Water Management,* 96: 931-938.

Li Y, Rao R, Bryan H, Olczyk T. Optimized irrigation schedule to conserve water and reduce nutrient leaching for tomatoes grown on a calcareous gravelly soil*1998*: Florida State Horticultural Society. pp. 58-61.

M.N. Rahman, M.G.M. Amin, M.K. Mondal, Humphreys E. 2014. Rabi crop establishment methods for increasing land productivity in the coastal zone of Bangladesh. International Water Management Institute (IWMI). CGIR Research Program on Water, Land and Ecosystems.

Mahmoud MI, Gupta HV, Rajagopal S. 2011. Scenario development for water resources planning and watershed management: Methodology and semi-arid region case study. *Environmental Modelling & Software*, 26: 873-885.

MGDS II. 2016. Malawi Growth and Development Strategy II. Malawi Ministry of Finance, Economic, Planning and Development

Moore S. 2012. Water resources issues, policy and politics. p. 1-10.IWA Publishing

NKC NKCL. 1997. Basic Design Study Report on Project for Bwanje Valley Smallholder Irrigation Development in Republic of Malawi. Nippon Koei Co., Ltd

Noborio K. 2001. Measurement of soil water content and electrical conductivity by time domain reflectometry: a review. *Computers and electronics in agriculture*, 31: 213-237.

Patrignani A, Ochsner T. 2015. *Canopeo: A Powerful New Tool for Measuring Fractional Green Canopy Cover,* vol. 107.

Peters RT, Desta KG, Nelson L. 2013. Practical use of soil moisture sensors and their data for irrigation scheduling. Washington State University Extension Fact Sheet • FS083E

Reynolds S. 1970. The gravimetric method of soil moisture determination Part IA study of equipment, and methodological problems. *Journal of Hydrology*, 11: 258-273.

Richards L, Neal O. 1937. Some field observations with tensiometers *Soil Science Society of America Journal*, 1: 71-91.

Risinger M, Wyatt W, Carver K. 1997. Estimating soil moisture by feel and appearance. *US Department of Agriculture, Pacific Region Pocket Handbook, Water Management Note, High Plains Underground Water Conservation District*.

Rosegrant MW, Cai X, Cline SA. 2002. *World water and food to 2025: dealing with scarcity*. International Food Policy Res Inst.

Saleh S, Liu G, Liu M, Ji Y, He H, Gruda N. 2018. Effect of Irrigation on Growth, Yield, and Chemical Composition of Two Green Bean Cultivars. *Horticulturae*, 4: 3.

SeedCo. 2010. Agronomy Manual. In: Zimbabwe SC editor. Harare Zimbabwe.

Smajstrla A, Koo R. Use of tensiometers for scheduling of citrus trickle irrigation*1986*. pp. 51-56.

Smajstrla A, Locascio S. 1996. Tensiometer-controlled, drip-irrigation scheduling of tomato. *Applied Engineering in Agriculture*, 12: 315-319.

Snapp S. 1998. Soil nutrient status of smallholder farms in Malawi. Communications in Soil Science and Plant Analysis- Commun Soil Sci Plant Anal. 29.2571-2588.10.1080/00103629809370135.

Stirzaker R. 1999. The problem of irrigated horticulture: matching the biophysical efficiency with the economic efficiency. *Agroforestry Systems*, 45: 187-202.

Stirzaker R. 2003. When to turn the water off: scheduling micro-irrigation with a wetting front detector. *Irrigation Science*, 22: 177-185.

Stirzaker R. 2005. Managing irrigation with a Wetting Front Detector CSIRO Land and Water ACT2601 Australia

Stirzaker R, Car N, Christen E. 2014. A traffic light soil water sensor for resource poor farmers: proof of concept. Aciar Gov.Au/Files

Stirzaker R, Stevens J, Annandale J, Maeko T, Steyn J, Mpandeli S, Maurobane W, Nkgapele J, Jovanovic N. 2004. *Building capacity in irrigation management with wetting front detectors*. Water Research Commission, Pretoria.

Stirzaker R, Steyn J, Annandale J, Adhanom G, Laan M, M'Marete C. 2010. Adapting the wetting front detector to small-scale furrow irrigation and providing a basis for the interpretation of salt and nutrient measurements from the water sample. *WRC Report (1574/1/10)*

UNCTAD. 2011. *Water for food, innovative water management technologies for food security and poverty alleviation*. New York and Geneva: United Nations.

Veldwisch GJ, Bolding A, Wester P. 2009. Sand in the engine: the travails of an irrigated rice scheme in Bwanje Valley, Malawi. *The Journal of Development Studies*, 45: 197-226.

Via.farm. 2015. Virtual Irrigation Academy available online at https://via.farm/the-tools/19/past/2015.

Via.farm. 2016. Virtual Irrigation Academy: Bwanje Irrigation Scheme. Available online at https://via.farm/visualisefarm/22/past/2016/.

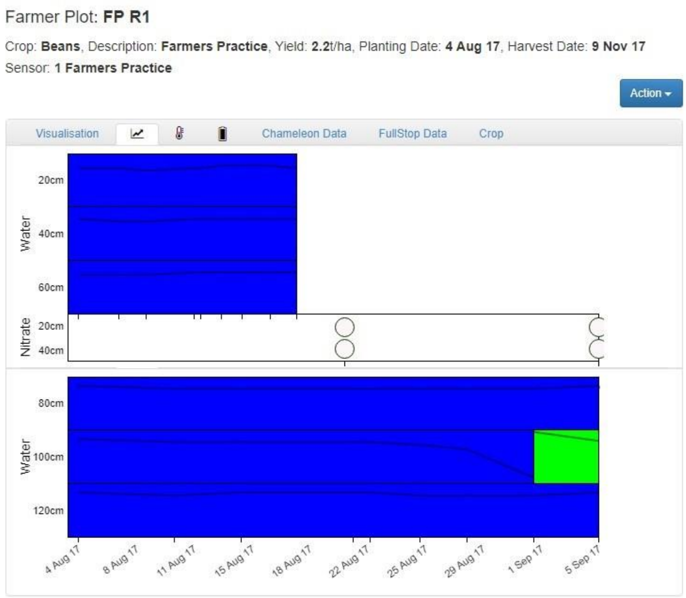
Via.farm. 2017. Virtual Irrigation Academy. Bwanje irrigation. Available online at https://via.farm/visualisefarm/128/past/2017/.

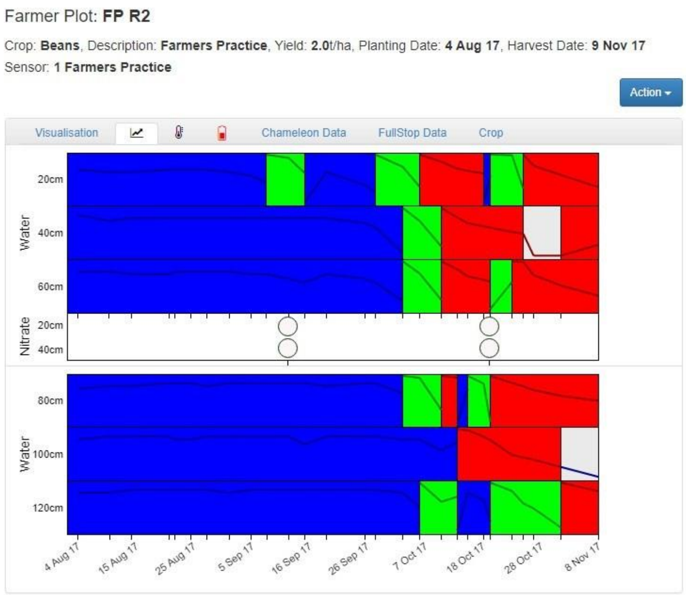
WWA. 2012. The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. Paris, UNESCO. *World Water Assessment Programme).* 1: 1-407.

WWAP. 2014. United Nations World Water Assessment Programme (WWAP). The United Nations World Water Development Report: Water and Energy; UNESCO: Paris, France.

Appendices

Appendix A: Chameleon crop patterns for different treatments.

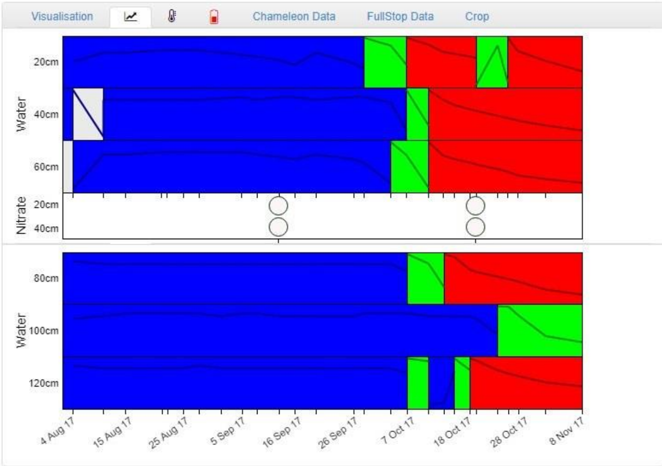




Farmer Plot: **FP R3**

Crop: **Beans**, Description: **Farmers Practice**, Yield: **2.1**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17**
Sensor: **1 Farmers Practice**

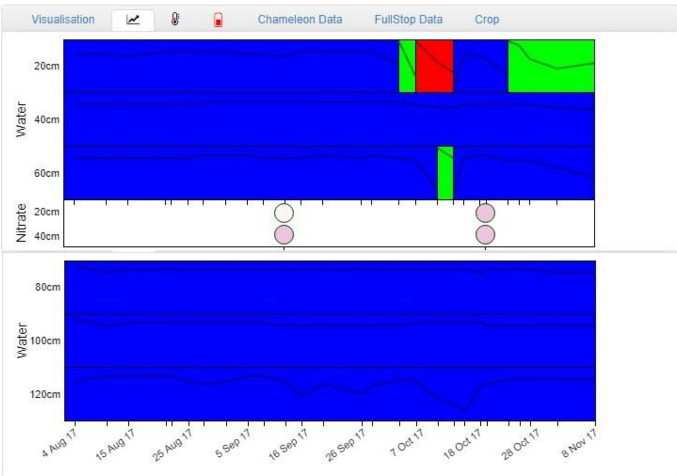
Action



Farmer Plot: **FILN R1**

Crop: **Beans**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **2.46**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Farmer Irrigation + Luxury Nutrients**

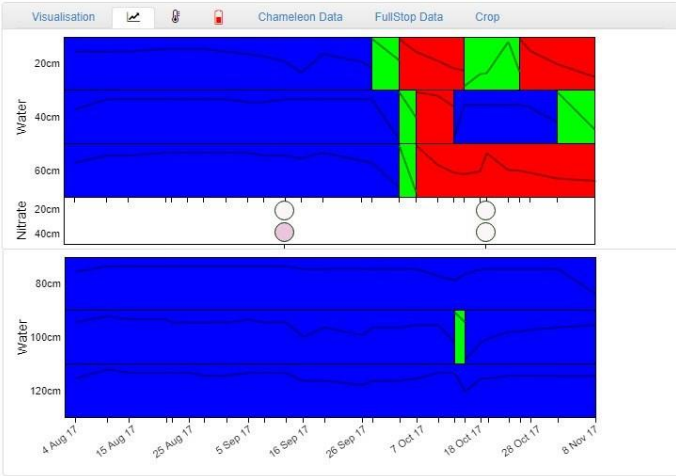
Action



Farmer Plot: **FILN R2**

Crop: **Beans**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **2.5**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Farmer Irrigation + Luxury Nutrients**

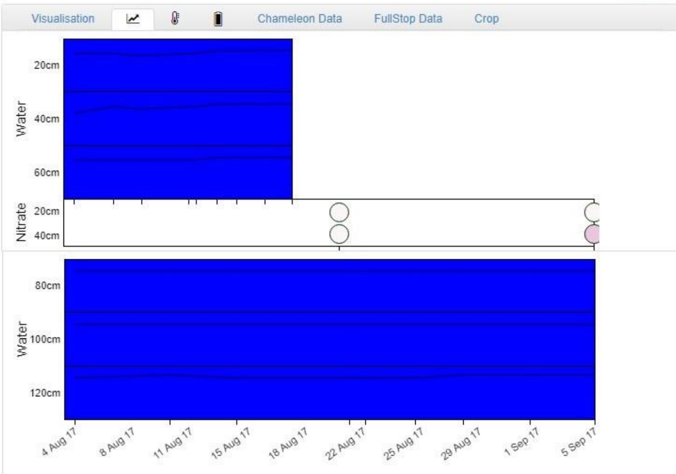
Action



Farmer Plot: **FILN R3**

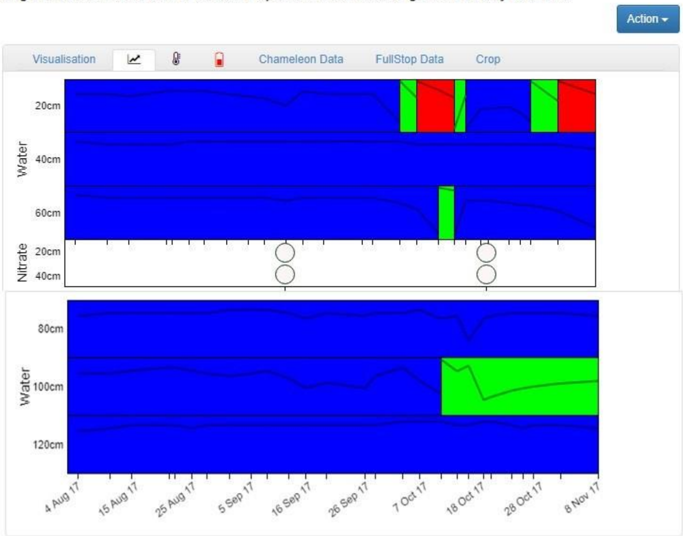
Crop: **Beans**, Description: **Farmers Irrigation + Luxury Nutrients**, Yield: **2.6**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Farmer Irrigation + Luxury Nutrients**

Action



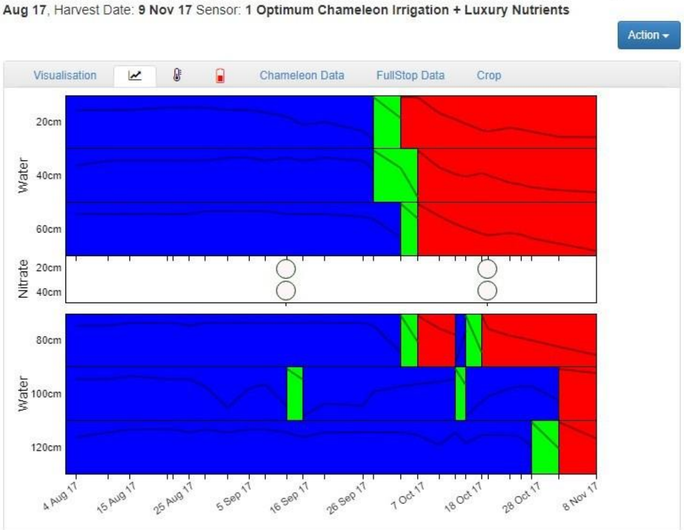
Farmer Plot: **OILN R1**

Crop: **Beans**, Description: **Optimum Chameleon Irrigation + Luxury Nutrients**, Yield: **2.7**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**



Farmer Plot: **OILN R2**

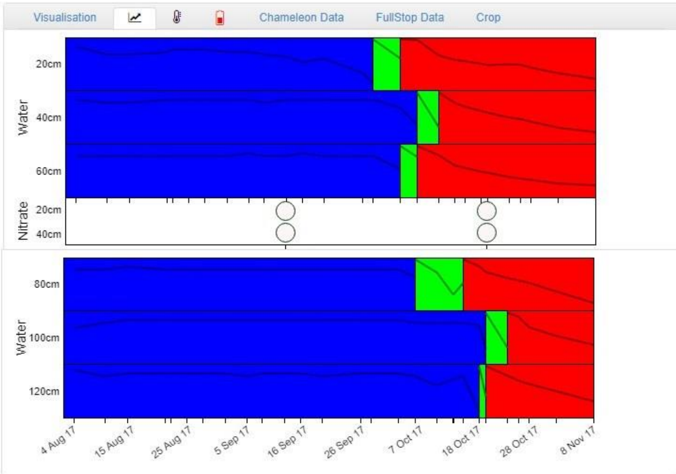
Crop: **Beans**, Description: **Optimum Chameleon Irrigation + Luxury Nutrients**, Yield: **2.76**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**



Farmer Plot: **OILN R3**

Crop: **Beans**, Description: **Optimum Chameleon Irrigation + Luxury Nutrients**, Yield: **2.78**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

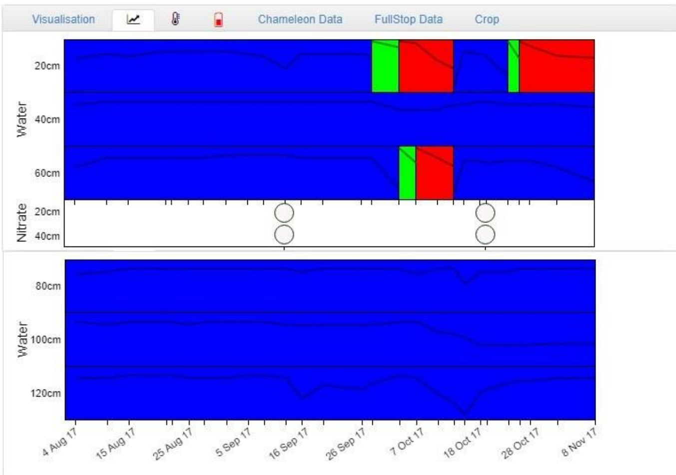
Action

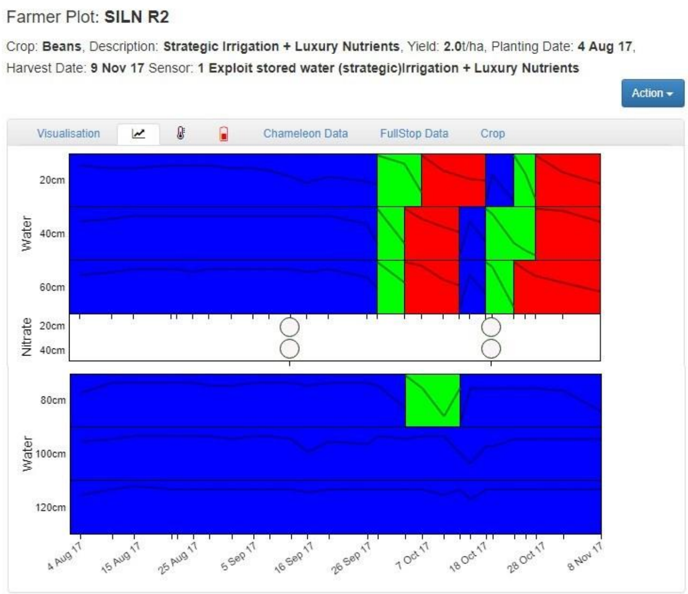


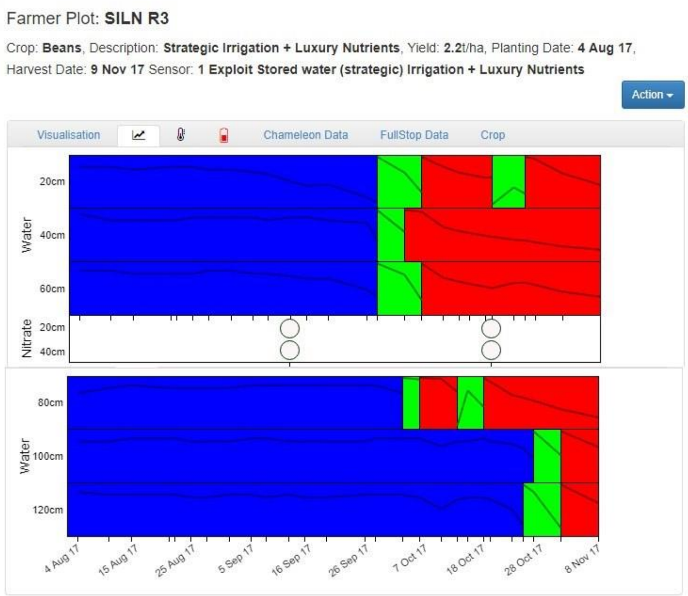
Farmer Plot: **SILN R1**

Crop: **Beans**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **2.4**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **9 Nov 17** Sensor: **1 Exploit stored water (strategic) Irrigation + Luxury Nutrients**

Action







Appendix B: Data for crop height and canopy cover percentage.

	Plant Heights (cm)			
No of Days	**FP**	**FILN**	**OILN**	**SILN**
14	4.38	5.85	4.94	4.94
21	10.00	11.23	11.53	11.76

35	23.43	25.82	27.64	28.16
49	42.37	44.58	45.36	46.32
57	51.67	54.16	59.24	56.83
71	60.73	59.10	61.12	60.96
85	69.99	67.32	71.78	70.21

Canopy cover (%)				
No of Days	**FP**	**FILN**	**OILN**	**SILN**
14	5.25	5.01	6.67	5.24
21	10.68	11.36	12.22	12.02
35	24.82	29.07	36.80	35.52
49	55.76	66.29	69.52	69.66
57	77.47	85.24	88.25	83.77
71	81.75	91.27	95.37	90.37
85	92.16	96.72	97.56	95.28