

WATER PRODUCTIVITY OF POTATO (*Solanum tuberosum*) UNDER DEFICIT SUB-SURFACE DRIP IRRIGATION AND SUPER ABSORBENT POLYMER IN CLAY LOAM SOIL

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A Thesis Submitted to the Graduate School in Partial Fulfilment of the Requirements for the Master of Science Degree in Agricultural Engineering of Egerton University

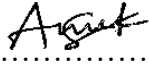
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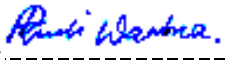
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DEDICATION

To the Mighty God and my parents Mr. Kennedy Oriosia and Mrs. Lilian Kwamboka for their dedicated prayers, support, and encouragement throughout the study. I also dedicate this work to my siblings Nancy Bosibori, Janet Kerubo, Edwin Oikoro, and Judith Mora.

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ABSTRACT

The annual agricultural freshwater withdrawal in Kenya is high. With climate variability and competition from other water uses, irrigated agriculture is facing water shortage. The lack of adequate conditions for production and freshwater availability is causing more challenges for farmers. This has caused the production of Irish Potato, which is the second most grown and consumed crop in Kenya, a challenge for most farmers in arid and semi-arid areas. It is not possible to grow this crop in water-scarce situations since crop water requirements cannot be met. The use of deficit subsurface drip irrigation in the production of other crops has shown good quality yields and high water productivity. However, the water-saving potentials and the combined effect of super absorbent polymers and Deficit Subsurface Drip Irrigation (D-SDI) on potato production in water-constrained environments have not been adequately investigated. The study therefore sought to assess the water productivity of Irish potatoes using a deficit subsurface drip irrigation system and super absorbent polymer. The field experiments were carried out under a transparent polythene shade in Tatton Agricultural Farm within Egerton University located in Nakuru County, Kenya. The field research was set out in a factorial experimental design, with twelve treatments, replicated three times. The treatments combined four quantity levels (0kg/ha, 6kg/ha, 10kg/ha, and 14kg/ha) of super absorbent polymer, and three irrigation levels (100%, 85%, and 70 %) of the crop water requirements (CWR). The study analyzed the impact of D-SDI and the amount of super absorbent polymer on potato yield and water productivity. The AquaCrop model was used to simulate the Irish potato and productivity in deficit irrigation and super absorbent polymer. The 100% water application level with 0 kg/ha super absorbent polymer was used for calibration and the other treatments were utilized to validate the model. The model predicted crop growth with R^2 of 0.92, RMSE of 10.6%, NSE of 0.9, and Wilmot's degree of agreement of 0.98. The use of SAP in the soil, however, affected the model performance in simulation for various treatments. This was because the SAP improved soil characteristics relevant to water holding capacity without changing the physical texture and structure of the soil. The SAP and SDI combination showed an average of 12% improved yields under deficit irrigation with up to 39% water savings. For optimum potato production a row application of 10kg/ha SAP and 70% of potato crop water requirement was obtained from the study. The findings of this research can be adopted in improving food security on areas with water scarcity.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ANOVA	Analysis of Variance
AGB	Above ground biomass
Ap	Area of plot under each treatment
ASALs	Arid and Semi-arid Lands
B	Total Biomass produced from potato growth
CC	Canopy Cover
CC ₀	Canopy Cover at the time, t=0
CC _x	Maximum canopy cover
CGC	Canopy Growth Coefficient
CI	Confidence Interval
d	Wilmot's index of agreement
D-SDI	Deficit Subsurface Drip Irrigation
DAP	Days after planting
Dfd	Degree of freedom in the denominator
Dfn	Degree of freedom in the numerator
DY	Dry yield
Ea	Field application efficiency
ET _c	Crop evapotranspiration requirement
ET _o	Reference evapotranspiration
ET	Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
FC	Field Capacity
HDPE	High-density polyethylene
HI	Harvest Index
INT	Irrigation Interval
K _c	Crop coefficient
K _y	Yield response factor
LSD	Least Significant difference
NRMSE	Normalized Root Mean Square Error

NSE	Nash-Sutcliff efficiency coefficient
O_i	Observed values
P_i	Predicted values
PVC	Polyvinyl Chloride Plastic Pipe
PWP	Permanent Wilting Point
r	Pearson's coefficient of correlation
R^2	Coefficient of determination
RC	Relative Cover
RMSE	Root Mean Square Error
R_n	Net solar radiation
SAP	Super Absorbent Polymer
SDGs	Sustainable Development Goals
SMS	Soil Moisture Sensor
SSD	Subsurface Drip
SWC	Soil Water Content
T	Temperature
T1...T12	Treatments used in this research
TAP	Tatton Agricultural Park
U	Wind speed
WP	Water Productivity
WUE	Water Use Efficiency
Y	Crop Yield
Z	Depth below the soil surface
Δ	Saturation vapour pressure curve slope
G	Soil heat Flux index
e	Vapor pressure
γ	Psychometric constant

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Freshwater is increasingly diminishing and becoming a more scarce commodity in arid and semi-arid regions (ASALs), and even in regions with abundant rainfall (Giordano et al., 2019). Every year, about two-thirds of the global population faces acute water shortages for at least one month (Mekonnen & Hoekstra, 2016). Water is the main production input to maintain agricultural development. Annually, the agricultural sector utilizes 59.3% of total freshwater withdrawals in Kenya (OECD, 2021). This implies that more freshwater resources are used for agricultural production than combined industrial, domestic and recreational water use.

Irrigated agriculture is the major consumer of freshwater resources and is currently facing a water shortage and this problem is expected to intensify in the future (Tewabe & Dessie, 2020). The increasing domestic and industrial water demand has resulted in reduced water availability for irrigated agriculture (Jin et al., 2014). With the scarce nature of freshwater and the growing demand for food from the increasing population, there has been an increasing need for the use of more efficient irrigation water application and management techniques. The sub-surface drip irrigation system is a more efficient water application method as it applies water to the crop root zone and minimizes water losses through runoff and evaporation (Adeboye et al., 2017). As a water management strategy, deficit water application and sub-surface drip irrigation have shown greater success in water-saving for many crops including tomatoes while at the same time maintaining high yields (Sang et al., 2020).

Soil conditioning, a common agricultural practice of amending soil with additives that improve both the structure and fertility of the soil has shown greater success over the years. The amendments commonly used in salt-affected areas are organic manure and compost. This is because their application has a positive impact on improving the leaching of salt by refining the structure and permeability of the soil (Lakhdar et al., 2011), supplying nutrients to plants and providing food to microbes (Maiti, 2012). Both organic and inorganic soil amendments have the property of improving soil water retention and infiltration by increasing aeration and reducing the bulk density of soil (Abuarab et al., 2017). Superabsorbent polymers however are capable of

retaining more water quantities for a long period and releasing it to plants on a need basis. Their application in the soil has led to high water saving and increased crop yield

The world production and consumption of potatoes is increasing every year for both developed and developing countries (FAO et al., 2020). Irish potato (*Solanum tuberosum L.*) is ranked number four among the world's most consumed and produced food crops following wheat, rice, and maize. Potatoes are a significant source of food, employment, and revenue in developing nations (Muthoni et al., 2017). In Kenya, potatoes now rank as the country's second food crop, following maize and preceded by rice among the top three crops. Statistics show that in 2017 Kenya's potato production was 1.345 Million metric tonnes (FAO et al., 2020). Over the year 2015, about 50 billion Kenya Shillings were realized from crop production as about 3.3 million people are employed indirectly in the potato industry (MOA, 2016). The most recent estimate shows that about 26 percent of the world's population was experiencing food insecurity and had irregular access to enough food in 2019 (FAO et al., 2020). Therefore, increasing food production in all its various forms will help to eradicate hunger and secure food for the growing population. Increasing agricultural production in a country like Kenya allows for the achievement of Sustainable Development Goal Number Two (SDG-2) which is Zero Hunger.

Traditionally, potato is produced at high altitudes of 1,500 to 3,000 metres above sea level on the slopes of Mount Kenya, the Aberdare mountains, Mount Elgon, the Mau Escarpment, Kericho and Kisii highlands, the Cherangani hills, and isolated regions in the Taita hills (Muthoni et al., 2013). To achieve agricultural intensification of potato production, expansion of potato farming to non-traditional potato growing areas and growing of potatoes in all seasons of the year is necessary (MOA, 2016). Most Kenyan producers rely mostly on rain-fed agriculture which makes them more susceptible to climate change (Gichovi, 2018). One of the most promising avenues for alleviating rising water scarcity is to minimise agricultural water consumption (Mekonnen & Hoekstra, 2012). In crop production, significant gains in agricultural output can be made by maintaining yield and reducing water losses, with the latter referring to not beneficial consumptive water usage at the farm level and unrecoverable losses at the system level.(Chukalla et al., 2015).

The rising need for planning and operation of improved management of water resources in agriculture has necessitated for development of various models that are used to predict

performance under different scenarios that can be evaluated for best operational plans. Some of the models developed are; the Food and Agricultural Organisation's (FAO) AquaCrop model, FAO Crop-Water (CROPWAT) model, Water Balance (WATBAL), and Crop Irrigation Water Requirement (CRIWAR). The AquaCrop model is a basic process-based model that simulates soil water content (SWC), crop water use, crop growth, total biomass output (B), and yield (Y) under various climatological and environmental circumstances and management practices (Horemans et al., 2017). AquaCrop simulations have been applied in rain-fed conditions, deficit irrigation, supplementary irrigation, and water management strategies on farms to increase the efficiency of water use in agriculture (Sang et al., 2020).

1.2 Statement of the Problem

The food produced from agriculture helps support human life, and agriculture is intertwined with freshwater availability (Asamatdinov, 2018; FAO et al., 2020). The freshwater supplies available globally continue to dwindle. That scarcity is spreading since water is needed to grow and process food, create energy, and serve the industry for the ever-growing human population (Śpitalniak et al., 2019). It is estimated that agriculture accounts for 59.3% of total freshwater withdrawals annually in Kenya (OECD, 2021). There is a need for improved agricultural water management approaches to reduce annual water withdrawals (Ndayitegeye et al., 2020). This can be achieved through the application of irrigation systems that have high water use efficiency. Such systems include deficit sub-surface drip irrigation systems (Sang et al., 2020) allied with the use of soil water content monitoring devices (soil moisture sensors) (McCarthy et al., 2002) increasing soil water holding capacity and providing a better environment for the roots by incorporating super absorbent polymers to conserve the irrigation water (Asamatdinov, 2018). However, information on the analysis of the combined effect of super absorbent polymers and Deficit Subsurface Drip Irrigation (D-SDI) on potato production and water-saving potentials is scanty. The use of deficit sub-surface drip irrigation as a means of meeting potato crop water demands in Njoro is limited. Additionally, the effect of both D-SDI and super absorbent polymers on potato development, yield, and water productivity is not fully quantified glob.

1.3 Objectives

1.3.1 Broad Objective

The main objective of this research was to simulate and assess the water productivity of Irish potato production under a deficit sub-surface drip irrigation system and super absorbent polymer soil amendment.

1.3.2 Specific Objectives

The specific objectives of this research were to

- i. Simulate crop water requirement, biomass production, water productivity, and yield of potatoes using the AquaCrop model
- ii. Assess the interactive effect of deficit subsurface drip irrigation and super absorbent polymer quantity on the yield and quantify the water productivity of potatoes

- iii. Optimize the potato production based on the interactive effect of deficit subsurface drip irrigation and the application rate of super absorbent polymer

1.4 Research Questions

- i. How can the AquaCrop model simulation of potato growth and productivity under the SAP system be accomplished?
- ii. How can an assessment of the interactive effect of deficit subsurface drip irrigation system and super absorbent polymer on the yield of potatoes be achieved?
- iii. How can the optimal effect of deficit subsurface drip irrigation and super absorbent polymer on potato production be established?

1.5 Justification

SDG 2 targets will only be possible when people have enough food to eat and if what they eat is both nutritious and affordable (FAO, 2020). One of the highly regarded potential food security crops is potato because it's able to provide a high yield of products within a shorter crop cycle per unit input than other cereal crops such as maize (Adane et al., 2010). Potato ranks fourth in terms of global crop production, behind wheat, maize, and rice, and first among root and tuber crops, followed by cassava, sweet potato, and yams in that order (FAO, 2020).

In Kenya, potato is a significant food and cash crop, second to maize (Janssens et al., 2013; Waaswa et al., 2022). Potato with its various products is a widely consumed meal in fast food establishments. In a year, potatoes can grow for three seasons but they are normally grown for only two seasons when there is rainfall. Irish potatoes have high water requirements, however, they can yield under rain scarcity which makes them ideal for deficit irrigation (MOA, 2016). However, water savings in crop production can be achieved primarily through better timing of deficit irrigation and depth of water application (Steduto et al., 2012).

The scarcity of freshwater resources and ever-increasing competition for water have led to reduced availability of water for irrigation. Additionally, the pressure from the growing population demand for food has made increased production of crops from less water a necessity. Achieving higher efficiency of water use is now a primary challenge and requires the employment of practices and techniques that will deliver water to crops in a more accurate manner. Subsurface deficit drip irrigation plays a crucial role in this context by ensuring increased water use efficiency (Badr et al., 2010). The use of super absorbent polymers (SAPs)

has led to increased potato yield and water saving in irrigation systems (Starovoitova et al., 2019).

Throughout the years AquaCrop simulation has been used in modelling water use efficiency and yield in various research fields and is effective in scenario analysis of irrigation methods emphasizing on water productivity, canopy cover, and total biomass (Kiptum et al., 2013). A calibrated and validated AquaCrop model can help in efficient water management of potato irrigation in arid and semiarid lands.

This research therefore sought to address the planning and operational needs and strategies to achieve high water productivity, increased production and application of modelling techniques to the potato production process. This has been identified as a very critical necessity for Kenya's potato production industry and of global need.

1.6 Scope and Limitation of the Study

The purpose of this study was to assess the Irish potato water productivity under a deficit subsurface drip irrigation system and super absorbent polymer for soil water management. The field experiments were set out under shade and in the open air. Irrigation and precipitation were used to supply water for crop transpiration requirements. The potato crop was observed for the whole of its growing period from January 2021 to the end of April 2022. A single growth cycle of Irish potatoes was considered and assumed uniform soil characteristics were used. The study focused on assessing the effect of the amount of irrigation water supplied and the amount of super-absorbent polymer applied in the soil on the growth rate and yield. The rate of fertilizer application at the planting stage was maintained throughout the whole field and soil texture was assumed constant. The groundwater table was assumed more than 4 meters below the root zone to allow the assumption of no effect of capillary rise of groundwater.

1.7 Definition of Terms

Agricultural	Is an economic growth stage where the traditional agricultural product
Diversification	mix is transformed into high-standard products which have a high potential to encourage production rates in the dynamic and commercial sector

Agricultural Intensification	Is the increase in agricultural production per unit of inputs which include labour, cash, time, land, fertilizer, or feed
Chatts	This is a class of harvested potato tubers that pass through 18mm by 18mm mesh
Crop Evapotranspiration	Is a physical process in which water passes from the liquid to the gaseous state while moving from the soil into the atmosphere and it refers to both evaporation from soil and vegetative surfaces and transpiration from plants.
Deficit irrigation	Is a water application strategy that allows a crop to sustain some degree of water deficit to reduce irrigation costs and potentially increase revenues
Drip Irrigation	Is a micro-irrigation system type that has water and nutrients saving potential by allowing water to slowly drip to the plant roots, either from above the soil surface or below the surface in the root zone.
Food Insecurity	The state of being without reliable access to a sufficient quantity of affordable and nutritious food.
Food security	Food and Agriculture Organisation of the United Nations (2003) defines food security as a situation when all people, at all times, have sufficient access both physically and economically to, safe and nutritious food that meets their dietary needs and food preferences for a healthy and active life. Conversely, food insecurity exists when people do not have adequate access to food physically, socially, or economically as previously stated (FAO, 2017).
Marketable yield	is the amount of tubers that can be sold from the total yield of potato tubers produced.
Soil amendments	Is any material additive to soil to improve the soil's physical properties and quality that encompass biochemical and structural functions.

Subsurface Irrigation	Drip	This is a high-efficiency; low-pressure irrigation system using buried drip tubes that apply water to the crop root zone, therefore, saving water and improving yields by eliminating surface water evaporation and minimizing the occurrence of weeds and diseases.
Water Productivity		The ratio of the yield of a crop in kilograms to the amount of water consumed through evapotranspiration in cubic meters.
Water Efficiency	Use	The ratio between effective water use and actual water withdrawal, that is, the ratio of water used in plant metabolism to water lost by the plant through transpiration.
Wares		This is a potato tuber class that indicates tubers that are retained in the 35-mm mesh. They have a minimum nominal diameter of 35mm.
Yield		Measurement of the amount of produce of crop grown in kilograms per area.

CHAPTER TWO

LITERATURE REVIEW

2.1 Irrigation Systems

Irrigation is the artificial application of controlled quantities of water to the land for either supplementing the natural rainfall or to aid in the production of crops as the only supply for crop water requirements. An irrigation system is a term used to imply the combination of conveyance, distribution, and application structures in which irrigation water flows from the source to the agricultural field of interest. The irrigation application methods are broadly divided into macro and micro-irrigation systems. Macro-irrigation systems are used to apply water to crops via high-volume, high-pressure devices. Macro systems include sprinkler irrigation, and surface irrigation systems (furrow, flooding, and basin). Micro-irrigation systems on the other hand uniformly distribute water to a crop through low-volume, low-pressure instruments that regulate water discharge rate, such as sub-surface irrigation and drip irrigation (Kelliher et al., 2017). Numerous water application systems have been developed. Details are described below.

2.2 Subsurface Drip Irrigation

Camargo et al. (2015) analysed the impact on potato growth and development of four irrigation treatments using sprinkler irrigation systems in Spain. This study observed the leaf area index, total dry matter, rate of crop growth, and the relative growth rate for all the treatments. It was found out that water application of more than 100% of ET_C did not influence the development and growth of the crop. It was also noted that the net assimilation rate was affected by the deficit water treatments. The research, therefore, recommended the use of deficit irrigation in water-scarce areas.

Drip irrigation involves the application of water to the field directly to crops by the use of an arrangement of pipes having openings fitted with an emitter (Bamohuni, 2011). A drip irrigation system is composed of water sources, filtration devices, mains, sub-mains, laterals, and drippers (emitters). Drip irrigation has a high application efficiency, approximately 90% and it is one of the irrigation methods normally employed to improve water use efficiency (Muthoni et al., 2017). In many studies involving the production of Irish potatoes, irrigation by use of drip has been widely employed and has proved to be well-suited for the production of row crop and

potatoes (Ghazouani et al., 2019; Poddar et al., 2021; Razzaghi et al., 2017; Smith & Kivumbi, 2002; Tayade et al., 2018).

Subsurface irrigation involves a network of pipes placed below the ground surface to apply irrigation water to the root zone of the plant with minimum surface evaporation and runoff. The pipes can also be above the ground with only the emitters below the ground surface. Subsurface irrigation requires little maintenance than surface irrigation and has fewer chances of saturating the surface and causing runoff (Adeboye et al., 2017).

Subsurface drip irrigation is the application of irrigation water using drip lines placed below the ground surface and delivering water directly to the crop root zone. This application method leads to reduced labour and maintenance costs of the drip system and also leads to greater water savings and yield (Sang et al., 2020). The subsurface drip irrigation method was applied in the study of water productivity of tomatoes. It was found that this irrigation method led to greater water savings and yield (Sang et al., 2020).

In as much as subsurface drip, irrigation has been proven to lead to greater water savings in its application, there is limited research on the assessment of water productivity of Irish potatoes using this method. Therefore, this method was used in this study.

2.3 Deficit Irrigation Strategies in Crop Production

Camargo et al. (2015) analysed the impact on potato growth and development of four irrigation treatments using sprinkler irrigation systems in Spain. This study observed the leaf area index, total dry matter, rate of crop growth, and the relative growth rate for all the treatments. It was found out that water application of more than 100% of ET_C did not influence the development and growth of the crop. It was also noted that the net assimilation rate was affected by the deficit water treatments. The research, therefore, recommended the use of deficit irrigation in water-scarce areas.

Deficit irrigation is an irrigation water optimization strategy in which less than the crop water requirement is supplied throughout the growth period subjecting the crop to some level of water stresses. In deficit irrigation, water is supplied to the crop in the growth stages that are drought-sensitive and in limited quantities outside these periods. Gultekin et al. (2018) evaluated the deficit irrigation effects on the development and quality of potato tubers, where surface drip

irrigation method was applied at 100, 85, 70, 55, and 40% ET_C . The results indicated that water stress had a significant effect on the yield, single tuber weight, percent of marketable tuber, and plant height. However, 100 and 85% ET_C treatments gave good yield and quality tubers.

Ierna and Mauromicale (2012) conducted a study to investigate the effect of four irrigation regimes on irrigation water productivity of Irish potatoes. In their study, four regimes of irrigation that were applied included plant emergence irrigation only, whole cycle irrigation, tuber initiation to 50% of tuber growth irrigation, and 50% of tuber growth to the end of tuber growth. Surface drip irrigation was used. From their research, it was clear that there was a strong and significant effect of the irrigation regime on tuber yield (40% reduction in yield), dry matter content of tubers, and irrigation water productivity. The study showed that it was possible to save water and maintain high yields of potatoes with high water productivity and tuber yield of good quality. However, with the use of a more efficient irrigation system that is subsurface drip under deficit water application, high and quality yields together with more water savings were guaranteed.

The use of deficit irrigation has significant effects on the growth, development, and yield of potatoes notwithstanding the positive impact it has on water conservation (Ghazouani et al., 2019; Razzaghi et al., 2017; Tayade et al., 2018). For best yields, it is recorded that enough water supply is needed at all times although moisture stress during bulking and tuber initiation stages will reduce yield more than any other development stage (Ierna & Mauromicale, 2012). This suggests that proper irrigation water management especially when applying deficit irrigation is required. With the emergence of more efficient methods like subsurface Drip irrigation (SDI) allied with the use of efficient soil water content monitoring devices such as soil moisture sensors; the practice of deficit irrigation in the production of Irish potatoes in water-constrained environments can improve yield due to increased efficiency of water application. Given that the use of an 85% deficit can be employed in semi-arid areas to produce good quality yields, employing, a 70% deficit proves to be beneficial in arid areas given that it has the potential of substantial water savings and yields. In this research deficit water application of 85% and 70% of crop water requirements were implemented.

2.4 Soil Amendments

Soil amendments are agricultural practices aimed at improving the quality of the soil mainly on biochemical functions and structure of the soil. The amendments used in mine sites after the mining process are purposive to improve soil stability and fertility. Several soil amendments used in such situations include fly ash, compost, and biochar (Maiti & Ahirwal, 2019). Soil amendments are classified into organic and inorganic or mineral amendments. Organic soil amendments are composed of materials obtained from plant biomass and or living things. Substances in this category are richly endowed with organic matter and microelements that help in increasing soil fertility through ameliorating conditions that give substrates for the growth of microbes. Organic amendments include animal manure, wood chips, compost, straw, geotextile, husk, and sewage manure. Studies indicate that the application of these materials on the soil surface has a significant effect on moisture content and rhizosphere temperature. Wang et al. (2017) reported that the use of organic amendments in the restoration of abandoned urban land led to a significant reduction of temperature by 12% because of the use of legumes and mulches.

Mineral or inorganic amendments contain minerals that are associated with the fertility of the soil. Gypsum is applied in the soil to reduce the pH by bonding lime or limestone and salts high in sodium thereby decreasing soil pH. Pardo et al. (2017) observed that both organic and inorganic soil amendments applied in the soil potentially increased the soil pH (3.2 – 7), stabilized the soil, and decreased trace metals solubility by over 80%. SAPs fall in the category of mineral amendments and they are capable of absorbing water and storing it for a lengthy time while making it readily available for plants (Kumar et al., 2012). They act as soil conditioners and microbes' food, as well as reduce runoff and soil erosion at the same time increasing the efficiency of the use of fertilizer. Bai et al. (2010) recorded that application of SAPs can raise the soil moisture by 6.2%-32.8% at the same time decrease the bulk density of the soil by 5.5%-9.4% as compared to soils without SAPs.

2.4.1 Super Absorbent Polymers (SAPs)

Superabsorbent polymers are swelling hydrogel materials that are applied to increase the water-holding capacity of soils in arid and semiarid areas (Asamatdinov, 2018). The SAPs are referred to as miniature water reservoirs in the soil. The plant utilizes the water absorbed by the SAPs by osmotic pressure difference. The polymer used in agriculture productions is mostly a cross-

linked copolymer of potassium and ammonium salts of acrylic acid in the form of loose white granules. The use of super-absorbent polymers has shown good results in their applications (Starovoitova et al., 2019). In a study to determine, the effect of using SAPs on potato yield, Starovoitova et al. (2019) found out that the yield of potato increased for the studied cultivars. The use of SAPs has far-reaching benefits for plants and soils alike (Malik et al., 2022). Therefore, its application combined with subsurface drip is projected will not only serve to conserve water, which is scarce but also seek to increase the potato yield, hence increasing agricultural production. The SAP applied in this study was Belsap, which is an 80% cross-linked potassium acrylate copolymer. This is a granular anionic superabsorbent polymer that has a high water absorption capacity. When applied in the soil, crop establishment, plant development, and yield all benefit from it (Gomez, 2015).

When the soil is watered after Belsap has been spread and mixed, the crystals quickly absorb water and expand. The crystals are designed to release moisture when there is lower moisture in the surrounding soil. This encourages the plant's root growth in response to the newly discovered moisture source that the hydrogels give (saturated SAP-soil mixture). This process promotes greater root mass, which leads to larger plants and higher crop production. The particle contracts and becomes prepared for the next stage of the process when the plant absorbs the water (Costa et al., 2021).

2.5 Irrigation Scheduling

Scheduling irrigation is a process of determining when to irrigate potatoes and the amount to apply based on soil-water-plant factors (Gheysari et al., 2015). The potato crop uses water primarily for transpiration and tuber production; therefore, proper irrigation is crucial from emergence to vine senescence. Transpiration involves the movement of water through the vine, from roots to leaves, to compensate for water loss at stomata (pores) that are open to allow gas exchange (oxygen and carbon dioxide) between the plant and the atmosphere thereby supporting plant photosynthesis and respiration (Linker & Kisekka, 2017). Irrigation scheduling involves a combination of soil-water factors that include; soil moisture, root zone depth, water holding parameters, effective precipitation, and daily water use. The key factors required in irrigation management are the determination of the amount of water getting into the soil, the amount of water the soil can hold, and the amount used by the plant.

Figure 2.1 shows the relationship between water available for the plant to use and the total storage reserve of the soil.

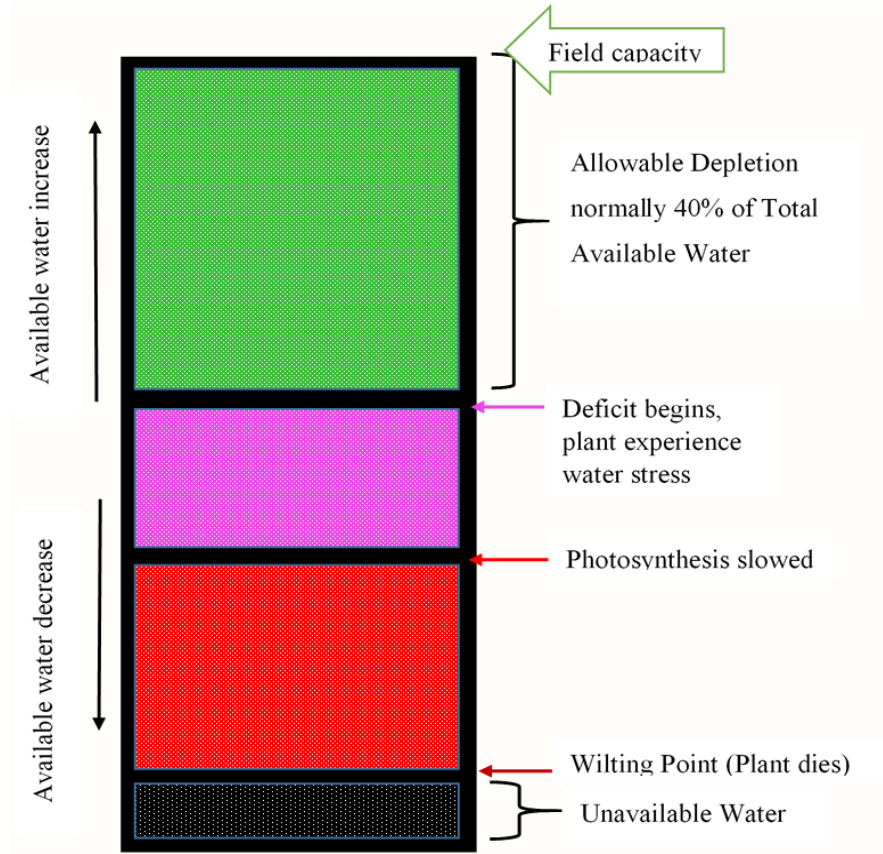


Figure 2.1: Water availability in the soil root zone and the total soil reserve

In irrigation scheduling, two methods are used; the first method is based on estimating the depth of irrigation application and the Irrigation Water Requirement (IWR) of the crop in the growing season and the second involves the use of the soil water balance method. The following steps as developed by FAO (1989) are applied in the estimation of the irrigation schedule:

- i. Estimation of the net irrigation depth (d_{net}) and gross irrigation depth (d_{gross}).

The net irrigation depth is determined locally by checking how much water is supplied per irrigation application with the field irrigation method and practice. In the absence of local data, the values in Table 2.1 are used to estimate net irrigation depth (Rai et al., 2017a).

Table 2. 1: Approximated Net Irrigation Depth per Irrigation (mm) (FAO, 1989)

Soil Type	Shallow Rooting Depth Crops	Medium Rooting Depth Crops	Deep Rooting Depth Crops
Shallow sandy soil	15	30	40
Loamy soil	20	40	60
Clayey soil	30	50	70

Gross irrigation depth is estimated using the Equation 2.1;

$$d_{gross} = \frac{d_{net}}{E_a} \times 100 \quad (2.1)$$

Where:

d_{gross} = gross irrigation depth (mm)

d_{net} = net Irrigation depth (mm)

E_a = field application efficiency (%).

The IN (irrigation water requirement) in millimetres for the i^{th} growing period may be calculated using Equation 2.2 (Rai et al., 2017b);

$$IN = ET_{ci} - P_{ei} \quad (2.2)$$

Where;

ET_{ci} = crop water demand for the i^{th} growing period (mm)

P_{ei} = effective rainfall during the i^{th} period (mm).

The number of irrigation applications over the total growing season may be estimated using the relation (Poddar et al., 2021);

$$N = \frac{IN}{d_{net}} \quad (2.3)$$

The INT (irrigation interval), in days, is then estimated as follows;

$$INT = \frac{ND_c}{N} \quad (2.4)$$

Where:

INT = irrigation interval in days

NDc = total growing period of the crop (days)

N = number of irrigation.

ii. Water Balance Method

This approach is based on the statement of the law of conservation of mass. The accounting procedure of all inflows, outflows, and storages involved within the farm hydrologic boundary during a given period is carried out (Scherer & Steele, 2019). This method is simply expressed as follows;

$$\Delta S = I - O \quad (2.5)$$

Where:

I= sum of inflows (mm)

O= sum of outflows (mm)

ΔS = change in storage

In the evaluation of two irrigation scheduling methods, Poddar et al. (2018) carried out a study in the north-western mid-hills of India to optimize irrigation scheduling for potatoes as a water-saving strategy. Various irrigation-scheduling models, which are based on root water uptake and the concept of degree of growing days, were used. The results obtained from the use of the O-R model depicted lesser irrigation events with the root zone having optimum moisture availability and a water-saving of 28.6% was obtained compared to the soil water balance-based model. The O-R prediction model was employed in this study to schedule irrigation events and the method outlined above was used for comparison purposes.

2.6 Food Security in Kenya

In Kenya, the level of food insecurity is on the high despite various measures to combat it. Ndirangu et al. (2017) indicated that close to 25% of Kenya's population is undernourished with about 15% requiring emergency food relief annually. A study carried out on levels of food insecurity in rural households in Kitui, Kenya indicated that 60.3 percent of households depend on their farms as the main source of food. It also showed that households were severely food insecure and are faced with hunger given that the level of agricultural production in the area is low despite that farming is their main occupation (Ocharo, 2019). A combination of various

factors contributes to food insecurity in Kenya including climatic conditions, extreme changes in weather, natural resources management, and the accessibility to agriculture-related inputs that are appropriate. Water is the limiting factor for agricultural productivity; it limits crop production and livestock rearing in drier areas of the country (MoA, 2016)

The Ministry of Agriculture rolled out a National Potato Strategy 2016 to increase potato production to help in combating food insecurity in the country. This is through the development of climate-resilient potato varieties and the adoption of irrigation in drier areas (MOA, 2016). However, the over-reliance of farmers on rain-fed agriculture in many parts of the country has rendered them susceptible to climate shocks that have increased due to climate change (Gichovi, 2018). Due to periods of natural calamities such as COVID-19, and drought that left the nation dilapidated, urgent steps are necessary to increase food production and ensure food security for the country. These include the adoption of efficient agricultural practices that encompass more efficient irrigation systems that assure production in water-scarce environments.

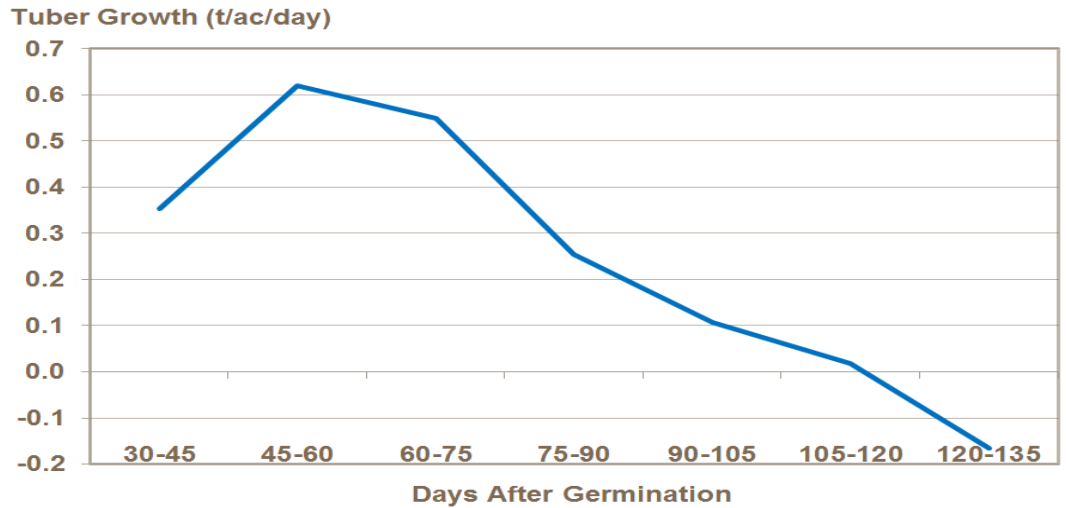
2.7 Potato Farming in Kenya

Irish potatoes are shrubby perennials with edible tubers. They are grown as cool-weather annuals in rows, raised beds, or containers. Potato is a cool-season vegetable that requires a sunny environment. It grows better in well-drained, medium-rich fertile soil with a pH range of 5.0 to 6.5. Cool temperatures and uniform soil moisture favour the growth of Irish Potatoes. There are five major traditional potato-growing regions in Kenya which are grouped based on geographic location, production practices, and various preferences. These areas include Mt. Kenya region, Aberdares and Rift Valley region, Mau region, Mt. Elgon region and Taita Hills (Muthoni et al., 2017). Increasing demand for potatoes has led to the expansion of potato production to areas like Kirinyaga, Naivasha, and Tana River. Other upcoming potato growing areas include Laikipia, Nyamira, Nandi, Baringo, and Kisii counties. This is mostly due to the availability of facilities for irrigation and sufficient conditions for potatoes to thrive (MOA, 2016).

Different varieties of potato are available, including many dozens grown widely by commercial farmers and home gardeners alike, with most lumped into groups based on tuber colour and starch content. Irish potatoes grown in Kenya are typically in the “white potato”, “red potato”, and “yellow potato” groups. The white potato group is characterized by light tan to cream-coloured skin and white flesh that has a waxy texture due to moderate to low amounts of starch.

Whereas the yellow potato group has yellow skin and a fairly good tolerance to heat, the red potato group is characterized by red skin and a late to medium maturity period. Some of the varieties grown include; potato cultivars Agria, Savalan, Satina, Caesar, Kennebec, Marfona, and Santé varieties (Hassanpanah, 2010). The Jalene Potato variety was released by the Holleta Agricultural Research Center in 2002. It is an early maturing variety (90-120 days) and grows well in areas with an altitude of 1600-2800 m above sea level and rainfall of 750-1000mm. Some of the potato varieties that are widely grown in Kenya include Shangri, Manitou, Sherehekea, Kenya mpya variety, Kenya karibu variety, Kenya mavuno potato variety, Nyota, Unica potato variety, Lenana, Tigoni potato variety, Wanjiku potato variety, and voyager among others (Waaswa et al., 2022).

Potatoes produce a fibrous root system. The roots are at their best no more than 60 cm deep. Hence potatoes have a shallow root system as compared to winter cereals, which can root at least 1000mm inches depth (MOA, 2016). As a result, potatoes normally utilize nutrients and soil moisture at 45 cm deep of the soil profile depth. The best and most active root development is at soil temperatures of about 20°C (Rykaczewska, 2015). The optimum temperatures for Leaf (haulm) and stolon growth are 25 °C (Steduto et al., 2012). Potato is highly sensitive to a deficit or excess water hence optimized supply of irrigation water is required for its proper growth (Poddar et al., 2021). Enough water is needed to be supplied in the period when there is the highest tuber growth to have enhanced crop yield and significant water savings can be realized after and/or before these periods (see Figure 2.2).



REF: Kolbe and Stephan-Beckmann - 1997

Figure 2.2: Relationship between potato tuber growth versus days of germination

According to Muthoni et al. (2017) the potato growth and development stages are broadly classified into four stages. The first stage is the vegetative (leafy) stage which involves establishment and stolon initiation. It takes approximately 30 to 70 days; the bigger plants indicate more yield. It requires warm conditions to thrive (27°C). Effective weeding at this stage is needed to enable the crop to develop healthy leaves and stems (Mugo et al., 2020). The second stage is tuber initiation and it is normally a two-week process but can take up to 20 days. In this stage, the number of tubers formed depends on hours of daylight, temperature, and available water in the period. Enough water application facilitates the production of more tubers. The critical growth period to avoid drought stress for potatoes is after the formation of tubers, from bloom to harvest. During this stage, 22.8 mm of total water application is mostly recommended. Proper hilling is necessary at this stage. The third stage is tuber bulking where tubers grow to larger sizes but do not increase in number. This stage takes 45 – 55 days (Ierna & Mauromicale, 2012). Adequate nutrients, enough water supplies and hilling are necessary at this stage. Effective hilling reduces exposure of the tuber to the surface, increases root aeration and contributes to the development of good-quality potatoes. The last stage as indicated by the Ministry of Agriculture (2016) is the ripening/maturity stage. This stage is characterized by canopy senescence; where the tops turn yellow and die the potatoes are ready for harvesting at this level.

2.8 Irrigation Control and Monitoring Systems

Water conservation in all uses is a growing area of concern in Kenya due to increased demands from a growing population. One of the areas of interest with great potential for reducing water consumption is residential outdoor water use, which includes water used for agriculture. Irrigation systems can use automation to help minimize water use losses by application of models that use weather data, soil moisture content, and plant-specific information to make informed irrigation application amount and timing decisions (Sample et al., 2016). Automated irrigation enhances an efficient and sound irrigation strategy that minimizes evaporation, runoff, deep percolation and leaching. An efficient irrigation system supplies the optimal amount of water directly to the plant roots to replenish root zone moisture before water stress adversely impacts the plant. (Sample et al., 2016). With the availability of irrigation control technology, water application efficiency in automated irrigation systems has improved significantly. The incorporation of soil moisture sensors (SMS) in particular, has led to a reduced number of unnecessary irrigation events (Cardenas et al., 2016).

2.8.1 Soil Moisture Monitoring

Soil Moisture Sensor (SMS) is a measuring device incorporated in an irrigation system that detects the amount of water at a given time in the active root zone before each scheduled irrigation. Soil moisture sensors measure plant-available water as a function of soil volumetric water content in real-time. They are normally placed in the plant root zone to monitor soil moisture content. A dry soil sample contains void spaces between the soil particles, a soil property known as porosity. As water infiltrates into the soil, these voids are filled. Some water drains through the voids due to the effects of gravity, but a portion remains held in the voids by forces exerted by the soil particles (Sample et al., 2016). Soil moisture sensors are designed to measure soil volumetric water content based on the soil bulk permittivity (dielectric constant) and osmotic pressure. The dielectric constant is the ability of soil to conduct electrical energy. The electrical conductivity of soil increases as the water content of the soil increases (Dukes et al., 2012). Soil moisture sensors have been applied in various areas as outlined by a sample of authors below.

Xie et al. (2020) carried out a study to investigate cassava production using drip irrigation systems controlled by soil moisture sensors. The study established that the SMS produced good

values of soil moisture content that were timely obtained and that were lower than the one predicted by the soil water balance method. The study also revealed that the use of SMS to monitor soil water content resulted in high water use efficiency and yield of cassava crops. The use of SMS in the production of potatoes has not been well utilized and researched in Njoro. This study will incorporate soil moisture sensors (SMS) to monitor soil water content in the potato root zone to increase water application efficiency of subsurface drip and help manage deficit irrigation.

2.9 Potato Crop Evapotranspiration

Potato evapotranspiration and water use have gained interest in research in various studies all over the world. The studies vary widely depending on the method of irrigation employed, irrigation events, technology, area climate, management options for fertilizer and other factors due to the local environment (Djaman et al., 2021). The crop water requirements for potatoes to give good yields of tubers are dependent on the local climate and soil type. As recorded by various studies, the water demand varies from the lowest of 316mm to 800mm. As indicated by Ortega et al. (2004) to ensure sustainable production, seasonal application of irrigation amount equated to a range of 0.85 to 0.97 of the considered maximum ET is necessary as well as taking into consideration the use of deficit irrigation. Parent and Anctil (2012) recorded seasonal ET for potatoes as 413.2 mm when using a drip system in loamy soil and evapotranspiration of 362.1 mm in clay soil in Valenzano, Italy. They also recorded that there was an average long-term evapotranspiration for rain-fed potatoes of 563.3 mm. Chen et al. (2019) recorded that the rainfed seasonal potato evapotranspiration in Gansu province in China, which is semiarid, was dependent on the conditions of the soil surface and ranged from 216.5 mm to 249.3 mm. However, this was relatively low when compared with findings from other studies. The determination of potato evapotranspiration requirement can be achieved through the method described below.

The reference evapotranspiration (ET_0) is calculated based on the FAO Penman-Monteith method Equation (FAO, 1998). The required climatic input parameters are monthly and ten-day maximum and minimum temperature, humidity, sunshine, and wind speed. Crop water requirements (ET_{crop}) throughout the growing season are then obtained from ET_0 and estimates of crop evaporation rates, expressed as crop coefficients (K_c), as given in Equation 2.6.

$$ET_C = K_C \times ET_0 \quad (2.6)$$

Penman-Monteith Equation (Sentelhas et al., 2010).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/T + 273)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2.7)$$

Where:

ET_0 = grass reference evapotranspiration in mm/day

Δ = saturated vapour pressure curve Slope (kPa °C⁻¹)

$$\Delta = \frac{4098 \left[0.6108 e^{\left(\frac{17.27T}{T+237.3} \right)} \right]}{(T + 237.3)^2} \quad (2.8)$$

R_n = net radiation (MJ m⁻² day⁻¹),

G = soil heat flux density (MJ m⁻²).

T = daily average of the maximum and minimum air temperature at 2 m (°C).

$$T = \frac{T_{MIN} + T_{MAX}}{2} \quad (2.9)$$

U_2 = wind speed at a height of 2 m above the ground surface (m/s)

$$U_2 = U_z \frac{4.87}{\ln(67.8z - 5.42)} \quad (2.10)$$

U_z = measured wind speed at z m above the ground surface (m/s)

z = height of measurement above the ground surface (m)

$$e_s = \frac{0.6108 \exp \left[\frac{17.27T_{max}}{T_{max} + 237.3} \right] + 0.6108 \exp \left[\frac{17.27T_{min}}{T_{min} + 237.3} \right]}{2} \quad (2.11)$$

e_a = the actual vapour pressure (kPa)

γ = the psychrometric constant (0.0677 kPa °C⁻¹).

When the CROPWAT model is used, the soil data input in this program includes information on the total available water content in the soil and for runoff estimates, the maximum infiltration rate. With the information on estimated rooting depth, a daily soil water balance is calculated, which predicts water content in the rooted soil through a water conservation equation, which takes into account the incoming and outgoing flow of water (Onyanha & Gachene, 2017).

2.10 AquaCrop Model

AquaCrop is a crop simulation model developed by the Land and Water Division of FAO to address food security and assess the effect of environment and management on crop production. It estimates the crop yield of herbaceous crops under water-limiting conditions (Sang et al., 2020). Its simplicity with low input parameter requirement and a sufficient degree of simulation accuracy makes it suitable for use in estimating crop productivity. On the other hand, the calculation procedures are grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system (FAO, 2018).

The AquaCrop model describes the interactions between the plant, and the soil together with the environment and the management practices. The plant extracts water and nutrients from the soil in the root zone, field management practices and soil fertility levels are considered as they affect the plant-soil interaction. The atmosphere interacts with the crop-soil system through the upper boundary, which is used to determine the evaporative demand (ET_0) and supplies CO_2 and energy for growth (solar). Water drains from the system to the subsoil and the groundwater table through the lower boundary. By capillary rise, the groundwater table if shallow enough can move upward to the system. This interaction is described in Figure 2.4 (FAO, 2017).

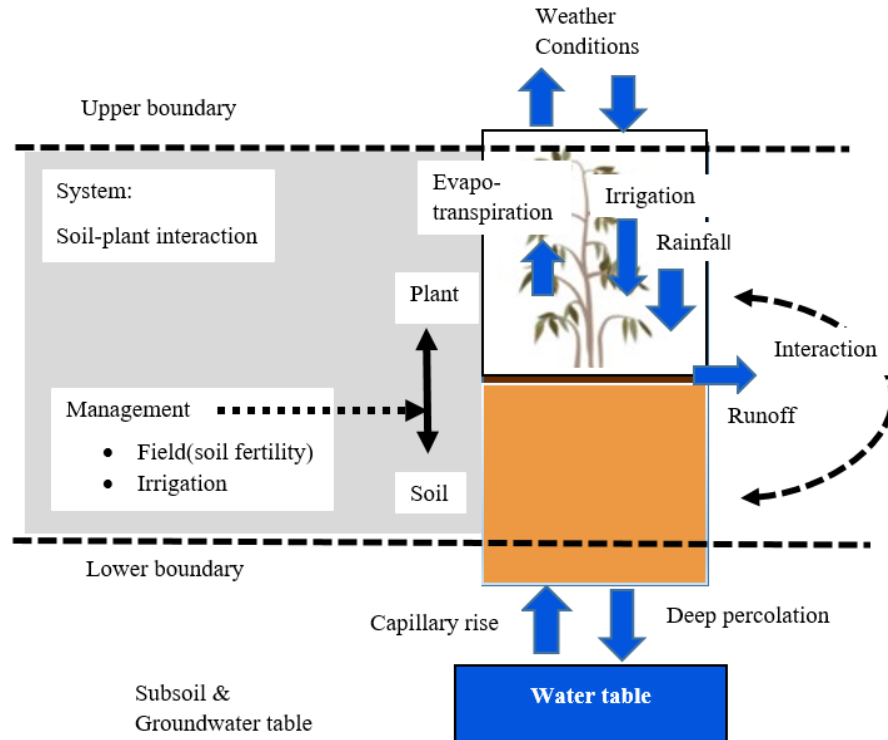


Figure 2.3: The Root zone-Crop-Environment interactions as described in AquaCrop

Source (FAO, 2017)

AquaCrop has a wide range of applications; it can be used as a planning tool and to assist in making management decisions for both irrigated and rain-fed agriculture. It is an educational tool for understanding crop responses to environmental change. The comparison of attainable and actual yields in fields, farms, and regions can be achieved through the use of the AquaCrop model. In the field, AquaCrop is used as a benchmarking tool to identify constraints to crop production and water productivity, in the development of irrigation schedules for maximum production such as seasonal strategies and operational decision-making, and for climate scenarios. In developing strategies for deficit irrigation and crop and management practices to maximize water productivity AquaCrop plays a vital role. It's also used in studying the effect of climate change on food production (for example by running AquaCrop with both historical and future weather conditions), supporting decision-making on water allocations and other water policies, and for planning purposes (Vanuytrecht et al., 2014; Steduto et al., 2012).

AquaCrop simulates the final crop yield in a series of four steps. The four steps are run in series for each daily time step and consist of the simulation of the development of the green Canopy Cover (CC), crop transpiration (T_r), above-ground biomass (B), and Crop Yield (Y) as described below.

2.10.1 Development of Green Canopy Cover

Canopy cover (CC), more precisely green canopy cover, is a crucial feature of AquaCrop. Its expansion, general growth, and senescence, along with its conductance as controlled by stomata, determine the amount of water transpired, which in turn determines the amount of biomass produced (Steduto et al., 2012). In AquaCrop, foliage development is expressed through green canopy cover (CC) rather than leaf area index. CC is the fraction of the soil surface covered by the canopy; it ranges from zero at sowing to a maximum value at mid-season as high as 1 when full canopy cover is reached. By adjusting the water content in the soil profile each day, AquaCrop keeps track of stresses that might develop in the root zone. Soil-water stress can affect the leaf and therefore canopy expansion; when severe it can trigger early canopy senescence (Vanuytrecht et al., 2014). Canopy cover (CC) is expressed by using Equation 2.11;

$$CC = CC_0 \times e^{CGC \times t} \quad (2.12)$$

Where:

CC = fractional coverage of the soil by the canopy at time t

CC_0 = initial CC (at $t = 0$) also infraction

CGC = canopy growth coefficient in fraction or percentage of existing CC at time t .

2.10.2 Above-Ground Biomass (B)

The quantity of aboveground biomass (B) produced is proportional to the cumulative amount of crop transpiration (ΣT_r); the proportional factor is known as biomass water productivity (WP). AquaCrop, WP is normalized for the effect of climatic conditions, making normalized biomass water productivity (WP^*) valid for diverse locations, seasons, and concentrations of carbon dioxide.

$$B = WP \times \sum T_r$$

(2.13)

The normalized biomass water productivity (WP^*) proved to be nearly constant for a given crop when mineral nutrients are not limiting, regardless of water stress except for extremely severe cases. Calibration of WP and normalization for evaporative demands is based on the equation:

$$WP^* = \left[\frac{B}{\sum \left(\frac{T_r}{ET_0} \right)} \right] \times [CO_2]$$

(2.14)

Where:

CO_2 = Carbon Dioxide concentration of the atmosphere and other parameters are as defined previously.

2.10.3 Crop Yield

The simulated above-ground biomass integrates all photosynthetic products assimilated by a crop during the season. Crop yield (Y) is obtained from B by using a harvest index, which is the fraction of B that is the harvestable product. The actual HI is obtained during simulation by adjusting the reference harvest index (HI_0) with an adjustment factor for stress effects using Equation 2.14 (Vanuytrecht et al., 2014).

$$Y = HI \times B$$

(2.15)

2.10.4 Yield Response to Water

FAO addressed the relationship between crop yield and water use in the late seventies proposing a simple equation where the relative yield reduction is related to the corresponding relative reduction in evapotranspiration (ET) expressed using a water production function (Smith & Kivumbi, 2002).

To quantify the effect of water stress on yield the relative yield decrease is related to the relative evapotranspiration deficit through an empirically derived yield response factor (K_Y) (Smith &

Kivumbi, 2002)). The yield response to ET is expressed using the water production function given by the Equation 2.15.

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right) \quad (2.16)$$

Where:

Y_a = actual yield (ton)

Y_x = maximum yield (ton)

ET_a = actual evapotranspiration (mm)

ET_x = maximum evapotranspiration (mm)

K_Y = yield response factor which is the effect of a reduction in evapotranspiration on yield losses

The K_Y values are crop specific and vary over the growing season according to growth stages and according to the value obtained it may imply the following; if K_Y is greater than 1, the crop is very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress. When K_Y is less than 1, the crop is more tolerant to water deficit meaning that it recovers partially from stress indicating less than proportional reductions in yield with reduced water supply. Finally, when K_Y is equal to one the yield reduction is directly proportional to reduced water used.

Based on the analysis of an extensive amount of the available literature on crop-yield and water relationships and deficit irrigation, crop coefficient, K_Y , values are derived for several crops are tabulated in the FAO website (Steduto et al., 2012). The yield response factor (K_Y) captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved. The relationship has shown a remarkable validity and allowed a workable procedure to quantify the effects of water deficits on yield (FAO, 2017; Steduto et al., 2012). The application of water production function to show the effect of irrigation water reduction on the yield was utilized with combination of other factors in evaluation of the optimum conditions for potato production in this study.

A number of studies applying the AquaCrop model have illustrated the essence of the tool in crop water requirement, biomass, and yield of potato prediction. As indicated by López-Urrea et

al. (2020), Tayade et al. (2018), Gebremedhin et al. (2015) and Razzaghi et al. (2017) AquaCrop model was suitable in simulating the potato growth, development, and yield at different irrigation treatments. This indicates the effectiveness of AquaCrop in the simulation of potato growth, biomass, and yield in different parts of the world. However, the application of the AquaCrop model has not been well utilized in potato farming in Kenya, although the tool has been used in other crops like tomato (Sang et al., 2020), cabbage (Kiptum et al., 2013), beans (Gichovi, 2018), and maize (Muigai, 2019). The suitability of the model in simulation of various growth parameters of potato is not well documented.

2.10.5 Limitations of AquaCrop Model

The AquaCrop model has a few limitations that include; it simulates daily biomass production and final crop yields for herbaceous crops with single growth cycles only, it is designed to predict crop yields at the single field scale (point simulations). The field is assumed uniform without spatial differences in crop development, transpiration, soil characteristics, or management. Only vertical incoming (rainfall, irrigation, and capillary rise) and outgoing (evaporation, transpiration, and deep percolation) water fluxes considered (De et al., 2009).

The above limitations can be managed by adapting the following mitigation measures that include; a single growth cycle of Irish potatoes considered, the experimental plot with uniform soil characteristics and the crop can be planted under a shade to ensure that the only measured ET supply is from irrigation.

2.10.6 Calibration and Validation of AquaCrop Model

The model requires to be calibrated when running simulations for a specific cultivar and in a specific environment. Parameters that need to be specified are specific for a given cultivar and therefore might be affected by field management practices, conditions in the soil profile, or the climate. Some of the parameters that need calibration include; calibration of crop response to soil fertility and crop response to soil salinity (Gichovi, 2018).

2.11 Literature Review Summary

Author	Treatment	Irrigation Method	Result	Gap
Gultekin et al.	100,85,70,55	& Surface drip	100 & 85% ETc	Subsurface drip

(2018)	40% ETc	irrigation	treatments	gave	irrigation and SAP
			good	quality	use on potato
			yield		
Ghazouani et al. (2019)	AquaCrop used to simulate biomass, tuber yield and water efficiency in potato production	Drip and sprinkler irrigation systems	and	Proved suitability simulating potato and yield	model in simulation the subsurface drip irrigation and SAP cases
Tayade et al. (2018)					
Starovoitova et al. (2019)	SAP and different potato cultivars yield	Rain		SAP use resulted in increased crop growth rate and yield	Water saving potential and effect on potato yield of combined SAP and subsurface irrigation

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was carried out in a polythene shade house at Egerton University's Tatton Agricultural Park (TAP) in Njoro Sub-county, Nakuru County, Kenya (see Figure 3.1). The Njoro Sub-county is approximately 780 km² in area at a distance of 200 km North West of Nairobi City and 18 km West South West of Nakuru City is located Njoro Town which is the headquarter of Njoro Sub-county and is at an average altitude of 2423 meters above sea level. Njoro lies between Latitudes 0° 15' 0 and 0° 42' 30 South and Longitudes 35° 45' 0 and 36° 10' 0 east (see Figure 3.1).

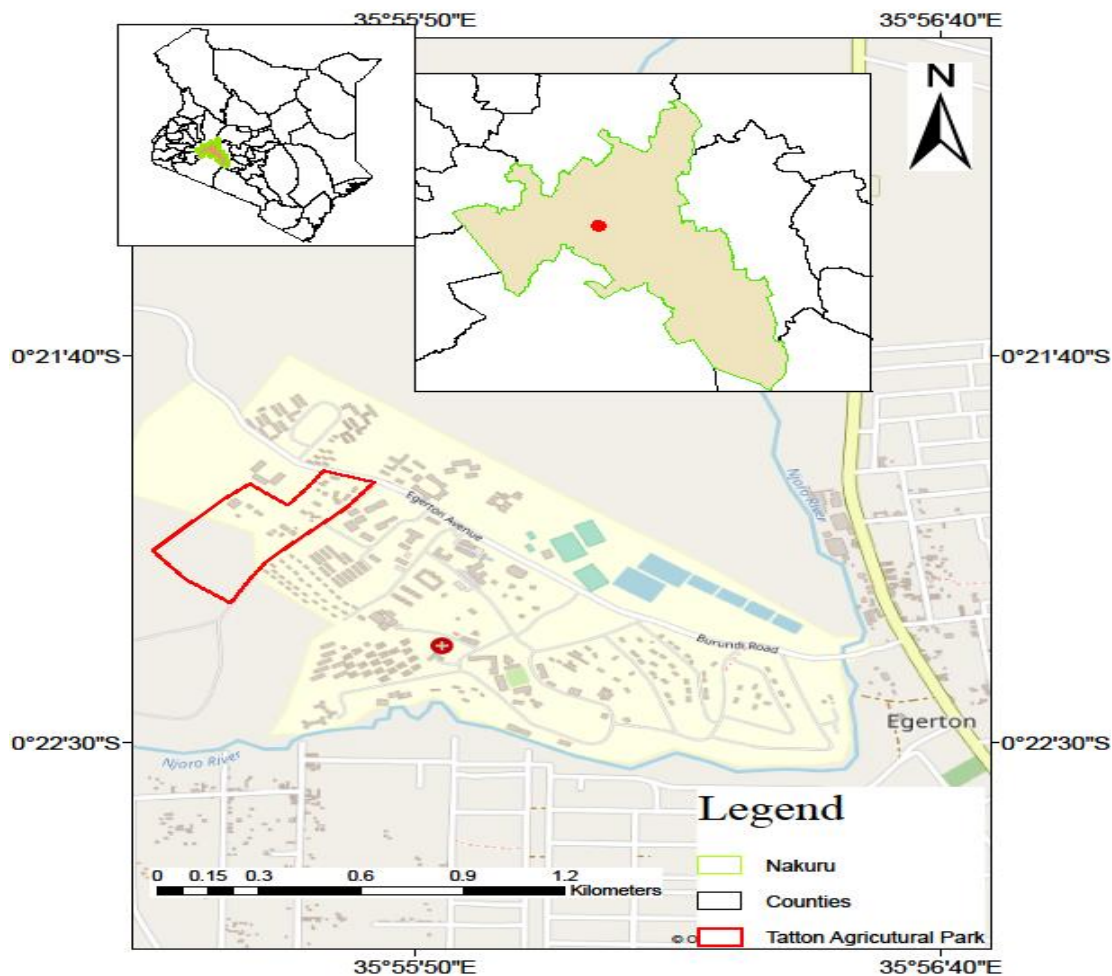


Figure 3.1: Map of Tatton Agricultural Park, Njoro Sub-County Kenya

The climate of the area is classified as warm and temperate. The mean annual precipitation as measured at Egerton University is 1073 mm. The least average rainfall of 20 mm occurs in January. Most of the rainfall is in April, averaging 140 mm. Trimodal rainfall pattern, which peaks in April, August, and November, is experienced in the study area. However, the rainfall pattern did not affect the experiment conducted in shade-house. It only applied to the rain-fed treatment. The average annual maximum and minimum temperatures for the area are 26.4°C and 7.8°C respectively (Sang et al., 2020).

Njoro sub-County exhibits various soil types that consist of erosive and lacustrine soils and loamy soils (Wambua et al., 2009). The drainage classes of the soil in the Njoro sub-county range from poorly drained, moderately well-drained, well-drained to excessively drained, with textures ranging from loam, clay to clay loam, and structures in the range of moderately strong to strong (Mainuri & Owino, 2013).

3.1.1 Experimental Design and Set-up

The shade-house field experiment was set up in a factorial experimental design consisting of twelve treatments (see Table 3.1) and three replications. The main factors were water application levels of 100%, 85%, 70 %, and SAP amounts of 0.6, 1.0, 1.4g/m² and No SAP. The factorial experimental design was employed in this study due to its ability to help in determining how water application level and SAP quantities individually affect yield, as well as show how the two interact when combined together. The treatment levels for SAP amount were based on the manufacturer specifications for row application of 0.8-1.0 g/m². Irrigation water was regulated by a soil moisture sensor-controlled drip irrigation system.

Table 3.1: Treatments, Irrigation levels and Polymer amount

Treatment Number	Irrigation level (%ETc)	SAP (Belsap) Amount (g/m ²)
T ₁	100	No SAP
T ₂	85	No SAP
T ₃	70	No SAP
T ₄	100	0.6
T ₅	85	0.6
T ₆	70	0.6

T ₇	100	1.0
T ₈	85	1.0
T ₉	70	1.0
T ₁₀	100	1.4
T ₁₁	85	1.4
T ₁₂	70	1.4

The experimental field was ploughed and the plots were laid as shown in Figure 3.2. Belsap polymer quantities of 0.6 g/m², 1.0 g/m², and 1.4 g/m² were applied per row for the specific plots as assigned in Table 3.2. The control experiment contained 100% irrigation level and 0 g/m² SAP.

Table 3.2: Allocation of treatments to plots

Plot 1 T ₃	Plot 2 T ₂	Plot 3 T ₁
Plot 4 T ₆	Plot 5 T ₅	Plot 6 T ₄
Plot 7 T ₉	Plot 8 T ₈	Plot 9 T ₇
Plot 10 T ₁₂	Plot 11 T ₁₁	Plot 12 T ₁₀
Plot 13 T ₃	Plot 14 T ₂	Plot 15 T ₁
Plot 16 T ₆	Plot 17 T ₅	Plot 18 T ₄
Plot 19 T ₉	Plot 20 T ₈	Plot 21 T ₇
Plot 22 T ₁₂	Plot 23 T ₁₁	Plot 24 T ₁₀
Plot 25 T ₃	Plot 26 T ₂	Plot 27 T ₁
Plot 28 T ₆	Plot 29 T ₅	Plot 30 T ₄
Plot 31 T ₉	Plot 32 T ₈	Plot 33 T ₇
Plot 34 T ₁₂	Plot 35 T ₁₁	Plot 36 T ₁₀

3.1.2 Layout of Field Plots

The study was carried out on 36 experimental plots that included control experiment and each of the plots was measuring 1.2 m by 3 m. The layout consisted of elevated Tank of 1000 litres capacity, mainline, sub-mainline, laterals and drippers. The source of water for irrigation was from the Egerton University water pan located at Biston and it was conveyed to the elevated tank through a network of pipes. The experimental set up for this research is as shown in Figure 3.2.

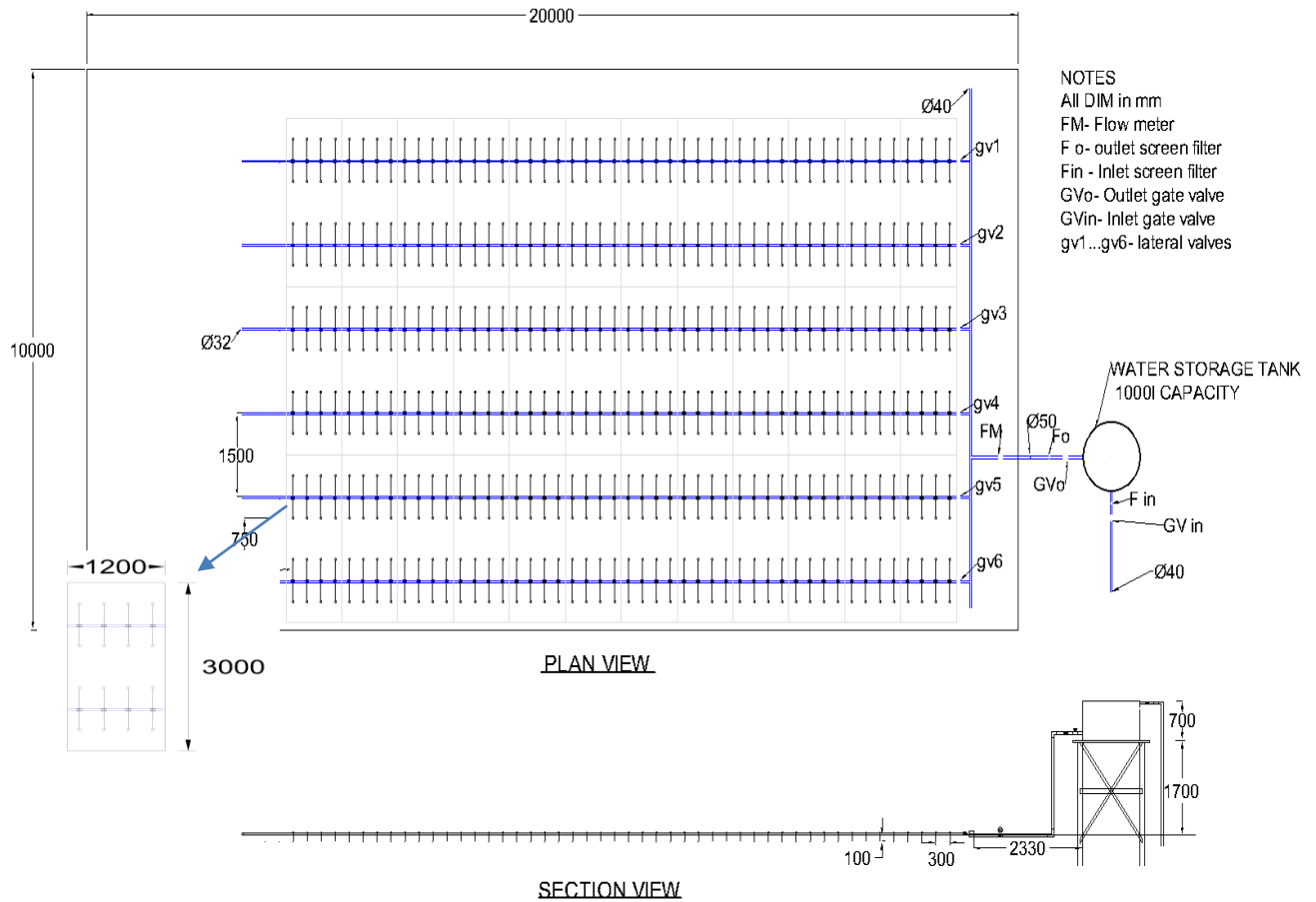


Figure 3.2: Experimental layout of plots and drip irrigation system

A HDPE pipe mainline of diameter 50mm, sub-main line of diameter 40 mm, and laterals of 32 mm in diameter composed the system. To ensure effective filtration, two disc filters were installed one at the inlet to the elevated tank and another at the tank outlet on the 50 mm mainline just after the gate valve (see Figure 3.2). Measurement of the amount of water supplied in to the drip system was achieved by a water flow meter that was installed at the main line after

the disc filter. Control valves were installed at each line to regulate and control the amount of irrigation water delivered through each line. For soil moisture measurements, a soil moisture sensor was used. The measurement of soil water content was carried out at the representative points that were selected for each plot to ensure efficient measurement of soil moisture. Water for crop growth was supplied to the potatoes via subsurface drip irrigation system through laterals running above the soil surface and emitters located below the soil surface at depth of planting (100 mm).

3.1.3 Land Preparation and Planting

The experimental site was thoroughly ploughed to remove weeds and to break soil for aeration. The land was split into plots measuring 1.2 m by 3 m, using a hoe, each plot was furrowed. Di-Ammonium Phosphate fertilizer was applied on the furrows at a rate of 500kg/ha (Nyongesa et al., 2008). On the rows of each plot, Belsap polymer was applied and thoroughly mixed with the 30 cm soil depth to achieve uniformity. Seed tubers of 24 to 45 mm diameter (egg sized) with 3 to 4 sprouts each were planted on the rows with 30 cm spacing (Iraboneye, 2021). Each seed tuber was supplied with one button dripper mounted at the end of a spaghetti tube placed at the depth of planting, 10cm (see Figure 3.3). The depth of dripper placement was selected based on the planting depth and the potato crop rooting depth of a maximum of 45cm. Ridging and weeding commenced 30 days after planting when the potatoes were above the soil (Nyongesa et al., 2021).

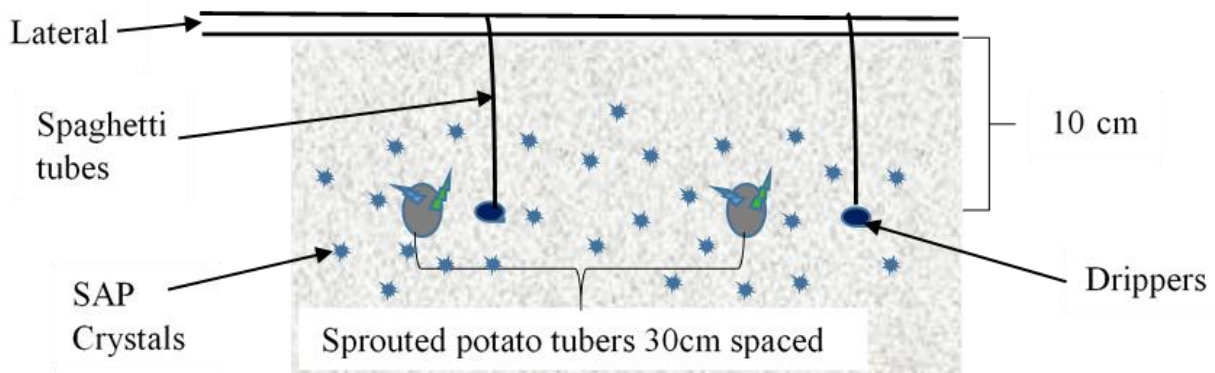


Figure 3.3: Depth of planting and subsurface drip installation below ground surface

3.2 Simulation of the crop water requirement, biomass production, water productivity, and yield of potatoes using the AquaCrop model.

The AquaCrop model version 6.0 was applied in simulation of the Irish potato production, canopy cover, and tuber yield, as an indicative measure of performance and water productivity. The input parameters needed for the simulation by the model were climate, crop, soil, irrigation and field management practices were collected and fed into the model as described in the following sections.

3.2.1 Crop data

Crop parameters required include planting date, maximum canopy cover (CC_x), the time to crop emergence, plant density, time to flowering, time to canopy senescence start, harvest index, time to maturity (crop cycle), and the maximum effective rooting depth and time to reach maximum root depth. This information formed the crop file in the AquaCrop model. The Irish potato tuber seeds were planted on the 28th December 2021 in rows. The spacing between rows was 75 centimetres and from one plant to the next plant within row spacing was 30 centimetres. The recommended plant density was approximated to 4.4 plants per square metre.

3.2.2 Climate Data

Climate data used in the model included temperature (T_{max} and T_{min}), rainfall, relative humidity, wind speed, and the number of sunshine hours of past years was retrieved from the Egerton weather station. From the given data, Reference evapotranspiration (ET_0) was calculated using CropWat software that is based on the Penman-Monteith method (Allen et al., 1998). Growing season rainfall, temperature, and the calculated reference evapotranspiration values were fed into the model to create the climate file.

3.2.3 Soil Data

The soil profile of the study site together with various soil parameters analysed created soil profile file menu in the AquaCrop program. The physical characteristics of the soil that includes bulk density, permanent wilting point, soil textural classes, and field capacity of the experimental field were analysed in the laboratory and the features obtained were input to the model. The groundwater table level in the area was taken to be much more than 4m below the root zone area to omit the effect of capillary rise (FAO, 2017).

Field test using Ksat constant head permeameter equipment was used to determine the hydraulic conductivity of the soil in the study site. The soil samples collected from various points on the study site were subjected to tests to determine soil texture, permanent wilting point, and field capacity. The pressure plate equipment was used to determine the field capacity (Cresswell et al., 2008) and at 15 bars tension and the soil permanent wilting point was obtained according to method stated by Romano and Santini (2002). The water content of the soil at a water potential of -1.5 MPa was taken as the permanent wilting point. Applying the method outlined by Gee and Or (2002) the soil texture analysis for the soil samples was carried out using the hydrometer equipment stated in Appendix I.

The bulk density of the soil was obtained by oven drying the soil samples at 105 °C and measuring the volume and mass of the oven dried sample Equation 3.1. The porosity of the soil was determined using Equation 3.2. This porosity was taken to be equivalent to the volumetric water content of the soil at saturation (Sang et al., 2020).

$$\rho_b = \frac{m_s}{v_s} \quad (3.1)$$

$$n = 1 - \frac{\rho_b}{\rho_p} \quad (3.2)$$

Where:

n = Porosity (ratio)

ρ_b = Bulk density (g/cm³)

ρ_p = Particle density (g/cm³)

m_s = mass of dry soil (g)

v_s = Volume of soil (cm³)

3.2.4 Field Management Practices

The management practices including the fertility level the soil, activities affecting the soil water balance, the irrigation method used, salinity of water used for irrigation, the time of irrigation events, and the application depth were established during the field study. The information on the use of mulch and other soil surface practices that affect surface runoff were input into the model to consist the management file in the model. Weed management with relative cover (RC) of the

weeds for the season set at 0% was used. Simulations were executed by setting the initial conditions per scenario and hitting the run button. The first simulation entailed the process of calibrating the model on which successive simulations were based. The successive simulations were conducted under different management scenarios by changing each of the initial conditions under evaluation and the days of growth as obtained from each treatment. The various management scenarios simulated include; full Irrigation Scenario and Conservation Agriculture Scenario. The full irrigation scenario included situation when there was no deficit application of water and conservation scenario encompassed simulation of yield under less water application than the quantity required by the crop.

3.2.5 Irrigation data

The irrigation file in the model was created by specifying the irrigation method used in the study (sub-surface drip) and the irrigation events. The amount of water applied and the day per irrigation schedule composed the irrigation events. The various irrigation events applied in this study are shown in the Appendix III.

3.2.6 Model Calibration and Validation

Part of the field collected data were used for model calibration while the remaining data was used in validation of the model. The data obtained from 100% ET_C and no SAP was used for model calibration.

The observed climate data, soil data, crop data, irrigation and observed tuber yield and canopy development data were fed into the model and respective parameters were adjusted so that the predictions were as close to observed values as possible. In validation of the model, the recorded field data, which included green canopy cover, aboveground biomass and soil water content, were also fed into the model to create the field data file. From the simulation process, the output files were crop development, tuber yield, soil water balance, irrigation requirement, biomass, and water productivity. The model performance and accuracy in simulation of Irish potato canopy cover, above ground biomass and tuber yield was executed using equations 3.10, 3.11 and 3.12.

3.3 Assess the interactive effect of deficit subsurface drip irrigation and super absorbent polymer on yield of potatoes.

Belsap polymer was used in this study because it is capable of extending time between irrigations, reduce soil compaction giving space for more tubers to develop and improve fertilizer

and water absorption efficiency. Belsap unlike other polymers is a water saving polymer, which has a capacity to absorb water and release later when needed by the crop. Potato tuber yield was determined from the total tuber mass of potatoes obtained for a given treatment per unit area of the plot. This was calculated using Equation 3.3.

$$Y_T = \frac{M_T}{A_P} \quad (3.3)$$

Where:

Y_T = the tuber yield of potatoes per treatment (t/ha)

M_T = total tuber mass per treatment (ton)

A_P = area of plot per treatment (ha)

3.3.1 Determination of Crop Water Requirement (ET_C)

The crop water requirement was estimated from multiplying the crop coefficient with reference evapotranspiration based on Equation 3.4.

$$ET_C = K_C \times ET_0 \quad (3.4)$$

Where:

ET_C = Potato Crop evapotranspiration (mm day^{-1})

ET_0 = Reference evapotranspiration (mm day^{-1})

K_C = potato crop coefficient (dimensionless)

The ET_0 was determined using FAO Penman-Monteith method (Equation 2.7). The potato crop coefficient factors for the season were adopted from FAO as shown in Table 3.3 (Badr et al., 2012).

Table 3.3: Potato crop coefficients

Growth stage	Period of application (days)	Kc Factor
Initial	25	0.5

Developmental	30	0.65
Middle	45	1.15
Tuber Maturity	30	0.75

The daily ET_0 was determined from the daily weather data for various climatic parameters measured at the Egerton University weather station. The monthly reference evapotranspiration was calculated by obtaining the averages of daily reference ET. The data used ET_0 estimations fell in the record period of January 2021 to April 2022. The ET_0 values obtained are as indicated in Appendix III.

3.3.2 Irrigation Scheduling

The O-R model was used to predict root water uptake and moisture status at the root depth of interest (Poddar et al., 2021) given by the Equations 3.5 & 3.6.

$$S_{\max} = \alpha \left[1 - \left(\frac{z}{z_{rj}} \right) \right]^\beta \quad 0 \leq z \leq z_{rj} \quad (3.5)$$

Where:

α, β are model parameters (dimensionless)

z = depth below the soil surface (m)

Z_{rj} = depth of the root on a j^{th} day, (m)

At $z = z_{rj}$, S_{\max} is zero from Equation (3.5). S_{\max} needs to satisfy the equation:

$$\int_0^{z_{rj}} S_{\max} dz = T_j \quad (3.6)$$

Where:

T_j (LT^{-1}) represents transpiration on a j^{th} day.

The soil moisture sensors were used for constant monitoring of the water content in the crop root zone. The crops were irrigated once allowable depletion of 50% of the available water was reached. The quantity of water irrigated was controlled by the treatment allocated to the plots according to Equation 3.7.

$$I_A = ET_C \times I_L \quad (3.7)$$

Where:

I_A = Irrigation water applied (mm/day)

ET_C = Crop evapotranspiration (mm/day)

I_L = Irrigation level %

The quantity of water scheduled for application was calculated by Penman Monteith equation (Equation 2.6). The actual amount of water applied per schedule was dependent on the soil moisture measurements. At the beginning of the potato growing season, the soil moisture content as determined using gravimetric moisture method was 20% of the field capacity. This implied that in the first irrigation water application, enough water was used to ensure the root zone was at field capacity in all the plots. The numbers of total events of irrigation water application were 23. The quantity of irrigation water applied per schedule for the whole growth cycle was recorded for every plot as shown in Appendix II.

Upon maturity, potato tubers were harvested. The number of tubers per plant, weight of tubers per class as sorted, weight of tubers from each plot and treatment, area of each plot and number of plants producing significant tubers from each plot recorded. The yield and yield components as affected by each treatment were calculated, recorded and exported for analysis using RStudio program. From the analysis, the effect of SAP and water level on yield was determined. The response of yield because of crop evapotranspiration supplied for each treatment was then evaluated by the water production function given by Equation 3.8.

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right) \quad (3.8)$$

Where:

Y_a = actual yield (kg)

Y_x = maximum yields (kg)

ET_x = maximum evapotranspiration (mm/day)

ET_a = actual evapotranspiration (mm/day)

K_Y = Crop yield factor (dimensionless)

3.4 Evaluation of water productivity for optimum potato production under D-SDI and Super Absorbent Polymer.

Potato water productivity was calculated from the tuber produced obtained the unit of water applied for the whole growth cycle. This was calculated using Equation 3.9.

$$WP = \frac{Y_T}{\sum ET_C} \quad (3.9)$$

Where:

WP = Water productivity (kg/m^3)

Y_T = total tuber yield of potatoes (kg/m^2)

$\sum ET_C$ = total water used to produce the potato tubers (m^3/m^2)

The data on tuber yield, total water applied per irrigation level and the water productivity for each of the treatment were analyzed for variance. The total quantity of water irrigated in relation to tuber yield in ton per hectare was selected to express production functions through multiple linear regression analysis. The specific crop parameter response to irrigation level applied was analysed. The treatment producing the best performance on the various crop parameters and the one with best results from the production function was identified as the optimum condition for potato production at Egerton Njoro.

3.5 Data collection

3.5.1 Canopy cover

The Irish potato CC was estimated by utilizing a method outlined by Wilson (2011) of a meter stick that was carried out between 30 minutes to midday and 30 minutes past noon every 5 days beginning from the day of crop emergence. Three randomly selected points at every plot were marked for measurement. A tape measure was placed on the flat ground and rotated at angles of 45, 90 and 135 while taking sum of canopy shade centimetres covered on the tape as percentage canopy cover (percentage CC). To obtain the percentage CC at a given point an average of at least five readings was determined. The percentage canopy covers from the three points were averaged to obtain the canopy cover for the plot.

3.5.2 Aboveground Biomass (AGB)

The aboveground biomass of potatoes was determined at the crop maturity by drying a sample of the selected plant green matter in the oven for a period of 72 hours at maintained temperature of 60°C. A digital weighing balance was used to weigh the dry sample weight to 0.5 grams precision. The conversion of the units obtained for biomass from grams per square meter to tons per hectare for the cropping density of 44,444 plants ha⁻¹ was done.

3.5.3 Tuber Yield parameters

The yield of potato tubers estimated by harvesting all the tubers from each plant that physically grew to maturity. All the tubers produced were counted in each plant and their weights were determined. The tubers obtained from each plant were sorted to different sizes as per classification by Aliche et al. (2019) in terms of gauge (nominal diameter). The tuber gauge sizes were beyond 60mm, 28mm to 60mm and less than 28mm; these were classified as ware, seed and chatts respectively. The numbers obtained per class (ware, seed and chatts) and the relative percent of the chatts by mass obtained were recorded. The total weight of tubers per plot were determined by obtaining the sum total of tuber weight per plant. The weights obtained were averaged for every treatment and the total wet yields calculated in tons per hectare. The marketable yield from each treatment was determined by obtaining the wet yield of tubers less chatts.

The dry yield of tubers harvested was obtained by chopping tubers from selected plants into small pieces and drying them in an oven for 24hours at 105°C temperature, then measuring the weights on a digital balance. The measured weights were extrapolated to dry yield in tonha⁻¹ using Equation 3.3.

3.5.4 Water productivity (WP)

WP is the measure of performance of agricultural practice. It is expressed as a ratio of total potato tuber yield (agricultural benefit) to the total amount of water supplied (see Equation 3.9).

3.5.5 Harvest index (HI)

This is an indicator used to measure the reproductive efficiency of a crop. For the case of Irish potatoes, the ratio of harvested tubers to whole plant weight as a percentage and it is as expressed using Equation 3.10.

$$HI = \frac{Y}{B} \quad (3.10)$$

Where:

Y = weight of potato tuber yield

B = weight of potato crop biomass (harvested tubers, plant stem and leaves)

3.6 Statistical Data Analysis

The simulated and observed potato yield, canopy cover, biomass and water productivity were subjected to analysis of variance using RStudio and R-programming software and performance evaluation to establish the goodness of fit. The ANOVA was used to determine the sources of difference in the means and the level of significance of the interactive effect of the subsurface irrigation levels and SAP amount on the yield of potatoes and the post hoc test to determine sources of differences in the means was performed using LSD (Least Significant Difference) at $P \leq 0.05$.

Testing assumptions under repeated measures ANOVA normality assumption that the data had normal distribution for each irrigation level and SAP quantity points, Shapiro test was conducted to test the null hypothesis that the data was normally distributed. For normal distribution, the data produced p-value greater than 0.05. The data grouped in two different ways produced the following distribution. Grouping the data in terms of SAP amount applied for the total yield obtained. A P-value greater than 0.05 indicating a normal data distribution. Grouping the data by irrigation level and total yield, a null hypothesis of normal data distribution was held with all the values being greater than 0.05.

The performance of the AquaCrop model was analysed by determining the correlation between actual and simulated values using the Root Mean Square Error (RMSE), the Nash –Sutcliffe Efficiency (NSE), and coefficient of determination (R^2) as described in the following sub-sections.

3.6.1 Nash –Sutcliffe Efficiency (NSE)

NSE was used to determine the relative magnitude of the residual in relation to measured data variance. Acceptable values of NSE are between 0.0 to 1.0, values less than zero indicate

unacceptable model performance (Muigai, 2018). The Nash and Sutcliffe Efficiency is given by Equation 3.11.

$$NSE = 1 - \frac{\sum_{i=1}^N (O_i - S_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (3.11)$$

Where:

S_i = the simulated values

O_i = observed (measured) values

\bar{O} = mean value of the sum of observed values

N = the number of observations.

3.6.2 Root Mean Square Error (RMSE)

This is a statistical indicator measuring the difference in means between observed values and simulated values and is expressed in Equation 3.12. A good model performance value is closer to zero whereas poor values tends to positive infinity (Tayade et al., 2018).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (3.12)$$

Where:

P_i = Predicted values

O_i = Observed values, and

n = Number of observations.

3.6.3 Coefficient of Determination, R^2

R^2 was used to measure the variance proportion in the data simulated using the model. It ranges from 0 to 1, values closer to 1 indicating a better model performance (Guo et al., 2020). It is given by Equation 3.13.

$$R^2 = \left[\frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})^2}{\sum_{i=1}^n (O_i - \bar{O}) \sum_{i=1}^n (P_i - \bar{P})^2} \right] \quad (3.13)$$

Where:

\bar{P} = Mean value of P_i , O_i & \bar{O} are as earlier defined in 3.11.

3.7 Sensitivity Analysis Using AquaCrop Model

Sensitivity analysis is measure that quantifies the impact of changes of input variables on the outcome of target variables (Guo et al., 2020). In this study, sensitivity measure was applied to determine the impact of the irrigation water level and super absorbent polymer amount yield, biomass production and harvest index of Irish potatoes.

A sensitivity analysis was developed according to Geerts et al. (2009) by changing crop, soil, and climatic inputs by about 25% in order to evaluate the robustness of the AquaCrop model for potato and the necessary quality of the input data. In the analysis, five primary soil physical characteristics (Ksat, SWC at FC, SWC at PWP, starting SWC, and REW), rainfall, and ET_0 were taken into account. With the exception of the parameter under review, simulations were ran for each change in input for each of the eight calibration field conditions using the calibrated crop file and the accompanying soil and climate data. The assessment took into account both the absolute and relative differences between simulated versions of Biomass and Yield.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Simulation of water productivity of potatoes

The simulation of the water productivity required the following subsequent data on soil characterization and crop-water requirements to guide on the irrigation scheduling.

4.1.1 Soil characterization of study site

The composition of various minerals in the soil was found to consist of 31% sand, 25.6% clay, and 43.4% silt. The soil was classified as clay loam based on this textural analysis results (Jensen et al., 2017). The soil bulk density was determined to be 1.38g/cm³ (see Table 4.1). Further analysis of soil samples collected at various soil layers up to 1 m depth indicated that the physical properties of the soil did not change with depth. In model simulations, a uniform soil profile was therefore used.

Table 4.1: Soil physical Properties of the study Field

Texture Analysis			Textural class	Bulk Density	Hydraulic Conductivity (m/day)	Volumetric water content at			
Sand %	Silt %	Clay %				Soil salinity (dS/m)	F C (%)	PWP (%)	Soil salinity (dS/m)
31	25.6	43.4	Clay loam	1.38	12.4	47	37	14	1.28

4.1.2 Irish potato Evapotranspiration requirement

The variation of the average recorded weather parameter values and the calculated reference evapotranspiration for the period November 2021 to June 2022 is presented (see Figure 4.1). The reference evapotranspiration (ET₀) was estimated using the FAO Penman Monteith equation (see Equations 2.6 to 2.10).

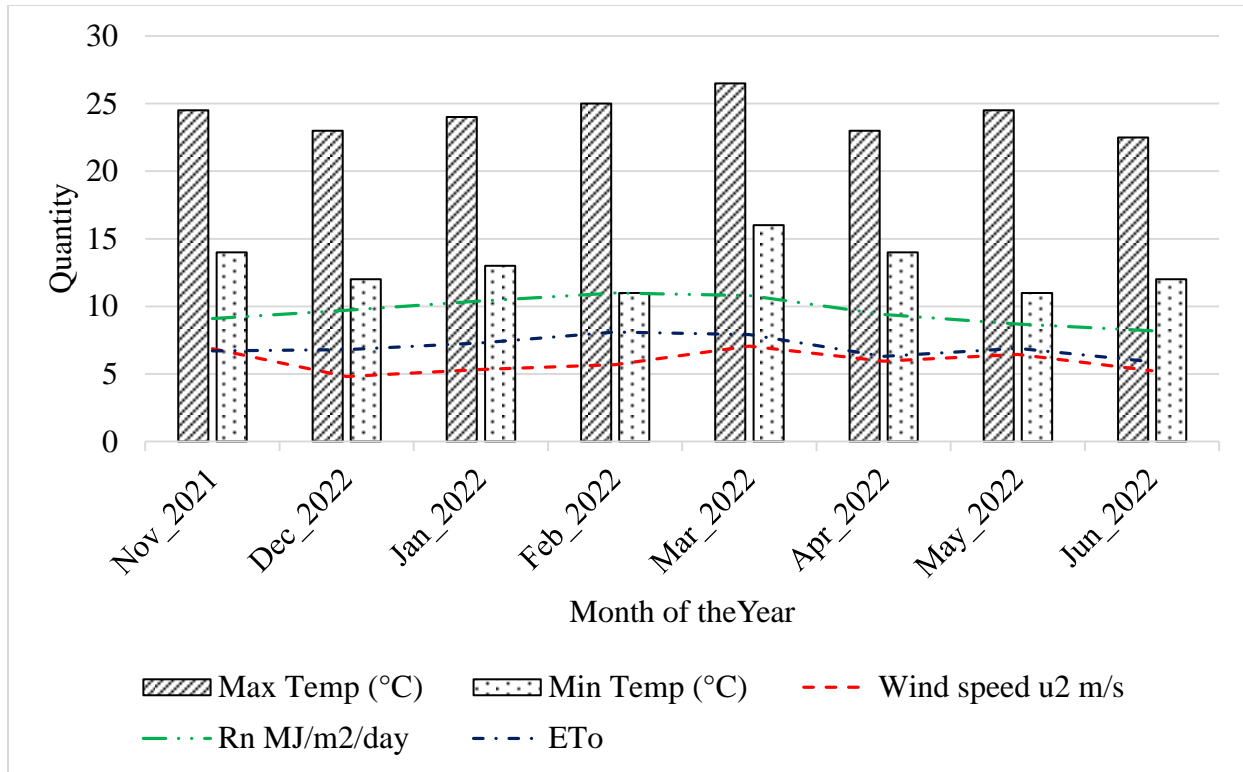


Figure 4.1: Average weather parameters variations for the growth period as recorded at the Department of Agricultural Engineering Weather Station

The highest reference evapotranspiration estimated was in February 2022 whereas the lowest was in the month of June same year (see Figure 4.1). This finding agrees with that of Sang et al. (2020) who obtained highest ET_C in the month of February and lowest in June. The high ET_0 attributed to high temperatures from dry periods mostly experienced in Nakuru County and the larger rift valley between November 2021 and February 2022.

The crop water requirement of Irish potato for Njoro sub-county was determined using Equation 2.6 that utilizes the estimated ET_0 and the Irish potato crop coefficients (see Table 3.3). The Irish potato crop coefficients used to determine the water requirement of potato were adopted from the Food and Agricultural Organization (FAO, 2022). The results for the crop water requirement calculated for the growth period is summarized in the Appendix III together with the actual amount applied by the subsurface drip system per irrigation event. The total amount of water applied per irrigation level for the whole growth period were 338 mm, 286 mm and 236 mm for 100%, 85%, and 70% respectively.

4.1.3 Irrigation

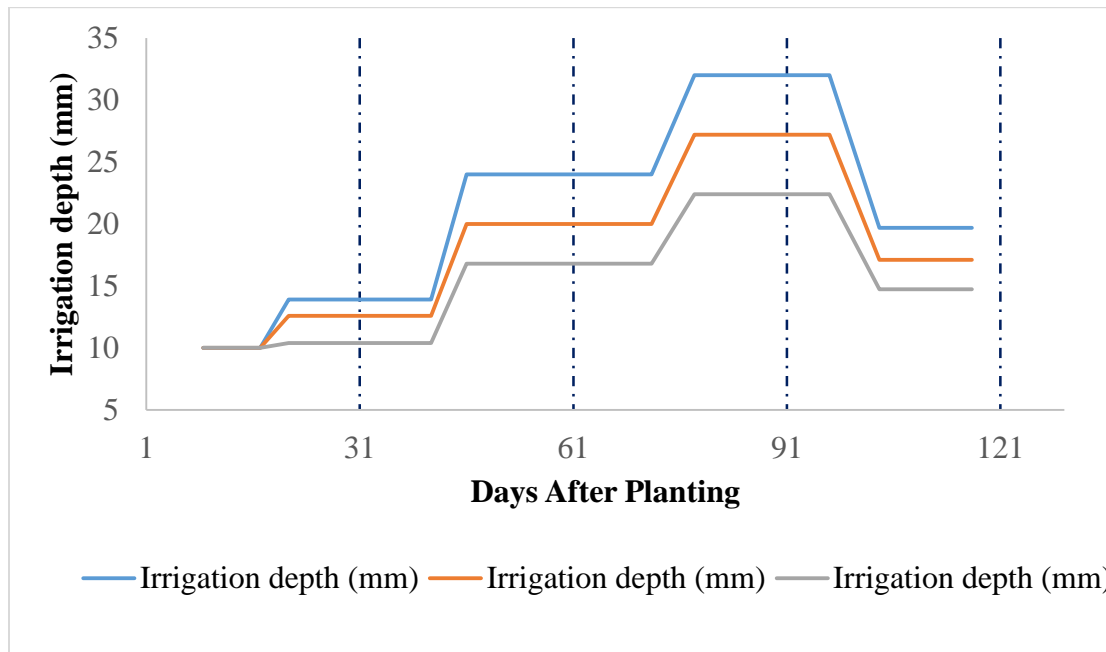


Figure 4.2: The evapotranspiration water requirement applied at each growth stage.

From the study four Irish potato growth stages were considered in this study and that each stage of growth took approximately one month. The development stages were as follows, initial stage that was from day one to day thirty after planting, tuber initiation and developmental stage followed from day thirty-one to sixty, tuber bulking from sixty-one to ninety and the tuber maturation from ninety-one to harvesting date. More water was applied during the tuber initiation and tuber bulking stages to ensure high yields (see Figure 4.2). Given that the crop had not emerged and water needs were only for sprouting purposes, the least evapotranspiration water was applied in the initial stage. The amount of water needed at tuber maturation phase reduced because more water application could not increase the yield further and can be considered to be water wastage. This is as reported by Wagg et al. (2021) that excess water application at tuber maturation stage has no-significant effect on the overall tuber yield.

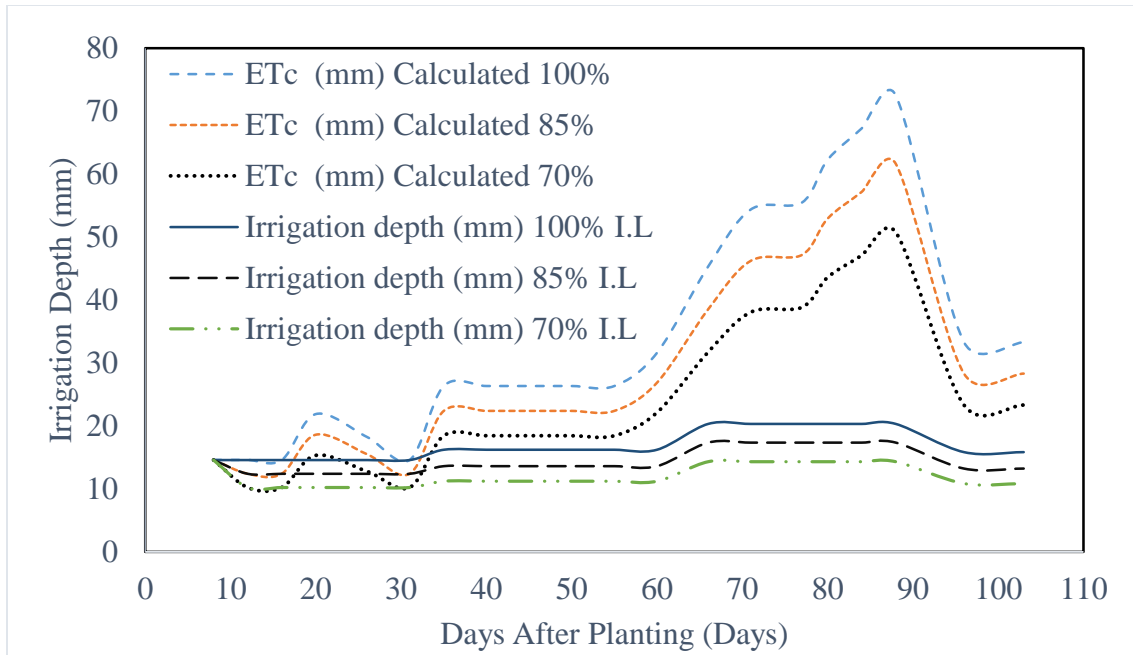


Figure 4.3: Comparison of the ET_C calculated using Penman Monteith method and the actual amount of water applied by SSD irrigation as monitored by the soil moisture sensor.

The amount of water estimated and irrigation depth varied throughout the potato crop development (see Figure 4.3). This was due to the variation of weather parameters recorded at each day. From the calculated ET_C it was observed that at 70 and 90 days after planting extreme water requirement values were obtained. This was because at the period commencing from day 70 after planting marked start of tuber bulking phase that requires more water for large and quality potato tubers. The estimated irrigation application at all crop development stages was higher than the amount applied by the irrigation system (see Figure 4.3). The water requirement calculator also indicated that the initial/ germination stage consumed less water as compared to other crop growth stage. The higher water requirement in potato growth cycle was calculated as the crop growth advanced to other stages including tuber initiation, tuber bulking, and maturity stages.

The use of subsurface drip system contributed to more water saving and the soil-water-crop interaction brought the disparity between the actual amount applied and the calculated (see Figure 4.3). There were no evaporation water losses from the free soil surface. In addition, approximately 39% of irrigation water was conserved in this study from 70% of CWR water

application using subsurface drip system and use of SAP. This finding concurs Martinez and Reza (2014) that the use of subsurface drip irrigation leads to increased water use efficiency.

The available soil water content dictated the frequency of irrigation. The variation of soil water content throughout the irrigation period is presented (see Figure 4.4). The lowest allowed soil water content before irrigation water was applied at 50% of the field capacity of the soil.

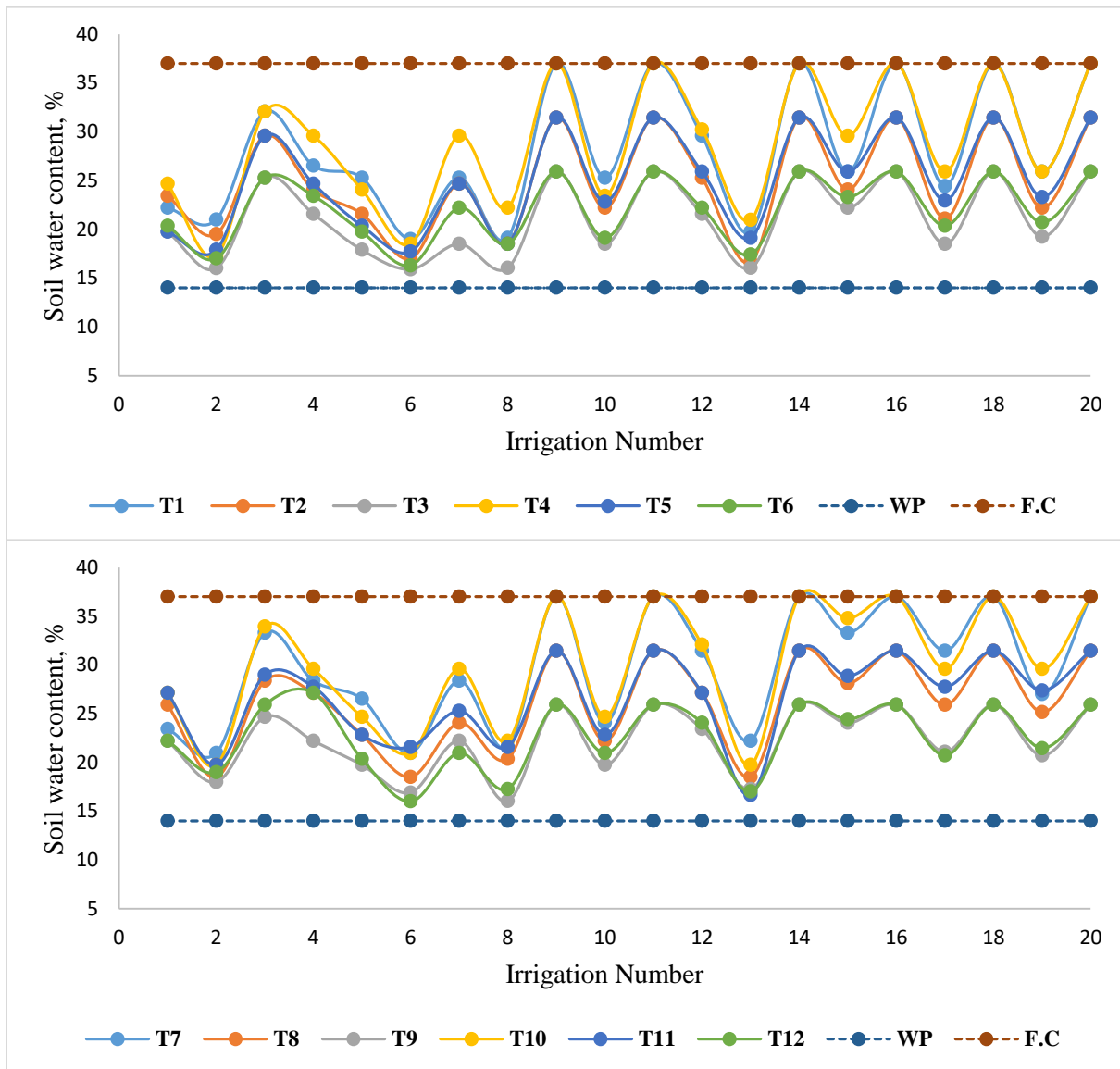


Figure 4.4: The soil water condition for T1 to T6 (A) and T7 to T12 (B) during growth period (2021/2022)

The water content in the soil did not drop below wilting point during the growth of potatoes for all the treatments (see Figure 4.4). In addition, the soil water content was at field capacity for every irrigation event for 100% irrigation level treatments of T1, T4, T7 and T10. The amount of moisture available in the soil varied per treatment depending on the level of irrigation and the amount of superabsorbent polymer that was applied. There were some differences in moisture content behaviour in the soil. From the graph, the difference is not quite significant for the initial irrigation events. However, in the later stages the irrigation events as from 15th irrigation event onwards showed significantly higher water contents for B than A. Given that for 70% irrigation level, SAP levels of 0kg/ha, 6kg/ha, 10kg/ha and 14kg/ha were applied on plots with treatments T3, T6, T9, and T12 respectively. A similar trend was observed in 85% and 100% irrigation level. The results agree with Islam et al. (2011) and Wu et al. (2021) whose results showed that super absorbent polymers can enhance the regularity of water distribution in the soil as well as its workability and compatibility within a suitable adding content. Islam et al. (2011) and Wu et al. (2021) agree that the use of superabsorbent polymer leads to increased water use efficiency and presence of moisture for long periods after irrigation even in moisture deficit environments.

4.1.4 Data Requirements for Simulation

The soil textural class, bulk density, hydraulic conductivity, saturation volumetric water content of the soil, permanent wilting point, field capacity, and the soil salinity measured for the study site were employed in creating the soil file in the model. Table 4.1 shows the soil properties that were measured at the study site. The soils in the study site were analysed in the Soil laboratories in the Agricultural Engineering and Crops, Horticulture and Soil Departments of Egerton University. The soil classification was clay loam and 1.28 d S/m as the soil salinity. The soil file created from the information in Table 4.1 was used in running the model for all other simulations.

The climatic parameters; maximum temperature, minimum temperature, reference evapotranspiration and wind speed that were used during the growth period (December 2021 to April 2022) of Irish potatoes are as presented in the Table 4.2.

Table 4.2: Mean Monthly Climatic parameters

Month	Tmax (°C)	Tmin (°C)	Solar Rad (MJ/m ² /day)	Wind speed at 2 m (m/s)	ET ₀ (mm/day)
Dec-21	23	12	9.7	4.80	6.76
Jan-22	24	13	10.4	5.32	7.29
Feb-22	25	11	11.0	5.69	8.10
Mar-22	26.5	16	10.8	7.05	7.88
Apr-22	23	14	9.4	5.94	6.34

The weather parameters were input into the AquaCrop model create the climate input file. The various climatic parameters were measured and recorded at the Egerton university weather station number 9035092 (see Table 4.2).

The planting date, plant density, time to crop emergence, time to maximum canopy cover achieved in the growing season, time up to flowering, period to canopy senescence start, time to crop maturity, harvest index, the highest effective depth of roots and time taken to reach maximum depth for the roots were collected during the site experiments (see Table 4.3).

Table 4.3: Irish Potato crop growth parameters used to calibrate AquaCrop model

Parameter Description	Quantity	Unit
Initial canopy cover (CC ₀)	0.13	%
Plant density	4.4	No. of plants per m ²
Canopy development		
Crop Emergence	21	Days
Max. canopy cover (CC _{max})	95	%
Max. canopy time	75	Days
Flowering time	79	Days
Time to Senescence	105	Days
Time to full grown	128	Days
Root deepening		
Maximum rooting depth	0.45	m
Time to reach max root depth	77	Days

The data from the control treatment, which contained 100% irrigation level applied through subsurface irrigation method with No Belsap superabsorbent polymer used in the soil. This crop data was used to calibrate the AquaCrop model for the other treatment-simulations (see Table 4.4).

Table 4.4: Potato Crop Data Used in Modelling

Parameter												
Description	T₁	T₂	T₃	T₄	T₅	T₆	T₇	T₈	T₉	T₁₀	T₁₁	T₁₂
Planting Date	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021	28-12-2021
Initial canopy cover (CCo)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Plant density	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Crop Emergence	21	21	21	21	21	21	21	21	21	21	21	21
Maximum canopy cover (CCx)	100	100	100	100	100	100	100	100	100	100	100	100
Time to Max. canopy	86	72	68	80	77	74	77	66	67	80	65	72
Time to flowering	77	63	65	71	70	68	71	59	60	75	59	68
Senescence	105	100	100	104	105	100	100	101	102	105	100	105
Maturity	128	128	128	128	128	128	128	128	128	128	128	128
Maximum rooting depth	0.45	0.44	0.42	0.4	0.41	0.39	0.37	0.38	0.36	0.31	0.3	0.3
Time to reach max root depth	77	65	68	75	72	70	73	65	68	72	64	69
Water productivity normalized for	17	17	17	17	17	17	17	17	17	17	17	17

climate and CO2

Reference harvest
Index

50 50 50 50 50 50 50 50 50 50 50 50

4.1.5 Simulation of Irish Potato Canopy Cover

The canopy cover change with days of growth as measured is indicated in the Figure 4.5. The maximum canopy cover (CC_x) of 100% was achieved at the tuber initiation growth stage.

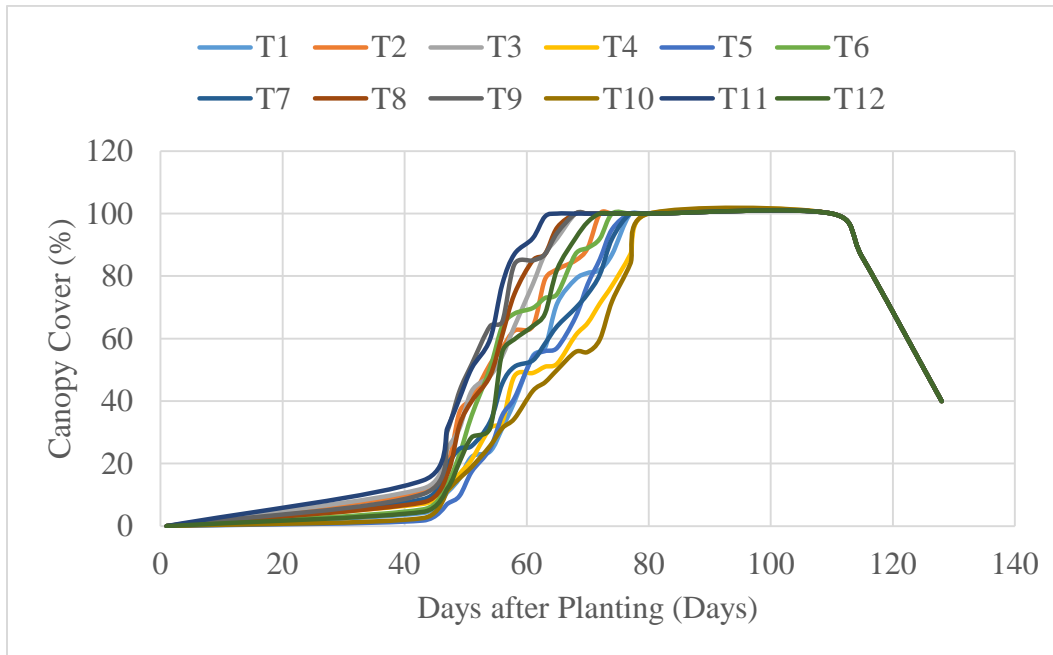


Figure 4.5: Actual Potato Canopy Cover measured Days after planting

The average time to crop emergence was 21 days. The crop began producing significant canopy cover and above ground biomass after 43 days after planting. The average period to reach maximum canopy cover was found to be 77 days. This is the time that was used in AquaCrop model Canopy cover simulations. Crop senescence began 110 days after planting. The Irish potato reached maturity and was harvested on 128th day (see Figure 4.5).

The model simulated canopy cover by producing Pearson's coefficient of correlation (R^2) values ranging from 0.86 to 0.98. The Root Mean Square Error (RMSE) values were between 7.7 and 10.6 %CC, whereas Normalized Root Mean Square Error (NRMSE) ranging 12.4% to 20.3%. The Nash & Sutcliffe Efficiency (NSE) between 0.84 and 0.96 were obtained. High Wilmot's Index of Agreement (d) values generated from the model were from 0.96 to 0.98. This indicated that there existed strong agreement between observed and simulated canopy cover (see Figure 4.6).

There was a high percentage, approximately 70%, of correctly predicted/simulated canopy cover values for all the observations with treatment T1 producing the highest accuracy of simulation.

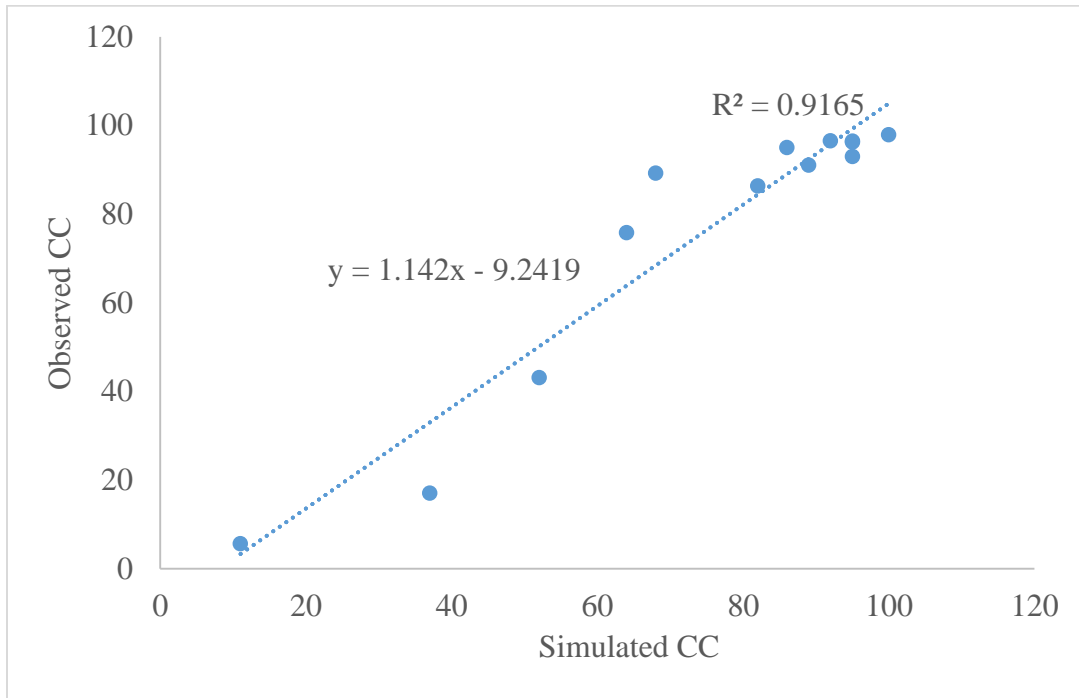


Figure 4.6: Simulated verses observed canopy cover

Comparing the simulated and observed canopy at various days of growth gave an average coefficient of determination of 0.92 (see Figure 4.6). The values of R^2 for all the treatments were in the range 0.77 to 0.94; this indicated a high model performance in simulation of Irish potato canopy cover. The results agreed with Razzaghi et al. (2017) and Wale et al. (2022) who found that the AquaCrop predicted canopy development of potato crop with $R^2 = 0.98$, Nash-Sutcliffe efficiency (E) = 0.92, RMSE = 9.6%, and index of agreement = 0.98.

4.1.6 Simulation of Soil Water Content and Biomass Production of Potatoes

A high model performance was recorded in simulation of biomass production. The Aqua-crop simulated aboveground biomass production producing a high coefficient of correlation, RMSE, NRMSE, NSE, and Wilmot's agreement index, d, range of 0.98, 0.8, 22.7%, 0.97, and 0.99 respectively. The script of the simulation is shown in Appendix V. The findings agreed with Wale et al. (2022) who carried out a research in Ethiopia and observed AquaCrop predicted biomass production with coefficient of correlation $R^2 = 0.98$, NSE = 0.96, and index of agreement, $d = 0.99$.

There was poor model performance in prediction of soil water content. The actual values observed for the water content in the soil were quite higher than the model-simulated values. This is because SAP improved water absorption efficiency which led to more soil water content. This was described by the model performance evaluation values produced from the simulation. The coefficient of correlation coefficient fell below 0.71 for most treatments; high RMSE value of more than 38.6, high values of NRMSE, negative values of NSE and low Wilmot's degree of agreement of less than 0.59 were obtained from the evaluation of the simulation results.

4.1.7 Simulation of Potato Tuber Yield

The model predicted dry yield values were higher than the measured yield from the field. Compared to observed yield, the predicted tuber yield was on range 30% to 42.8% than the measured (see Figure 4.7).

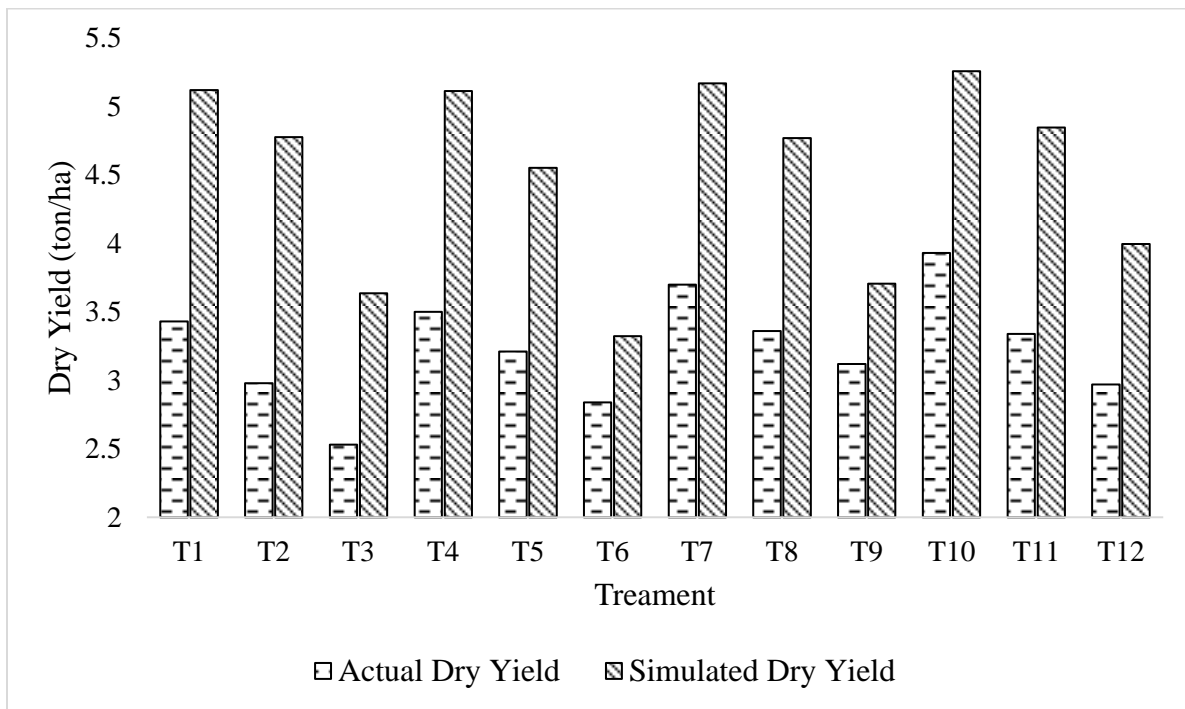


Figure 4.7: Simulated and Actual dry tuber yield

The difference between the actual observed and predicted dry tuber yield is lower for treatments T2, T6 & T9, however the difference in the dry yield for all the treatments were significant. The yields from T3 was the lowest (see Figure 4.7). The residual mass coefficient obtained from this study was -0.388. This indicated that AquaCrop model overestimates the potato crop yield. This

finding agree with Tayade et al. (2018) that AquaCrop model overestimates potato yield by giving coefficient of residual mass of -0.386 for biomass and -0.480 for yield.

4.1.8 Simulation of Potato Water Productivity

The data on climatic parameters, crop growth, soil data and the field management practices were entered to the AquaCrop model to simulate the potato water productivity for the growing period. The values obtained are indicated in Appendix V.

The comparison for the simulated water productivity and the actual water productivity is presented in the Figure 4.8. From the Aqua-crop model simulations, the highest water productivity for all the treatments was obtained from treatment T5 simulation.

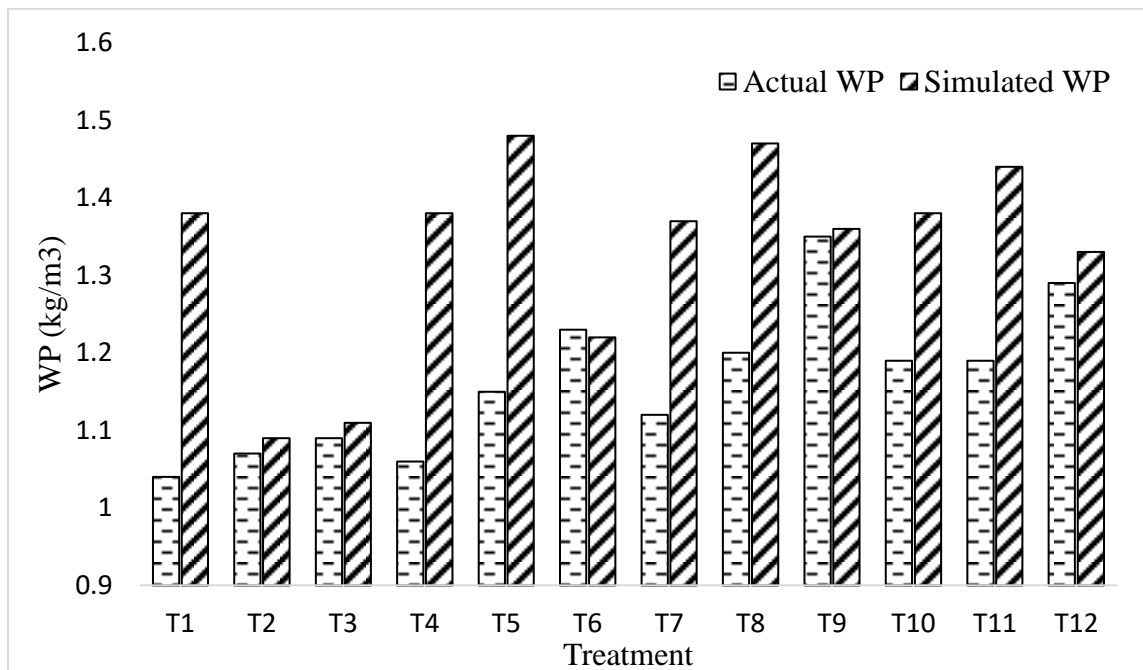


Figure 4.8: Simulated vs Actual water productivity

The simulated and observed water productivity for the treatments T2, T3, T6, T9 and T12 had less marginal differences. The simulated water productivity was higher than observed for treatments T1, T4, T5, T7, T8, T10 and T11. The least predicted WP was for T2 treatment. From the observed data treatment, T9 produced the highest WP while T1 gave the least (see Figure 4.8). The percentage of correctly simulated WP by the model was 42%. This indicated that AquaCrop is capable of predicting water productivity with low margin of error. However, the lack of a feature in the model that allows inclusion of soil additives such as SAP, that affect

water storage capacity and soil bulk density led to reduced performance of the model in simulation of water content of the soil and water productivity for SAP applied treatments. By inputting actual amount of water applied by D-SDI and doing comparison between ET_C -calculated (from penman Monteith) and irrigation water supplied (D-SDI – actual amount supplied) The results concur with Razzaghi et al. (2017) that the AquaCrop when well calibrated can be used to predict potato development and production under temperate conditions, making it a highly helpful tool for decision-making over when and what amount to water.

4.2 Effect of deficit subsurface drip irrigation and super absorbent polymer quantity on potato crop yield

4.2.1 Data Analysis Results Overview

A normal data distribution was obtained for data grouped in terms of irrigation level effect on number of tubers. However, the null hypothesis was rejected for 70% irrigation level which had a P-value of $0.0239 < 0.05$. In addition, the normality null hypothesis was nullified for the case of grouping the data by irrigation level effect on the number of ware tubers per plant since all the p-values fell below 0.05. Grouping the data in terms of the effect of SAP amount applied on quantity of tubers from each plant and number of wares obtained from each plant indicated a normal data distribution in cases. The output from the Shapiro test using RStudio is shown in the Table 4.5. Outliers check indicated that there were no outliers.

Table 4.5: Statistical Summary of Data Analysis

Irrigation level	Variable	n	mean	SD	Statistic	p	Normal p>0.05
	Dry						
70%	Yield	4	2.9	0.279	0.871	0.300	Normal
	Dry						
85%	Yield	4	3.25	0.209	0.964	0.801	Normal
	Dry						
100%	Yield	4	3.64	0.225	0.938	0.644	Normal
	Dry						
No SAP	Yield	3	2.98	0.45	1.000	0.966	Normal
6kg/ha	Dry	3	3.18	0.331	0.995	0.684	Normal

	Yield						
	Dry						
10kg/ha	Yield	3	3.39	0.291	0.990	0.266	Normal
	Dry						
14kg/ha	Yield	3	3.5	0.411	0.993	0.403	Normal
70%	Tubers	4	8.5	0.577	0.729	0.0239	
85%	Tubers	4	9.75	0.957	0.863	0.272	Normal
100%	Tubers	4	11.5	1.29	0.993	0.972	Normal
No SAP	Tubers	3	9.00	1.00	1.00	1.00	Normal
6kg/ha	Tubers	3	9.33	1.53	0.964	0.637	Normal
10kg/ha	Tubers	3	10.3	2.00	0.964	0.637	Normal
14kg/ha	Tubers	3	11	1.53	0.964	0.637	Normal
70%	WP	4	1.24	0.109	0.964	0.803	Normal
85%	WP	4	1.15	0.061	0.878	0.330	Normal
100%	WP	4	1.1	0.067	0.944	0.680	Normal
No SAP	WP	3	1.06	0.029	1.00	0.981	Normal
6kg/ha	WP	3	1.14	0.086	1.00	0.994	Normal
10kg/ha	WP	3	1.22	0.118	0.97	0.667	Normal
14kg/ha	WP	3	1.22	0.055	0.781	0.069	
70%	Chatts	4	12.1	4.64	0.99	0.882	Normal
85%	Chatts	4	13.6	2.51	0.896	0.409	Normal
100%	Chatts	4	11	0.61	0.977	0.882	Normal
No SAP	Chatts	3	11.4	2.02	0.75	0	
6kg/ha	Chatts	3	14.1	3.32	0.966	0.646	Normal

10kg/ha	Chatts	3	12.1	2.76	0.867	0.288	Normal
14kg/ha	Chatts	3	11.4	4.4	0.998	0.921	Normal

In the analysis of repeated measures ANOVA (type III test) using RStudio program, F indicate that we compared to an F-distribution (F-test); where (2, 6) indicated the degrees of freedom in the numerator (DFn) and the denominator (DFd) respectively. An F-statistic value of 64.273 was obtained. The *ges* (0.858) value generated by the program indicated the generalized effect size (see Table 4.5). This implied the amount of variability due to the within-subjects factor. The type III test results obtained from the RStudio program are tabulated in the appendices.

4.2.2 Deficit sub-surface drip irrigation Effect on the Potato Crop Yield

The repeated measures ANOVA indicated that irrigation level had a statistical significant effect on the total yield for given SAP amount applied. This was shown by a p-value of 0.0000887 that is less than 0.05 produced from the analysis. As shown in Figure 4.9, the total yield significantly increased with increased irrigation water applied.

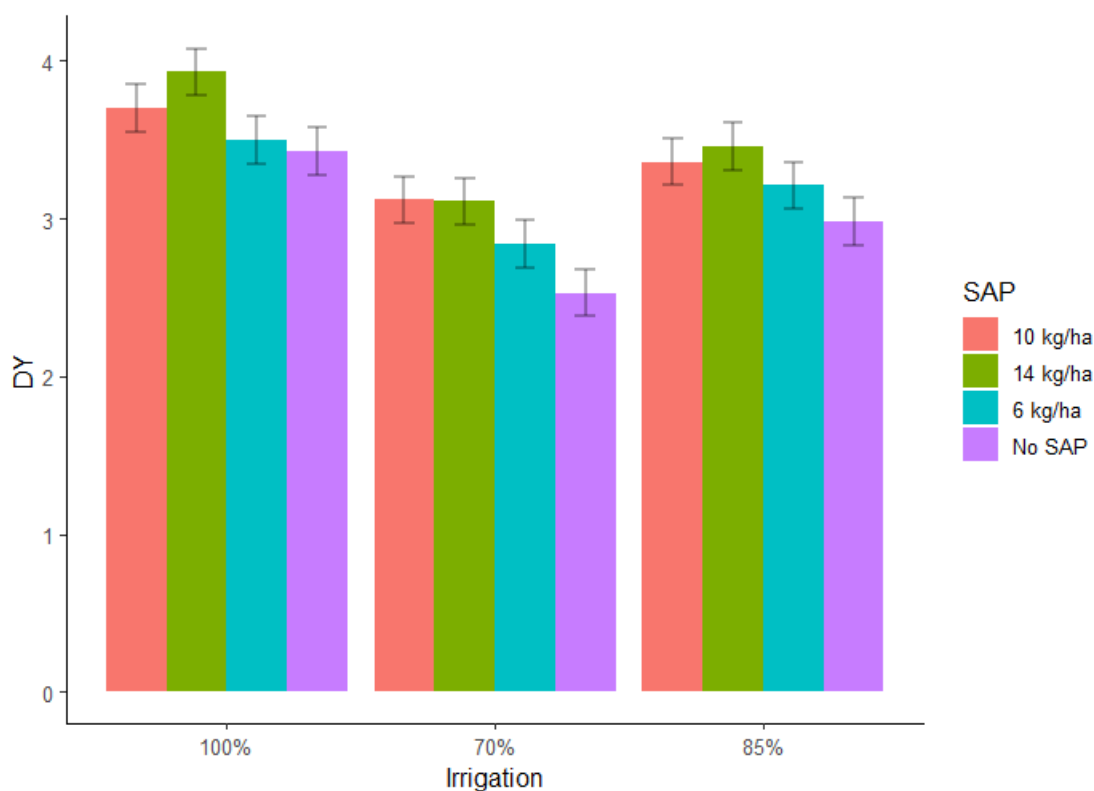


Figure 4.9: Irrigation level effect on total dry yield of Irish potatoes

There was a marked increase in the total tuber yield with increase in water application level (see Figure 4.9). The highest tuber yields were recorded in the 100% irrigation treatment. The lowest yields were obtained from 70% irrigation level. The 85% irrigation level produced dry yields ranging from 3.21 ton/ha to 3.46 ton/ha for the SAP treatments with the high yields observed in 10kg/ha SAP. By applying water at 85% of full irrigation, about 15% of irrigation water was saved and 0.34 to 0.47 ton/ha reduction of yield from full irrigation application were obtained. In general, the findings showed that deficit irrigation practice results in decrease of yield of potato tubers. These results concurred with Gultekin and Ertek (2018) who found out that water restriction caused noticeable impact on tuber weight, yield and marketable tuber portion. They also found out that treatment with 100% water application produced the highest yields per unit water applied. The practice of using sub surface drip system led to increased yield of the crop as 80% irrigation level produced comparable yield with 20% water saving potential as reported by Badr et al. (2010) and Martinez and Reza (2014).

4.2.3 Irrigation level effect on the weight, Number, and Quality of harvested Tubers

The number of tubers produced per plant varied gradually with change in the application level of irrigation water. The impact of irrigation level on the number of tubers produced per plant is shown in Figure 4.10.

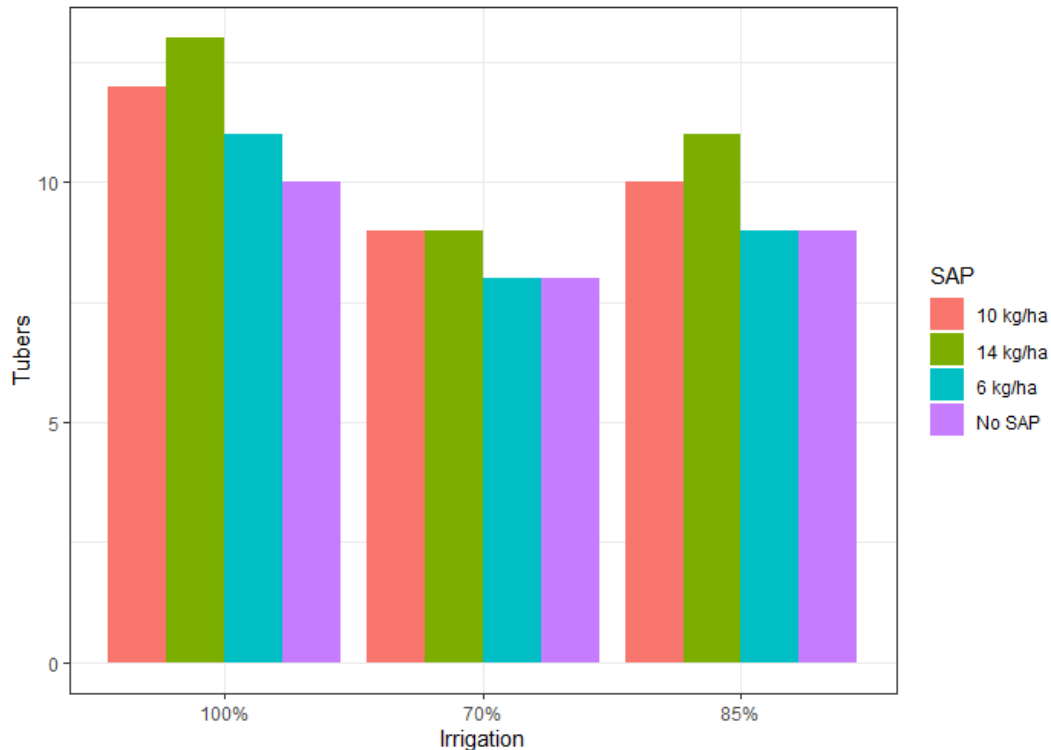


Figure 4.10: Variation of number tubers produced per plant against irrigation level

The number of tubers produced increased with increase in application levels of water (see Figure 4.10). The ANOVA type III test indicated a statistically significant impact of the irrigation level on the number of tubers produced. This was indicated by the p-value of 0.000141 obtained from analysis. The highest number of tubers were produced from 100% irrigation while 70% application level yielded the least number of tubers. This can be linked to tuber yield in that high Irrigation level guaranteed more water availability for production of more tubers. When less water was applied, it limited the number of tubers that plant could produce. The amount of water applied did not heavily affect the quality of tubers produced. The quality of tubers assessed in terms of surface roughness and shape regularity did not vary over the water application levels, however, the size of tuber produced increased with water application level. These results concur with Crosby and Wang (2021) who found out that increased water application amount does not have significant effect on quality of tubers at harvest. High irrigation levels increased total yield and led to reduced water use and irrigation efficiency.

4.2.4 SAP effect on root zone Temperature

There was a noticeable temperature variation for SAP containing plots and plots that did not contain SAP. The NO SAP plots had an average temperature at the root zone of 25 °C while the plots with SAP measured 27 °C root zone temperature. This showed a slight increase of 2 °C on the root zone temperature for plots containing super absorbent polymer than plots without the SAP. The maintained temperature levels were recorded throughout the growth cycle of the Irish potatoes. The findings concur with Yang et al. (2020) who found out that the application of superabsorbent polymer led to gradual increase of soil temperature and effectively reduced soil surface temperature variation and therefore led to a more stable maize growth in arid and semi-arid areas. In addition, SAP use not only led to increased temperature of the maize leaf surface, but also 6% increase of the normal crop yield because of SAP use.

4.2.5 SAP effect on the Number, weight, and Quality of Tubers produced

The distribution of number of tuber per SAP application rate is shown in Figures 4.11 & 4.12.

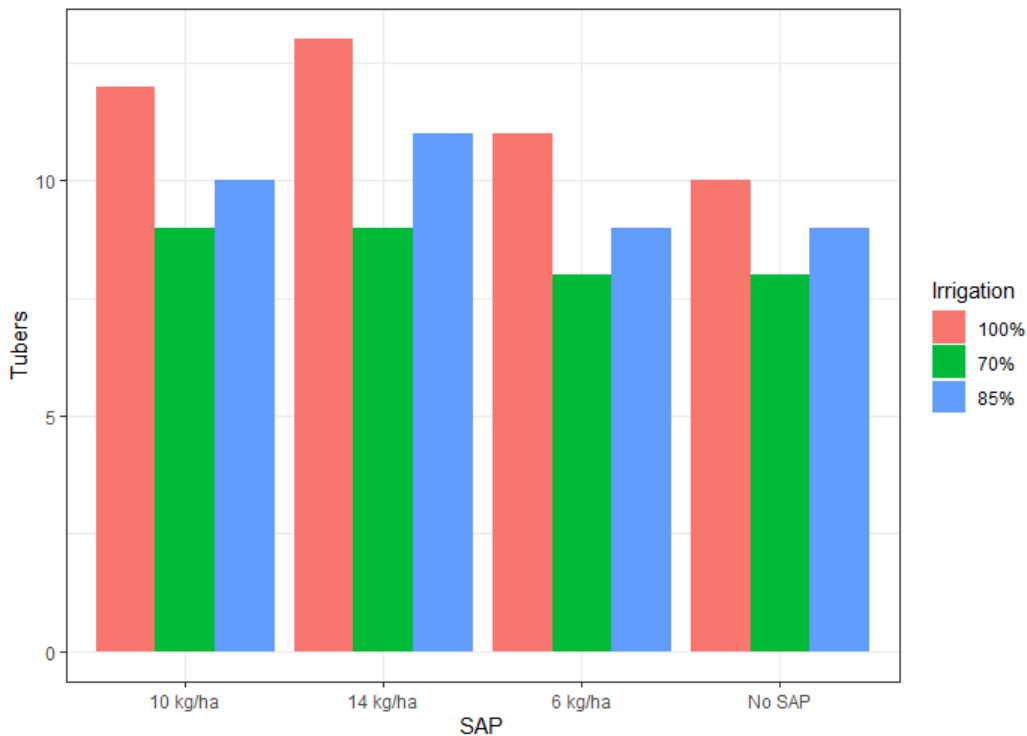


Figure 4.11: Effect of SAP amount on the number of tubers

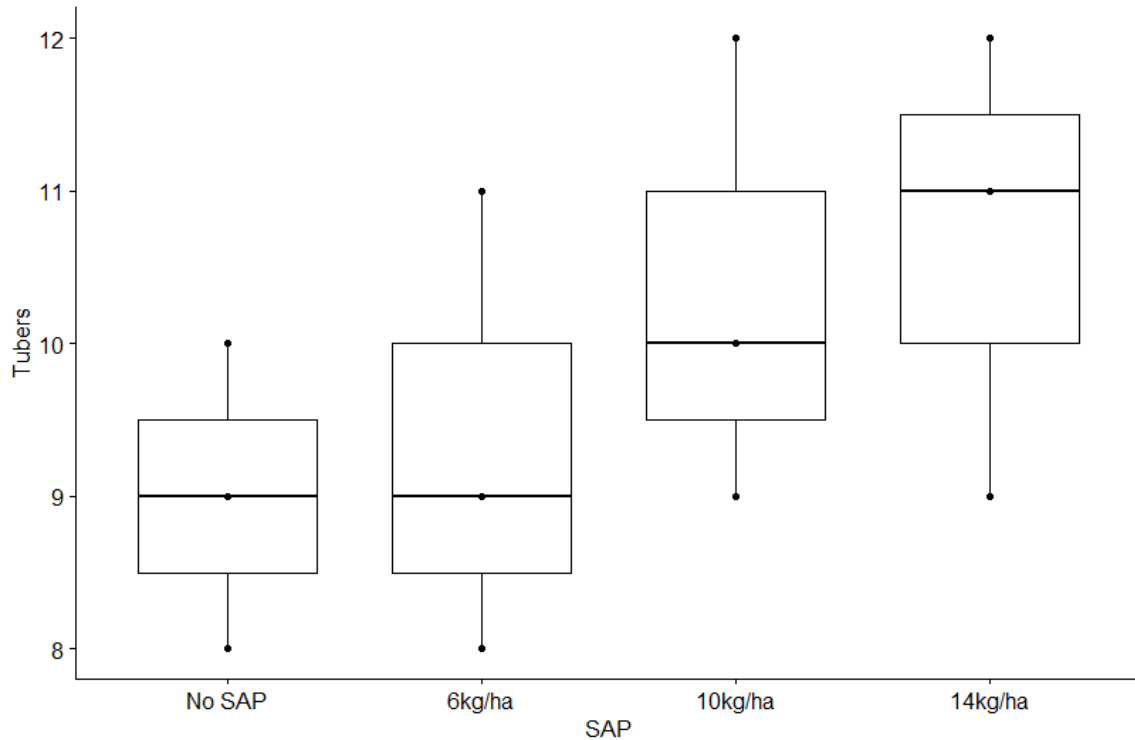


Figure 4.12: Boxplot of number of tubers per plant against the SAP amount applied

The amount of Bel SAP applied had a significant effect on the number of tubers produced per plant (see Figures 4.11 & 4.12). The weight of tubers produced from each plant varied from one treatment to the next. Statistical analysis indicated that the weight declined with decreased SAP rate application.

The quality of tubers produced from SAP treatments improved significantly compared with the control. Tubers from treatments without SAP had deep tuber eyes and irregular shapes with rougher surface textures than tubers harvested from Bel SAP treatments. The weight per tuber size for SAP increased for Bel SAP treatments as compared to treatments without SAP. This was attributed to the high water storage capacity for soil containing SAP that is the major feature of superabsorbent. SAP reduced soil compaction, improved fertility, and water absorption efficiency that resulted to less irrigation events having more tubers hence more yields.

4.2.6 SAP effect on soil water content and root characteristics

The properties of Belsap polymer of holding water and maintaining it at a particular depth where they are contained affected the rate of root deepening, distribution and presence of water in soil

root zone of Irish potato significantly. Most root concentration was from 0 to 30-centimetre depth. The quantity of water available after subsequent irrigation events increased for plots containing super absorbent polymer. This reduced the amount of water supplied to SAP containing plots. The depth and lateral length of roots decreased significantly with increase in the SAP amount applied. These findings concurred with those of Hou et al. (2022) out that the increase of SAP dosage in the soil has a significant effect on the water available in the root zone after 24 hours of irrigation, root anchorage and distribution in the soil.

4.2.7 Effect of Super Absorbent Polymer on Total Tuber Yield

The total yield was statistically significantly different at the different SAP application rates ($p = 0.044$). This meant that there was significant rise in the total tuber yield of potato with increased quantity of SAP applied. Figure 4.12 shows the variation of dry tuber yield at different SAP application rates.

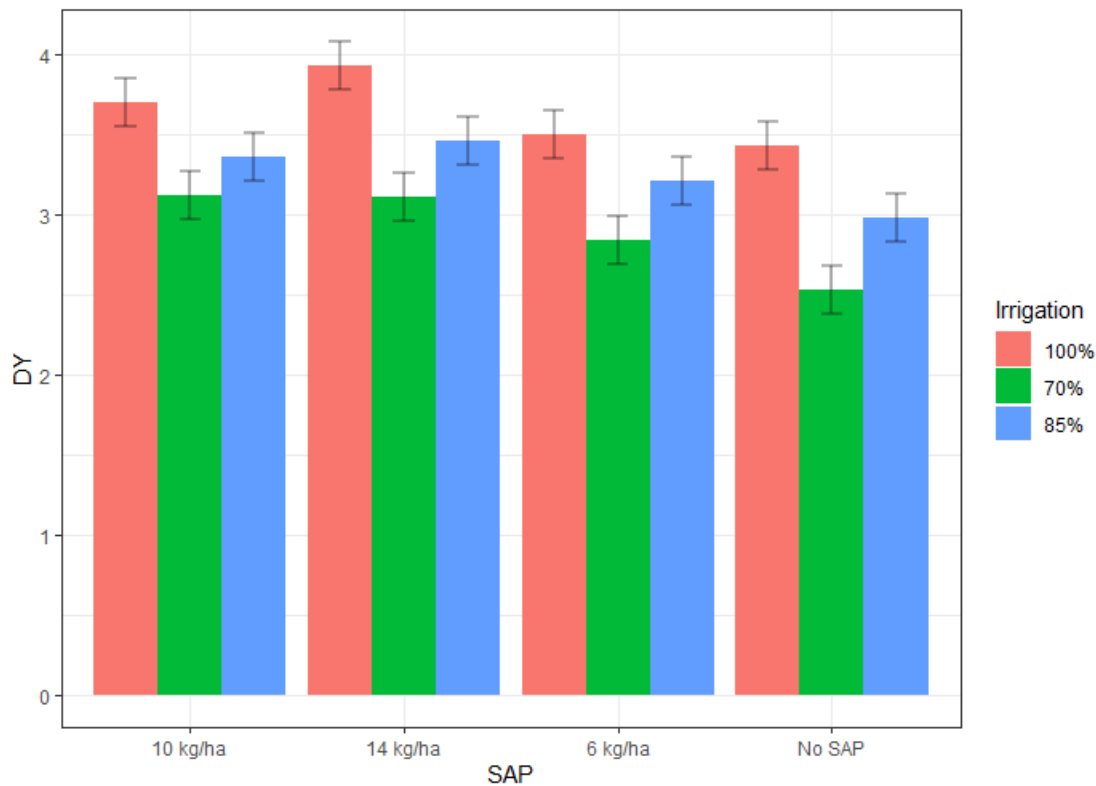


Figure 4.13: Effect of SAP Amount on the total Dry Total yield

DY-dry yield in ton/ha SAP-superabsorbent polymer

There was a noticeable increase in the total yield of tubers harvested with increase of the amount of superabsorbent polymer applied (see Figure 4.13). This is indicated by the marked increase in the total yield with increased amount of SAP, this is because the more the SAP the more the soil water storage in the plant root zone. Therefore, irrigation supplied water was available to the plant throughout its growth period and less was lost. There was high water storage capacity for Belsap treatment plots than treatment without the SAP that resulted in high yields. The results agree with Hou et al. (2017) who conducted a study to establish the influence of Wote SAP on the physical properties of the soil and tuber yield of potatoes in dry land farming. In addition, the use of SAP had a huge positive influence on the soil water conservation and potato growth that was indicated by higher stem diameter and height of the plant than the No SAP plot. The use of Wote SAP had a significant effect on the potato yield. Salavati et al. (2018) conducted a study of superabsorbent effect on Irish potato crop and obtained similar results. Parvizi (2020) found out that the use of SAP in moisture deficit conditions increased the yield of potatoes by 10.15%.

However, a different trend was observed in the 85% and 70% irrigation level as shown in Figures 4.14, 4.15, & 4.16. For the 85% irrigation level, the total yield produced slightly increased from 2.98 ton/ha in No SAP to 3.21 ton/ha in 6 kg/ha SAP application. The total yield increased for 10 kg/ha SAP level and then slightly decreased for 14kg/ha SAP application level (see Figure 4.14). From the 85% irrigation water application level, the highest yield was collected from the plots which had superabsorbent polymer applied at a rate of 10 kg/ha. For 85% irrigation level, the highest yield was observed on the plots that contained 10 kg/ha SAP and the lowest yield was obtained from the 6 kg/ha SAP plots. However, no significant difference for total tuber yield from 0 kg/ha SAP and 14 kg/ha SAP application rate. This was also observed in the boxplot Figure 4.15 that showed insignificant difference between the upper and lower yield values for 85% Irrigation level.

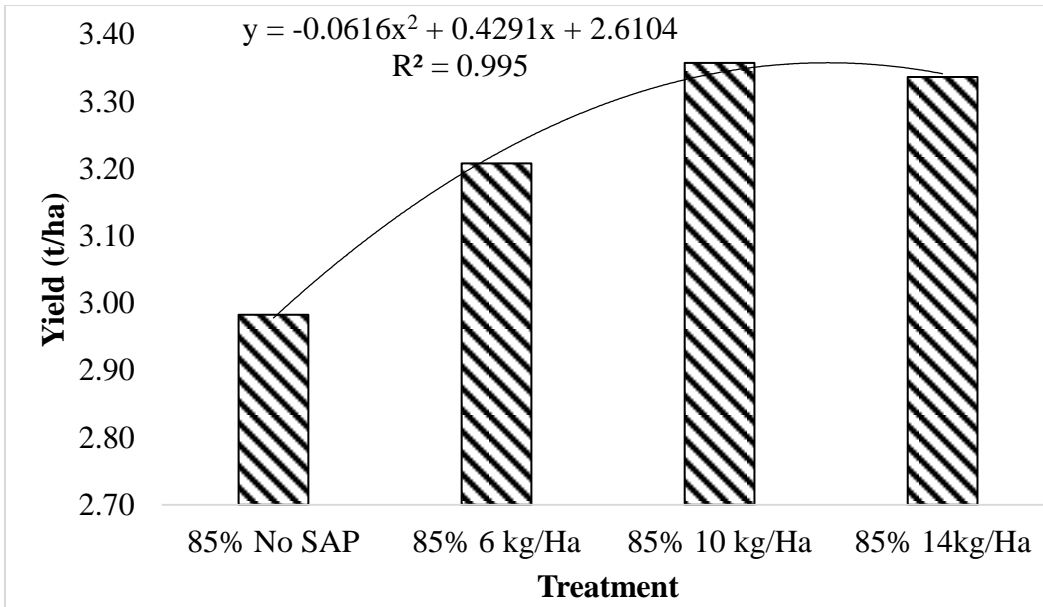


Figure 4.14: Potato yield variation for 85% Irrigation level

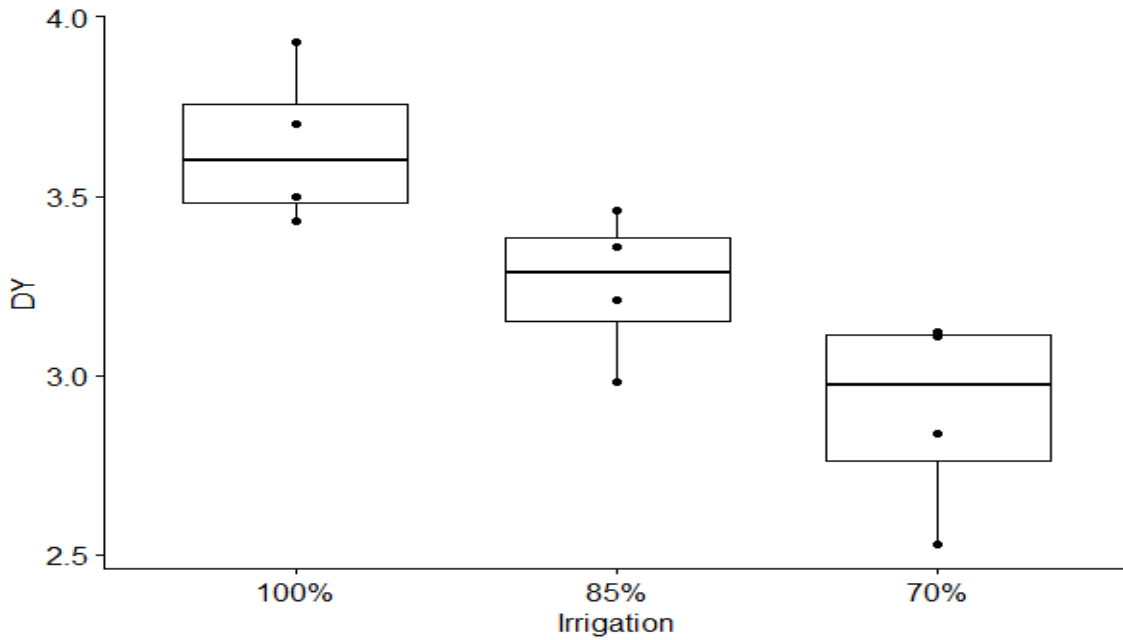


Figure 4.15: Boxplot of total yield changes with changes in irrigation level

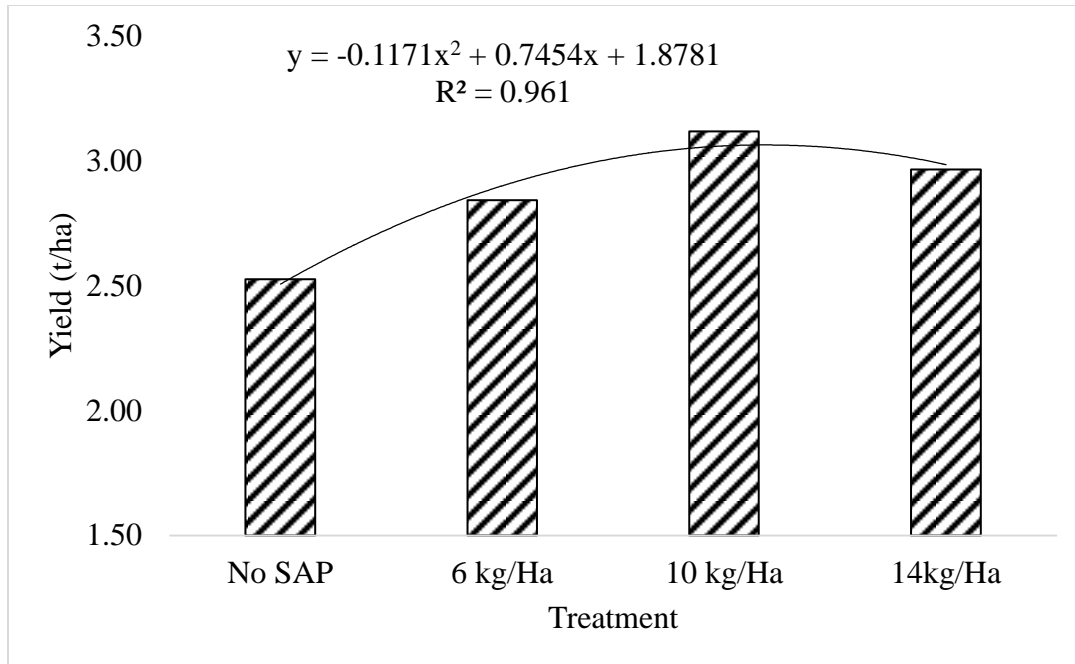


Figure 4.16: Potato yield variation for 70% Irrigation level

In the 70% irrigation level, there was a significant change in the yield of Irish potatoes for plots with SAP application rates to a maximum at 10 kg/ha superabsorbent polymer application rate (see Figure 4.16). This concurs with findings of Parvizi (2021) that the application of superabsorbent polymer positively impacted the yield of potatoes grown under moisture stress conditions by 10.15%. In this study however, there was a marked decrease in the total tuber yield for 14 kg/ha SAP application rate. This indicated that the optimum amount of polymer that can be used for 70% irrigation water application level together with having positive impact on the yield of Irish potato tubers is 10 kg/ha. Further increase in the SAP application rate will cause a decline in the total yield of tubers produced. This is because increased use of the polymer at deficit water application led to high osmotic potential generated by the Sap hence restricting the crop's ability to take in water from the soil.

These findings agree with Starovoitova et al. (2019) who carried out a study between the years 2015 to 2017 in Moscow, Russia Lyubersty district that recorded that the yield of potato under use of superabsorbent polymer in conditions of moisture deficiency increased significantly. These results also concur with Bell industries recommendations that the use of Bell superabsorbent polymer on soils for production of potatoes has a positive impact on the total

yield to a certain level of application. Increased application rate of the polymer causes a reduction of the yield of tuber.

4.2.8 Interactive effects of Irrigation level and SAP amount on Total Yield

The combined effect of irrigation level and SAP application on the dependent variable, total yield, was analysed. A two-way ANOVA with interaction was conducted out to establish the effect of various interactions of irrigation level and SAP amounts on the tuber yield. There was no significant difference in the effect created by the interaction between 85% irrigation level and all the SAP amounts on the total tuber yield of Irish potatoes.

Within effect analysis showed that, the difference in total yields from the 10 kg/ha and 14 kg/ha SAP rate for 85% irrigation level were not statistically significantly different (see Figure 4.17). The effect of the interaction between SAP amount and Irrigation water applied on yield and number of tubers per plant is presented in Figure 4.17.

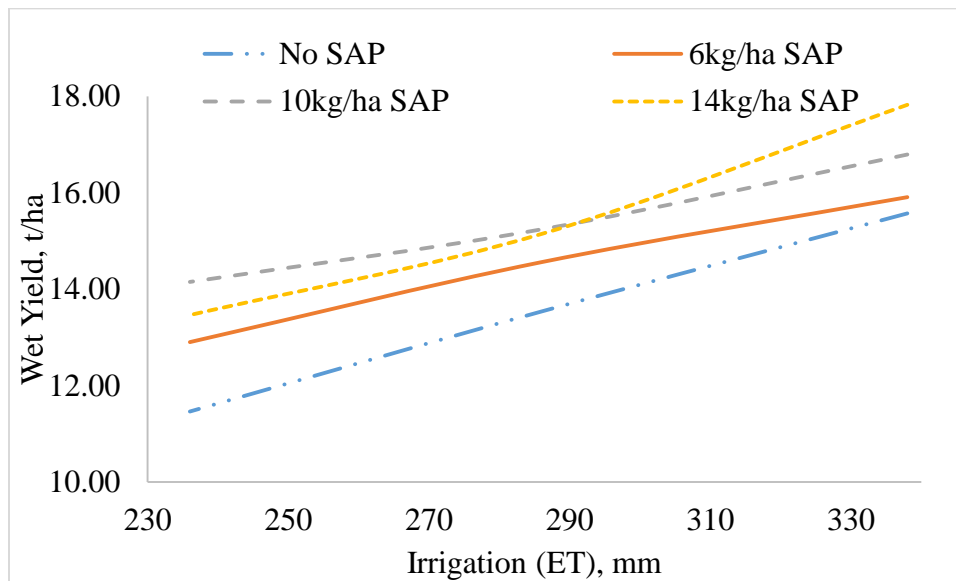


Figure 4.17: Relationship between Irrigation water use and dry yield for all SAP rates

The subsurface drip irrigation and superabsorbent polymer soil amendment had a significant effect on the dry tuber yield. The crop yield increased with increased amount of irrigation water used to grow the crop. The yield also increased with the rate of SAP applied in the soil. No SAP treatments had low yields than SAP containing treatments (see Figure 4.17). At high application rates of SAP and low irrigation water use, there were low crop yields obtained. This can be seen

from Figure 4.17, 14 kg/ha yield trend line and 10 kg/ha trend line; the yield is high for 10 kg/ha, SAP compared to 14 kg/ha SAP at same low irrigation level. However, at 100% irrigation levels the yield obtained from the 14 kg/ha SAP treatment exceeds the yield from 10 kg/ha SAP treatment. As a result of use of SAP for all the irrigation levels applied in this study, the yield of potatoes significantly increased by an average of 7%, 15% and 15% for 6kg/ha, 10 kg/ha, and 14 kg/ha respectively. The percent change in yield at a particular SAP application rate significantly increased with decrease in irrigation amount. The highest percent increase in yield between treatments lacking SAP and treatments containing SAP was recorded in plots that had 10 kg/ha SAP application rate. Table 4.4 shows the percent increase in yield for each rate of SAP application. The values in the table are wet yields in tons per hectare.

Table 4.6: Percentage increase of yield with SAP

Irrigation level	No SAP	6kg/ha	% Change	10kg/ha	% Change	14kg/ha	% Change
	Yield (ton/ha)	SAP Yield		SAP Yield		SAP Yield	
100	15.58	15.92	2.04	16.80	7.87	17.83	14.58
85	13.55	14.57	7.72	15.25	12.75	15.15	12.08
70	11.47	12.91	12.25	14.16	23.32	13.47	17.39

Figure 4.18 shows the change in marketable yield from total yield harvested from each treatment. The reduction is due to presence of small tubers that cannot be sold due to their relative sizes.

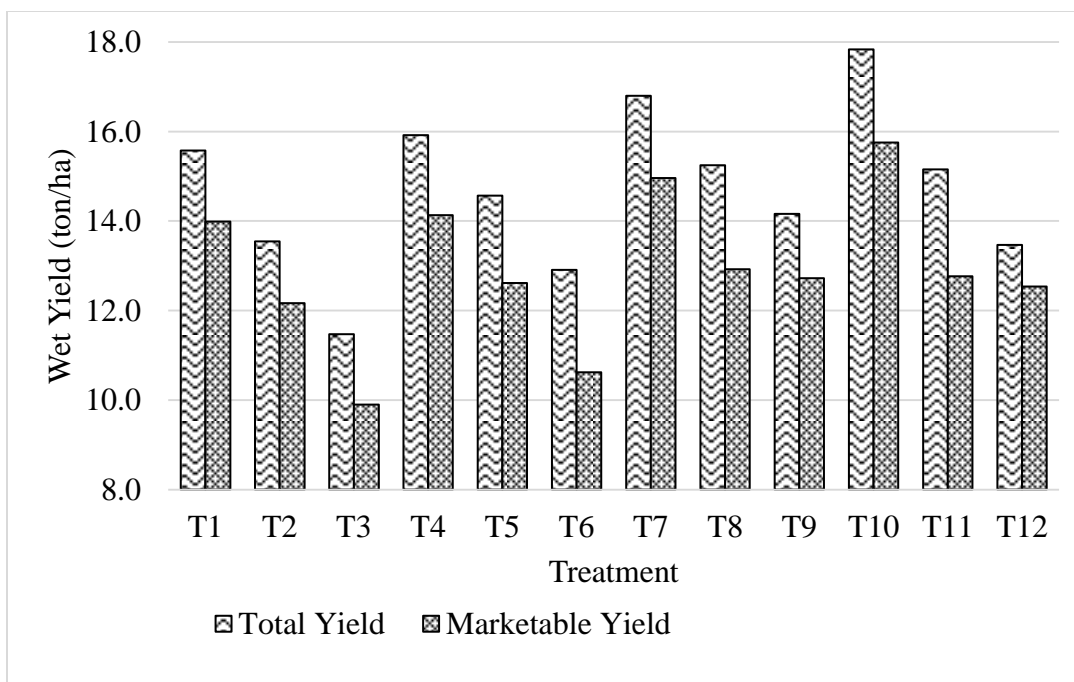


Figure 4.18: Total and Marketable dry tuber Yield variations

There was a reduction of marketable yield across all the treatments. The difference between total and marketable yield in T2, T9 and T12 is lower than other treatments, indicating that less chatts were produced from these treatments (see Figure 4.18). The reduction in marketable yield for all the treatments was mainly due to presence of chatts (small tubers) that could not be classified as either ware or seed tubers. Their sizes were significantly small. The percentage per weight of chatts varied non-uniformly over the treatments. The percent chatts for treatments at 10 kg/ha and 14 kg/ha SAP levels and 85% & 70% irrigation rates were lower compared to chatts produced at 0kg/ha and 6 kg/ha SAP rates. This is because the high concentration of superabsorbent polymer led to availability of water for more tubers to grow larger. Therefore, the use of SAP had a significant effect on the number of chatts produced at low irrigation levels and hence marketable yield. The yield obtained from the rain-fed potatoes compared with the 100% level irrigated potatoes showed no significant statistical difference. However, there was significant statistical difference in the number of tubers produced. Rain-fed treatment had lower number but large sized tubers than tubers obtained from treatments under irrigation. This was mainly due to the limited water availability for the growth. The findings agree with Starovoitova et al. (2019) who found out that the yield of the examined cultivars increased when superabsorbent polymers were used in an average of three years, by 1.6 to 3.4 t/ha.

4.3 Optimization of potato production based on deficit sub-surface drip and superabsorbent polymer systems

The analysis of variance type III test indicated that the water productivity was significantly different at different irrigation levels and superabsorbent polymer application rates. The p-value obtained was less than 0.05; this can be referred from the summary statistical table in the Appendix VIII. Figure 4.16 shows a general distribution of water productivity over all the treatments applied in this study.

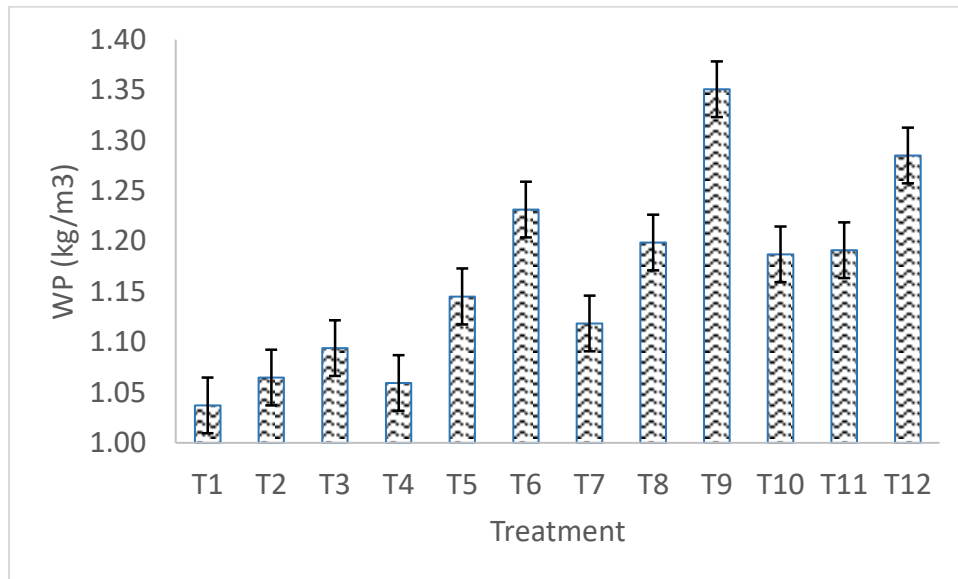


Figure 4.19: Water productivity distribution over the treatments

There was a significant increase in water productivity from treatment T1 to T12. Treatment T1 produced the least water productivity whereas treatment T9 gave the highest water productivity (see Figure 4.19). Treatments with high irrigation levels gave low water productivity than treatments under deficit water application. There was high water productivity in 70% irrigation level than in the 100% irrigation level. Also, the water productivity increased with increase in application rates of SAP. Better water productivity results were obtained from superabsorbent polymer application rate of 10kg/ha while treatments with no SAP gave the lowest results. This indicated that the use of SAP had a significance on the water productivity of potatoes. This is indicated in boxplot of WP distribution over the SAP rates (see Figure 4.20).

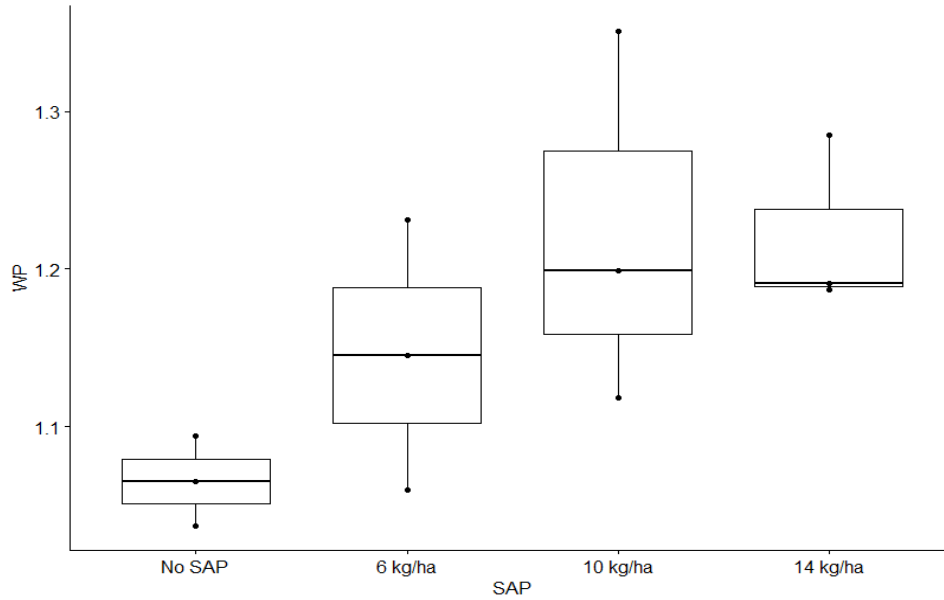


Figure 4.20: Water productivity distribution different Superabsorbent polymer treatments

The water productivity increased from NO SAP to 10 kg/ha SAP then reduced for 14 kg/ha SAP. Therefore, the optimum SAP application rate for sandy clay loam soils of the experimental site was found as 10kg/ha for row application method. This is due to significant decline in the water productivity with further increase in the amount of SAP use higher than 10kg/ha.

Figure 4.21 shows the variation of water productivity over the three irrigation levels employed in this study.

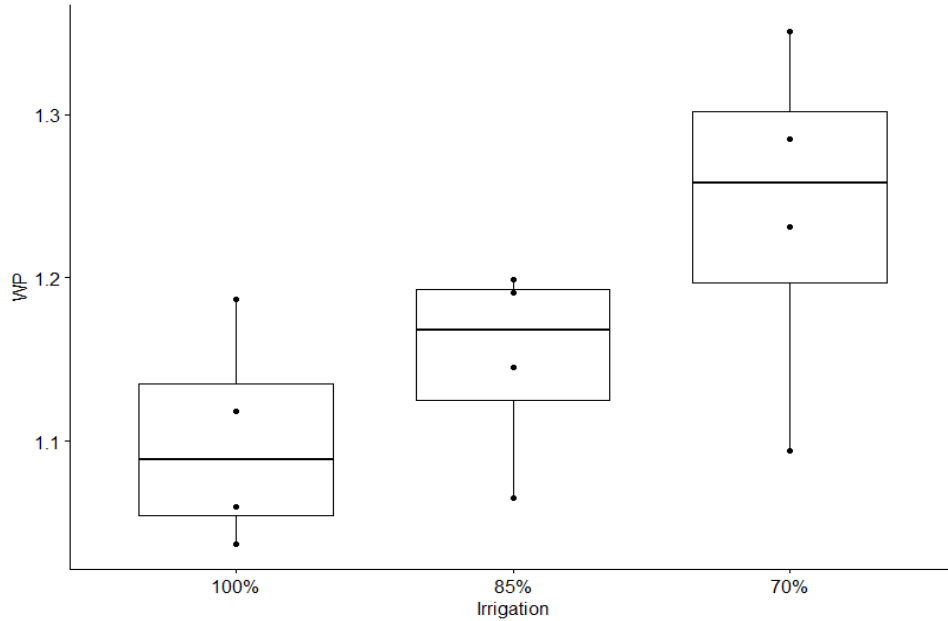


Figure 4.21: Water productivity distribution at the three Irrigation levels

There was higher water productivity in 70% irrigation level at all SAP application rates than 100% water application level. However, as indicated by dots, the variance of WP (water productivity) values in 70% irrigation level was wider than the range of WP values in 100% and 85% irrigation (see Figure 4.21). This indicated that there was a high variance effect on water productivity caused by the application of superabsorbent polymer for the potatoes grown under deficit irrigation (70% irrigation level). This can also be seen from the analysis of variance results in the Appendix IX. Therefore, it can be concluded that the optimal level for production of Irish potatoes in water constrained environment was at a superabsorbent polymer row application of 10 kg/ha SAP and 70% irrigation level. The combination gave the highest water productivity with high water saving and comparable yields.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research sought to assess and model the water productivity on production of Irish potatoes using subsurface deficit irrigation and superabsorbent polymer soil amendment. The field experiments were set from January to May 2022 at Egerton University, Kenya and subjected to 12 treatments. Data was collected from the field both during growth and after maturity were analyzed and the following conclusions were deduced.

- i. By closely comparing both observed and simulated results from validation, it was concluded that AquaCrop model simulated the potato crop development under the various irrigation levels with a coefficient of correlation of 0.92. However, due to application of SAP in the soil, the model was not able to simulate soil water content to acceptable accuracies. The calibrated model was successfully applied in simulating WP and yield response of the three water treatment levels for 0kg/ha SAP, however, due to absence of a factor for SAP it was not able to model for treatments with 6kg/ha SAP, 10kg/ha SAP and 14kg/ha SAP.
- ii. The application of superabsorbent polymer increased water availability in root zone with its effect most felt with increase in application rate. This was due to their capacity for water absorption and retention, SAPs have the ability to dramatically reduce soil moisture migration and build-up. The combined use of superabsorbent polymer and subsurface drip irrigation system contributed to 39% water saving at deficit irrigation and improved yield at deficit irrigation. The combined application of SAP and subsurface drip irrigation systems significantly increased the water productivity of Irish potatoes. Hence, the two systems can be used in production of Irish potatoes in areas experiencing severe water stresses.
- iii. The superabsorbent polymer row application of 10 kg/ha SAP and subsurface drip irrigation level of 70% is the ideal level for growth of Irish potato in a water-scarce setting. Combining these factors resulted in the maximum water productivity of 1.35kg/ha, significant water savings, and equivalent yields.

5.2 Recommendations

The various recommendations listed are proposed to boost potato crop productivity, decrease potentially negative consequences of water stress, and enhance water use and subsurface drip irrigation system efficiency;

- i. Farmers can employ the calibrated model as a resource for making decisions about when to schedule irrigation to get the intended yields.
- ii. The future versions of AquaCrop should incorporate a factor within the model to enable accurate simulations of soil water content for fields containing soil amendments. Therefore, further research to establish the factor for soil amendments such as superabsorbent polymer is recommended moving forward.
- iii. In order to conserve water, produce high quality and good yield potatoes in water constrained areas farmers are advised to employ subsurface drip irrigation and row SAP application of 10kg/ha at 70% crop water requirement.
- iv. Further research to assess the combined effect of subsurface drip irrigation system and superabsorbent polymer on other crops is proposed.
- v. Climate conditions are unpredictable because of the consequences of climate change, which are already here. Farm owners need to adopt the deficit subsurface drip irrigation and superabsorbent polymer systems approach in order to maintain adequate yields as well as ensure water conservation.

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APPENDICES

Appendix I: Gee & Or Soil Textural Analysis Method

Particle Size Analysis

Introduction

The size distribution of individual particles in a soil sample is determined using particle-size analysis (PSA). The primary characteristics of PSA include destroying or dispersing soil aggregates into discrete units using chemical, mechanical, or ultrasonic procedures as well as separating particles based on size restrictions using techniques like sieving and sedimentation, among others (diffraction).

The size of soil particles ranges widely, from larger pebbles and stones (more than 0.25 m) to submicron clays (less than 1 m). Arbitrary limits and ranges of soil-particle size have been established using a variety of size classification schemes. Sands, silts, and clays are the three main size categories for soil particles smaller than 2000 m. These collections, which are also known as soil separates, can be broken into smaller size classes. In soil research, particle-size analysis is frequently employed to assess soil texture. Rarely does a soil have only one size range. The various mixtures of sand, silt, and clay fractions that make up a soil sample's particle-size distribution that determine the texture of the soil.

Sample Preparation

Apparatus used include

1. Drying trays
2. Wooden rolling pin
3. Na-HMP solution (50 g L⁻¹)
4. Sieves. Large 20.5-cm (8 in.) diameter sieve with a 2-mm (2000- μ m) square-hole screen. Other screen sizes needed include 5, 20, and 75 mm (USDA, 1982); 5 mm (#4), 13 mm (1/2 in.), 20 mm (3/4 in.), 25 mm (1 in.), 50 mm (2 in.), and 75 mm (3 in.) (ASTM, 2000d).
5. Ruler or calliper capable of measuring to 250 mm (10 in.)

Method for Sample Preparation

Spread the bulk sample thinly (in layers no thicker than 2 to 3 cm) on trays and let it air dry. Mix the sample thoroughly and roll it with a wooden rolling pin to break up clods so that it may flow through a 2-mm sieve. Filter off the fractions larger than 2mm. Rolling and sieving should continue until the 2-mm screen is solely covered by coarse fragments that do not slake in water or an HMP solution. For samples with easily crushed coarse pieces, use a rubber roller. To get the percentage of the entire sample that is smaller than 2 mm, sieve larger size fractions, note weights, and utilize total sample weight.

Hydrometer Method

Particle-size analysis can be performed easily with a hydrometer, which allows for non-destructive sampling of settling suspensions. The hydrometer approach allows for many measurements on the same suspension, allowing for the most detailed particle-size distributions to be acquired with the least amount of work.

Apparatus and Reagents

1. Standard hydrometer, ASTM no. 152 H, with Bouyoucos scale (g L^{-1}) (Fig. 2.4–8)
2. Electric stirrer (malted-milk-mixer type, with 10 000-rpm motor) or horizontal shaker
3. Plunger or rubber stoppers for 1000-mL sedimentation cylinders
4. Sedimentation cylinders with 1-L mark 36 ± 2 cm from the bottom of the inside
5. Metal dispersing cups and 600-mL beakers
6. Amyl alcohol
7. Na–HMP solution (50 g L^{-1})
8. Set of sieves—7.6-cm (3-in.) diameter square mesh woven bronze wire cloth, with the following openings: 1000, 500, 250, 106, 75, and $53 \mu\text{m}$
9. Electric oven and weighing jar

Method

The hydrometer method used is modified procedure by Gee and Bauder (1986).

Calibration of Hydrometer. Fill a cylinder with 100 mL of the HMP solution and fill to 1 L with room-temperature distilled water. Record the temperature after thoroughly mixing with a plunger. Lower the hydrometer into the solution and calculate RL, the (blank) solution's

hydrometer-scale reading. Examine the upper border of the meniscus that surrounds the stem. During the hydrometer testing, retest RL on a regular basis. In the analysis, the calibration value RL is employed to compensate for solution viscosity and soil solution concentration, C.

Dispersion of Soil. In a 600 mL beaker, place 40.0 g of soil, 250 mL of distilled water, and 100 mL of the HMP solution. Let the sample soak for the night. The precise sample size is determined on the soil's texture. 10 to 20 g may be sufficient for silty or clay soils or soils with fine textures. To get repeatable results with coarse grains, between 60 and 100 g will be required. Before testing, most soils from the temperate zone can be air-dried. However, samples must be kept at field wetness for a lot of tropical soils and volcanic soils. To calculate the oven-dry weight of the soil, weigh a second sample (about 10 g). Dry for one 105°C overnight, then cool and weigh.

Place the HMP-treated sample in a mixing cup and combine for five minutes with can pour the suspension into 500-mL shaker bottles and shake them overnight on a horizontal shaker, or use the electric mixer. We have found that shaking overnight on a typical horizontal shaker table, employing a 5-cm stroke and a 2-s cycle, is just as effective as mechanical mixing with soils ranging from coarse sand to silts. Transfer the suspension to a sedimentation cylinder, then top it off with 1 L of distilled water.

Hydrometer Measurement. Give the suspension some time to reach thermal equilibrium before taking the temperature. Place the plunger inside the cylinder, then thoroughly stir the mixture. Hold the cylinder's base to keep it from toppling. Use the plunger to forcefully lift the silt from the bottom. Add two or three more calm, fluid strokes to complete the stirring. A different method of mixing is to stop the cylinder and shake it end over end for a minute. If the surface of the solution is covered in foam, add a drop of amyl alcohol. The hydrometer should be lowered into the suspension as soon as the mixing is finished. Readings should be taken after 30 seconds and again after one minute. The hydrometer should be removed, washed, and dried. Take readings at 3, 10, 30, 60, 90, 120, and 1440 min, carefully reinserting the hydrometer about 10 seconds before each reading. The reading schedule can be changed as necessary. After each reading, remove the hydrometer and clean it. Take note of the reading R each time. After submerging the hydrometer in a fluid devoid of soil, read the result, and for each reading, note the temperature and the blank reading as RL.

Separation of Sand Fractions. Pour the sediment and suspension from the 1-L sedimentation cylinder through a 53- μm (270-mesh) sieve in a precise amount. Over a sink, a sieve with a 20-cm (8-in.) diameter is positioned. A wash bottle or a soft stream of water is used to wash the sediment onto the 53- μm screen. To increase the screen's wettability and hasten the flow, the 53- μm screen can be submerged in a soap solution.

Sand should be transferred to an aluminium or tared beaker, dried at 105 degrees, and weighed. Transfer the dry sand to the nest of sieves, which are placed 1000, 500, 250, 106, and 53 μm from top to bottom. For three minutes, shake the sieve. Weigh each sand fraction as well as any silt or clay that is still present after passing through the 53- μm filter.

Calculation of Particle Size. Determine C, the concentration of soil in suspension (g L^{-1}), using $C = R - R_L$. R and R_L are taken at each time interval. Determine P, the summation percentage for the given time interval, using Equation, $P = (C/C_0)100$. Determine X, the mean particle diameter in suspension (μm) at time t, using Equation, $X = \theta t^{-1/2}$.

For the special case that X and t are reported in micrometres and minutes, respectively, and all other terms expressed in centimetres–grams–seconds units, the sedimentation parameter is commonly written as

$$\theta = 1000(Bh)^{1/2}$$

Plot a summation percentage curve (P vs. $\log X$) using hydrometer readings taken over a time period from 0.5 min to 24 h coupled with sieve data. From this curve determine sand, silt, and clay percentages.

For routine textural analysis, a summation percentage curve has more detail than is required; hence, the following procedure may be used.

Simplified Clay Fraction Procedure. Take hydrometer readings at 1.5 and 24 h only (record both R and R_L values). Determine effective particle diameter X and summation percentage P for 1.5- and 24-h readings.

Compute $P_{2\mu\text{m}}$ (summation percentage at 2 μm) as follows:

$$P_{2\mu\text{m}} = m \ln(2/X_{24}) + P_{24}$$

Where X_{24} is the mean particle diameter in suspension at 24 h, P_{24} is the summation percentage at 24 h, $m = (P_{1.5} - P_{24})/\ln(X_{1.5}/X_{24})$ and is the slope of the summation percentage curve between X at 1.5 h and X at 24 h, $X_{1.5}$ is the mean particle diameter in suspension at 1.5 h, and $P_{1.5}$ is the summation percentage at 1.5 h.

Sand Fraction Calculation. Using the same method as for $P_{2\mu\text{m}}$, calculate the 50- μm summation percentage, replacing 2 with 50 and using the 30- and 60-s hydrometer readings instead of the 1.5- and 24-h readings, respectively. To get the sand percentages, subtract the calculated $P_{50\ \mu\text{m}}$ value from 100. A 53- or 47- μm screen should be used to conduct a typical sieve study for comparison. The sieve analysis is often the best method for obtaining the sand fraction.

Silt Fraction Calculation. By using the difference as follows, calculate the silt percentage.

$$\% \text{ silt} = 100 - (\% \text{ sand} + \% \text{ clay})$$

An easy way to calculate the amounts of sand, silt, and clay is with a programmable desk calculator or a microcomputer. There are several computer programs that can transform size fraction values into textures (Christopher & Mokhtaruddin, 1996; Gerakis & Baer, 1999)

Since the hydrometer method doesn't involve pre-treatment, flocculation of clay by soluble salts or gypsum during sedimentation may lead to considerable inaccuracies. Kaddah (1975) suggests raising the HMP concentration to levels sufficient to keep the dispersion. If higher concentrations are employed, the blank solution must have the same amount of HMP in it as the soil solution did in order for the blank reading, RL, to account for the increasing density and viscosity of the solution. Pre-treatment processes, removal methods (Rivers et al., 1982), or chemical treatment (Hesse, 1976) may be required if the soil contains a lot of soluble salts or gypsum.

Appendix II: Irrigation Water application Schedule

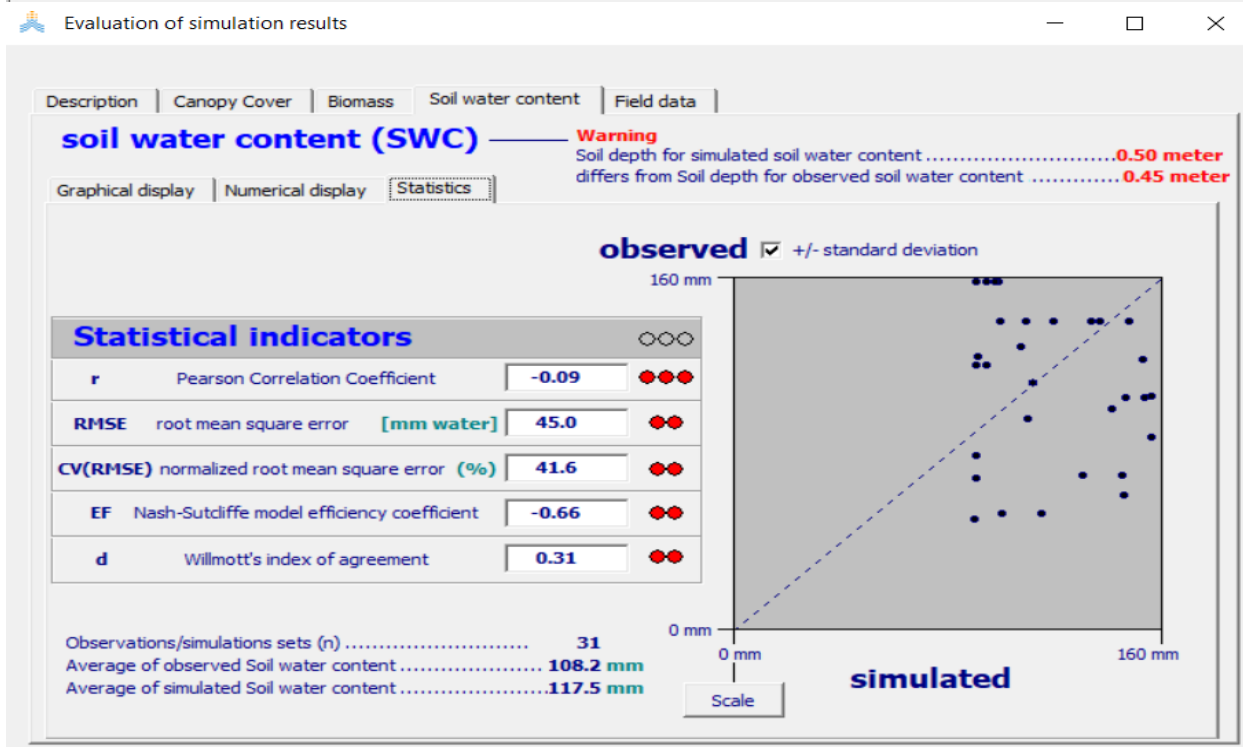
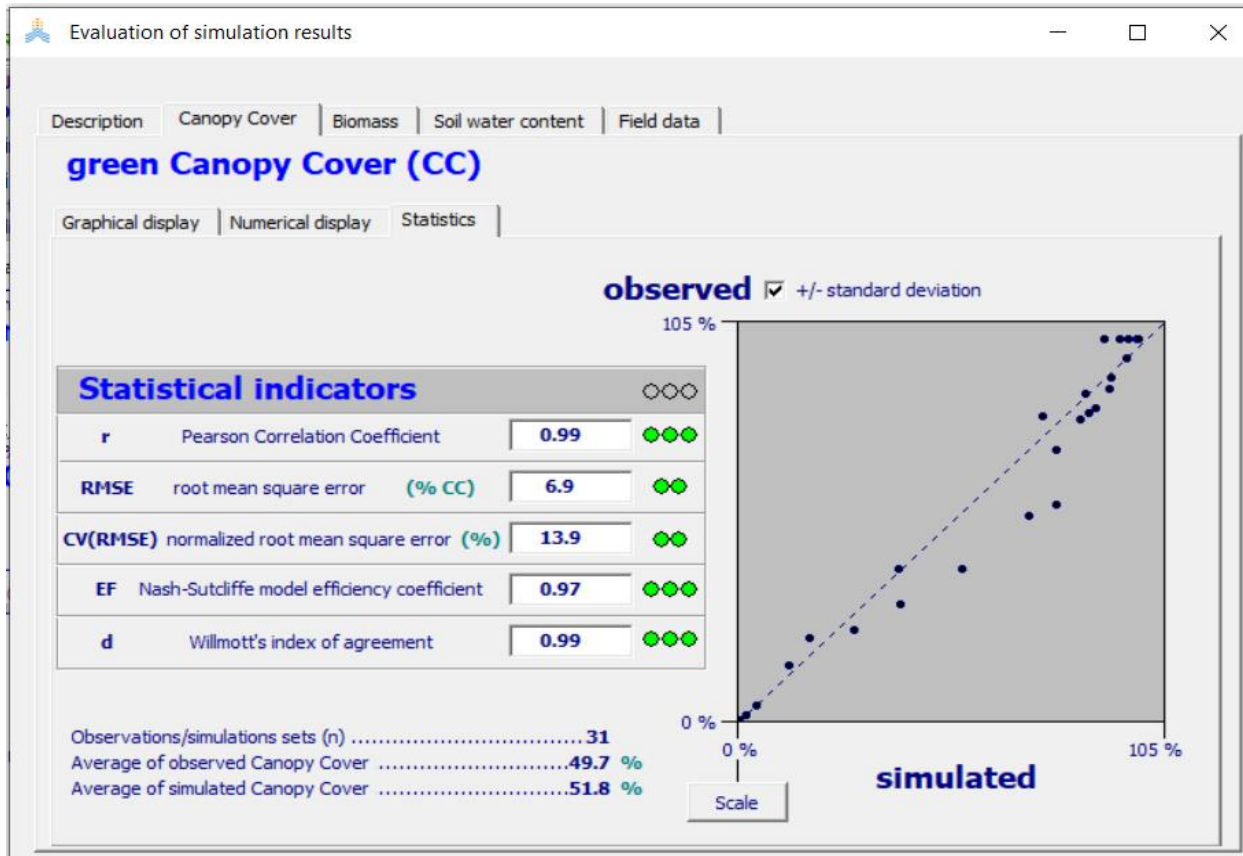
D.A.P (days)	Irrigation Event Date	Irrigation depth (mm)			Calculated ETc (mm)		
		100% I.L.	85% I.L.	70% I.L.	100% I.L.	85% I.L.	70% I.L.
9	5/1/2022	10	10	10	14.58	14.580	14.580
13	9/1/2022	10	10	10	14.58	12.392	10.208
17	13/1/2022	10	10	10	14.58	12.392	10.208
21	17/1/2022	13.9	12.6	10.4	21.87	18.588	15.312
27	23/1/2022	13.9	12.6	10.4	18.225	15.490	12.760
32	28/1/2022	13.9	12.6	10.4	14.58	12.392	10.208
36	1/2/2022	13.9	12.6	10.4	26.325	22.375	18.430
41	6/2/2022	13.9	12.6	10.4	26.325	22.375	18.430
46	11/2/2022	24	20	16.8	26.325	22.375	18.430
51	16/2/2022	24	20	16.8	26.325	22.375	18.430
56	21/2/2022	24	20	16.8	26.325	22.375	18.430
61	26/2/2022	24	20	16.8	31.59	26.850	22.116
67	4/3/2022	24	20	16.8	45.31	38.515	31.715
72	9/3/2022	24	20	16.8	54.372	46.218	38.058
78	15/3/2022	32	27.2	22.4	27.186	23.109	19.029
81	18/3/2022	32	27.2	22.4	36.248	30.812	25.372
85	22/3/2022	32	27.2	22.4	36.248	30.812	25.372
89	26/3/2022	32	27.2	22.4	72.496	61.624	50.744
97	3/4/2022	32	27.2	22.4	33.285	28.294	23.303

104	10/4/2022	19.7	17.11	14.73	33.285	28.294	23.303
111	17/4/2022	19.7	17.11	14.73	28.53	24.252	19.074
117	23/4/2022	19.7	17.11	14.73	23.775	20.210	16.645

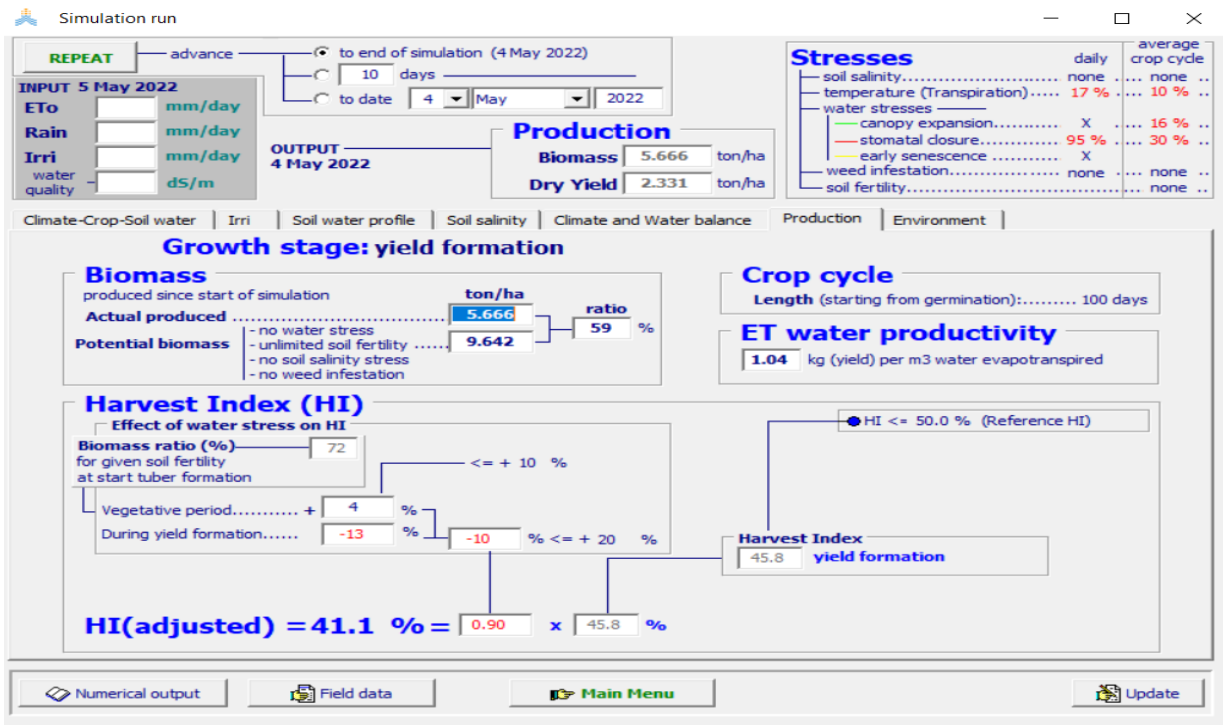
Appendix III: Climatic parameters for growth period.

Month	Max Temp (°C)	Min Temp (°C)	e _a (kPa)	e _{sat} (kPa)	Wind speed u ² m/s	Sun Shine hours	Solar Radiation MJ/m ² /d	Net Radiation (MJ/m ² /d)	ET ₀
Jan-21	24	17	1.938	2.984	4.4	11.4	25.56	10.43	6.9
Feb-21	23.5	12.5	1.449	2.896	4.9	11.4	27	11.02	7.5
Mar-21	26	14.5	1.651	3.361	8.0	11.3	26.28	10.72	7.9
Apr-21	25	14	1.599	3.168	4.6	11.1	22.68	9.25	6.9
May-21	24.5	11	1.313	3.075	6.4	11.2	21.24	8.67	6.9
Jun-21	22.5	12	1.403	2.726	5.2	11.2	20.16	8.23	5.9
Jul-21	24.5	12	1.403	3.075	5.9	11.1	19.44	7.93	6.4
Aug-21	25	12	1.403	3.168	4.9	11.2	20.88	8.52	6.8
Sep-21	23.5	11	1.313	2.896	7.1	11.2	23.4	9.55	7.0
Oct-21	24.5	12.5	1.449	3.075	6.1	11.3	23.4	9.55	7.1
Nov-21	24.5	14	1.599	3.075	6.9	11.2	22.32	9.11	6.7
Dec-21	23	12	1.403	2.809	4.8	11.5	23.76	9.69	6.8
Jan-22	24	13	1.498	2.984	5.3	11.4	25.56	10.43	7.3
Feb-22	25	11	1.313	3.168	5.7	11.4	27	11.02	8.1
Mar-22	26.5	16	1.818	3.462	7.1	11.3	26.58	10.84	7.9
Apr-22	23	14	1.599	2.809	5.9	11.1	23	9.38	6.3

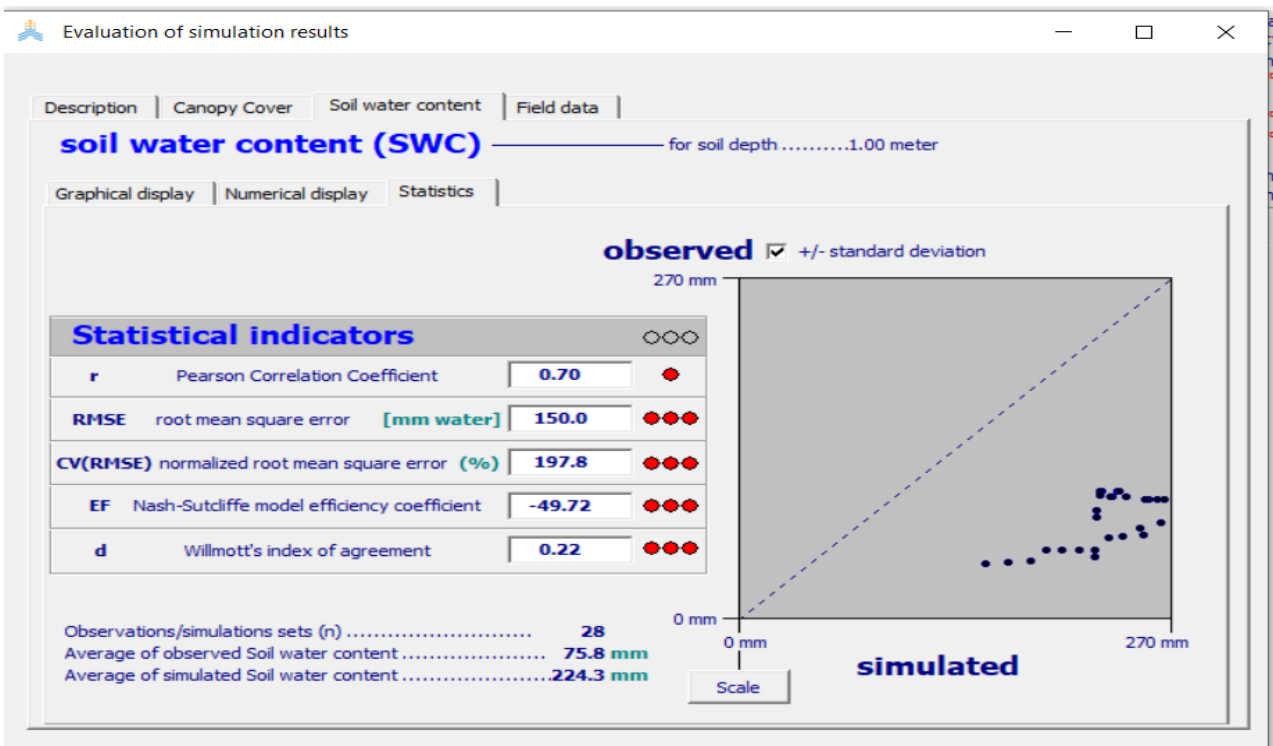
Appendix IV: AquaCrop Simulation Results Scripts



Harvest Index, Biomass, Water Productivity and Dry Yield output



SWC simulation for SAP containing treatment



Appendix V: AquaCrop Simulation Results

Model Performance Indicator		Treatment											
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Canopy Cover	R2	0.98	0.92	0.86	0.94	0.94	0.88	0.92	0.77	0.9	0.93	0.86	0.92
	RMSE	7.7	19.9	10.6	9.5	9.1	11.6	13.7	19.6	12.5	20.8	13.6	10.2
	NRMSE	15.5	26.8	14.4	20.3	13.7	17.8	29.1	29.4	19.1	46.4	18.6	15.3
	NSE	0.96	0.49	0.84	0.94	0.93	0.83	0.87	0.69	0.8	0.7	0.84	0.9
	d	0.99	0.97	0.96	0.98	0.98	0.96	0.97	0.91	0.95	0.93	0.96	0.97
Soil water content	R2	0.38	0.71	0.62	0.33	0.79	0.35	0.06	0.64	0.4	0.01	0.49	0.66
	RMSE	34.4	131.3	138.9	36.6	142.1	145.8	39	130.4	145.1	38.6	122.5	161.4
	NRMSE	31.8	154.2	204.3	30.6	163.3	192.3	32.6	149.9	191.4	32.3	140.8	212.8
	NSE	0.03	-33.18	-44.98	-0.02	-47.65	-46.89	-0.16	-39.94	-46.44	-0.14	-35.16	-57.67
	d	0.52	0.26	0.23	0.59	0.24	0.22	0.55	0.25	0.22	0.55	0.25	0.22
Actual Dry Yield		3.43	2.98	2.53	3.5	3.21	2.84	3.7	3.36	3.12	3.93	3.34	2.97
Actual WP		1.04	1.07	1.09	1.06	1.15	1.23	1.12	1.2	1.35	1.19	1.19	1.29
Irrigation (mm)		463	400	339	463	400	339	463	400	339	463	400	339
Biomass													
Simulated Dry Yield		5.12	4.776	3.637	5.112	4.552	3.324	5.17	4.769	3.707	5.259	4.846	3.995
Simulated WP		1.38	1.09	1.11	1.38	1.48	1.22	1.37	1.47	1.36	1.38	1.44	1.33
Irrigation (mm)		478	401	347	478	401	347	478	401	347	478	401	347
Biomass		10.41	7.96	6.852	10.451	7.73	6.809	9.61	8.155	6.852	10.711	8.381	7.648
Harvest Index (HI)		49.2	43.6	53.1	48.9	58.9	48.8	48.7	58.5	54.1	49.1	57.8	52.2

Appendix VI: Summary Statistical Table

Irrigation							Normal
level	Variable	n	mean	SD	Statistic	p	p>0.05
70%	Dry Yield	4	2.9	0.279	0.871	0.300	Normal
85%	Dry Yield	4	3.25	0.209	0.964	0.801	Normal
100%	Dry Yield	4	3.64	0.225	0.938	0.644	Normal
No SAP	Dry Yield	3	2.98	0.45	1.000	0.966	Normal
6kg/ha	Dry Yield	3	3.18	0.331	0.995	0.684	Normal
10kg/ha	Dry Yield	3	3.39	0.291	0.990	0.266	Normal
14kg/ha	Dry Yield	3	3.5	0.411	0.993	0.403	Normal
70%	Tubers	4	8.5	0.577	0.729	0.0239	_____
85%	Tubers	4	9.75	0.957	0.863	0.272	Normal
100%	Tubers	4	11.5	1.29	0.993	0.972	Normal
No SAP	Tubers	3	9.00	1.00	1.00	1.00	Normal
6kg/ha	Tubers	3	9.33	1.53	0.964	0.637	Normal
10kg/ha	Tubers	3	10.3	2.00	0.964	0.637	Normal
14kg/ha	Tubers	3	11	1.53	0.964	0.637	Normal
70%	WP	4	1.24	0.109	0.964	0.803	Normal
85%	WP	4	1.15	0.061	0.878	0.330	Normal
100%	WP	4	1.1	0.067	0.944	0.680	Normal
No SAP	WP	3	1.06	0.029	1.00	0.981	Normal
6kg/ha	WP	3	1.14	0.086	1.00	0.994	Normal
10kg/ha	WP	3	1.22	0.118	0.97	0.667	Normal
14kg/ha	WP	3	1.22	0.055	0.781	0.069	
70%	Chatts	4	12.1	4.64	0.99	0.882	Normal
85%	Chatts	4	13.6	2.51	0.896	0.409	Normal

100%	Chatts	4	11	0.61	0.977	0.882	Normal
No SAP	Chatts	3	11.4	2.02	0.75	0	_____
6kg/ha	Chatts	3	14.1	3.32	0.966	0.646	Normal
10kg/ha	Chatts	3	12.1	2.76	0.867	0.288	Normal
14kg/ha	Chatts	3	11.4	4.4	0.998	0.921	Normal
70%	plantWT	4	0.292	0.026	0.967	0.825	Normal
85%	plantWT	4	0.329	0.017	0.872	0.307	Normal
100%	plantWT	4	0.372	0.022	0.938	0.644	Normal
No SAP	plantWT	3	0.305	0.047	1	0.988	Normal
6kg/ha	plantWT	3	0.325	0.034	0.995	0.87	Normal
10kg/ha	plantWT	3	0.347	0.03	0.989	0.795	Normal
14kg/ha	plantWT	3	0.348	0.049	0.983	0.754	Normal

Appendix VII: Repeated Measures ANOVA

ANOVA Dry Yield

Effect	DFn	DFd	F	p	p<0.05	ges
Irrigation	2	6	90.538	0.000033	***	0.68
SAP	3	6	26.366	0.000746	**	0.297

ANOVA Chatts

Effect	DFn	DFd	F	p	p<0.05	ges
Irrigation	2	6	0.606	0.576	ns	0.143
SAP	3	6	0.419	0.746	ns	0.148

ANOVA Number of Tubers

Effect	DFn	DFd	F	p	p<0.05	ges
Irrigation	2	6	46.714	0.00022	*	0.675
SAP	3	6	13	0.005	*	0.282

ANOVA Water Productivity

Effect	DFn	DFd	F	p	p<0.05	ges
Irrigation	2	6	11.797	0.008	*	0.399
SAP	3	6	9.83	0.01	*	0.5

ANOVA Tuber weight per plant

Effect	DFn	DFd	F	p	p<0.05	ges
Irrigation	2	6	60.676	0.000105	**	0.74
SAP	3	6	12.181	0.006	*	0.223

Appendix VIII: Sample Output from RStudio program analysis

```

      Effect DFn DFd    F      p p<.05 ges
1 Irrigation  2   6 64.273 8.87e-05 * 0.858
> res.aov <- anova_test(data = Yield, dv = Total.Yield, wid = Irrigation, within = SAP)
> get_anova_table(res.aov)
ANOVA Table (type III tests)

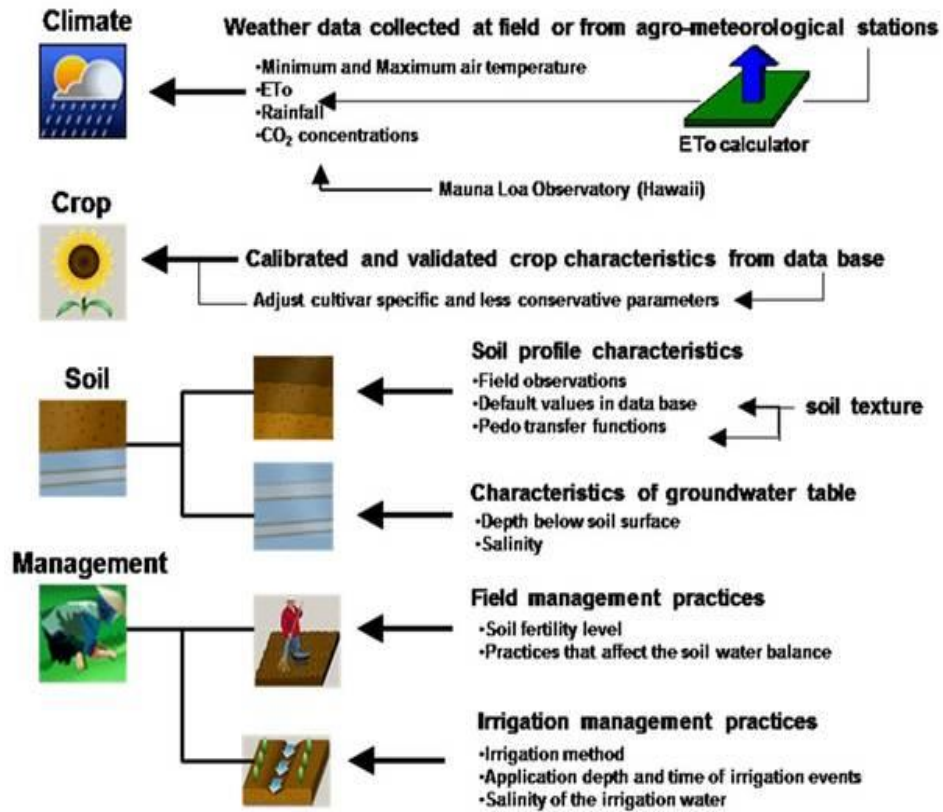
      Effect DFn DFd    F      p p<.05 ges
1     SAP    3   6 5.082 0.044 * 0.102
> res.aov <- anova_test(data = Yield, dv = Tubers, wid = Irrigation, within = SAP)
> get_anova_table(res.aov)
ANOVA Table (type III tests)

      Effect DFn DFd    F      p p<.05 ges
1     SAP    3   6 13.6 0.004 * 0.262
> res.aov <- anova_test(data = Yield, dv = Tubers, wid = SAP, within = Irrigation)
> get_anova_table(res.aov)
ANOVA Table (type III tests)

      Effect DFn DFd    F      p p<.05 ges
1 Irrigation  2   6 54.6 0.000141 * 0.7
> # pairwise comparisons
> pwc <- Yield %>%
+   pairwise_t_test(
+     Total.Yield ~ SAP, paired = TRUE,
+     p.adjust.method = "bonferroni"
+   )
> pwc
# A tibble: 6 x 10
  .y.      group1 group2    n1    n2 statistic    df    p p.adj p.adj.signif
* <chr>    <chr>  <chr>  <int> <int> <dbl> <dbl> <dbl> <dbl> <chr>
1 Total.Yield 10kg/ha 14kg/ha    3     3  0.0485    2 0.966 1      ns
2 Total.Yield 10kg/ha 6kg/ha     3     3  2.96     2 0.098 0.587 ns
3 Total.Yield 10kg/ha No SAP    3     3  2.33     2 0.145 0.87  ns
4 Total.Yield 14kg/ha 6kg/ha     3     3  3.46     2 0.074 0.446 ns
5 Total.Yield 14kg/ha No SAP    3     3  2.71     2 0.113 0.678 ns
6 Total.Yield 6kg/ha No SAP     3     3  0.571    2 0.625 1      ns
> |

```

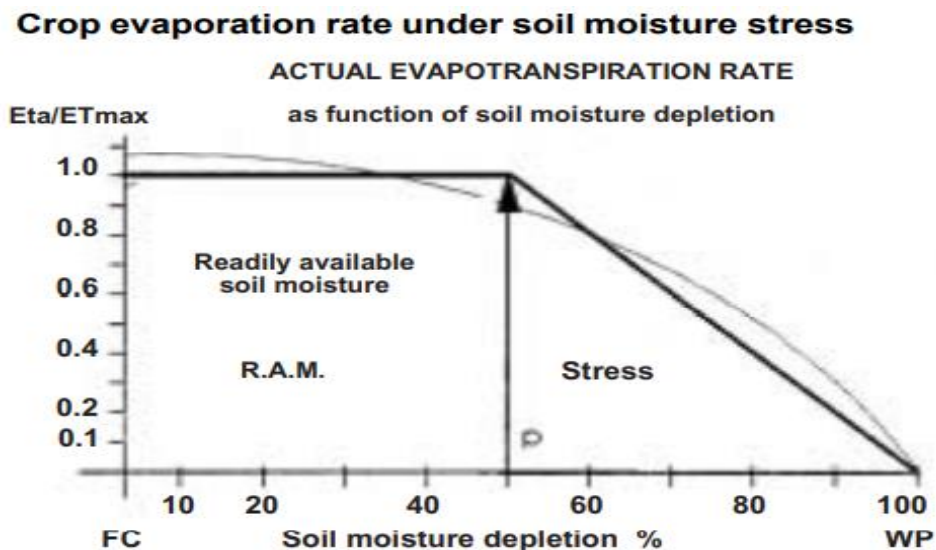
Appendix IX: AquaCrop Model Input Requirements Summary



Source (Steduto et al., 2012)

Appendix X: Actual Crop Evapotranspiration rate as a function of soil moisture depletion

(Smith & Kivumbi, 2002)



Appendix XI: Experimental field Plates



Drip Sytem lateral allignment



Button dripper attached to spaghetti tube supplied to each potato tuber



A week after crop emmergence, measurement of crop height.



Crop radial cover measurement (canopy cover)



Root zone soil moisture measurement using moisture sensor before irrigation event



Root zone soil temperature monitoring using temperature sensor



Developmental phase of the crop growth



Flowering stage full canopy cover achieved



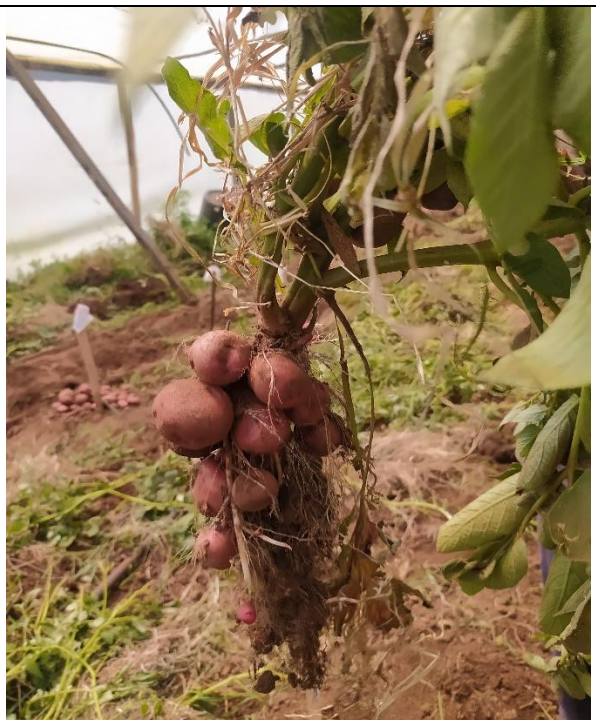
Canopy senescence start



Harvested potatoes for plot P3 with 70% irrigation level and 0kg/ha Superabsorbent polymer treatment



Above ground and below ground biomass at the time of harvesting



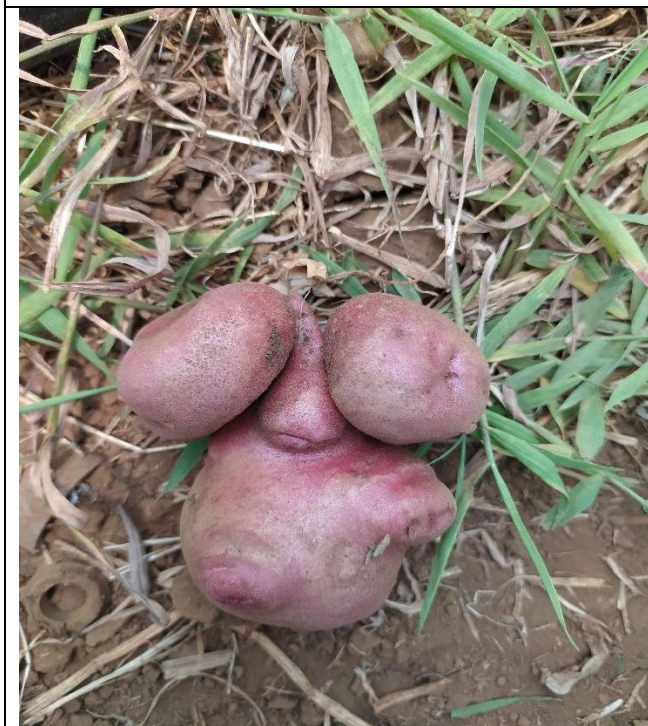
Potato tubers per plant harvested for plot with 10kg/ha SAP



Crop root and tubers distribution



Sorting of harvested potatoes



The irregular shape typical for potatoes grown under 70% irrigation level and 0kg/ha SAP



Sampled potato sizes for measurement of weights for each class sorted



Harvested tubers for potatoes grown under rainfed environment



Potato dry weight determination

Appendix XII: NACOSTI Research License

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Appendix XIII: Abstract of Paper Published from Work

MODELLING OF POTATO CROP WATER PRODUCTIVITY AND YIELD RESPONSE UNDER SUBSURFACE DRIP IRRIGATION SYSTEM

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ABSTRACT:

The need for increased food production by applying low water quantity is posing more challenges to farmers. The production of Irish Potatoes in Kenya in arid and semi-arid areas is challenging for most farmers due to low yields. The purpose of the study was to simulate potato crop water productivity. A field experiment was conducted at Egerton University during the 2021-2022 dry season. The effect of deficit subsurface drip irrigation allied with superabsorbent polymer soil amendment on growth parameters and yield of potatoes was evaluated. Twelve treatments composed of three water application levels 70%IL, 85%IL, 100%IL and four super absorbent polymer (SAP) application rates No SAP, 6 kg/ha, 10 kg/ha, and 14kg/ha laid in factorial experimental design were applied in December 2021 to May 2022 season. Irrigation was undertaken when the allowable water depletion reached 50%. The AquaCrop model was utilised to predict soil water content, biomass, canopy cover, dry yield, and water productivity (WP). The 100% water application level with 0kg/ha SAP was used in model calibration, whereas the remaining treatments were used to validate the model. The model simulated results compared with observed canopy cover, biomass and WP produced a good performance fit with R² range of 0.86 to 0.98, root mean square error (RMSE) of 10.6%, NSE of 0.9, and Wilmot's degree of agreement of 0.98. However, the model underestimated the water content due to the application of SAP in the soil. Because the SAP improved soil characteristics relevant for water holding capacity without changing the physical texture and structure of the soil. The findings indicated that the combined effect of SAP and subsurface drip resulted in increased yield in deficit water application. The calibrated model was successfully applied in simulating WP and yield. The calibrated AquaCrop model can be applied in planning, operation and management of potato-irrigated farms that will lead to improved water productivity and yield in water constrained areas like semi-arid Kenya.

Keywords: *Water Productivity, AquaCrop Model, Soil Water Content, Super Absorbent Polymer, Deficit Subsurface*