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Rainwater harvesting for smallholder farmers in northern Ghana

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Abstract

In this study, suitable rainwater harvesting techniques are investigated for smallholder farmers in northern Ghana, in order to reduce the impact of dry spells during the growing season. Dry spells and water shortage during the growing season have a negative impact on food production in northern Ghana, where 95% of the farms are rainfed. A potential solution for rainwater harvesting for smallholder farmers is adding organic materials to the soil. Here, we conduct a local field experiment comparing two plots in a maize field, one treated plot with added sheep excrement and one untreated plot as control plot. Results show twice as large grain yield for the treated plot, while observed soil moisture levels are not significantly different between the two plots. The behaviour of water in the maize field is analysed with a water balance model, which reproduces the overall dynamics of soil water storage, but overestimates peaks in response to precipitation events. The model confirms that soil water levels remain well above the wilting point in both plots during the growing season. The measured soil moisture is also used to calibrate an AquaCrop model, which is an FAO crop model giving yield outputs. The crop output of the AquaCrop model shows no difference between a field with and without manure, indicating again that soil moisture in this case is not the determining factor for yield differences found in the field experiments. A possible explanation for the difference in yield is the release of nutrients from the manure throughout the season, which were not yet captured in the soil sampling. Besides that, no dry spells occurred during the growing season, so the effects on a real dry soil could not be measured. A multi-criteria analysis is used to assess the suitability of rainwater harvesting solutions that are suitable for smallholder farmers in northern Ghana. It is found that multiple in-situ and micro-scale rainwater harvesting technologies are suitable, like deep tillage, adding manure and conservation agriculture. It should be noted that having the required knowledge to apply these rainwater harvesting technologies successfully is essential.

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1
Introduction

Short dry spells and water shortage during the growing season have a negative impact on food production in countries in Sub-Saharan Africa (SSA) [41][47][50][60]. Especially smallholder farmers in the northern part of Ghana, where over 95% of agriculture is rainfed [20][46][72]. Water shortages during the growing season have resulted in a yield reduction of 50 to 70% in the past years for these farmers [5][12]. The unpredictability of rainfall due to climate change effects is expected to increase such adverse impacts of increasing dry spells [39][60]. Rainfed agriculture in African countries already shows the poorest productivity globally, while it is the biggest economic driver of many countries. With the UN striving to reduce the people in food insecurity situations by 50% worldwide, it is essential to elaborate risk mitigation strategies to lessen hunger in the world [47]. It is vital to understand climate variability and measures that reduce the impact of dry spells during the growing season in order to increase crop yield for smallholder farmers in northern Ghana [20]. This will then lead to a decrease in the number of fields in the region to look like Figure 1.1.

Figure 1.1: A maize field in northern Ghana showing dead plants after a multiple-day drought

The farmers in northern Ghana are amongst the poorest people in the country, with a poverty rate of 70.7% in the Upper West region [72]. The main crops that farmers grow in northern Ghana are maize, millet, sorghum, yam, cowpea and groundnuts, of which maize is the most common [57][72]. It is common for smallholder farmers to gradually grow their cattle herds after a good season in order to have a buffer and be able to sell the cattle again after a season with a lower crop yield [57]. However, most of the poor smallholder farmers do not have this buffer and are forced to sell other household valuables in order to have some money after a bad season. This results in a downward spiral and reduces the chance to improve their farms even more [57]. Due to lack of financial means, the majority of the smallholder farmers can not invest in irrigation technologies and therefore stick to rainfed production [47][85].

To reduce the impact of dry spells during the growing season, rainwater harvesting (RWH) is a potential solution with proven results. RWH covers a range of methods in which local surface runoff is collected and stored, evapotranspiration is reduced and the infiltration capacity of a soil is increased. RWH in general results in better soil moisture retention compared to conventional tillage and so it could be a beneficial method to reduce water scarcity for farmers [47][69]. For agricultural production the water could be stored underground, where it is protected from evaporation. There is a great variety in RWH solutions, ranging from large-scale to small-scale and from high-tech to low-tech [20][47][54].

Over the years, both governmental and non-governmental organisations have tried to improve productivity of farms in northern Ghana. They have tried implementing policy focusing on minimising the impact of agriculture on the environment while improving the agricultural production, but also the usage of new seeds every season, a responsible use of fertilisers and crop rotation. However, none of these attempts have had the desired effect on a large scale. Therefore, other possible solutions need to be investigated in order to reduce food insecurity and poverty in northern Ghana [64][71].

Mitigation strategies that reduce the impact of climate change on food security and crop yield in northern Ghana should be designed in order to minimize the effect of dry spells during the growing season. Some of the richer farmers are already implementing risk reduction strategies, like growing multiple crops and having a cattle herd [57][71].These are, however, mitigations that secure the farmer's income, but do not necessarily contribute to large scale food security. A more reliable availability of water would really have an impact on crop yield and thus food security.

1.1. Research objective and questions

The aim of this study is to identify suitable rainwater harvesting techniques for smallholder farmers in northern Ghana, in order to reduce the impact of dry spells during the growing season, and test one of the potential techniques, adding extra materials to the soil, for its effect on crop water availability and yield.

In order to find an answer to this aim, five research questions are answered. Three research questions are related to field experiments and two are related to the application of rainwater harvesting.

Field experiments

1. What is the soil water variability during the growing season in a typical maize field in northern Ghana?

2. How does the addition of sheep excrement as manure to the top layer of a dry soil influence crop development?

3. How does manure influence the soil water holding capacity?

Rainwater harvesting application

4. How do smallholder farmers in northern Ghana deal with dry spells for their crops?

5. What are suitable rainwater harvesting solutions for smallholder farmers in northern Ghana to reduce the impact of dry spells?

2

Background

2.1. Smallholder farmers in northern Ghana

The vast majority of farmers in northern Ghana is smallholder, which means that they cultivate an area of less than two hectares [19][24]. Besides the cultivated land area, there are no other clear characteristics that define smallholder farmers, although a larger part of the smallholder farmers have limited money, high exposure to drought related risks and low input of technologies [24][56]. Smallholder farmers are unique for all being organised in their own way, not one smallholder farm is organised exactly like another.

The farmers in northern Ghana used to produce around 40% of the grains and vegetables in the country in the past, which has decreased to only 25% [30]. Water shortages during the growing season have resulted in a yield reduction of 50 to 70% in the past years [5][12]. Over the years, there has been a shift in the main crops grown by smallholder farmers in northern Ghana. The production of maize, casava and rice is increasing, while the production of millet and sorghum is decreasing[24][53]. However, many farmers grow many different crops, with sorghum and millet still being two of the most commonly grown crops, together with rice, maize and groundnut [18][58][61][62].

Besides crops, animals are also an important part of Ghanaian smallholder farms [18][53][58]. The animals are kept as a source of food for the farm household itself, but also as a source of income, especially in years of low yields [56][57][58]. The larger animals are also used for their draught power in field preparation [56].

(a) Farm field right next to the houses

(b) Farm village in northern Ghana

Figure 2.1: Impression of the farm villages in northern Ghana

It is becoming more common amongst smallholder farmers in northern Ghana to use tractors instead of animals for land preparation before sowing [53]. Mechanisation of the agricultural practices and investments in technology are said to have a positive effect on crop yield. The yields in northern Ghana are still very low, with an average maize production of 1.6 tons per hectare, which gives an opportunity for technological advances to increase crop yields [24].

Smallholder farmers in northern Ghana have difficulty getting access to farm credit [24][61]. Farm credit gives the smallholders the opportunity to invest in their farms by spending it on better land preparation or purchase farm inputs like fertilisers. This helps reducing the uncertainty in crop yield [30][53][61]. The lack of money with smallholder farmers due to low income and low access to farm credit results in a poor access to resources. Farmers do not have the money to invest in technologies like irrigation systems that would help improve their farm practices and increase crop yield [19][24].

Many smallholder farmers in northern Ghana are continuously trying to adjust their farming practices to cope with the changing climate [58]. They use more resilient seeds, crop diversification and early maturing crops [30].These changes are however mainly on individual farm basis and very limited compared to what is possible. Even though measures like crop diversification, livestock and having the entire household helping on the field are all low cost measures to increase the crop yield, the smallholder farmers are still too dependent on reliable rainfall and vulnerable to dry spells in the rainy season [18][28].

2.2. Climate change

Climate change is expected to bring more unpredictable weather to Sub-Saharan Africa, resulting in more intense and longer drought in Sub-Saharan Africa [30][39][60]. The onset of the rainy season is already delaying, the rainy season is becoming shorter and dry spells during the season are getting longer [41][59]. The increasing variability in climate shows negative effects on the agricultural production, especially for rainfed agriculture [41][50]. This will be a crisis situation for the country, that is already struggling in the battle against the low food production [64][72]. The hot temperatures in the area furthermore result in high decay rates of the organic matter in the soil, which results in a lower water holding capacity [17].

2.3. Rainwater harvesting

In areas where rain events with an intensity above thirteen mm/h occur, it is likely that part of the rainfall gets lost as runoff, because the infiltration rate of most soils is too low [69]. Furthermore, up to 50% of the rainfall in semi-arid regions can be lost from a field through soil evaporation [22][79]. Water lost through surface runoff and evaporation is an important limiting factor in drought-prone regions in crop production, especially in areas where agriculture is purely rainfed [13][22][54][74]. This means that in the semi-arid northern Ghana, with rain intensities of up to 35 mm/h, a lot of water is lost through runoff and soil evaporation [8][87].

Rainwater harvesting (RWH) focuses on the collection and storage of rainwater. The techniques focus on collection of precipitation or runoff, on the reduction of runoff, or on the storage of water in the soil [54][69][74]. Thus, RWH is applied to reduce these water losses. Research in Tanzania noted that both an increase in yield and long term financial benefit are observed for farmers that applied RWH [50]. Another research has shown an increase of 50 percent of the yields after the application of rainwater harvesting [77]. RWH techniques are mainly grouped in three categories: In-situ, micro-scale and macro-scale.

2.3.1. In-situ rainwater harvesting

With in-situ RWH technologies the rainwater is stored directly underneath the surface on which it falls [47]. In-situ RWH is applied to reduce runoff and evaporation as well as increase the infiltration capacity of the soil [20][54]. Previous research performed in multiple locations in Africa has shown that applying in-situ rainwater harvesting solutions can reduce runoff and increase the soil water content [20]. Multiple known in-situ rainwater harvesting technologies are discussed below.

Deep tillage

With tillage the soil is softened by breaking up the soil and rip hardpans at the surface. Conventional tillage, which goes down to a depth of up to 15 centimeters, is used all over the world by the majority of farmers [2][16]. Deep tillage goes down to a depth of around 30 to 45 centimeters and reduces the bulk density and strength of a soil, which gives crops the chance to root deeper [2][16][54]. Deep tillage results in an increasing infiltration capacity and lower runoff [54]. Deep tillage does require a higher draft power compared to conventional tillage. This results in the need for heavier machinery like tractors to help in the land preparation [54].

Tied ridges

Tied ridges are elevated strips of land surrounding small bits of the arable land. With the application of tied ridges the farmland is divided into smaller bits, separated by the ridges [82]. The technology has shown to be beneficial for reducing runoff and preventing soil erosion, which resulted in an increased crop yield [40][69]. A disadvantage of the closed tied ridges is the possibility of water logging in case of heavy rainfall [20].

Contour farming
The land is cultivated along the contour lines and the crops are also planted along these same contour lines [38][54]. In fields with a slope between two and ten percent, contour farming is usually applied to reduce runoff and erosion [38][54]. The most simple way of contour farming is to just plant the crops along the contour lines, which is sufficient for the shallowest sloped farmlands. With steeper slopes of over three percent however, other types of cultivation might be required, such as the creation of ridges or infiltration pits [54]. Contour farming reduces both soil erosion and runoff water significantly [38].

Adding manure
Adding manure has shown to increase the water holding capacity of a soil as the organic content can bind water efficiently [77][94]. The organic content not only increases the water holding capacity, it also reduces the soil compactness of the soil [68].

Mulching
The soil is partly covered with a layer of organic or non-organic material like plastic, which is common in for example Spain and China [20][51][54]. Mulching decreases runoff and erosion, while increasing the infiltration [3][66]. Mulching also benefits soil moisture retention and decreases the soil evaporation [3][51][66]. Mulching has proven to be useful in semi-arid areas with erratic rainfall, especially for growing high-value crops [51].

Conservation agriculture
Conservation agriculture contains three principles that should together help improve the soil conditions: minimal soil disturbance, permanent soil organic cover and crop diversification [34][89]. Bulk density in plowed fields and fields without tillage is comparable, in contrast to what most farmers believe [88]. Besides that, no-tillage in general also shows higher organic content in the soil compared to tillage [88].

2.3.2. Micro-scale rainwater harvesting

Micro-scale rainwater harvesting systems are designed such that runoff on the farmland is triggered and discharged towards the plants, where it infiltrates and is stored in the soil [20][47][54]. In different studies in Tanzania, Burkina Faso and Ethiopia, the potential of micro-scale rainwater harvesting technologies has shown to give an increase in both soil moisture and crop yield [20]. Micro-scale systems are often used for crops with a medium water requirement, like maize and millet [54]. Multiple known micro-scale rainwater harvesting systems are discussed below.

Strip catchment tillage
With strip catchment tillage the crops are planted in straight lines with strips in between the crop lines. These strips stay bare and the rain that falls on them will flow towards the crops where it infiltrates, increasing the soil moisture for the plants [54][92]. These strips are naturally used as pathways to walk through the field, which results in soil compaction. This results in a decrease in infiltration in the strips and more runoff towards the plants [92].

(a) Ridges (b) Strip catchment tillage

Figure 2.2: Examples of rainwater harvesting technologies applied in northern Ghana

Pitting
Planting pits are holes often filled with livestock manure or other organic matter to increase the water holding capacity. The crops are planted on the sides of the planting pits [20][54]. Pitting is beneficial for both surface runoff reduction and increasing yields [49][69]. The technology is easily applied by hand cultivation and therefore there is no need for heavy machinery [42].

Contour bunds
Small trash, earth or stone embankment along the contour lines of a farm field form contour bunds [20][54]. The water gets trapped upstream of the contour bunds, where it infiltrates into the soil. The contour bunds are easy to construct, but do require heavy machinery power to move materials in large volumes [54].

Fanya juus
Fanya juu is a type of terracing where ditches are combined with earth embankments. The soil dug from the ditches is thrown upslope [69][93]. Sometimes grass is planted along the embankments for stabilisation and against erosion [69]. In general, fanya juus result in a reduction of surface runoff and an increase in both soil moisture retention and yield.

Semi-circular bunds
Semi-circular bunds are small basins surrounded by an earth bund. Runoff water flows into the bund and infiltrates at the lowest point, where the crops are planted [4][20]. The semi-circular bunds are dug in lines along the contour lines.

Meskat-type system
In a Meskat-type system the land area is divided into two parts, a harvest and a planting area. In the harvest area the soil is kept bare and is compacted to induce runoff. This runoff flows downstream to the planting area, which is enclosed by a u-shaped bund. In this planting area the crops are planted [42][54].

2.3.3. Macro-scale rainwater harvesting
Macro-scale harvesting systems cover a larger area that also contains land outside of the farmland. Water is collected from this larger area and guided towards a downstream point where it is stored for later use [20][47][54]. Multiple examples of known macro-scale rainwater harvesting technologies are discussed below.

Hillside runoff utilisation
In areas with high rainfall farmers grow their crops on flat lands at the bottom of hill slopes, where water flows downhill to the crops on the flat area. When the rainfall is not that much, farmers create bunds to harvest more of the down flowing water for their crops [42][54]. The water can also first be stored in for example open ponds, from where it can later be used for irrigation or other purposes [20].

Floodwater harvesting within the stream bed
By building barriers in the stream bed to block the water flow, water is guided to and spread across adjacent areas where it infiltrates. This area can then be used for agriculture [42][54].

Ephemeral Stream Division
With ephemeral stream division the water is diverted off its natural stream and guided towards the agricultural fields to infiltrate. Sowing of the fields usually happens only after the floods have gone and the soil is fully saturated [20][54]. Small dams are places at the upstream side of the fields to manage the inflow of water onto the fields [42][74].

Rainwater harvesting with storage
When more water is harvested with a macro system than can directly be used in the field, there is a need for storage of the excess water, especially when later times without precipitation might ask for water [54]. In this case dams can be constructed, holes can be dug or polytanks can be placed to store the excess water [20][74].

2.4. Organic material and water holding capacity

Soil moisture is an important limiting factor in crop growth [77]. Even though soil moisture is not something farmers can directly control, increasing the organic content of the soil, which is able to bind water efficiently, is something farmers can do [83][94]. This is especially effective in areas where high temperatures cause high decay rates in organic material in the soil [17]. Different studies have shown that increasing the organic content of a soil increases the capability of the soil to retain more water [68][77][80][94]. Animal excrement as manure or crop residue can be used to increase the soil organic content [77]. Manure improves the soil structure and increases the water holding capacity while increasing the organic matter and micro fauna population [15][29][68].

3
Data description

3.1. Study area

The study is conducted in West Africa. In the northern region of Ghana the town of Nyankpala is located, surrounded by agricultural fields. The majority of these agricultural fields are rainfed and thus the availability of water for the crop purely depends on precipitation [24][53]. The most commonly grown crops in the region are maize and rice, while the production of sorghum and millet is decreasing [24][53]. The climate in the area is defined by the Inter-Tropical Convergence Zone (ITCZ). The rainy season starts in May when the ITCZ passes in northward directions [14][59]. The peak precipitation is in September, after which the ITCZ passes in southward direction again, ending the rainy season [14][56][59][72]. The average annual precipitation varies between 800 and 1200 mm, and the temperatures in the rainy season can go up to 30 degrees celsius [46]. The research is done in collaboration with the CSIR | Savannah Agricultural Research Institute (CSIR-SARI), the agricultural research institute located in Nyankpala.

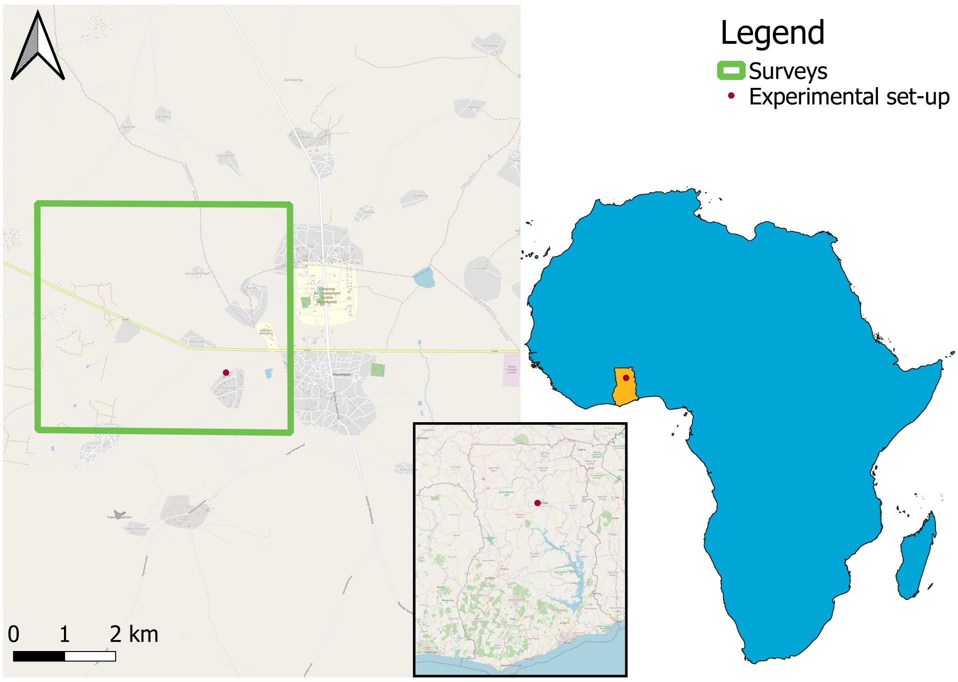

Figure 3.1: Map of the study area indicating the location of the experimental set-up and the area where surveys were conducted

3.2. Data sources

3.2.1. Field experiments

An experimental set-up is built in the area as indicated in Figure 3.1. The set-up contains two plots, an untreated plot that is left in its natural state and a treated plot, where an equivalent of five tons of sheep excrement is added as manure. Both plots are 2.4 by 2.4 meters and bordered with metal sheets to prevent water from flowing into and out of the plot. At the downstream side of each plot, a PVC gutter is installed with a width of fifteen centimeters, reducing the surface of the plot to $2.4 \cdot 2.25 = 5.4m^2$ that is planted with 70 day maize. A 100 liter bucket is placed in the most downstream corner of each plot, underneath the gutter. Finally the slopes in both plots are equalised to have as equal starting conditions as possible. A schematic visualisation of the set-up is shown in Figure 3.2.

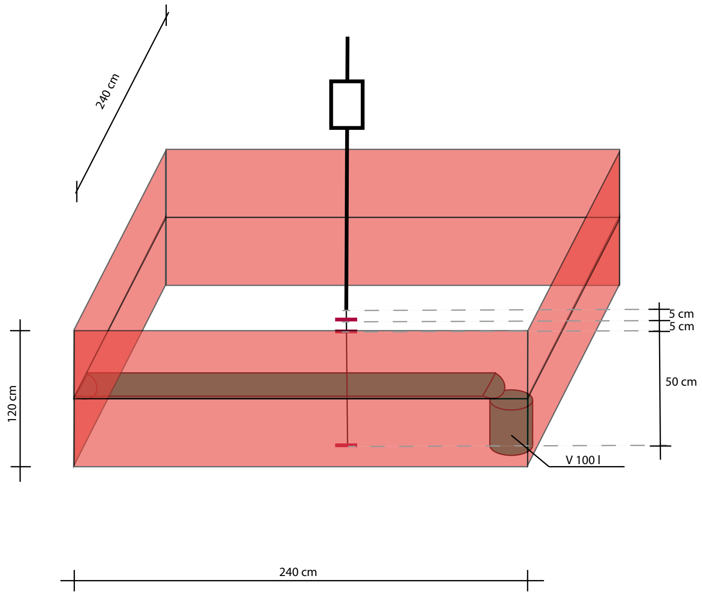

Figure 3.2: Schematic visualisation of the experimental field set-up, with at the downstream side of the plot the gutter and bucket for runoff collection, the TAHMO weather station on a pole in the center of the plot and the soil moisture sensors below the pole

Visual inspection of the soil down to 60 centimeters gives a division into separate soil horizons, as shown in Figure 3.3. Soil samples of approximately one liter are taken from the different identified horizons and analysed in the soil lab at CSIR-SARI in Nyankpala to find the saturation, field capacity and wilting point.

Meteorological data from the Trans-African Hydro-Meteorological Observatory (TAHMO) of station TA00616, which is located at the location of the plots, is used in this study [87]. From the TAHMO station rainfall, temperature, incoming shortwave radiation and soil moisture are used at a five minute time resolution. The climate data retrieved from the station are between 1 May and 29 November 2022. The TAHMO station contains an ATMOS 41 All-in-One Weather Station from METER Group [65]. Furthermore, the weather station measures the incoming shortwave solar radiation using a Pyranometer [86].

Soil moisture in the untreated plot is measured by TEROS 11 soil moisture sensors connected to the TAHMO station at three depths below the plot, at 5, 10 and 60 centimeters. These sensors measure the soil moisture with a resolution of 0.001 m^3/m^3 and an accuracy of 0.03 m^3/m^3 [44].The time resolution of the sensors is one minute and the sensor gives the average of the one minute measurements in a chosen interval.

The soil moisture in the treated plot is measured by three 5TE soil moisture sensors made by METER Group, placed also at 5, 10 and 60 centimeters depth. The sensors have a resolution of 0.0008 m^3/m^3 and an accuracy of around 0.03 m^3/m^3 [43]. These sensors also measure with a time interval of one minute and give the average of the one minute measurements in a chosen interval.

A TD-diver DI801 is placed in the bucket in each plot. The sensors measure the water pressure in cmH2O, with a time resolution of five centimeters [48]. In addition to the two divers a Baro-Diver DI800 barometer is attached to the pole of the TAHMO station. This barometer is used to compensate for the atmospheric pressure. The water pressure is measured in the period from 15 August until 24 October.

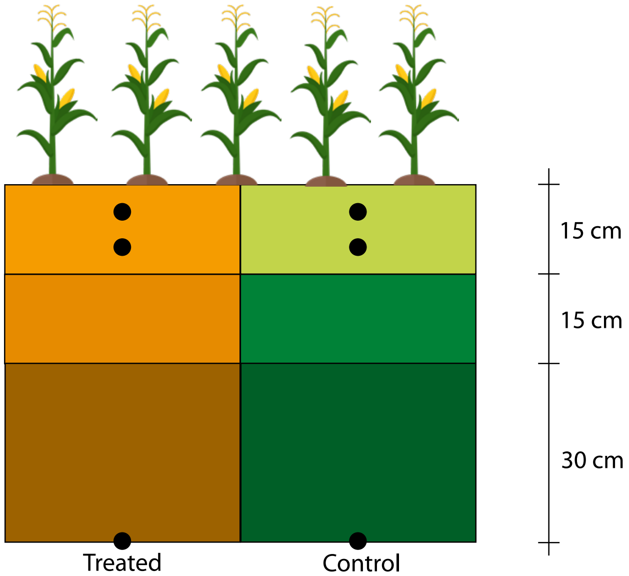

Figure 3.3: Cross section of the soil with the three identified soil horizons and the locations of the soil moisture sensors in both the untreated and the treated plot

3.2.2. Crop development monitoring

Monitoring the development of the maize plants throughout the growing season gives information on how water availability can influence the crop growth. With the use of the VegMon smartphone app the crop height, canopy cover and VIGreen are monitored [9]. This app is based on the ODK platform, a tool to collect data via smartphones and store it in an online environment [73].

The plant height and canopy cover give an indication on how well the crop develops throughout the season and can show how the development is influenced when water shortages occur. The VIGreen is an NDVI proxi and gives an indication on the health of the plant based on the greenness [9]. This gives an indication on the health of the plant, which could also be influenced by water shortages. Crop monitoring with the VegMon app is done every few days throughout the season to capture the influences of daily changes and possible shortages in the soil moisture.

Every few days pictures of the untreated and the treated plot are taken at an angle of 45 and 90 degrees, showing only the plants and soil. It should be avoided as much as possible to have other things than the plants and soil in the picture to prevent disturbance of the analysis. The picture taken at a 45 degrees angle are used for the VIGreen analysis. The pictures taken at a 90 degrees angle are used for both the VIGreen analysis and the canopy cover estimation.

At the end of the season, the crops are harvested and the yields are measured. In both plots the number of plants will be counted. In addition, the total dry weight or biomass of all the plants in the field is measured as well as the total grain weight, which represents the final yield.

3.2.3. Surveys

The local social and cultural aspects are factors that determine failure or success of techniques that are implemented [54]. It is therefore important to talk to the people in order to find their priorities and make sure that a solution fits the local context and will be used by the farmers.

An effective way of getting knowledge from the community is by taking semi-structured interviews [21]. During these interviews, a fixed list of questions is used as a guideline, while additional followup questions can be asked based on the response of the interviewee [52]. The questionnaire for this research contains 25 questions about the farm in general, how the farmers experience water shortages, and if there is anything they (can) do to prevent or limit the damage of water shortages. The full list of questions can be found in Appendix A.

Next to the semi-structured interviews, observation walks around the farms are taken to also get a better understanding of the surroundings of the farmers and the communities [21]. During these observation walks pictures of the fields of the farmers are taken and a checklist with common RWH techniques, as given in Appendix B, is used to see whether farmers use any type of RWH, possibly without knowing it.

As the majority of the farmers does not speak English a translator joins the farm visits to translate both questions and answers. The translator is a farmer himself and is closely related to CSIR-SARI, the Savannah Agricultural Research Institute, which is partnering in this research.

A total of 25 farmers is visited and interviewed. The goal is to have an as diverse group of farmers as possible, with male and female farmers, old and young. The translator, together with the researchers at CSIR-SARI, made the selection of farmers that are visited. In this selection process it was taken into account to have farmers growing different crops in both high- and lowland areas, owning animals or not and being from multiple villages. The surveys are taken in the period between 12 and 23 September, with the specific locations of the farms indicated in Figure 3.1.

4
Methodology

This chapter elaborates on the methods used and a short overview of the pathway at the beginning of each section. The data collection in the field experiments and farm visits have all been performed in the period between July and October 2022.

4.1. Framework of analysis

The data gathered in the field experiments is used in a water balance model and an AquaCrop model to gain more insights in the water balance and crop development. Furthermore, literature will be combined with the survey data to find suitable rainwater harvesting solutions through a multi-criteria analysis (MCA).

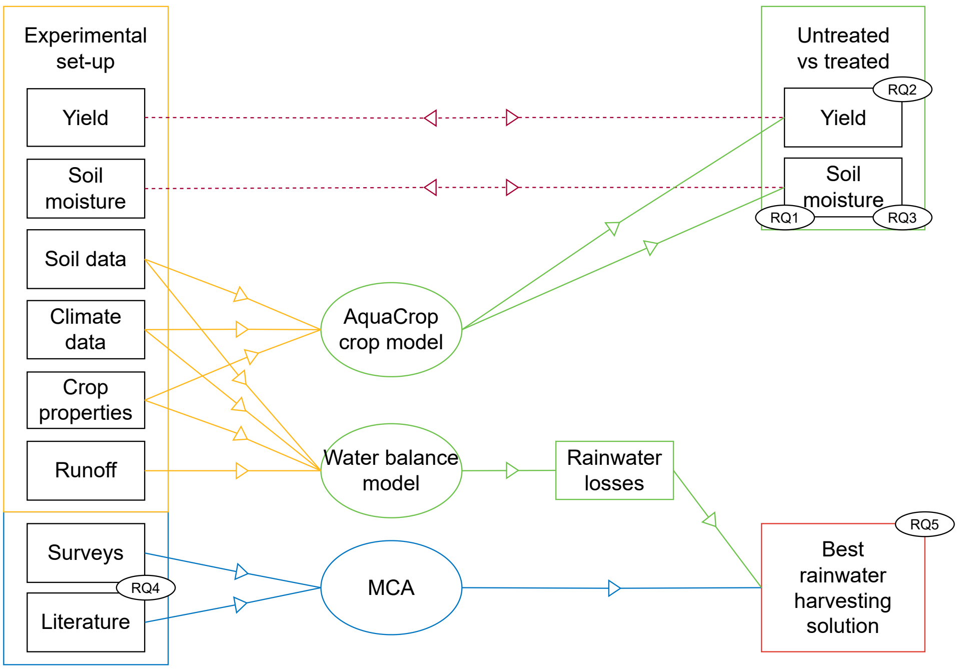

Figure 4.1: Framework of analysis outlining the flow of data gathering and processing data to finding conclusions

4.2. Water balance model

The water balance, as used in the modelling, is displayed in a schematic way in Figure 4.2. The precipitation turns partly into runoff (*R*) and partly into infiltration (*I*). In reality, part of the precipitation is intercepted by the maize canopy, which develops over the season. The other fraction of precipitation reaches the soil as throughfall or stemflow [90][95]. However, as the interception capacity is usually below one millimeter, thus accounts for a minor part of the precipitation, it will not influence the order of magnitude of the fraction of precipitation that reaches the soil [23][70].

A soil specific maximum infiltration rate determines how much water can infiltrate in a specific amount of time. When the water available for infiltration exceeds this infiltration rate the remainder of the water is lost as runoff [55]. The infiltrated water adds to the soil moisture storage (*S*) up to reaching saturation, where again excess water is lost as runoff.

The soil moisture can reduce due to soil evaporation, crop transpiration and deep percolation. For this research, soil evaporation and crop transpiration are combined into evapotranspiration (*E*). Evapotranspiration takes place when the soil moisture is above wilting point, the point where the plants cannot take up any water from the soil. When the soil moisture is above field capacity deep percolation (*D*) takes place. With deep percolation the soil moisture percolates down to the deeper soil layers.

The water balance model uses the meteorological TAHMO data as inputs, combined with the measured soil moisture and water pressure in the buckets. Furthermore, the field capacity and wilting point found from the soil analysis in the CSIR-SARI lab, given in Appendix I, are used as inputs. The final output of the model is an average soil moisture content over the depth, modelled for the full growing season between 15 August and 27 October with a five minute time interval.

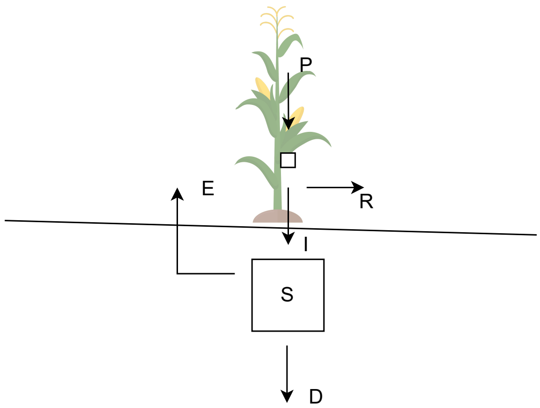

Figure 4.2: Water balance in the maize field as assumed for the analysis

4.2.1. Model description

First, the measured water pressure in the buckets is translated from cm into mm runoff in order to compare it to the measured precipitation from the TAHMO station. Knowing the surface area of the bucket, the water pressure can be converted into a volume, which is divided by the area of the plot to get the runoff per time step in millimeters. The final input values for the water balance model are given in Table 4.1.

$$I = P - R[mm/5min] \tag{4.1}$$

Where I is the infiltration, P the precipitation and R the runoff. The infiltration rate of a soil normally follows an exponential decay, with an initial infiltration rate that decreases to a lower constant rate [67]. In this model the infiltration rate will however be taken as a constant rate over time for simplification of the model. The maximum infiltration capacity is determined at five mm per hour. This is a calibrated value, adjusted until the modelled soil moisture fits in order of magnitude with the measured soil moisture at five and ten cm depth.

$$I[5min^{-1}] = I[mm/5min]/(n \cdot d) \tag{4.2}$$

Where n is the porosity of the soil and d is the infiltration depth in mm. The porosity of the soil is taken as 0.45, which is based on the saturation values found in the soil tests. The infiltration depth is taken to be 60 cm, which is the depth of the deepest soil moisture sensor.

$$S_t = S_{t-1} + I[5min^{-1}] - E - D \tag{4.3}$$

Where S is the soil moisture storage in m^3/m^3, E the evapotranspiration and D the deep percolation. The evapotranspiration is approximated in three steps as shown in Figure 4.3. First, the reference

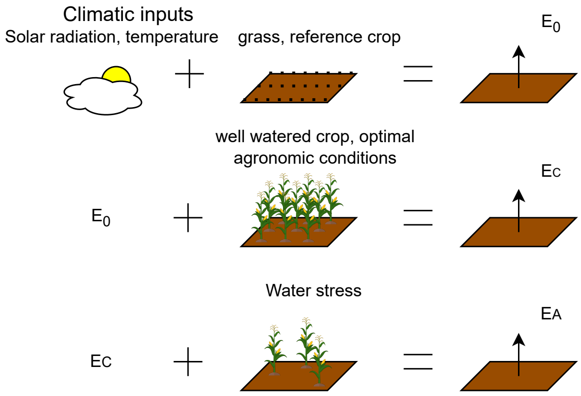

Figure 4.3: Steps to calculate the adjusted evapotranspiration from solar radiation and temperature, using crop characteristics as well as water stresses

evapotranspiration is calculated using Makkink's equation. Subsequently, the crop specific evapotranspiration for maize is calculated, assuming optimal conditions. Finally, the corrected evapotranspiration is estimated, considering possible water and environmental stresses.

Makkink's equation uses the incoming shortwave radiation and temperature, measured by the TAHMO station, to calculate the evaportranspiration for a tall grass field with uniform height between eight and fifteen centimeters [26]. This field is assumed not to be short of water. Equation 4.4 shows how the reference evapotranspiration according to Makkink is calculated.

$$E_0 = \frac{\alpha}{8179.2} \frac{\Delta}{\Delta + \gamma} \cdot R_s \tag{4.4}$$

In this equation α depends on the ratio between the net radiation and the incoming shortwave radiation, as well as on the Priestley-Taylor parameter, which is an adjustment factor [75]. The Priestley-Taylor parameter has a global average of 1.26. The global average ratio between the net radiation and the incoming shortwave radiation is 0.5, but for West Africa specifically calculated to be 0.53 [25][26][81]. Therefore, for this research α equals $0.53 \cdot 1.26 = 0.67$.

Furthermore, $8179.2 = 28.4 \cdot 24 \cdot 12$ is used for unit conversion, to change from Wm^{-2} to $mm \cdot 5min^{-1}$. Δ is the slope of the saturated vapour pressure cure, which is calculated using Equation 4.5 [35]. γ is the the psychometric constant in $kPa°C^{-1}$, which is location dependent and can be calculated using Equation 4.6 [35]. Finally R_s in Equation 4.4 [35] is the incoming shortwave radiation in Wm^{-2}.

$$\Delta = 4098 \cdot \frac{6.1095 \cdot e^{\frac{17.27 \cdot T}{T + 237.7}}}{(T + 237.7)^2} \tag{4.5}$$

In this equation, T is the temperature in $°C$.

$$\gamma = \frac{C_p \cdot P}{\epsilon \cdot \lambda} \tag{4.6}$$

In which C_p is the specific heat at constant pressure, which equals 1.013 $\cdot 10^{-3} MJkg^{-1} °C^{-1}$. P is the atmospheric pressure in kPa, which is location specific and calculated using Equation 4.7 [35]. ϵ is the ratio molecular weight of water vapour / dry air, which equals 0.622. Finally, λ is the latent heat of vaporisation, which is 2.45 $MJkg^{-1}$.

$$P = 101.3 \cdot (\frac{293 - 0.0065 \cdot z}{293})^{5.26} \tag{4.7}$$

In this equation, z represents the elevation above mean sea level in meters for the specific location. The data logger connected to the soil moisture sensor in the treated plot shows to be at 188 meters above sea level [45]. Considering that the data logger is placed 1.5 meters above the ground, the value for z for the specific location is 186.5 meters. This gives an atmospheric pressure P of 99.1 kPa.

Subsequently, a psychometric constant γ of 0.066 $kPa°C^{-1}$ is found, which equals 0.66 $hPa°C^{-1}$. This results in the final Makkink equation used as given in Equation 4.8.

$$E_0 = \frac{0.67}{8179.2} \frac{\Delta}{\Delta + 0.66} \cdot R_s \tag{4.8}$$

A single crop coefficient approach is used to calculate the crop specific evapotranspiration, where both the effects of transpiration of the plants and soil evaporation are taken in one coefficient [33]. This crop coefficient changes over the season with the growth of the plant, following a pattern as can be seen in Figure 4.4. The actual values for the crop coefficient are determined from the plant height and canopy cover development with the VegMon app.

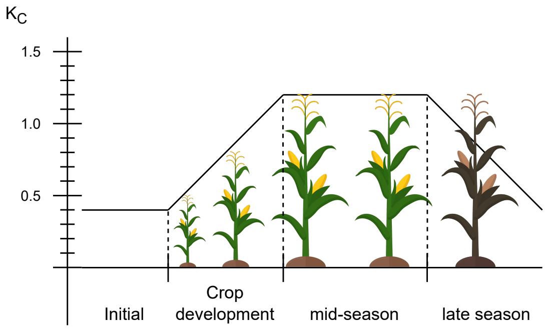

Figure 4.4: Crop development stages of the maize plants with corresponding general crop factors, which can deviate with local conditions [33][36]

A water stress coefficient is introduced that is multiplied with the crop specific evapotranspiration to get the corrected evapotranspiration. A soil moisture content between the field capacity and readily available water (RAW) in the root zone gives a water stress coefficient of 1.0, as the plant does not have problems extracting water from the soil. As the soil moisture content goes below the RAW, the water stress coefficient linearly reduces towards zero at the wilting point, as illustrated in Figure 4.5.

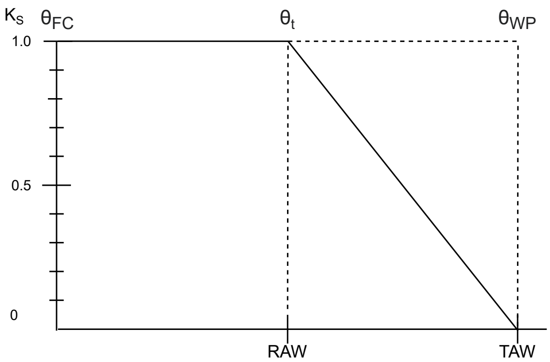

Figure 4.5: Crop water stress factor k_s in relation to field capacity, wilting point, total available water and readily available water

The RAW is a fraction of the total available water (TAW), which is the difference between the field capacity and the wilting point and is calculated with Equation 4.9 [37].

$$TAW = 1000(\theta_{FC} - \theta_{WP}) \cdot Z_r \tag{4.9}$$

In this equation, Z_r is the maximum rooting depth of the plant, which is between 1.0 and 1.7 for maize, where a value of 1.0 is common in Sub-Sahara Africa [10]. Multiplying the TAW with the specific fraction, which is 0.55 for maize, the RAW is calculated [37].

Deep percolation is modelled with the exponential decay function given in Equation 4.10. In this equation y_0 is the initial value for soil moisture content and k is the decay rate constant. These values are found by fitting Equation 4.10 through multiple dry-down events, when the soil moisture is above field capacity and when the sun is not shining. The sun cannot be shining to ensure evapotranspiration to be zero, thus all soil moisture loss is due to percolation.

$$y = y_0 \cdot e^{-kt} \tag{4.10}$$

As the soil moisture calculation in the water balance model does not depend on a time t Equation 4.10 is rewritten into an equation that does not depend on a specific time step, but on the soil moisture concentration in the previous time step. Equation 4.11 shows the equation used in the water balance model. It only takes the soil moisture concentration in the previous time step and the fitted decay rate constant into account to calculate the soil moisture concentration in the current time step.

$$y[t] = y[t-1] \cdot e^{-k} \tag{4.11}$$

The events used to fit the decay function as well as the plots of the fits are given in Appendix C. A decay value k for the untreated plot is found to be -0.000276 and a decay value k of -0.00016 is found for the treated plot.

4.2.2. Input parameters

The final input parameters used in the water balance model for the untreated and the treated plot are given in Table 4.1. The field capacity and wilting point for both the untreated and the treated plot are significantly higher than derived from the soil analysis. This is a result of fitting the model with the measured soil moisture data, as the initial field capacity and wilting point values gave very unrealistic soil moisture model values.

Table 4.1: Input data for the water balance model for both the untreated and the treated plot. n: porosity, d: infiltration depth, FC: field capacity, WP: wilting point, Z_R: maximum rooting depth, I_{max}: maximum infiltration rate

	n [m^3/m^3]	**d [m]**	**FC [m^3/m^3]**	**WP [m^3/m^3]**	**Z_R [m]**	**k [-]**	**I_{max} [mm/h]**
Untreated	0.45	0.6	0.26	0.087	1	- 0.000276	5
Treated	0.45	0.6	0.275	0.092	1	- 0.00016	5

4.3. Crop development model: AquaCrop

4.3.1. Model description

The crop growth is modelled using AquaCrop [32]. AquaCrop is developed by the FAO to model crop growth using water as the limiting factor, with crop yield as the final output product. The model calculates yield in four steps at a daily time step, as visualised in Figure 4.6. In the first step AquaCrop calculates the green canopy cover (CC), followed by calculation of the crop transpiration in the second step. In the third and fourth steps, AquaCrop calculates the above-ground biomass and crop yield.

AquaCrop requires climate data, crop parameters, soil data, management practices and initial conditions as input data [31]. The climate data should at least contain daily, 10-daily or monthly maximum and minimum air temperature, mean reference evapotranspiration and rainfall data. The maximum and minimum temperature, as well as the precipitation are measured by the TAHMO station, as mentioned before. The earlier explained Makkink reference evapotranspiration calculation is used for the reference evapotranspiration. All of these data sets are available with a daily time step, which will therefore be used as it is the most accurate AquaCrop can take. The mean annual CO_2 can also be given as input. However, AquaCrop takes the global mean annual data when this is not provided.

The crop input parameters of AquaCrop are planting date, plant density, maximum canopy cover, lengths of the different stages in the crop cycle, the harvest index and the maximum effective rooting depth. With the planting data aquaCrop knows when the cycle starts. Most of these parameters are either known or measured using the VegMon app. Only the maximum rooting depth cannot be observed in the field and depends on the conditions of the soil in the root zone. Therefore, a maximum rooting depth of 1.0 meters is used [10]. All the input crop parameters as used in the AquaCrop model for both the untreated and the treated plot are given in Table 4.3.

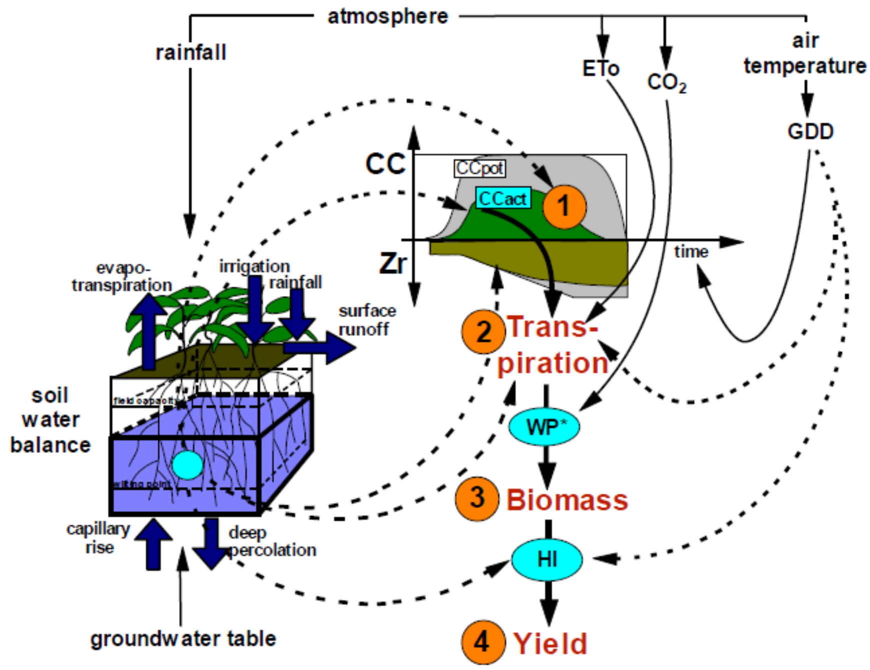

Figure 4.6: Schematic visualisation showing the four modelling steps of AquaCrop [31]

Aquacrop requires different soil parameters to determine the soil water content throughout the growing cycle. The soil water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP) are key parameters needed, as well as the saturated hydraulic conductivity (Ksat) and the depth of the soil layers. The depths of the soil layers are measured in the field and the properties from the soil analysis are translated into the required parameters for a first estimation of the above mentioned parameters using SPAW [84].

Management practices that could be applied in AquaCrop are practices affecting soil evaporation of runoff, rainwater harvesting technologies, and irrigation data. As none of these are applied to the field, no management data will be given as input data to the AquaCrop model. Specific initial conditions are also not given to the model, as the climate data start well before the seeds are sowed, which is expected to result in realistic conditions at the start of the growing cycle.

AquaCrop gives different parameters that could be used for validation of the model, namely crop canopy cover at various times over the season, above ground biomass and final crop yield [31]. Besides these parameters, there are also the soil moisture content at specific moments at specific depths which can be used for validation. AquaCrop models the soil moisture throughout the season over the depth of the soil. From this soil moisture profile point data is extracted and compared to the soil moisture measurements in the field at different depths.

First the soil moisture modelling in AquaCrop is compared to the measured soil moisture at different depths. SAT, FC and PWP are three parameters used for calibration of the soil moisture in AquaCrop to fit with the measured soil moisture. Ksat could also be used for calibration, however small changes in this parameter do not give visible changes in the modelled soil moisture. The same accounts for the curve number (CN), a parameter linked to Ksat that determines the rate of surface runoff. Also the readily evaporable water (REW), which tells how much water can get lost as soil evaporation, does not have a significant impact on the soil moisture behaviour [76]. The hydraulic parameters determining the soil moisture in AquaCrop as used for both the untreated and the treated plot are given in Table 4.2.

After the soil moisture in AquaCrop is calibrated with the measured soil moisture the modelled yields are compared to the measured yields in the field. In order to find the influence of soil moisture on the yield as modelled in AquaCrop, the same crop file is used as input. In this crop file, as mentioned, the lengths of the different growing stages are adjusted according to the crop development monitoring. The same accounts for the maximum canopy cover. Besides that, two important parameters are the water productivity (WP) and harvest index (HI). WP accounts for the biomass produced, which is correlated to the transpired water through the plant. The value used for WP is 15.3 g/m^3 [6][10]. HI determines what fraction of the biomass is the actual yield, which is taken to be 28% [1].

4.3.2. Input parameters

The final input parameters for the AquaCrop model for the untreated and the treated plot are given in Table 4.3 and Table 4.2. The field capacity, wilting point and saturation are all higher than the values found in the soil analysis. This is a result of fitting the modelled soil moisture with the measured soil moisture.

Table 4.2: Input data for the AquaCrop model, where CN: curve number, REW: Readily Evaporable Water, PWP: permanent wilting point, FC: field capacity, SAT: saturation, Ksat: saturation hydraulic conductivity

	CN [-]	REW [mm]	Horizon [cm depth]	PWP [Vol%]	FC [Vol%]	SAT [Vol%]	Ksat [mm/day]
Untreated	10	0	0-15	15	25	27.5	1000
			15-30	15	27.5	32.5	1000
			30-60	10	25	40	1000
			60-120	10	25	40	1000
Treated	10	0	0-15	15	30	32.5	1000
			15-30	15	26	30	1000
			30-60	10	15	40	1000
			60-120	10	15	40	1000

Table 4.3: Input data for the AquaCrop crop file, where max CC: maximum canopy cover, WP: Crop Water Productivity, HI: Reference Harvest Index, A: days to emergence, B: days to max CC, C: days to maximum rooting depth, D: days to start of canopy senescence, E: days to mature, F: days to flowering, G: length building up HI, H: duration of flowering.

Development	Production		Crop Calendar							
max CC [%]	WP [g/m2]	HI [%]	A	B	C	D	E	F	G	H
99	15.3	28	11	51	50	65	94	59	27	8

4.4. Multi-criteria analysis

The potential rainwater harvesting techniques, as elaborated in Section 2.3, are assessed using a Simple Multi-Attribute Rating Technique, to find the most suitable solution, both technically and fitting into the local context [91]. This form of a multi-criteria analysis (MCA), which is one of the most straightforward models, is applicable for any type of weighing. The different techniques will be assessed on the need for materials, the need for maintenance and installation, the required prior knowledge and the effectiveness of the technology. Data collected in the surveys is combined with literature data in the MCA.

The required maintenance throughout the season indicates which technologies require a lot of maintenance and which do not require maintenance at all. Required knowledge for successful implementation shows whether a farmer can just implement a technology or whether it is requires some education before implementing to ensure an effective functioning of the technology. In the scoring of the knowledge it is taken into account whether the farmers in the area already know about the technology or not. Finally effectiveness of the technology shows how effective the specific technology is in reducing water losses, specifically for the study area.

For all of these criteria each technology receives a score between 1 and 5. where 1 is the most negative and 5 is the most positive. The ranking for each of the criteria will be done in relation to the other techniques, as individual aspects cannot easily be translated into numbers by themselves. The results of the MCA are visualised in a large table to make the different technologies easy to compare.

5
Results

In this chapter results of the field experiments, modelling analysis and interviews are presented. The results are discussed in Chapter 6.

5.1. Field experiments

Soil moisture measured with a five minute time step at 5, 10 and 60 centimeters depth in both the untreated and the treated plot is shown in Figure 5.1. It can be seen that in both the untreated and treated plot the soil moisture increases with precipitation.

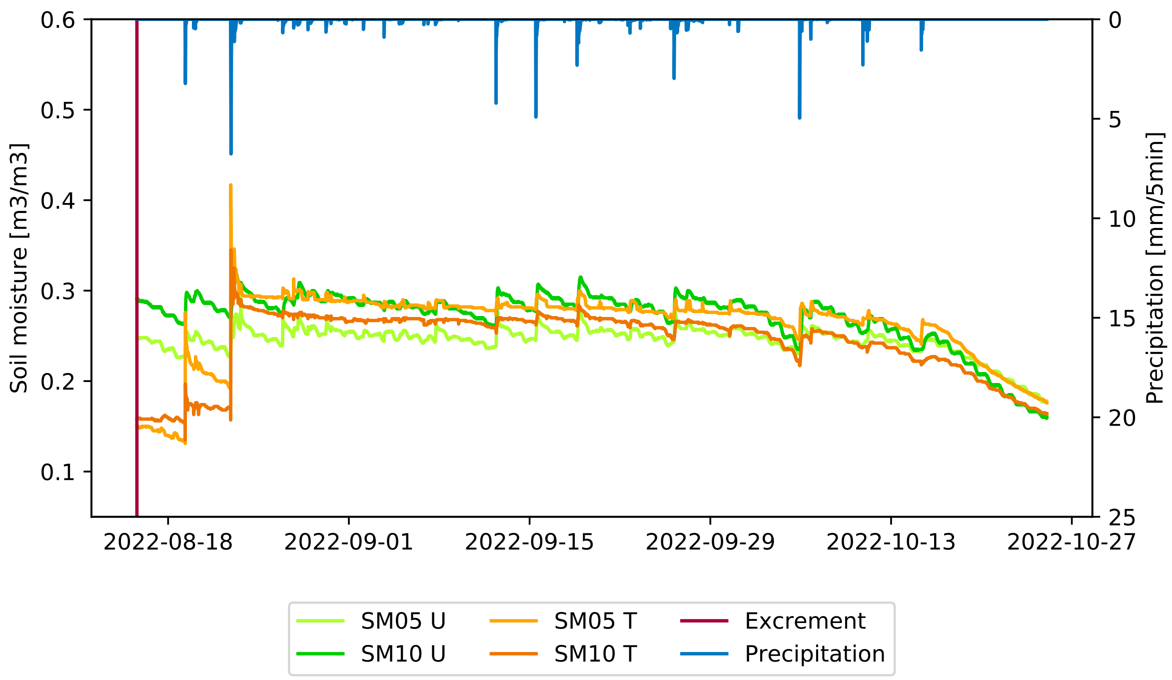

Figure 5.1: Soil moisture in the untreated and treated plot at 5 and 10 cm depth throughout the growing season of the maize plants from August until October 2022, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM10 U: measured soil moisture at 10 cm in the untreated plot, SM05 T: measured soil moisture at 5 cm in the treated plot, SM10 T: measured soil moisture at 10 cm in the treated plot, Excrement: moment sheep excrement is added

Figure 5.2 shows the reference evapotranspiration calculated according to Equation 4.8, with the temperature and incoming shortwave radiation. The figure also shows a combination of the crop factor and water stress factor for both plots that is used to calculate the corrected evapotranspiration.

The monitored plant height for both the untreated and the treated plot is shown in Figure 5.3. The canopy cover and VIGreen, calculated with use of the VegMon app, is shown in Appendix D for the two plots.

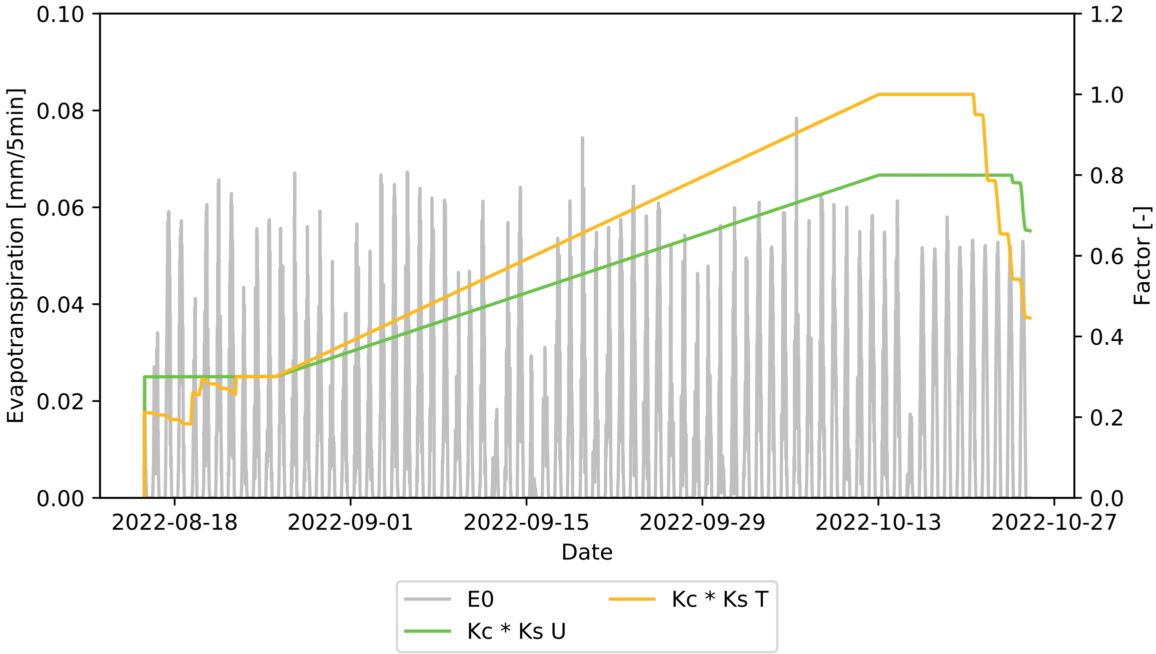

Figure 5.2: Evapotranspiration throughout the growing season of the maize plants from August until October 2022, where E0: reference evapotranspiration, Kc * Ks U: multiplication of the crop factor and water stress factor for the untreated plot, Kc * Ks T: multiplication of the crop factor and water stress factor for the treated plot

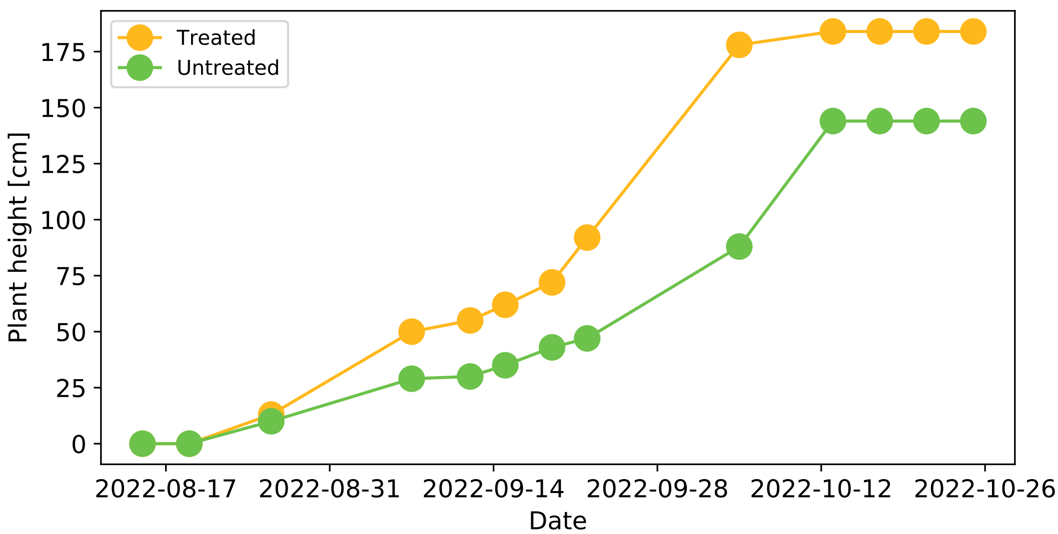

Figure 5.3: Plant height in the untreated and treated plots throughout the growing season of the maize plants from August until October 2022, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM10 U: measured soil moisture at 10 cm in the untreated plot, Mod U: modelled soil moisture in the untreated plot, FC: field capacity in the untreated plot, WP: wilting point in the untreated plot, P: precipitation

5.2. Modelling results

5.2.1. Water balance model

The soil moisture modelled with the water balance model for the untreated plot is shown in Figure 5.4. For the treated plot the modelled soil moisture is shown in Figure 5.5. For both of the plots the modelled soil moisture represents mean soil moisture in the top 60 cm of the soil. It is compared to the measured soil moisture at five and ten centimeters depth, as well as the measured precipitation. Besides that the wilting point and field capacity used as model inputs are shown in both figures.

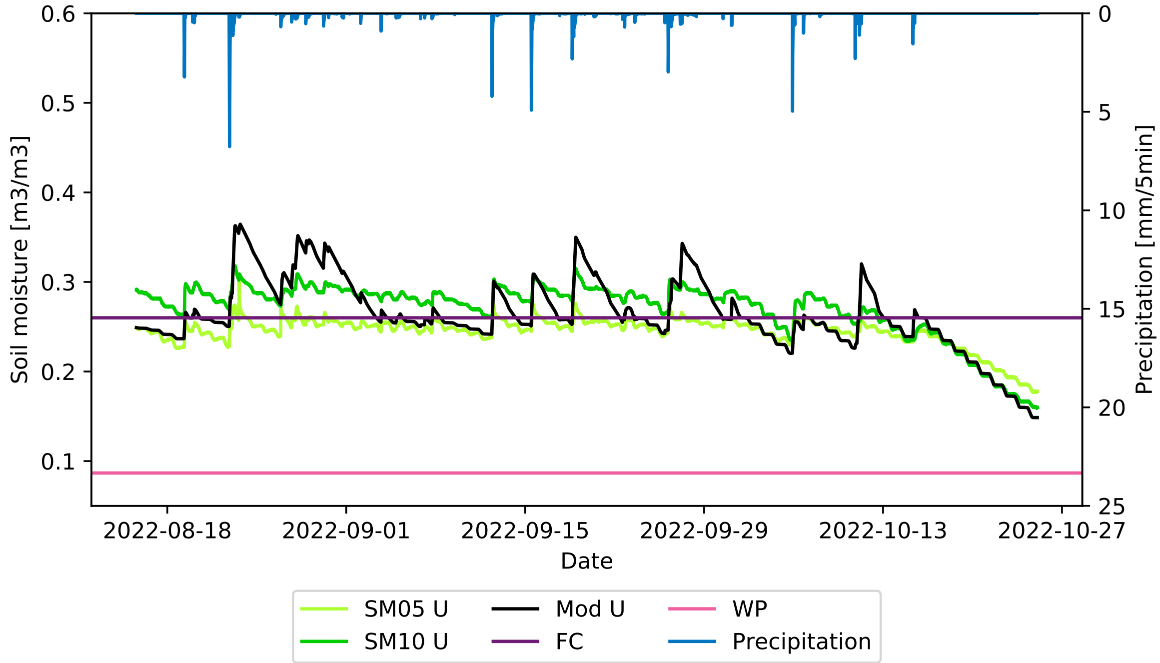

Figure 5.4: Modelled soil moisture with the water balance model for the untreated plot throughout the growing season of the maize plants from August until October 2022, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM10 U: measured soil moisture at 10 cm in the untreated plot, Mod T: modelled soil moisture in the untreated plot, FC: field capacity in the untreated plot, WP: wilting point in the untreated plot

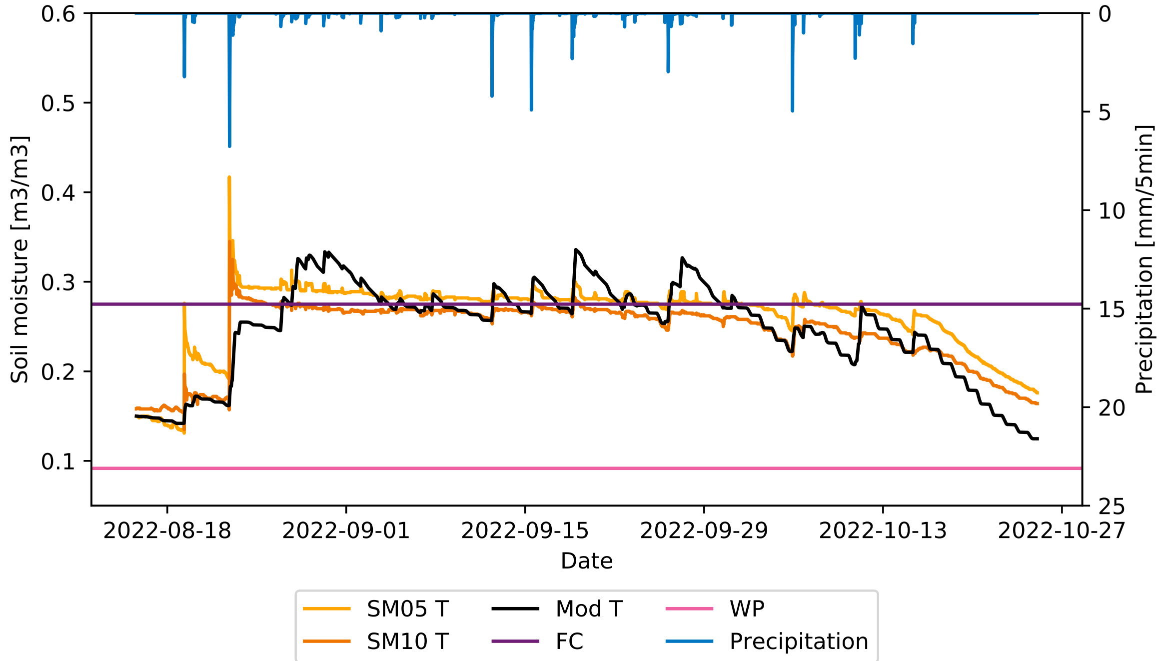

Figure 5.5: Modelled soil moisture with the water balance model for the treated plot throughout the growing season of the maize plants from August until October 2022, with SM05 T: measured soil moisture at 5 cm in the treated plot, SM10 T: measured soil moisture at 10 cm in the treated plot, Mod T: modelled soil moisture in the treated plot, FC: field capacity in the treated plot, WP: wilting point in the treated plot

5.2.2. AquaCrop model

The daily soil moisture content as modelled in AquaCrop at five centimeters depth for the treated plot is shown in Figure 5.6 and compared to the observed soil moisture at the same depth. The soil moisture at ten centimeters depth for the treated plot, both modelled in AquaCrop and measured in the field, is given in Figure 5.7. The graphs for the soil moisture in the treated plot at sixty centimeter and the plots for the soil moisture modelled at five, ten and sixty centimeters for the untreated plot are given in Appendix E. In addition to that the root zone depletion throughout the season as modelled in AquaCrop for both the untreated and the treated plot is given in Appendix F. The harvest output from the AquaCrop model is given in Table 5.1 together with the harvest data measured in the field. The complete data set of the harvest as measured in the field is given in Appendix G.

Table 5.1: Biomass and yield harvest data in tons per hectare as measured in the field and modelled in AquaCrop for the untreated and treated plots

	Untreated		**Treated**	
	Measured	Modelled	Measured	Modelled
Biomass	8.2	7.619	11.4	7.621
Yield	1.3	1.676	2.7	1.676

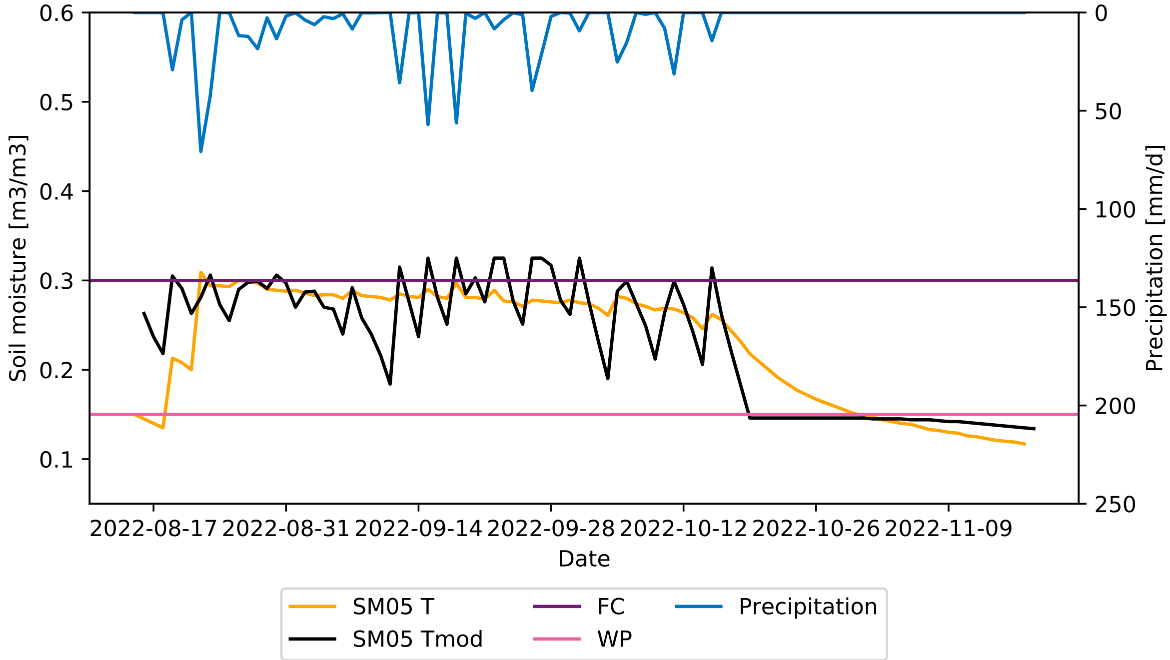

Figure 5.6: Measured and modelled daily soil moisture at five centimeters depth in the treated plot, with SM05 T: measured soil moisture at 5 cm in the treated plot, SM05 Tmod: AquaCrop modelled soil moisture at 5 cm in the treated plot, FC: field capacity in the treated plot at 5cm, WP: wilting point in the treated plot at 5 cm

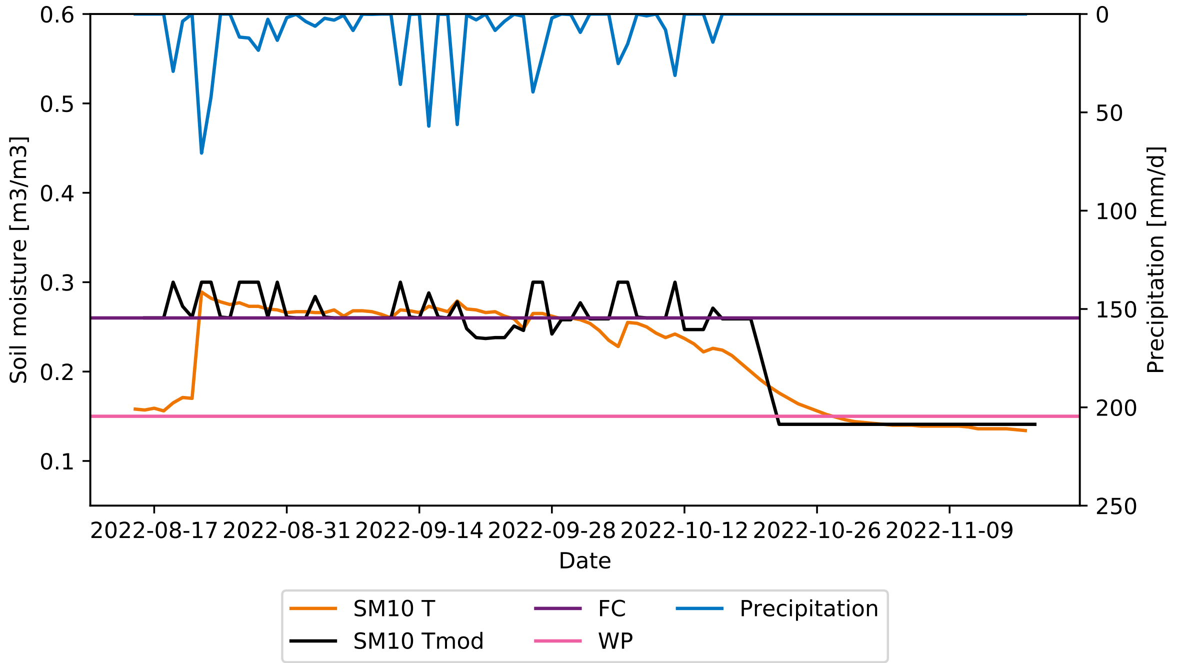

Figure 5.7: Measured and modelled daily soil moisture at ten centimeters depth in the treated plot, with SM10 T: measured soil moisture at 10 cm in the treated plot, SM10 Tmod: AquaCrop modelled soil moisture at 10 cm in the treated plot, FC: field capacity in the treated plot at 10 cm, WP: wilting point in the treated plot at 10 cm

5.3. Survey

A total of 25 farmers is interviewed, of which only one is a woman and 24 are men with an age range between 27 and 80 years old. Except for one farmer only farming maize and pepper, all farmers farm at least three different types of crops, with one farmer even growing eight different types of crops. Few farmers have changed some of the crops they grow, with regular crop rotation is mentioned as the main reason. Twenty of the 25 interviewed farmers have multiple animals. All of them said they use the animal excrement in the farm, however the animals walk around freely resulting in far from all the excrement being gathered and spread on the farm. Four of the farmers feed the crop residue to their animals, while eighteen spread it on the farm and the other three burn it.

The interviewed farmers all experience water shortages on the farm in the form of dry spells during the growing season, which gives water shortages for the crops, resulting in reduced yields and sometimes even crop loss. Only four farmers mentioned a change in the water stresses, where two said that it was always better years ago and the two others mentioned that there is a shift in the start of the rainy season. All the other farmers only said that some years there are water shortages, while other years there are not. The vast majority of the farmers use chemical fertilisers in their fields, while only one uses just the manure and five say not to use any fertiliser as the prices have risen too high to afford it.

(a) Ridges

(b) Strip catchment

(c) No rainwater harvesting

Figure 5.8: Impression of applied RWH technologies in the agricultural fields in the study area

The farmers all agreed that most of the rain that falls flows away, either to the lowland area or to the river. Only a small part of the water stays in the field, especially when there are potholes. The only thing farmers do in case of water shortages for the crops is hope for the rain. Five farmers did mention that they create bunds in the rice fields to capture water and one farmer mentioned making dugouts to capture some more rain. Bunds are useful for rice, but not for many other crops is what the farmers mentioned, as for example maize would drown because of the large amounts of water that are captured by the bunds. One farmer showed that he sometimes closes some of the ridges in his fields to create ponds and hold more water.

Only a small part of the farmers actually mentioned that they applied a way of RWH during the interviews. During the farm walks after the interviews however more RWH technologies were seen in the field besides bunds and dugouts. Figure 5.9 shows how many of the 25 interviewed farmers apply specific RWH technologies in their farm. An example of ridges in a farm visited is shown in Figure 5.8.

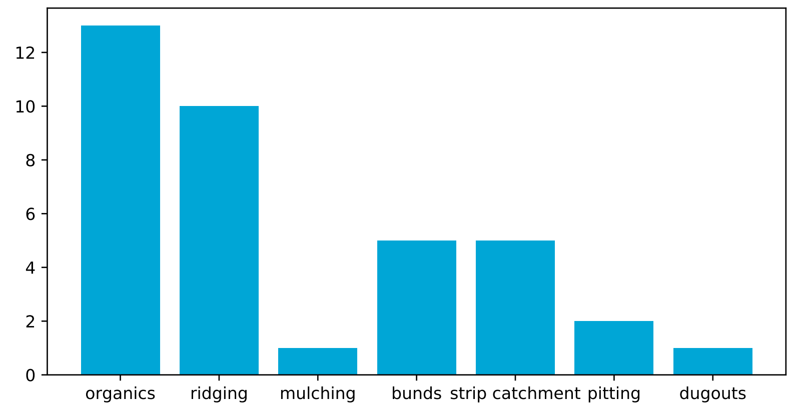

Figure 5.9: RWH technologies applied. For each technology it is shown how many of the 25 interviewed farmers apply it

5.4. Multi-criteria analysis

The results of the multi-criteria analysis are given in Figure 5.10. The scores are an interpretation of literature and interview results. A more detailed analysis with reasoning behind each of the scores is given in Appendix H.The score for the need for materials is based on the literature on rainwater harvesting combined with information gathered from the surveys. Literature tells what materials are needed, where the surveys give an idea of what is locally available. The same accounts for the need for installation.

The need for maintenance is purely based on literature saying whether maintenance is required and to what extend. The scoring for both knowledge and effectiveness is based on a combination of literature and survey data. For knowledge it is assessed whether specific knowledge is required for effective implementation from the literature, while the survey data tell whether this the farmers already have this knowledge or not. Literature furthermore tells what is needed for the technology to be effective, where the survey data give information on whether this is possible for the study area.

	Technology	Materials	Installation	Maintenance	Knowledge	Effectiveness
In-situ	Deep tillage	5	1	5	5	3
	Tied ridges	5	3	2	3	3
	Contour farming	5	4	5	3	4
	Adding manure	3	3	5	4	4
	Mulching	2	2	5	3	5
	Conservation agriculture	2	2	5	1	5
Micro-scale	Pitting	3	2	5	3	4
	Strip catchment tillage	5	5	5	4	3
	Contour bunds	3	2	3	3	4
	Fanya juus	4	2	2	3	4
	Semi-circular bunds	3	2	3	4	4
	Meskat-type system	5	3	3	2	1
Macro-scale	Hillside runoff	3	2	3	2	1
	Floodwater harvesting	2	1	1	1	1
	Ephemeral stream division	2	1	1	1	1
	With storage	1	1	2	5	5

Figure 5.10: Results of the multi-criteria analysis, with different rainwater harvesting technologies scored from 1 to 5, with 1 being the lowest and 5 being the best score, on five criteria: materials needed for the technology, difficulty of installation, required maintenance throughout the season, required knowledge for successful implementation, effectiveness in reducing water losses

6 Discussion

In this chapter the inaccuracies in the different methods of data gathering, modelling and analysis are discussed.

6.1. Data gathering

6.1.1. Field observations

There are multiple factors in the experimental set-up and field measurements that cause uncertainties in the data gathered.

Soil properties

First of all, digging into the soil for sampling and installing the soil moisture sensors disturbed the soil. Even though it was tried to separate the soil layers and have different piles from the different layers, it is inevitable to have some mixing. The soil also needed time to settle and get back to its natural state after the digging, causing small pits to appear in the field after the first rains. Also, in the soil moisture measurements a reset at the start of the measuring period is observed. Figure 5.1 shows that for both the untreated and the treated plot the soil moisture increases a lot with the first two larger rain events, after which it finds its equilibrium.

Furthermore, the soil data gathered from the analysed soil samples does not match with the behaviour in the field. From the samples, field capacities between ten en fifteen percent are found using the USDA hydraulic properties calculator [84], while the measured soil moisture fits better with higher field capacities, between fifteen and thirty percent. The same accounts for the wilting point and saturation, where the soil moisture fits better with higher values. Besides that, the bulk densities found with the soil analysis, as given in Appendix I, correspond with higher values for the hydraulic properties [31]. A possible explanation is that field samples were not representative, as the samples were taken at one location in the plots and not at multiple locations.

Looking at the gathered soil data in Appendix I, especially at the organic carbon content (OC), causes confusion. The sheep excrement was added to the treated plot, however the untreated plot shows a higher organic carbon content. The excrement is only added to the top layer, so it is expected that the OC in the top layer would be higher for the treated plot, which is not the case. As the decomposition of organics is a slow process, it is possible that an effect can only be observed after multiple years [11][15][29]. Besides that, the locations of the two plots could have an influence. The untreated plot is located at the TAHMO station, where the farmers did not cultivate the soil for years, as they were afraid of damaging the sensors. Not cultivating soil for years causes a natural increase in OC [88]. The treated plot is on the other hand placed in a part of the field that is plowed every year, thus disturbing the soil and decreasing the natural OC.

Runoff data

Besides that, the gutters collecting the runoff were sometimes misplaced, due to the soil pressing against them. This caused an extending edge blocking the flow of runoff into the gutters, resulting in an underestimation of the measured runoff. Displacement of the gutters also resulted in the water in the gutter flowing into the wrong direction, resulting in an underestimation of the runoff. Moreover, the buckets needed emptying after every rain event. Putting the buckets back into the soil sometimes, however, resulted in the buckets not being deep enough, causing water in the gutter to flow in the wrong direction. Finally, precipitation falling in the gutter directly turns into runoff and non of it infiltrates. This results in a slight increase in measured runoff, however, the area of the gutter is only $0.15 \cdot 1.90 = 0.285 m^2$, which is only around 5% the 5.4 m^2 plot area. The runoff is likely underestimated at most times due to these inaccuracies.

Soil moisture observations
Looking at the soil moisture dynamics in both the untreated and the treated plot, it is seen that the sensors at five and ten cm depth in the treated plot show more abrupt behaviour compared to the sensors in the untreated plot. The sensors were only installed in the treated plot, as the untreated plot already contained soil moisture sensors of the TAHMO station. It could be that the sensors are not installed properly and that preferential flow paths in the soil have an influence on the soil moisture behaviour around the sensors.

Furthermore, having only three sensors over a depth of sixty cm, with a gap between ten and sixty cm, leaves for large uncertainties in the soil moisture behaviour.The soil moisture behaviour of ten and sixty cm is very different and assumptions have to be made for the actual hydraulic properties of the entire soil horizon between thirty and sixty cm. Also, the infiltration depth of the soil is unknown and is assumed. Having more sensors over the depth will help to create a more accurate soil moisture profile.

Evapotranspiration
In the calculation of the evapotranspiration multiple assumptions are made that cause uncertainty. The use of a single crop coefficient to calculate the crop specific evapotranspiration is a simplification. More accurate estimations can be made using a dual crop coefficient, where soil evaporation and crop transpiration are separated. The dual crop coefficient would especially make a more accurate estimation of the soil evaporation right after a precipitation event. However, for the dry periods in between the precipitation event the difference will not be significant. The use of a dual crop coefficient will also decrease the simplicity of the model [33]. The order of magnitude in the evapotranspiration will not change when using a dual crop coefficient instead of a single crop coefficient, therefore the inaccuracy of using the single crop coefficient is very small.

As only the incoming shortwave radiation is measured and not the net radiation, it is not possible to use the Penman-Monteith equation, leaving Makkink's equation to be used. The Makkink equation does not take wind speed and humidity into account, but only considers the radiation. Radiation is the dominant source for evapotranspiration and the wind speed and humidity are corrected for in the crop coefficient. It can therefore be assumed that the evapotranspiration calculated with Makkink can be assumed to be in the right order of magnitude and that this inaccuracy is negligible [26][36].

Crop data
The number of seeds was not counted before sowing, therefore it is not known what percentage of seeds germinated in both plots. Soil temperatures above 28 degrees Celsius can result in low germination rates of maize seeds [78]. As can be seen in Figure 6.1, the soil temperature in the treated plot was higher at the start of the season when the seeds germinated. Later on in the season the temperature measured in the untreated plot was higher. This is likely caused by the fact that the soil in the treated plot at the location of the sensor was covered by leaves, while in the untreated plot the soil above the sensor was exposed to sunlight. The higher temperatures could lead to a reduction of 30% in germination, which makes it a significant inaccuracy [27].

In the crop monitoring the height of one individual plant in the untreated and the treated plot is measured. Even though it is more accurate if the height of multiple plants is measured and averaged per plot, the chosen plants showed to be average for the entire plot and therefore this inaccuracy is negligible.

The pictures taken for the VIGreen and canopy cover estimation are taken at different times during the day, with different weather conditions and different cameras. All of these factors could play a role in the data uncertainty. The different lighting of the different pictures could especially influence the VIGreen estimation. The results of the VIGreen monitoring are not used in the analysis and therefore this inaccuracy can be neglected.

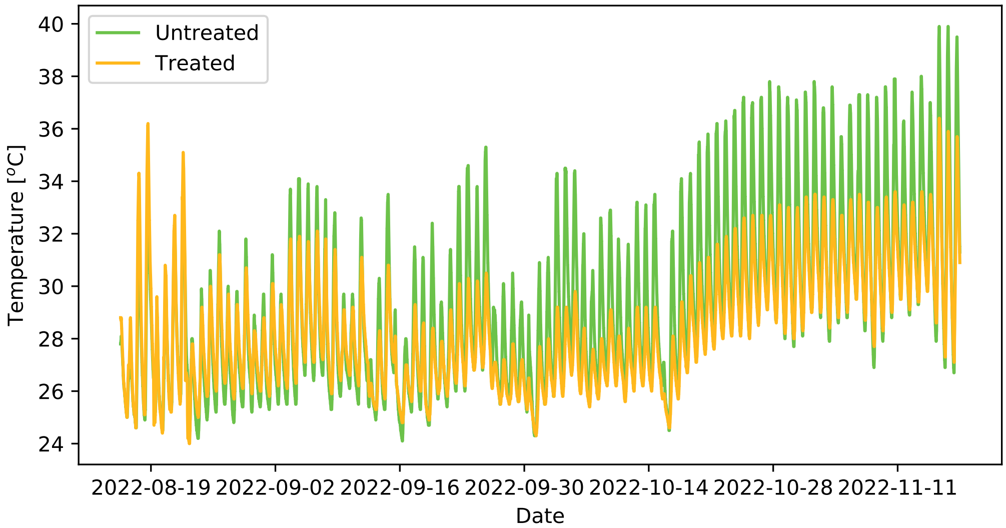

Figure 6.1: Soil temperature in the untreated and the treated plot measured at five centimeters depth throughout the growing season

6.1.2. Surveys

Not all the farm field of each farmer are visited. Multiple farmers have field that were too far to walk to. It is very well possible that the farmers apply a form of rainwater harvesting in these fields. Especially the rice fields, that were not visited with any farmer, have a chance of containing bunds as some farmers told during the interviews. If this is the case it would have a significant effect on the interview results.

The interviewed communities are carefully selected before going into the field. However, in one of the communities visited almost everybody was gone to a funeral, leaving only two farmers to be interviewed. The idea was to have eight interviews in this community, which results in a gap in the number of taken interviews. It is unlikely that this specific community is for example more advanced in the use of rainwater harvesting, as all different communities tend to help each other in farming. Therefore no significant impact on the interview data can be expected due to missing part of the community.

Only one female farmers is interviewed and the interviewed farmers seemed not to be sure about their age. Both gender and age do not have any influence on the interview results and this uncertainty is therefore negligible.

6.2. Modelling

6.2.1. Water balance model

The results of the water balance model show dynamics that match with the measured soil moisture at five and ten cm depth, both in the untreated and the treated plot. The order of magnitude also matches pretty well generally. However, the peaks in the soil moisture show an overestimation in the model for both the untreated and the treated plot when compared to the measurements at five and ten cm depth.

The maximum infiltration rate is taken as a constant and not as dynamic, which could have an impact on the modelled soil moisture. Also, the value of the maximum infiltration rate has significant influence on the modelled soil moisture. A maximum infiltration rate of 5 mm/h gives a modelled soil moisture that fits with the mean measured soil moisture. However, the maximum infiltration rate that matches the soil analysis data is 23 mm/h for the untreated plot and 36 mm/h for the treated plot [55]. Figures 6.2 and 6.3 show what the higher maximum infiltration rates give as modelled soil moisture. From this it can be concluded that the infiltration rate of the soil is not as high as what is found in literature that matches the soil properties. The large differences with the different infiltration rates show the significance of the uncertainty of the infiltration rates.

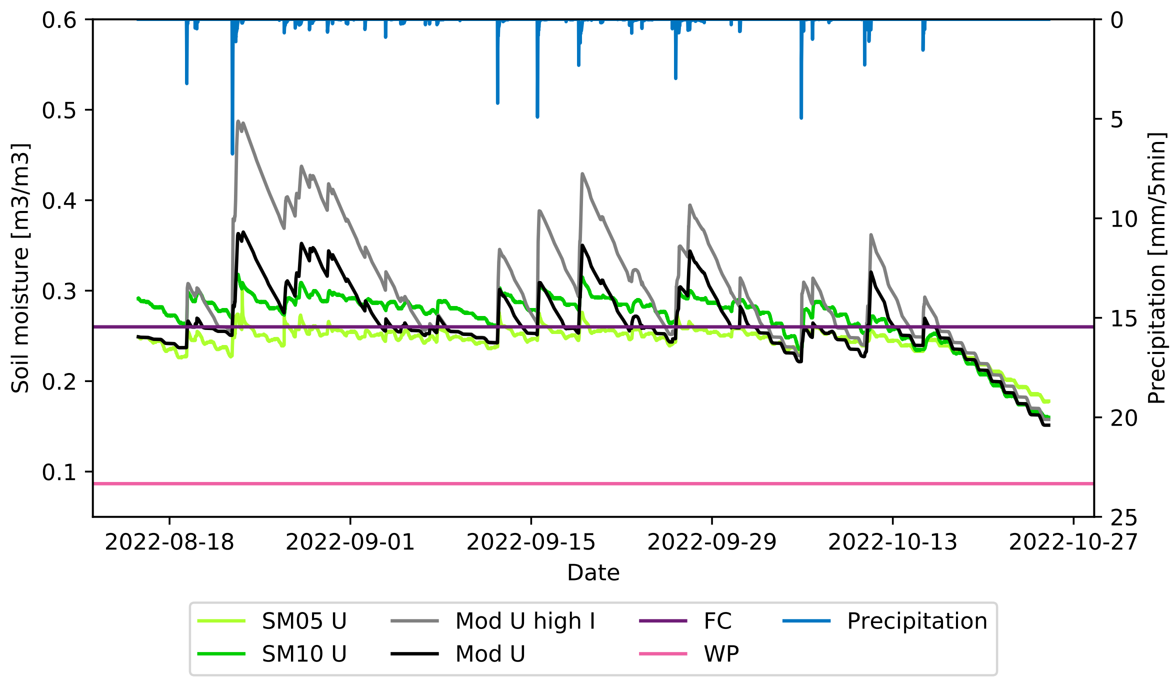

Figure 6.2: Soil moisture in the untreated modelled with the water balance model with a higher maximum infiltration rate of 23 mm/h, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM10 U: measured soil moisture at 10 cm in the untreated plot, Mod U high I: modelled soil moisture in the untreated plot with a maximum infiltration rate of 23 mm/h, Mod U: modelled soil moisture in the untreated plot with a 5 mm/h infiltration rate, FC: field capacity in the untreated plot, WP: wilting point in the untreated plot

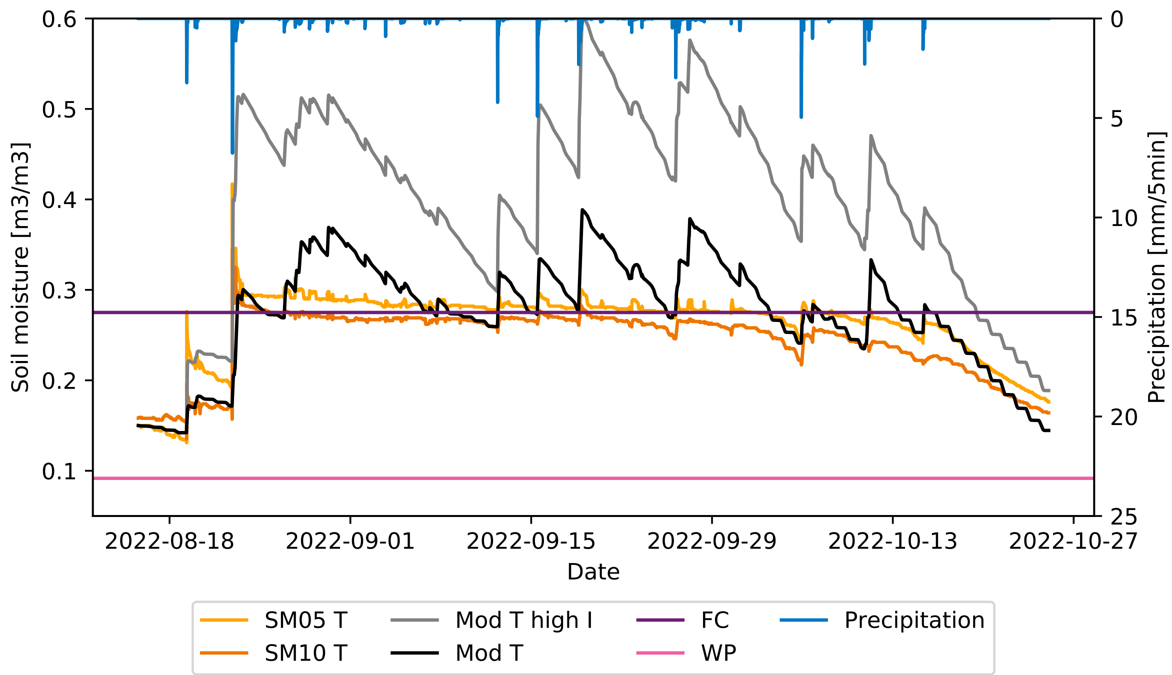

Figure 6.3: Soil moisture in the treated modelled with the water balance model with a lower maximum higher rate of ten 36 mm/h, with SM05 T: measured soil moisture at 5 cm in the treated plot, SM10 T: measured soil moisture at 10 cm in the treated plot, Mod T high I: modelled soil moisture in the treated plot with a maximum infiltration rate of 36 mm/h, Mod T: modelled soil moisture in the treated plot with a 5 mm/h infiltration rate, FC: field capacity in the treated plot, WP: wilting point in the treated plot

As there is an uncertainty in the runoff measurements, it is interesting to look at the sensitivity of the modelled soil moisture to the runoff data. In Figure 6.4 the modelled soil moisture in the untreated plot is shown with a maximum infiltration rate of 23 mm/h and a twofold higher runoff. This results in a slight decrease in the soil moisture peaks due to the increase in runoff. The impact of the uncertainty in the runoff measurements is therefore not very significant.

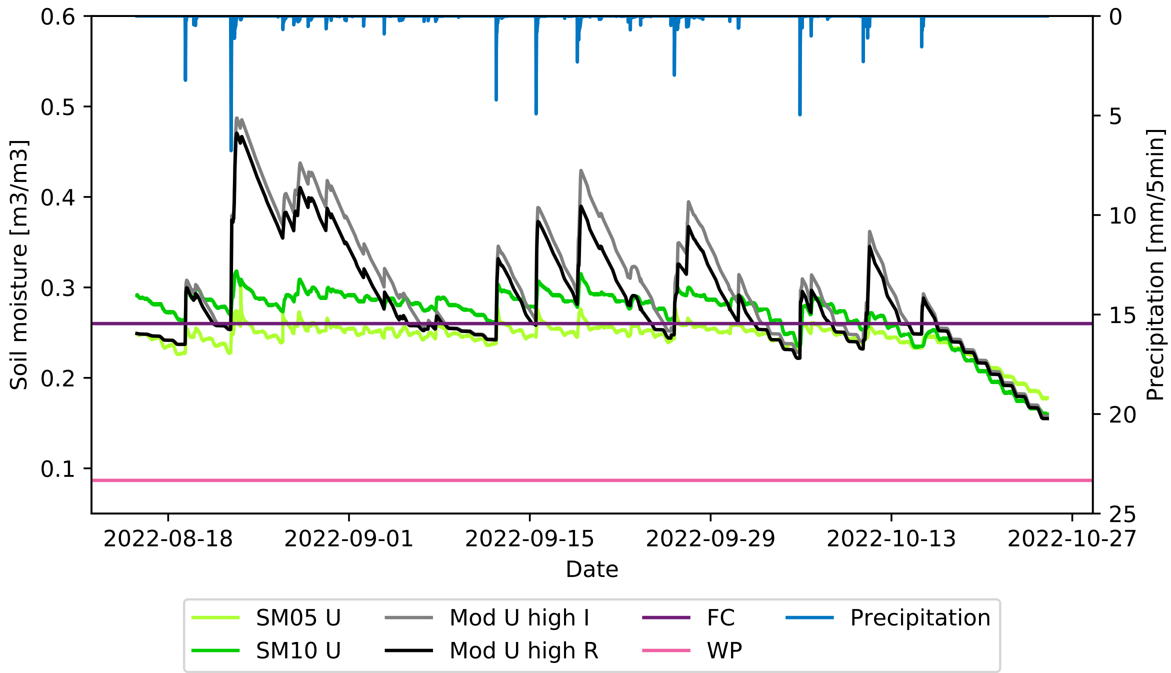

Figure 6.4: Soil moisture in the untreated modelled with the water balance model with a doubled runoff, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM10 U: measured soil moisture at 10 cm in the untreated plot, Mod U high I: modelled soil moisture in the untreated plot with a maximum infiltration rate of 23 mm/h, Mod U high R: modelled soil moisture in the untreated plot with a high infiltration rate of 23 mm/h and doubled the runoff, FC: field capacity in the untreated plot, WP: wilting point in the untreated plot

6.2.2. AquaCrop model

Comparing the harvest output from AquaCrop with the measured data in Table 5.1 shows large deviation, both for the untreated and the treated plot. AquaCrop overestimates the yield for the untreated plot and underestimates the yield for the treated plot. The mean soil moisture modelled in AquaCrop is in the same order of magnitude as the measured soil moisture at the same depths. However, both the high and low peaks in the modelled soil moisture are more extreme than in the measured soil moisture.

There is sufficient soil moisture for the plants throughout the season in both plots in the AquaCrop model. The measured soil moisture also shows enough water in both plots, therefore a difference in soil cannot be the explanation for the differences in modelled and measured yields. Differences in nutrient content in the untreated and treated plot are not taken into account. Although it would make sense that the addition of nutrients would improve crop development, the soil data in Appendix I show that there are no significant differences in nutrient content between the two plots. Other factors, like the differences in soil temperature and possible different starting conditions of the two plots could have influenced the difference in crop development and finally the yield differences. However, no detailed analysis on the effect of soil temperature on crop development has been done. Also, the starting conditions of the two plots have not been analysed in enough detail to be able to conclude anything about the influence on crop development. The uncertainty in the cause of the differences in yield is one of the most important uncertainties of this research.

The model shows significant errors in the soil moisture modelling. However, the dynamics do follow the dynamics of the measured soil moisture, only in a much more extreme way. Previous research has also shown that errors in the soil moisture modelling in AquaCrop occur more often, however the errors that are found in this research are larger compared to previous research [7][63]. Especially the modelled and measured soil moisture in the top layer show significant difference. A cause could be that the AquaCrop model gives one average value for a ten centimeters soil horizon, while point measurements were taken in the field experiment. The larger difference in the top layer could be caused by the AquaCrop model considering perfect conditions for the soil layer, while local influences in the field could have an impact on the measured soil moisture. With the shortest time step in AquaCrop being daily, it will be difficult to find the exact cause of the extreme behaviour of the modelled soil moisture. With a shorter time step the effects of individual fluxes could be analysed, possibly leading to the cause of the soil moisture behaviour. The daily time step therefore causes quite some uncertainty in the model.

6.3. Multi-criteria analysis

The multi-criteria analysis scores the different technologies relative to each other based on five criteria. The scores are based on a combination of literature data and survey data, but have not been discussed with the farmers. As the scores are an interpretation and have not been verified by the farmers there is an uncertainty in the exact grading.

7 Conclusion

The aim of this study is to identify suitable rainwater harvesting techniques for smallholder farmers in northern Ghana, in order to reduce the impact of dry spells during the growing season. With that, one promising potential rainwater harvesting solution is investigated in a field experiment. The sub-questions are answered before getting to the general conclusion of the research.

What is the soil water variability during the growing season in a typical maize field in northern Ghana?
No significant meteorological dry spells occurred during the experiments. From the field experiments data the conclusion can be drawn that no soil water shortages occurred during the growing season of 2022. The water balance model also did not show any soil water shortages during the growing season. The same conclusion can be drawn from the AquaCrop model, which does not show any soil water shortages throughout the season.

How does the addition of sheep excrement to the top layer of a dry soil manure influence crop development?
Looking at the measured plant heights throughout the season, it is clear that the plants in the treated plot are growing a lot faster than the plants in the untreated plot. The plants in the treated plot also grow higher than the plants in the untreated plot, develop their canopy more rapidly and show higher VIGReen values. This indicates that throughout the development the plants in the treated plot were more healthy than the plants in the untreated plot. This altogether indicates a positive relation between the addition of manure and the crop development.

There is furthermore a clear difference between the harvest in the untreated and the treated plot, as measured in the field. Where the treated plot gave a yield of 2.7 tons per hectare, the untreated plot gave a yield of 1.3 tons per hectare. This indicates that there is a positive influence of manure on the crop growth and yield. The AquaCrop harvest output does not show a difference in harvest between the two plots. In the AquaCrop model the addition of nutrients in the manure is not taken into account. As this research does not focus on the nutrient content, further research into the nutrients is necessary before being able to conclude something about this.

How does manure influence the soil water holding capacity?
The measured soil moisture does not show a clear influence of the sheep excrement added as manure on the soil moisture. Even though the soil moisture at five cm was higher in the treated plot than in the untreated plot, the measurements at ten cm were the inverse. From these results no clear conclusion about the influence of manure on the water holding capacity can be drawn.

The field capacity in the water balance model for the treated plot is slightly higher than the field capacity used for the untreated plot model. This is, however, a small difference. These numbers are determined by fitting the modelled soil moisture with the measured soil moisture at five and ten cm depth.

The field capacity in the AquaCrop model for the top layer in the treated field is higher than the field capacity for the untreated plot model: 0.30 versus 0.25. These values are determined by fitting the modelled soil moisture in AquaCrop with the measured soil moisture at the same depth. This indicates a higher water holding capacity. However, the results from the AquaCrop model show extreme behaviour, thus it is difficult to determine whether the used field capacity values for the two plots are accurate. Therefore, the AquaCrop model cannot give a clear conclusion on the influence of manure on the water holding capacity of the soil.

How do smallholder farmers in northern Ghana deal with dry spells for their crops?

All of the 25 interviewed farmers said that they experience water shortages in their farms, resulting in low yields and crop loss. Many of the farmers said that the only thing they can do when there is a drought is hope for the rain. However, part of the farmers mentioned that they construct bunds in the rice fields, which help to harvest water. For other crops, however, bunds capture too much water, resulting in drowning of the crops. Besides that, the farm walks showed that many farmers construct ridges in which they plant their crops. This is done to prevent the plants from washing away during heavy rain, is what they gave as a reason. It also serves a rainwater harvesting purpose, as the ridges block the flow of runoff. The main shortcomings are the knowledge on rainwater harvesting and how to effectively apply it. That is also what farmers mentioned.

What are suitable rainwater harvesting solutions for smallholder farmers in northern Ghana to reduce the impact of dry spells?

Deep tillage is an effective rainwater harvesting technology, as it increases the infiltration capacity and reduces the runoff. However, heavy machinery is needed for deep tillage, which makes it an expensive solution for northern Ghana. Adding manure, mulching and conservation agriculture require either manure or other organic material to be added to the field. These three technologies are effective. However, especially conservation agriculture requires significant knowledge to be used effectively.

Except for the meskat-type system, all micro-scale systems have a good effectiveness. None of these require large investments or special equipment, as they all mainly imply movement of soil using. However, some do require more labour or possible additional material to be constructed. For example, pitting requires additional organic materials, while bunds can also be constructed of other materials than soil.

From the multi-criteria analysis it can be concluded that the macro-scale systems are not suitable to apply for rainwater harvesting in northern Ghana. Either the effectiveness of the technology is low or too many materials are needed.

In short, it depends on the availability of materials and labour which rainwater harvesting technologies can be applied. Additionally, knowledge on how to apply the technologies is important for effective implementation and usage. As some technologies are more effective for specific crops than others, like bunds for rice, it is of great importance to look at what crops a farmer grows before deciding on what rainwater harvesting technology to apply.

As a final conclusion, mainly micro-scale and in-situ rainwater harvesting technologies are suitable for smallholder farmers in northern Ghana. It is, however, essential that the farmers have the right knowledge to apply these rainwater harvesting technologies. Micro-scale and in-situ rainwater harvesting technologies require less investment compared to macro-scale systems. Furthermore, the smaller systems are easier to apply by individual farmers and on single fields, making it easier and quicker to implement.

Adding organic content is said to be an effective way of increasing the water holding capacity of the soil, thus harvesting more rainwater. The addition of sheep excrement as manure in the research has not shown any clear impact on the water holding capacity of the soil. The manure does seem to increase yield, which is likely caused by the increase in nutrients released over the course of the growing period, or differences in soil structure. The nutrients and their effect on crop development have not been investigated in this research, so the actual effect of the nutrients needs further research.

8
Recommendations

In this chapter the recommendations for future research are explained. The recommendations focus on how to improve the data gathering and how this affects accuracy of the analysis and modelling. Furthermore, also recommendations for possible implications of the results of the research are given.

8.1. Future research

8.1.1. Experimental set-up

The experimental set-up, as used for this research, is recommended to be used again. An additional plot could be created where, next to the manure, another source of organic material can be tested. The farmers always have a lot of crop residue and so it is interesting to see how adding crop residue to the top layer of the soil influences the soil water balance and crop development.

Next to that, it is interesting to know the behaviour of the water during precipitation. As it is difficult to be in the field at time of precipitation, it could be interesting to add a camera to the set-up, to be able to see what happens with the water during precipitation.

8.1.2. The water balance

Measuring the soil moisture at five, ten and sixty cm leaves a large gap of uncertainty in the soil moisture behaviour. For future research it is recommended to add more soil moisture sensors, at every ten cm, to be able to better monitor the soil moisture and create a soil moisture profile over the depth. This will also help to increase the accuracy of both the water balance model and the AquaCrop model. The soil moisture profile can be translated into a total soil moisture storage, which can be compared to the modelled soil moisture storage in the water balance model. Besides that, the infiltration depth can be estimated more accurately from the soil moisture profile. The soil moisture profile will finally help to improve the calibration of the AquaCrop model, as it can be compared to the soil moisture profile as modelled with AquaCrop.

Next to that, the infiltration rate of the soil can be determined with an infiltration test. Knowing the infiltration rate of the soil will help increase the accuracy of the water balance model. Uncertainties in the runoff measurements can be reduced by installing the gutter and bucket in a more robust way. The gutter can be installed under a steeper angle to make sure that all the runoff flows to the bucket. Next to that, the additional camera to the set-up will help to know if all the runoff is captured.

8.1.3. Soil analysis

Prior to a next measuring campaign it is recommended to take soil samples in both the untreated and the treated plot, to determine the soil hydraulic characteristics. More accurately knowing saturation, field capacity and wilting point helps to increase the accuracy of both the water balance model and the AquaCrop model.

8.1.4. Crop development monitoring

Making sure that the crop development is monitored more frequently, preferably every two or three days, results in a better monitoring of the reaction of the crops to dry spells. For this research the crop development was measured up to the moment that the canopy cover reached its maximum. For more accurate modelling it is recommended to monitor the crop development in the later stages as well. The water balance model uses the crop development stages to estimate the crop factor, used to calculate the crop specific evapotranspiration. AquaCrop also uses the different stages of the crop development as input for the modelling.

Next to that, it is recommended to take all the pictures for the VegMon monitoring with the same phone. The pictures should be taken from the same angle and preferably at around the same time during the day, to have as equal lighting as possible and to make the monitoring as accurate as possible.

Using maize with a longer growing period, up to 120 days, increases the chance of capturing a dry spell during the crop development. The number of seeds put into the soil should furthermore be known to determine a germination rate and see if there is indeed a difference between the plots. Finally the distance between the seeds in the two plots should be similar to have as equal as possible starting conditions.

8.1.5. Multi-criteria analysis

The multi-criteria analysis can be done more extensively. Working together with CSIR-SARI in the scoring of the technologies could lead to more specific information on what technologies could be applicable for norther Ghana and under what specific conditions.

8.2. Implications

Even though the influence of the addition of sheep excrement as manure on the soil water holding capacity is uncertain, the yields are much higher in the plot where the manure is added. Through CSIR-SARI the results of the research can be shared with the farmers in the area, so they know what impact manure has on crop development and yield.

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A
Survey questions

In this appendix the list of question that is used during surveys is given. These questions are used as a guideline for the conversation, while followup questions are asked based on the answers if the interviewee. The questions are subdivided into four categories: general questions, questions on the experience of crop water shortages, questions on how the farmers reacts to dry-spells, and questions on the (unknowingly) use of rainwater harvesting.

General

1. For how long have you been farming on this location?
2. What crops are you growing?
3. What crops have you been growing in the past?
4. (If they changed the crops grown) Why did you change the crops you are growing?

Make a clear distinction in the answers between a crop rotation cycle and changes to due other reasons (economic, climate, etc.)

5. Do you have animals? If yes, what animals have you got?

Crop water shortages

6. Do you experience water shortage on the farm?
7. Do dry spells occur on the farm during the growing season?
8. Do you have a local name for these dry spells?
9. Do you experience water shortage for the crops?
10. Specific fields or crop types?
11. How do your crops react to water shortages?
12. Does crop loss occur due to a lack of water?
13. Do you experience reduced crop yield due to water shortages?
14. How has the water stress changed over the years?
15. If yes, how has it changed?
16. If yes, what changes are you experiencing?

Check if it is only for specific crops or fields.

17. When it rains, what happens to the water that falls?
18. Where does the rainwater go when it falls onto the field?
19. Does the water stay on the field or flow off the field after rain?

Preventing / overcoming water shortage

20. What do you do in case of water shortage?
21. How do you limit damage to your crops due to water shortages?
22. How do you to prevent water shortage?

(Unknowingly) use of rainwater harvesting

23. How do you prepare the field before sowing?
24. What type of fertilizers do you apply?
25. (if animals present) What happens to the manure of your animals?
26. What happens to the plant leftovers at the end of the season?
27. Do you apply a technique to capture rainwater for your crops?
28. Do you apply a technique to store more water for your crops?

B

Survey observation walk checklist

The checklist below is used during the farm walks. Whenever one of these techniques seems to be present it is ticked and a picture of the field is taken. Especially when the farmer indicates that there are differences between the fields, it is interesting to look for the techniques below. Besides that, it is also good to check for differences between the good and not good performing fields.

- Presence of organics
- Mulching
- Ridging
- Strip catchment
- Contour farming
- Bunds
- Pitting
- Runoff utilisation (external)
- With storage

C

Water balance percolation

In this appendix the events used to find the decay value k and initial soil moisture content y_0 are given, together with the fit values in Table C.1. For both the untreated and the treated plot the five events are plot and fit for a five minute and hourly time step.

Table C.1: Fitted k and y0 values for the five events that have a soil moisture content above the field capacity and show decay at night, when the sun is not shining, including the average of all five events and the average of events 2,4 and 5, which are most representative for the treated plot

			Untreated				**Treated**			
Event	**Date**	**Size [mm]**	**k hourly**	**k 5 min**	**y0 hourly**	**y0 5 min**	**k hourly**	**k 5 min**	**y0 hourly**	**y0 5 min**
1	23-08-22	113	-0.0023	-0.0002	0.2656	0.2659	-0.0001	-0.0000	0.2943	0.2945
2	27-08-22	15	-0.0032	-0.0003	0.2624	0.2621	-0.0017	-0.0001	0.3004	0.3001
3	07-09-22	9	-0.0017	-0.0001	0.2595	0.2597	1.43E-9	-1.6E-11	0.2890	0.28900
4	15-09-22	57	-0.0020	-0.0003	0.2653	0.2667	-0.0012	-0.0002	0.2922	0.2931
5	19-09-22	56	-0.0049	-0.0004	0.2721	0.2734	-0.0018	-0.0002	0.2967	0.2973
Average			-0.0028	**-0.0003**	0.2650	0.2656	-0.0009	-0.0001	0.2945	0.2948
Average events 2,4,5			-0.0034	-0.0004	0.26660	0.2674	-0.0015	**-0.0002**	0.2965	0.2968

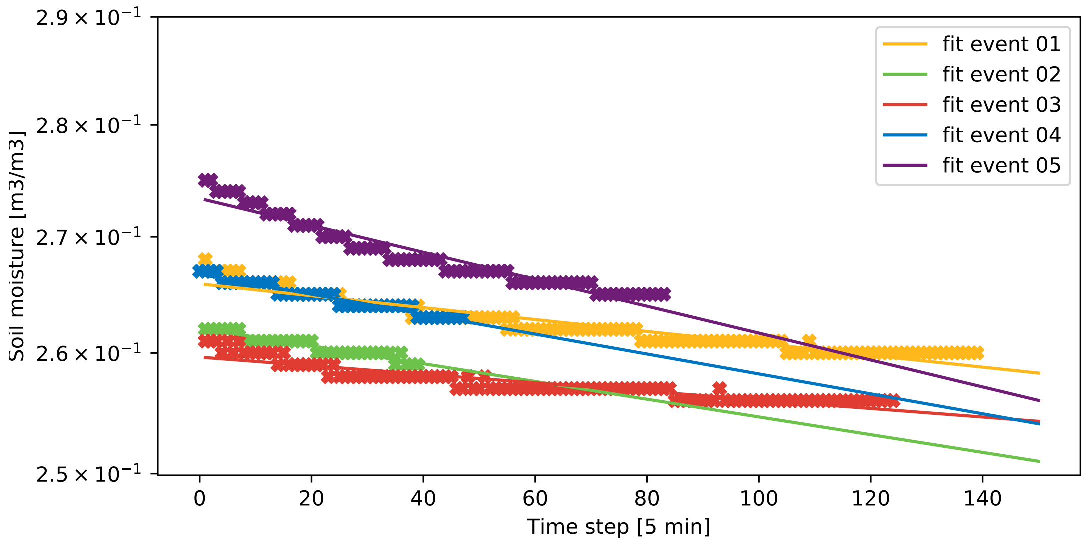


Figure C.1: Percolation k values for the untreated plot with a 5 minutes time step

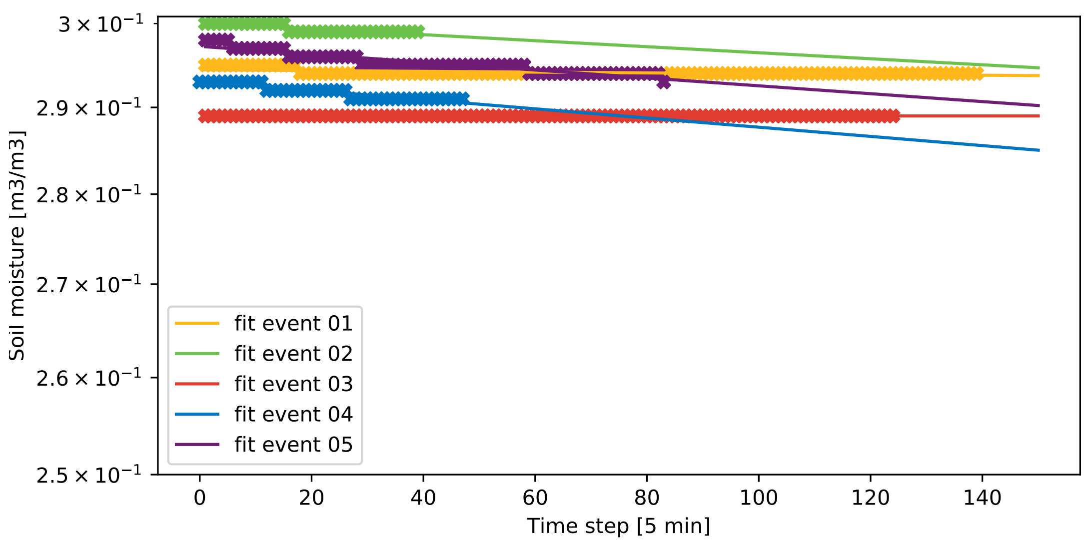


Figure C.2: Percolation k values for the treated plot with a 5 minutes time step

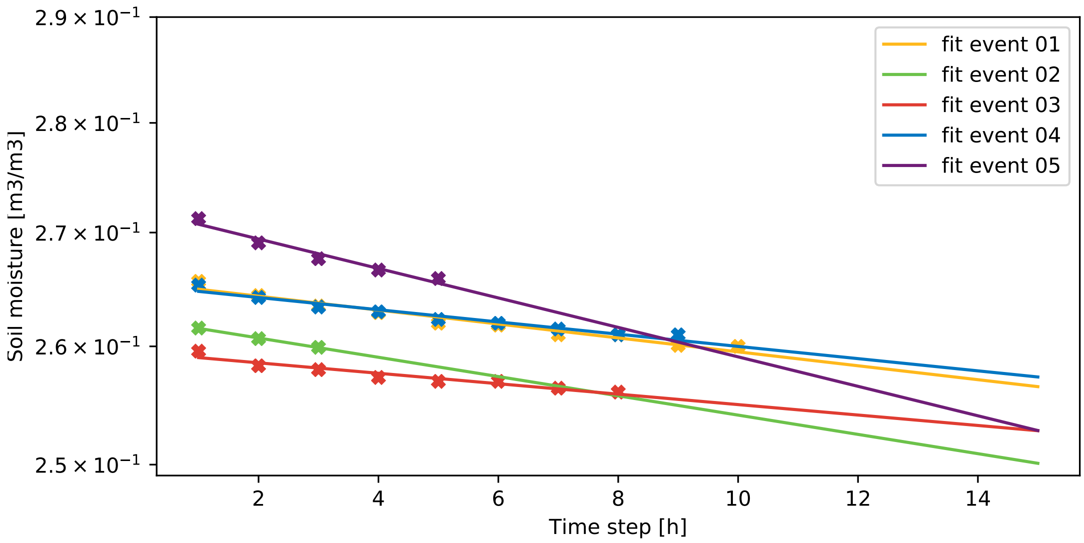


Figure C.3: Percolation k values for the untreated plot with an hourly time step

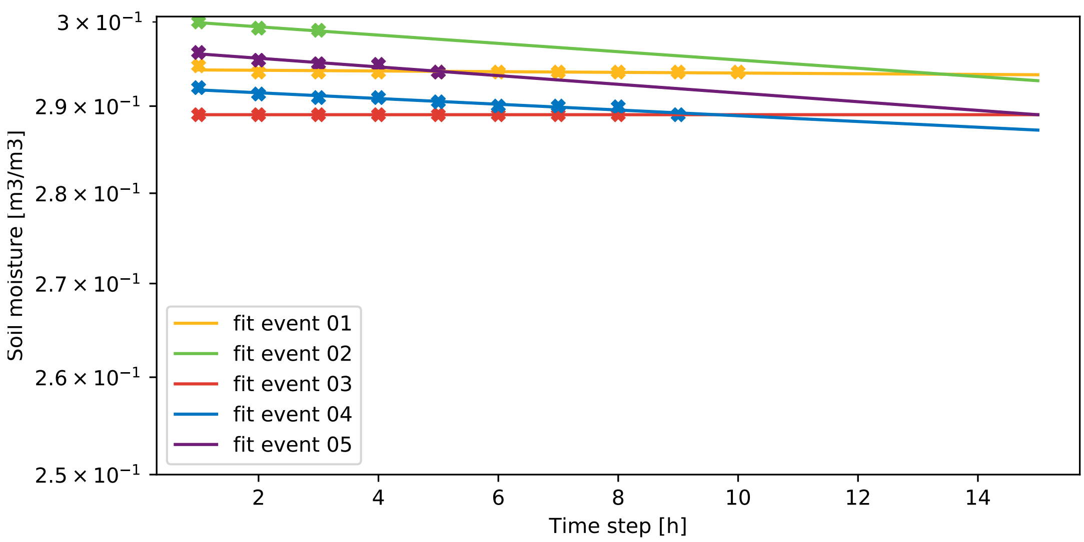


Figure C.4: Percolation k values for the treated plot with an hourly time step

D

VegMon crop development monitoring

In this appendix the canopy cover development and VIGreen as gathered using the VegMon app are given.

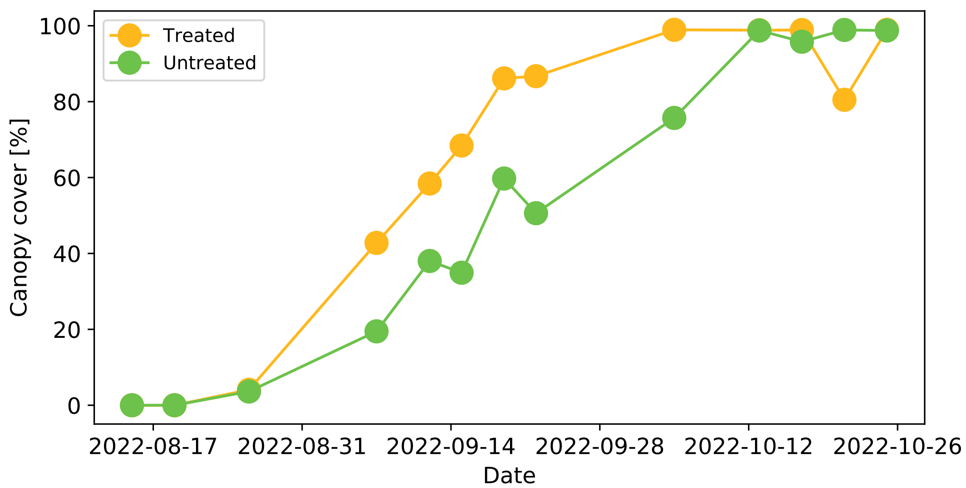


Figure D.1: Canopy cover in the untreated and treated plots throughout the growing season of the maize plants from August until October 2022

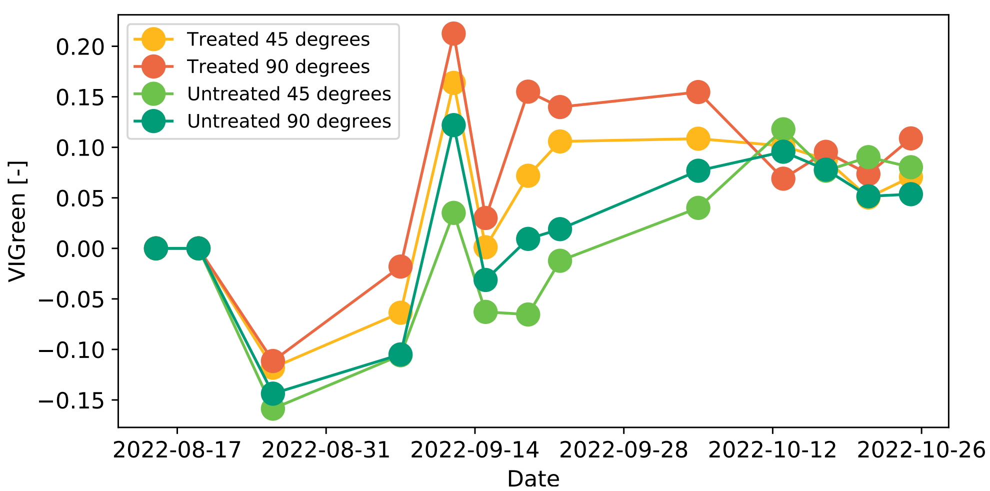


Figure D.2: VIGreen in the untreated and treated plots throughout the growing season of the maize plants from August until October 2022

E
AquaCrop soil moisture modelling

In this appendix the soil moisture as modelled with AquaCrop in the untreated plot at five, ten and sixty centimeters is given. Besides that the soil moisture as modelled with AquaCrop in the treated plot at sixty centimeters is given.

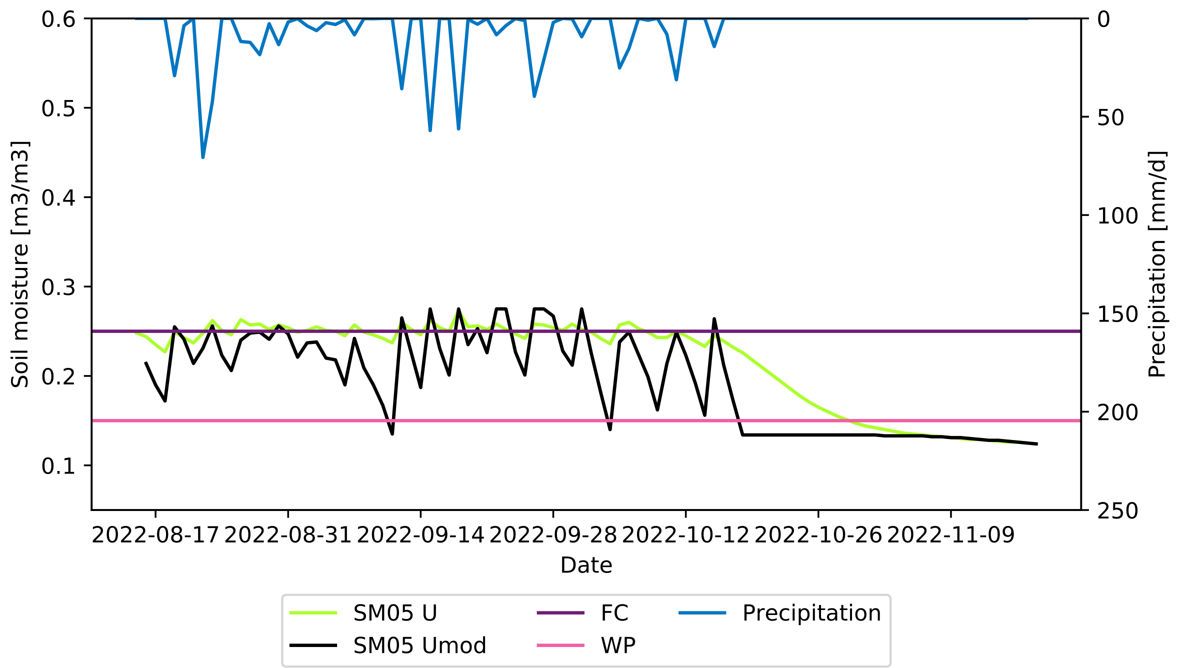


Figure E.1: Measured and modelled daily soil moisture at five centimeters depth in the untreated plot, with SM05 U: measured soil moisture at 5 cm in the untreated plot, SM05 Umod: AquaCrop modelled soil moisture at 5 cm in the untreated plot, FC: field capacity in the untreated plot at 5 cm, WP: wilting point in the untreated plot at 5 cm

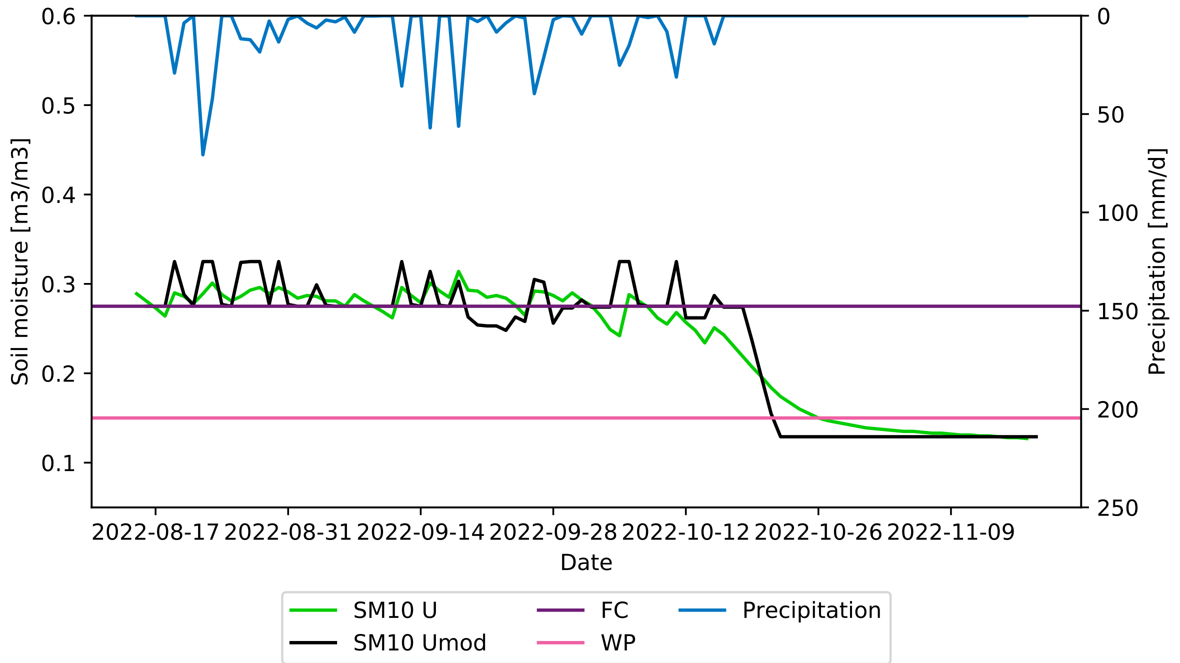


Figure E.2: Measured and modelled daily soil moisture at ten centimeters depth in the untreated plot, with SM10 U: measured soil moisture at 10 cm in the untreated plot, SM10 Umod: AquaCrop modelled soil moisture at 10 cm in the treated plot, FC: field capacity in the untreated plot at 10 cm, WP: wilting point in the untreated plot at 10 cm

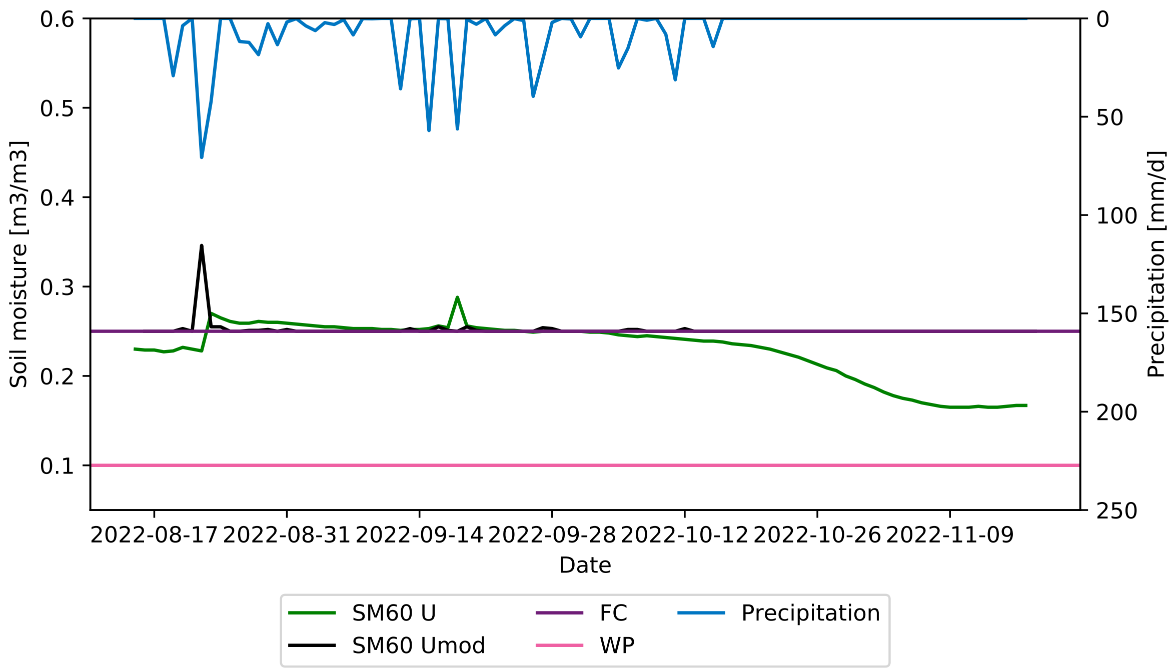


Figure E.3: Measured and modelled daily soil moisture at sixty centimeters depth in the untreated plot, with SM60 U: measured soil moisture at 60 cm in the untreated plot, SM60 Umod: AquaCrop modelled soil moisture at 60 cm in the untreated plot, FC: field capacity in the untreated plot at 60 cm, WP: wilting point in the untreated plot at 60 cm

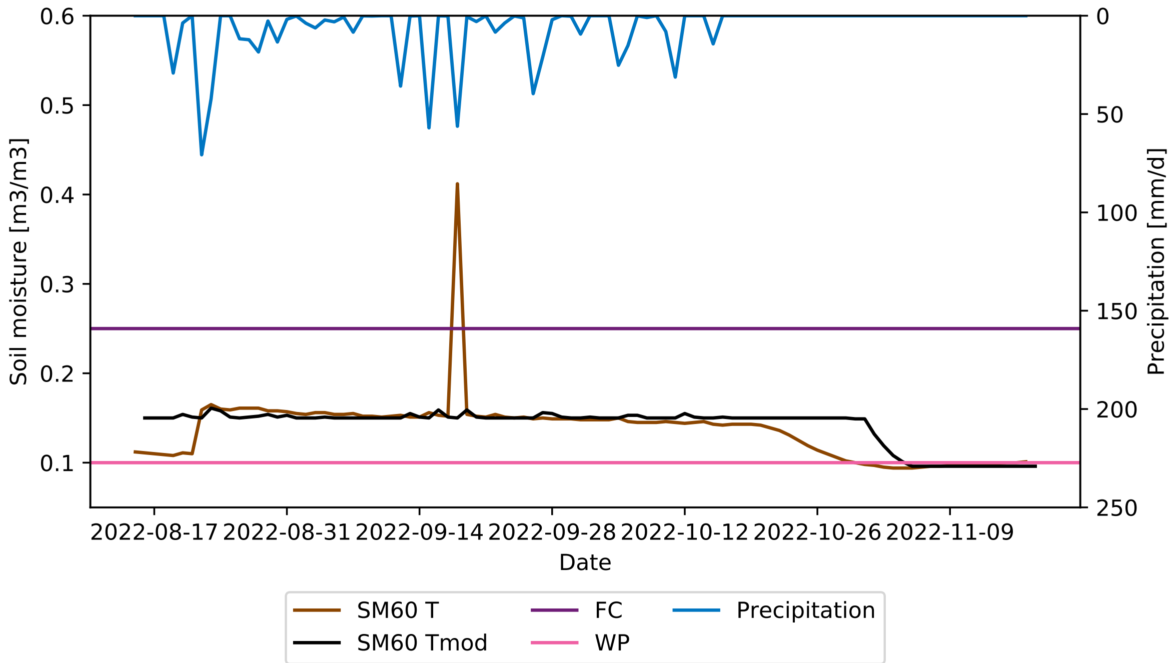


Figure E.4: Measured and modelled daily soil moisture at sixty centimeters depth in the treated plot, with SM60 T: measured soil moisture at 60 cm in the treated plot, SM60 Tmod: AquaCrop modelled soil moisture at 60 cm in the treated plot, FC: field capacity in the untreated plot at 60 cm, WP: wilting point in the untreated plot at 60 cm

F
AquaCrop root zone depletion

In this appendix the root zone depletion as modelled with AquaCrop is given for both the untreated and the treated plot.

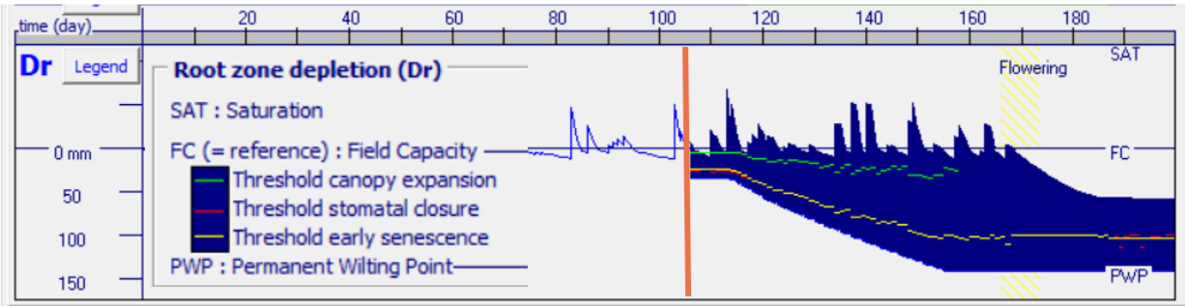


Figure F.1: Root zone depletion throughout the season in the untreated plot, with the orange line indicating when the sowing took place

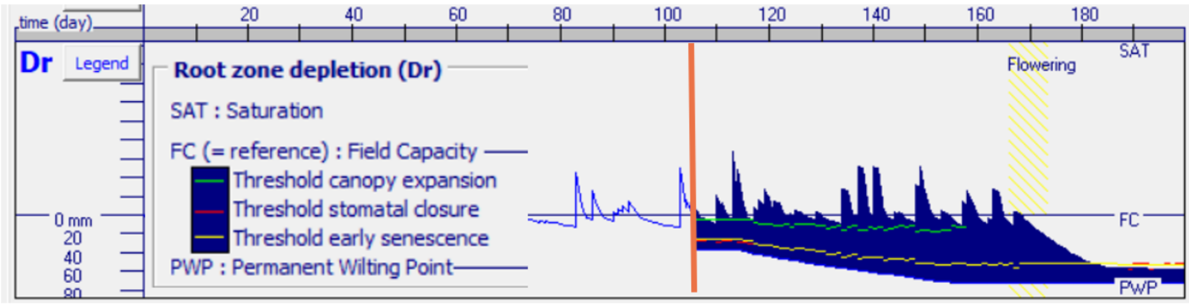


Figure F.2: Root zone depletion throughout the season in the treated plot, with the orange line indicating when the sowing took place

G
Field harvest data

In this appendix the total harvest data as gathered in the field for both the untreated and the treated plot is given.

Table G.1: Harvest data measured in the field

	Untreated		Treated	
	[grams/plot]	[tons/ha]	[grams/plot]	[tons/ha]
No of plants	45	83,333	44	81,481
Total dry weight	4441	8.2	6175	11.4
Husked cob wt	1541	2.9	2678	5.0
Wt dehusked cobs	1168	2.2	2225	4.1
Wt husks	373	0.7	453	0.8
Stalk stover wt	2900	5.4	3500	6.5
Grains	685.5	1.3	1474.5	2.7
Wt cob spindle	482.5	0.9	750.5	1.4
Wt total stover	3755	7.0	4703.5	8.7
Harvest index	0.15		0.24	
Threshability husked cobs	0.44		0.55	
Threshability dehusked cobs	0.59		0.66	
Wt of 100 grains				
sample 1	16.3		18.9	
sample 2	15.8		18.6	
sample 3	15.6		18.5	
sample 4	15.7		18.6	
sample 5	16.2		19.1	

H

Extended results multi-criteria analysis

In this appendix the scores given to the different rainwater harvesting technologies in the multi-criteria analysis are elaborated. Per technology the scores for the five criteria are given and explained.

Deep tillage

- Materials - 5: no additional materials are needed
- Installation - 1: requires high draft power of for example tractors
- Maintenance - 5: does not require maintenance during the season
- Knowledge - 5: is done a lot already in the area
- Effectiveness - 3: increases infiltration

Tied ridges

- Materials - 5: no additional materials are needed
- Installation - 3: takes relatively much labour to construct all the ridges
- Maintenance - 2: high risk of clogging, so need regular maintenance
- Knowledge - 3: knowledge is needed for optimal effect
- Effectiveness - 3: reduced runoff, however not applicable for all crops

Contour farming

- Materials - 5: no additional materials are needed
- Installation - 4: planting along the contour lines does not require a lot of extra labour
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 3: knowledge is needed for optimal effect
- Effectiveness - 4: reduce runoff and increases soil moisture content

Adding manure

- Materials - 3: a lot of manure is needed for effective implementation
- Installation - 3: the manure needs to be spread
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 4: is done in the area by some farmers
- Effectiveness - 4: increases soil moisture retention

Mulching

- Materials - 2: depends on the type of mulching, but a lot of materials are needed to cover a complete field
- Installation - 2: labour is needed place all the mulching material
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 3: knowledge is needed for optimal effect
- Effectiveness - 5: decreases soil evaporation and runoff, increases infiltration and soil moisture retention

Conservation agriculture

- Materials - 2: materials for the mulching are needed
- Installation - 2: labour is needed place all the mulching material
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 1: specific knowledge is needed for optimal effect
- Effectiveness - 5: decreases soil evaporation and runoff, increases infiltration and soil moisture retention

Pitting

- Materials - 3: manure and organics are needed to fill the pits
- Installation - 2: labour is needed to dig the pits and place the organics
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 3: knowledge is needed for optimal effect
- Effectiveness - 4: increases infiltration and soil moisture retention

Strip catchment tillage

- Materials - 5: no additional materials are needed
- Installation - 5: no additional labour is needed for installation
- Maintenance - 5: no maintenance is required during the season
- Knowledge - 4: minimal knowledge is needed for optimal effect
- Effectiveness - 3: increases infiltration where the plants grow

Contour bunds

- Materials - 3: depending on the type of bunds additional materials are needed
- Installation - 2: construction of the bunds requires quite some labour
- Maintenance - 3: the bunds need to be maintain for optimal effect
- Knowledge - 3: knowledge is required, however some farmers in the area already construct bunds
- Effectiveness - 4: decreases runoff, increase infiltration

Fanya juus

- Materials - 4: in some cases grass is needed for stabilisation
- Installation - 2: requires a lot of labour to construct
- Maintenance - 2: requires significant maintenance
- Knowledge - 3: requires specific knowledge for optimal effect
- Effectiveness - 4: reduces runoff, increases soil moisture retention

Semi-circular bunds

- Materials - 3: depending on the type of bunds additional materials are needed
- Installation - 2: construction of the bunds requires quite some labour
- Maintenance - 3: the bunds need to be maintain for optimal effect
- Knowledge - 4: knowledge is required, however some farmers in the area already construct bunds
- Effectiveness - 4: decreases runoff, increase infiltration

Meskat-type systems

- Materials - 5: no additional materials are needed
- Installation - 3: installation requires some labour
- Maintenance - 3: require some maintenance
- Knowledge - 2: requires specific knowledge for optimal effect
- Effectiveness - 1: is only effective in areas with low-intensity precipitation

Hillside runoff

- Materials - 3: sometimes additional materials are needed
- Installation - 2: the fields require adjustment
- Maintenance - 3: require some maintenance
- Knowledge - 2: requires knowledge for optimal effect
- Effectiveness - 1: only effective in areas with steep slopes

Floodwater harvesting

- Materials - 2: materials are needed to construct the barriers
- Installation - 1: a lot of labour is needed to construct barriers
- Maintenance - 1: the system needs regular maintenance for optimal effect
- Knowledge - 1: specific knowledge is required
- Effectiveness - 1: a large stream is required

Ephemeral stream division

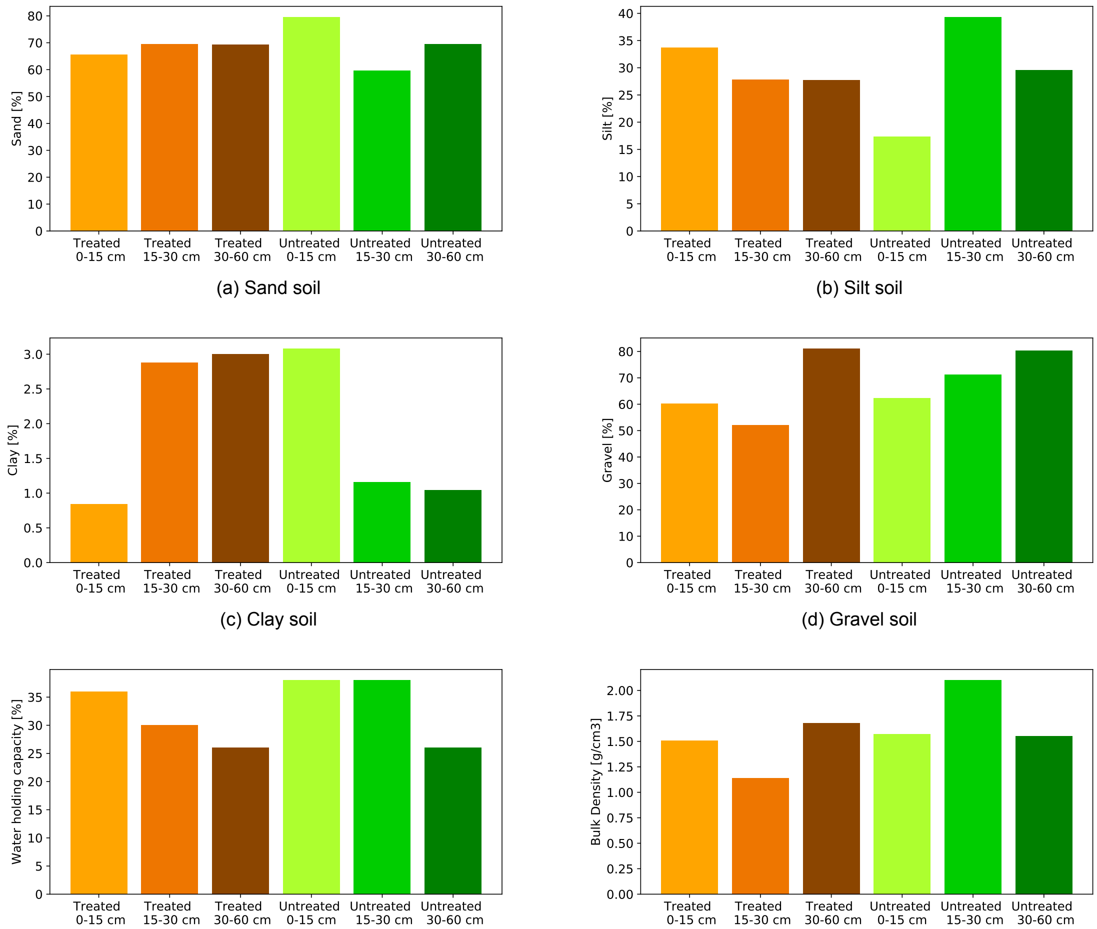
- Materials - 2: materials are needed to construct the diversions
- Installation - 1: a lot of labour is needed to construct diversions
- Maintenance - 1: the system needs regular maintenance for optimal effect
- Knowledge - 1: specific knowledge is required
- Effectiveness - 1: a large stream is required

With storage

- Materials - 1: materials are needed to store the water in
- Installation - 1: installing storage systems requires a lot of labour
- Maintenance - 2: storage systems require regular maintenance
- Knowledge - 5: the farmers in the area know about storage already
- Effectiveness - 5: it is very effective

Field soil data

In this appendix the soil characteristics, as found from the soil analysis in the CSIR-SARI lab, are given. First, the physical soil characteristics are given in Figure I.1, followed by the soil characteristics defining the nutrient content, given in Figure I.2. Finally, the derived saturation, field capacity, wilting point and soil hydraulic conductivity for each of the soil horizons is given in Table I.1.

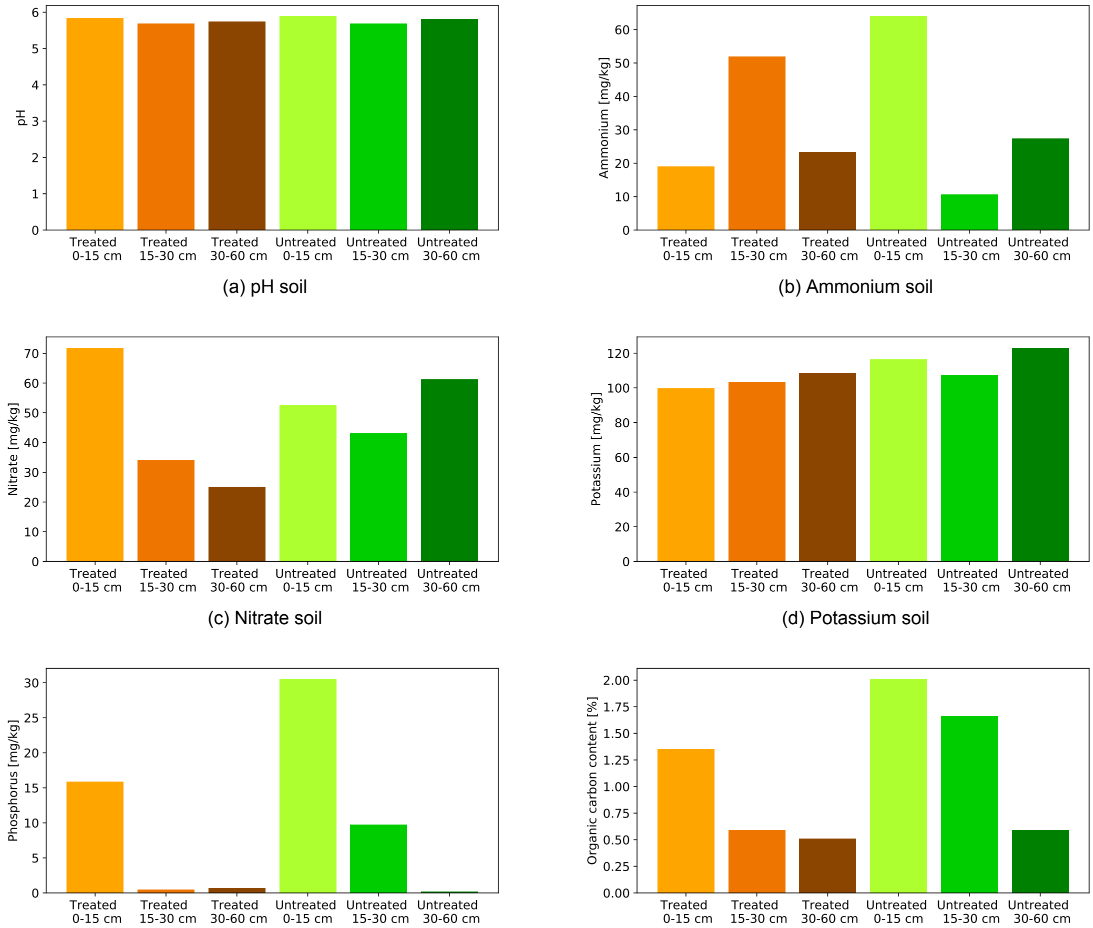


(a) Sand soil (b) Silt soil

(c) Clay soil (d) Gravel soil

(e) Water holding capacity soil (f) Bulk density soil

Figure I.1: Physical soil parameters



(a) pH soil (b) Ammonium soil

(c) Nitrate soil (d) Potassium soil

(e) Phosphorus soil (f) Organic carbon content soil

Figure I.2: Nutrient soil parameters

Table I.1: Soil hydraulic properties for the untreated and treated plot as calculated with the USDA hydraulic properties calculator using the soil properties found in the CSIR-SARI soil lab from the sampled soils, where Sat: saturation, FC: field capacity, WP: wilting point, Ksat: saturation hydraulic conductivity

	horizon [cm]	**Sat [-]**	**FC [-]**	**WP [-]**	**Ksat [mm/hr]**
Untreated	0-15	0.453	0.103	0.034	48.36
	15-30	0.437	0.146	0.034	29.96
	30-60	0.409	0.105	0.021	34.09
Treated	0-15	0.432	0.122	0.024	41.72
	15-30	0.408	0.107	0.021	37.82
	30-60	0.405	0.106	0.020	33.18

J Raw experimental data

In this appendix the graphs of the raw data gathered in the field experiments are given. First, the climate data from the TAHMO station are given, with the precipitation in Figure J.1, the temperature in Figure J.2 and the incoming shortwave radiation in Figure J.3. Next, the runoff in mm is given for the untreated plot in Figure J.4 and for the treated plot in Figure J.5. Finally, the soil moisture measured at 5, 10 and 60 cm is given for the untreated in Figure J.6 plot and for the treated plot in Figure 5.5.

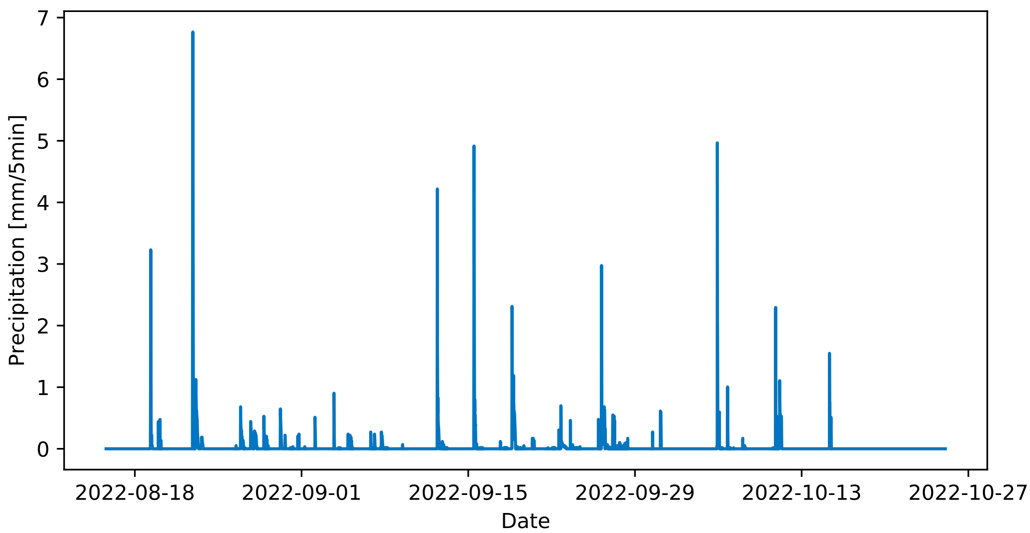


Figure J.1: Precipitation throughout the growing season of the maize plants from August until October 2022

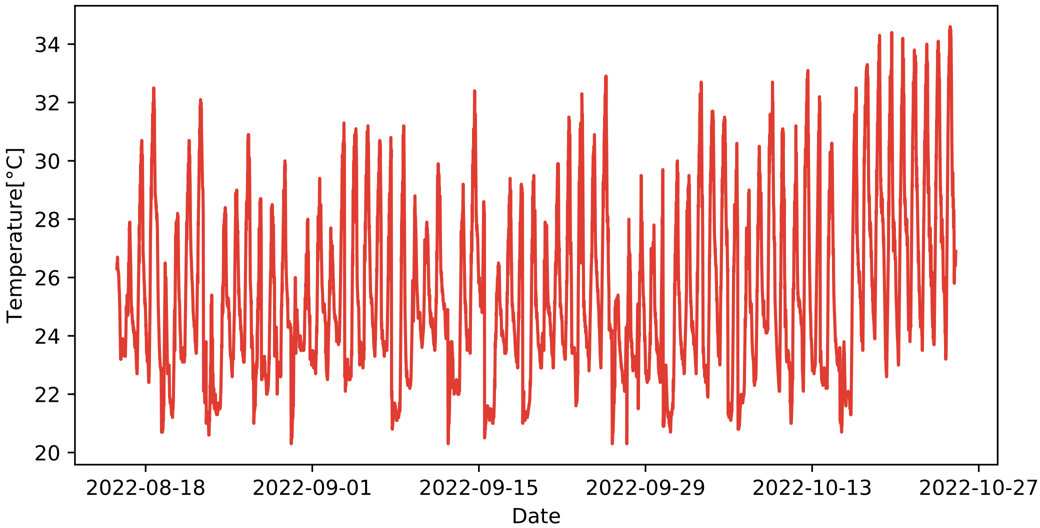


Figure J.2: Temperature throughout the growing season of the maize plants from August until October 2022

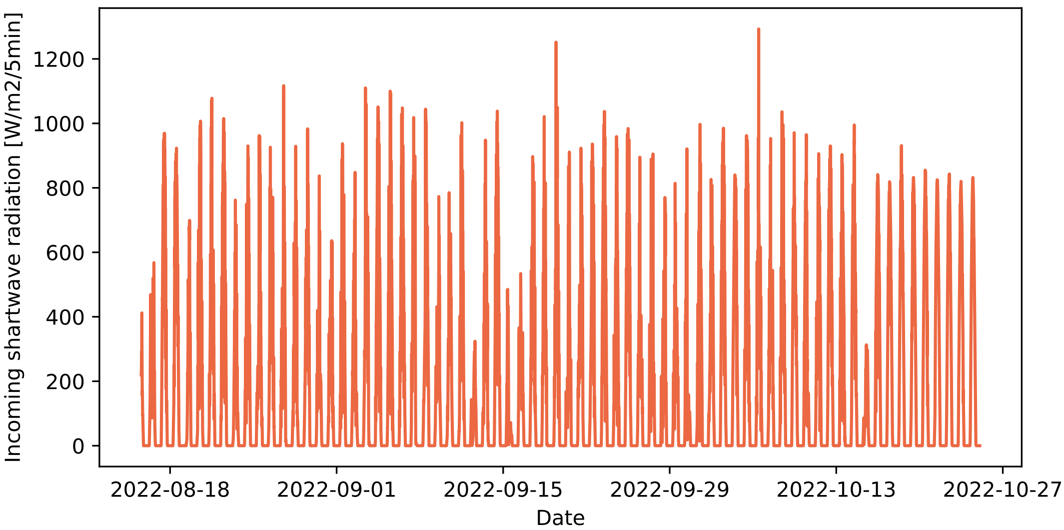


Figure J.3: Incoming shortwave radiation throughout the growing season of the maize plants from August until October 2022

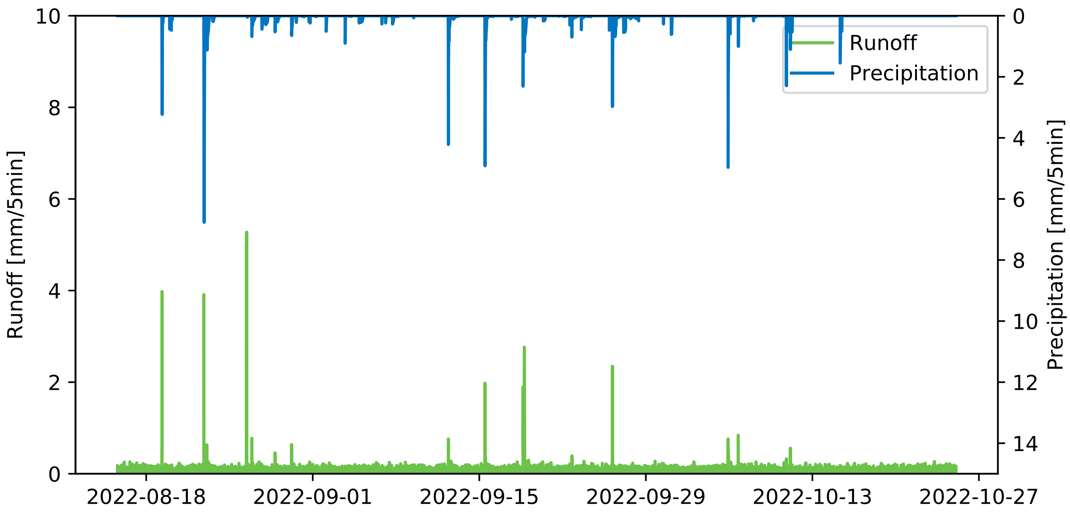


Figure J.4: Runoff in the untreated plot throughout the growing season of the maize plants from August until October 2022

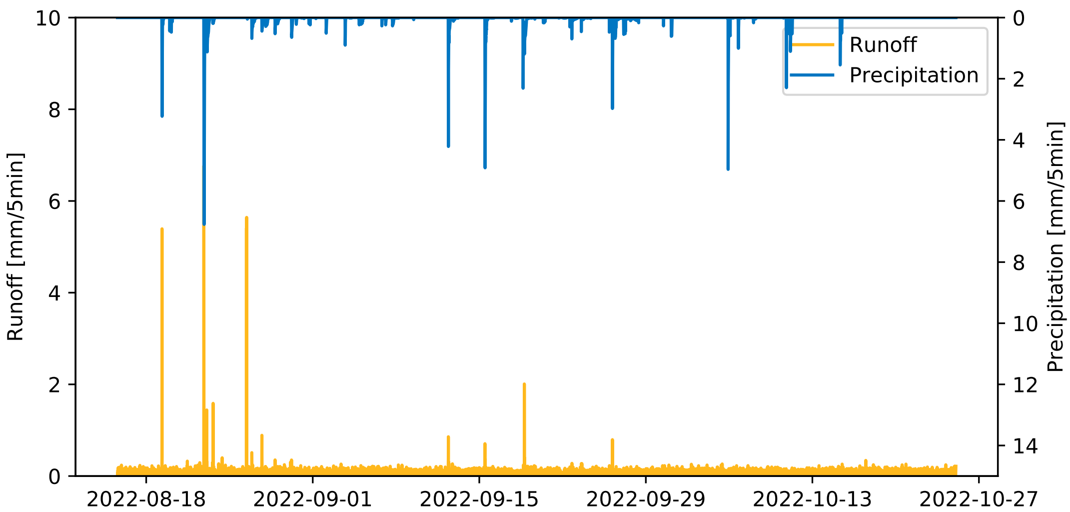


Figure J.5: Runoff in the treated plot throughout the growing season of the maize plants from August until October 2022

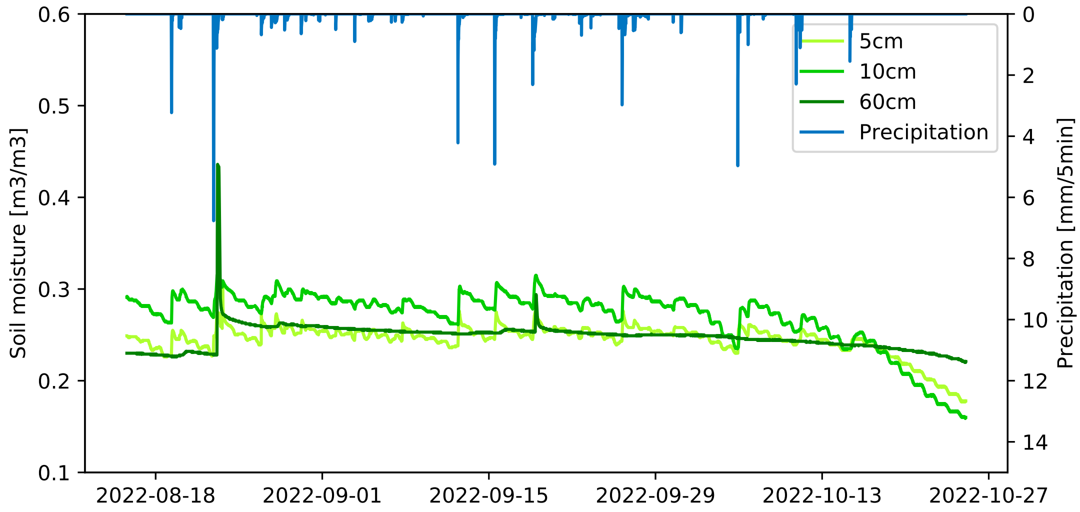


Figure J.6: Soil moisture in the untreated plot throughout the growing season of the maize plants from August until October 2022

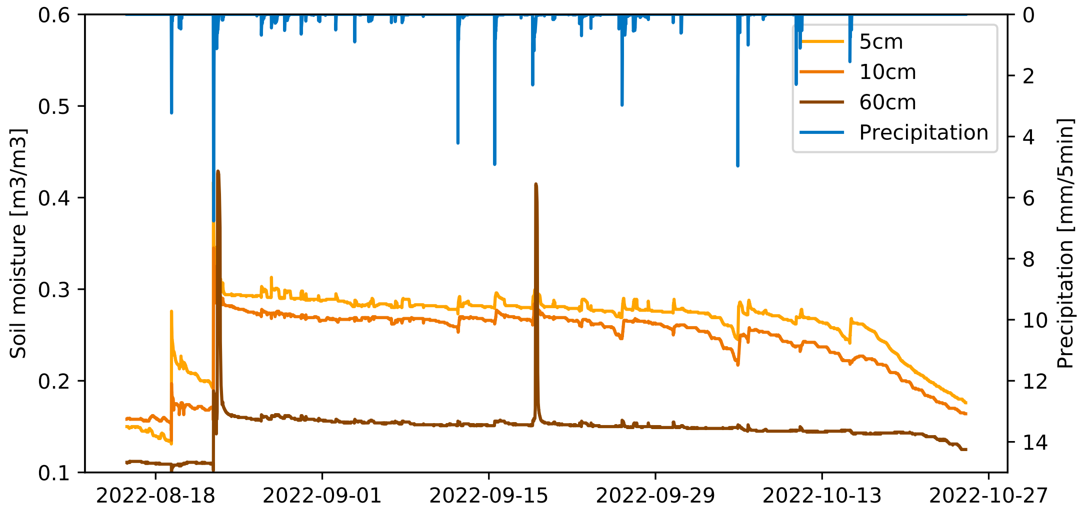


Figure J.7: Soil moisture in the treated plot throughout the growing season of the maize plants from August until October 2022