Optimizing irrigation water management during periods of drought in the Magdalena-Cauca macro-basin, Colombia

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Abstract

Droughts affect more people than any other climatic hazard worldwide. The occurrence of droughts has a direct impact on domestic water supply, affecting food security and public health. Moreover, droughts will alter economic sectors dependent on water, such as irrigation and hydroelectric production. The impact of droughts can increase by the unsuitable use of water and other natural resources. In this report, the effect of droughts is studied by looking to the vulnerability of crop production in dry periods for two irrigation districts. The droughts are studied on a global scale with the Multivariate ENSO Index and a local scale with the 6-month SPEI drought index.

The Saldaña and Coello irrigation districts are located in the Magdalena-Cauca macro-basin, central Colombia. In these two irrigation districts, the production of rice was studied during periods of drought, hereby considering the water availability and reducing the amount of irrigation water to obtain an optimized irrigation schedule during periods of drought.

The El Niño Southern Oscillation (ENSO) and the main local droughts of the Saldaña and Coello irrigation districts, classified by the 6-month SPEI drought index, have a high correlation for most of the droughts. The El Niño events of 1991-1992, 1997-1998 and 2015-2016 all correlate to droughts in both irrigation districts, the El Niño event of 1982-1983 has a correlation to drought in the Coello district, while the El Niño that occurred in 1987-1988 did not cause any drought in both districts. With the onset of an ENSO event, the water managers could prepare with changing the irrigation schedule, considering the ENSO event will also result in droughts in the Coello and Saldaña irrigation districts.

The AquaCrop model of the Food and Agriculture Organization of the United Nations was used to analyze the production of rice and the required water used for each growing cycle during each period of drought of the past 40 years. Hereby the climatic data of local stations, the soil properties for the total areas that are suited for the irrigation of rice, and as precise as possible the local irrigation practices as obtained during fieldwork were used. The irrigation schedules consist of the irrigation schedules as they are practiced in the two districts during normal conditions and periods of drought. Furthermore, other irrigation schedules were created to obtain the same results, although with reduced water supply for the growing cycle. Through the runs of the various irrigation schedules, the total water use for each growing cycle was calculated. The irrigation water amounts of maize and sorghum, the other main crops in the two districts, were determined with the AquaCrop model with optimal irrigation water.

The irrigation scenarios for rice, the irrigation requirements for maize and sorghum and the total areas of the two irrigation districts were used to calculate the required average discharge for the irrigation of the whole Saldaña and Coello districts during each period of drought. The irrigation runs showed that the irrigation water requirements vary broadly and the irrigation schedule that is currently used in Coello and Saldaña during droughts is not the most optimal in water use. In Coello, the most severe droughts occurred in 1983, 1997, 2012 and 2015, while in Saldaña the most severe droughts occurred in 1992, 1997, 2012 and 2015. Most of these severe droughts occurred in the period of an El Niño event. The most severe droughts were used to create a universal irrigation schedule that could serve both districts in the future and could cope with low precipitation rates and low water levels. This irrigation schedule reduced the discharge from 25 m^3/s to at least 16 m^3/s during the growing cycle of all crops for the both irrigation districts.

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1. Introduction

During the last decennia, the diversity and amount of water-related challenges increased substantially as a result of climate change and population growth (Lopez Lopez, 2018). The consequence is that many river basins have a changed water-balance, and water is limited in some periods throughout the year. Droughts affect more people than any other climatic hazard (Wilhite et al., 2007). The impacts that occur from drought are a result of the interplay between natural events and the demand placed on water (Wilhite et al., 2007). The impact of drought can increase by the unsuitable use of water and other natural resources. Drought is perceived here as a temporary lack of water caused by abnormal climate conditions, which is damaging to an activity, group or environment (Kallis, 2008). Effects of extreme weather events are evaluated by analyzing the vulnerability of exposed communities. This is mostly done by looking to the vulnerability to crop production in periods of drought. Understanding the vulnerability and how it relates to the natural climate and climate change, particularly in periods of extreme weather, is an initial step in managing climate change risks (Hoyos et al., 2013).

Drought is a period of temporary, below-average availability of water resources due to the variability of natural conditions. Drought is a complex natural hazard that impacts ecosystems and society, and many of these impacts are associated with hydrological drought (van Loon, 2015). Other types of drought are characterized by Kallis (2008) as meteorological, agricultural and water supply droughts. Meteorological droughts are defined as abnormal precipitation deficits. Agricultural droughts are defined as abnormal soil moisture deficits. Hydrological droughts are defined as abnormal streamflow, groundwater and reservoir deficits. Finally, water supply droughts are defined as temporary failures of supply to meet the water demand. This distinction between the different types of droughts is not just linguistic (Kallis, 2008). They interfere with each other. When there are precipitation deficits, later there will be soil moisture deficits, while long periods of meteorological droughts can cause hydrological droughts (Kallis, 2008). The occurrence of droughts has a direct impact on domestic water supply, affecting food security and public health. Moreover, droughts will alter economic sectors dependent on water, such as irrigation and hydroelectric production (Garrido, 2014).

Generally, drought is the result of climatic fluctuations. In the tropics, the El Niño-Southern Oscillation (ENSO) is recognized as the most prominent mode of climate variability that operates from seasonal to inter-annual time scales (Zebiak et al., 2015). ENSO has a strong effect on precipitation, river discharge and soil moisture (Poveda et al., 2001). The ENSO events differ largely in intensity and duration time. El Niño events occur every two to seven years, with extreme variation in duration and intensity (Poveda et al., 2001). The typical duration of El Niño ranges from 14 to 22 months. Often an El Niño event starts early in the year, and it peaks in the following boreal winter (Diaz, 2005). Also, during an ENSO year, there is a difference in which months are mostly affected. Of all land surfaces, 20-30% is affected by an increase or lack of precipitation during El Niño. Most of these regions are located in the tropics (Zebiak et al., 2015). Climatic, hydrological and oceanographic disturbances related to ENSO events had dramatic global socioeconomic and environmental impacts, but since the El Niño event of 1982-1983, the public attention for El Niño and research on this phenomenon grew (Zebiak et al., 2015).

In the Magdalena basin in Colombia, El Niño results in relatively dry periods, and La Niña is associated with periods of excessive rainfall (Grootveld, 2019). The main cities of Colombia, including Bogota, Medellin, Cali, Bucaramanga and Barranquilla, are located in the Magdalena basin. In total 79 percent of the Colombian population lives in the Magdalena basin, with a density of 120 inhabitants/km^2 (IDEAM, 2001). Grootveld (2019) used four large scale hydrological models to quantify the hydrology of the whole Magdalena basin, followed by quantification of five different drought indices to determine the correlation between droughts and ENSO. Droughts were found to occur most often in the southeast of the basin, which is due to the effect of the Chóco Jet, which supplies moist air. During El Niño events, the drought-affected area starts in the northeast of the Magdalena River Basin and moves to the southwest of the basin in the period of three to five months (Grootveld, 2019). Correlation with ENSO was found to be the strongest for the 6-month ensemble mean of the Standardized Precipitation Evapotranspiration Index (SPEI) drought index (Grootveld, 2019).

The last decades in the Magdalena basin changes occurred in land use, water resources, soil losses and natural resource exploitation, which rapidly increased during the economic development in the last decades. These recent changes increased the pressure on the quantity of freshwater in the basin that is used for agriculture, domestic use, industrial activities and hydropower generation (Restrepo and Syvitski, 2006). Agriculture is the largest user of water, and the agricultural sector is the most sensitive industry because climate change impacts the rainfall pattern and drought (Yoo et al., 2015). During droughts crop yield decreases and water resources reduce, affecting millions of people. El Niño causes droughts that affect crop yield from Mexico through Colombia and east to the Caribbean and northern Brazil (Poveda and Mesa, 1997). The connection between droughts and crop production is more complex for irrigated than for rainfed crops as irrigation buffers the impact of climate variability on crops. Water has always been the main factor limiting crop production in parts of the world where rainfall is insufficient, in certain periods, to meet crop demand. It is important to understand the effect of droughts on crops, to optimize the planning and management of water in agriculture, especially in periods of a changing climate. Crop growth models are inexpensive tools that can help to understand climate effects and water requirements on crop growth and yield (Tongson et al., 2017).

This thesis aims to optimize and improve the water and crop management of the Coello and Saldaña irrigation districts that are located in the southern part of the Magdalena basin. The research analyzed the irrigation system management and the climatic fluctuations of the past. By applying an irrigation scheduling model (AquaCrop), the water management was optimized to cope with drought and minimize the drought-related damage. The following objectives were defined for the study:

I. Quantification of droughts in the Saldaña and Coello irrigation districts and correlation with ENSO driven droughts.
II. Determination of the irrigation water requirements, by the use of AquaCrop, in the Saldaña and Coello irrigation districts, based on crop water requirements and the cropping areas.
III. Analyzation of existing water management practices and evaluate crop water availability during drought periods.
IV. Developing water management strategies for the two irrigation schemes that can cope with severe droughts.

2. Study area and background

This chapter describes the total study area of the Magdalena River Basin, the hydrology and droughts (2.1 and 2.2), the irrigation districts with its climatic factors (2.3), followed by the history of water management of the two irrigation districts (2.4) and information of the main crops (2.5).

2.1 Magdalena River Basin

The study area is in the Magdalena River Basin (Figure 1). The Magdalena River Basin is located in the west of Colombia and is the largest and most important fluvial system in Colombia, draining approximately 257,000 km^2, which is roughly 25% of Colombia's territory. The basin comprises two main rivers, the Cauca River in the west and the Magdalena River in the east (Restrepo et al., 2006).

The Magdalena River Basin forms a valley in the Andes of Colombia consisting of the Western, Central and Eastern Cordilleras. These three mountain ranges are north-south orientated and nearly parallel. In the south of Colombia, these mountain ranges merge into a single range near Ecuador's border (Restrepo et al., 2006; Restrepo and Syvitski, 2006).

The Magdalena Basin is characterized by high precipitation rates, with an average rainfall of 2050 mm/year (Restrepo et al., 2006). The complex topography of the Magdalena River Basin makes it difficult to present generalizations of rainfall patterns. In the basin, precipitation ranges from 1000 mm/year in the eastern mountains to more than 5000 mm/year in the western part of the basin (IDEAM, 2001). The average annual potential evapotranspiration is approximately 1630 mm per year, although it varies a lot due to the topography. The Magdalena River has a length of 1612 km, and its headwaters are located at a lake in the Huila department at an elevation of 3685 m (Restrepo et al., 2006).

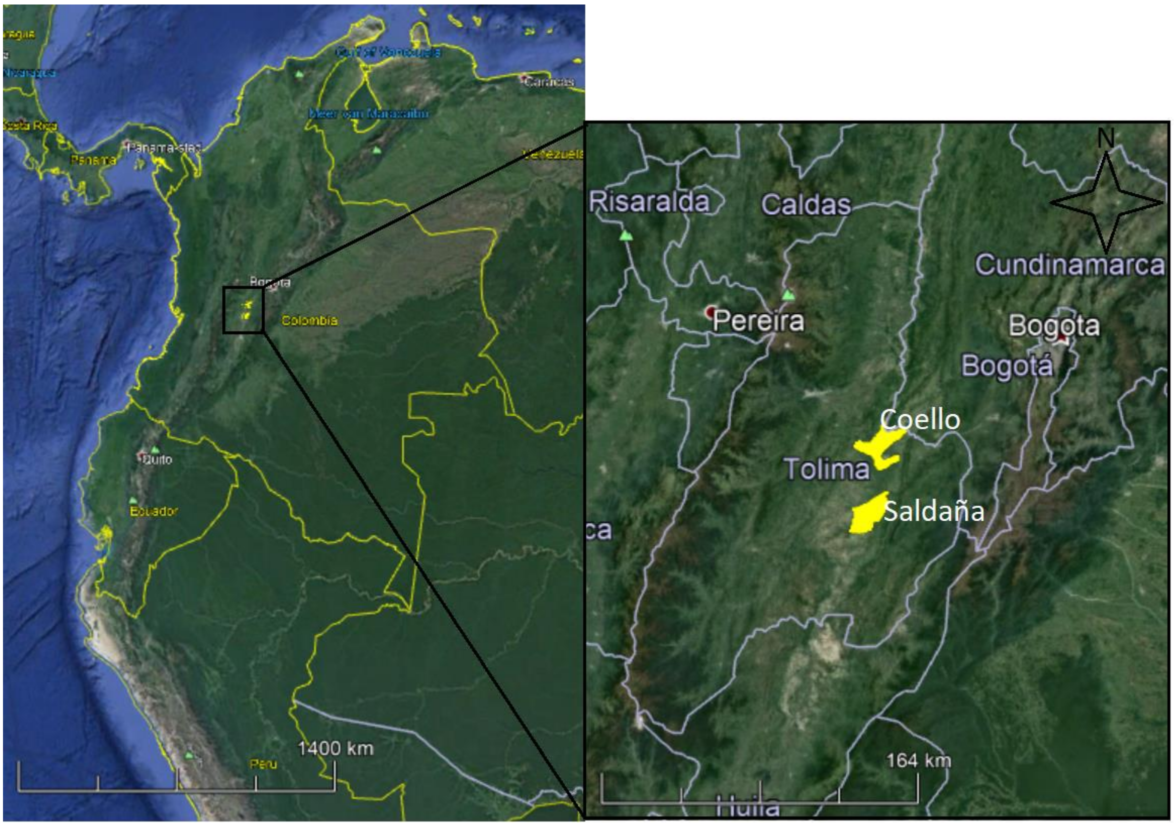


Figure 1 Map of Colombia (left) and map of Tolima and the Coello and Saldaña irrigation districts (right) (Google earth, 2020).

2.2 Hydrology and drought

The most important factors controlling the annual hydrological cycle in Colombia are the inter-tropical convergence zone (ITCZ), superimposed on regional patterns caused by the orographic influence of the Andes, evapotranspiration of the Amazon Basin, the dynamics of the low-level western Colombian wind, the surrounding Pacific and Atlantic ocean and the continental-atmosphere interactions (Poveda and Mesa, 1997; Hoyos et al., 2013). Usually the catchment area is characterized by high rates of precipitation and extreme rainfall events. There are two wet and two dry seasons during the year in the basin's upper and middle regions. In general, December-March and June-September are periods with low precipitation rates. During March-May and October-November are periods with higher precipitation rates. In the lower Magdalena basin, a single wet period occurs in May-November. The wet seasons are comparable in length and intensity, only in the upper area of the Magdalena River Basin the first wet season is more prolonged (Restrepo et al., 2006).

There is much inter-annual variability in precipitation, mainly due to the ENSO phenomenon (Hoyos et al., 2013). During El Niño, anomalous Hadley cells develop with descending atmospheric motion over the northern part of South America. Then the centre of the ITCZ is positioned southwest of its normal position (Poveda et al., 2001). The warm water from the western Pacific and the accompanying high air pressure system move to the east in the period of El Niño. The Chocó Jet that moves from the Pacific Ocean to the Colombian ocean is becoming weaker with El Niño. This results in a decrease of water-vapour advection in this region (Poveda and Mesa, 2000). Furthermore, the air temperature rises, this results in an increase in evapotranspiration, a decrease in soil moisture, a decrease in rainfall, and therefore, the average flow discharge is very low in this period. There is a decrease in plant activity during El Niño, which is consistent with lows in precipitation, streamflow and soil moisture (Poveda et al., 2001). During La Niña, the opposite is observed, which is mainly characterized by abundant and intense rainfall events, high average flow discharge and flooding events (Poveda et al., 2001).

Grootveld (2019) described the data, models and drought indices used to model the occurrence, intensity, propagation and the spatial spreading of droughts in the Magdalena River Basin. In that study, the daily time series of precipitation, minimum and maximum temperature and river discharges provided by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) were used. Two land surface and two global hydrological models were evaluated on their performance. To give an overview of the propagation of the droughts in the basin, five different drought indices were used and the indices were calculated for each of the four models. Droughts occur everywhere in the catchment. However, the drought differs per month, year and temporal aggregation period. A few general trends are shown in the basin. There are slightly more dry months in the southeast of the catchment, and droughts occur most often in this part of the catchment, likely because this region is less affected by the Chocó Jet (Grootveld, 2019). Also, during El Niño, the northeast of the Magdalena River Basin is first affected by droughts, and this moves to the southwest in the period of multiple months. This agrees with the weaker Chocó-Jet during an increase in intensity of the El Niño, enabling the drier easterly trade winds to reach further to the west (Grootveld, 2019). Moreover, the north of the catchment area recovers earlier to the normal state because of the higher precipitation rate in this part. The correlation with ENSO is strongest in the western part of the catchment, and Grootveld (2019) states that ENSO correlates best with the 6-month ensemble mean of the SPEI. With SPEI, droughts can be found everywhere in the catchment and there is a pattern of droughts shifting from the north to the south of the catchment. The correlation between other drought indices and the MEI (Multivariate ENSO Index) is weaker for strongly positive MEI values (Grootveld, 2019).

2.3 Coello and Saldaña irrigation districts

The two irrigation districts selected for this study are located in the Magdalena River Basin (Figure 1). The Coello and Saldaña irrigation districts are in the Tolima Valley at an elevation of approximately 380 meter. The average annual precipitation in the valley is 1000 to 1500 mm, which is low compared to the rest of the valley. The rainfall distribution here is bimodal. The annual mean temperature is 27.9 °C and the annual pan evaporation is 1800 mm (Vermillion and Garcés-Restrepo, 1996).

South American rivers show a strong seasonal discharge and sediment variability by a factor of 5 to 10 between low and high monthly discharge, independent of the river's size. The inter-annual variability associated with the ENSO cycle is significant, typically contributing to a factor 2 to 4 comparing high and low annual discharges (Kremer et al., 2002). The main river that runs through the valley is the Rio Magdalena, while two tributaries of the Rio Magdalena, the Rio Coello and the Rio Saldaña, flow through the two districts. The Coello river has a catchment area of 1580 km^2, a river length of 108 km, a mean annual discharge of 40 m^3/s and its headwaters are at an elevation of 3750 m and merges into the Rio Magdalena at 252 m (Restrepo et al., 2006; IDEAM, 2003). The Saldaña river has a catchment area of 7009 km^2, a river length of 199 km, a mean annual discharge of 320 m^3/s and its headwaters are at an elevation of 2060 m and merges into the Rio Magdalena at an altitude of 275 m (Restrepo et al., 2006). High erosion rates on the hillsides of the mountains create a high sediment load in the rivers and the irrigation canals. In the Magdalena Basin, the Coello and Saldaña rivers are two of the few rivers with a significant higher sediment yield than other rivers in this region, with the rivers containing a sediment load of 1.6 and 8.6 ton/km^2 annually for the Coello and the Saldaña river, respectively (Restrepo et al., 2006).

2.4 Management history

In 1977 farmers of the irrigation districts took over the right to manage of the irrigation districts instead of the government. This turnover of the management had an impact on the cost of irrigation to the farmers and the government. After the turnover, the gross value of output per hectare and per unit of water increased dramatically, while the irrigation cost to farmers remained the same. Policies restricted the production of rice in sandy areas, thereby reducing the average volume of water delivered per hectare. These policies diversified the crops and raised the value of irrigated output (Vermillion and Garcés-Restrepo, 1996). Since the 1970s, rice was the main irrigated crop, and since the late 1990s also maize, sorghum, fruit and vegetables are irrigated in the valley. Both irrigation districts have river diversion systems, where the two main rivers supply water. The river diversion irrigation system is a system with a main channel, and that channel diverts water through tributary channels to supply water to the cropping field areas. The Coello irrigation district has a lateral intake with a design capacity of $28m^3/s$. This channel supplies water when there are low river levels in the dry season in the agricultural area. The Rio Saldaña diverts water with a design capacity of 30 m^3/s into the main conveyance canal (Vermillion and Garcés-Restrepo, 1996). This canal conveys water to three partially lined branch canals, and each branch leads to secondary and tertiary canals to divert the water. Both irrigation schemes have composite underflow and overflow cross regulators to manage the water levels along the main canals. In the Coello and Saldaña districts, water is allocated to the farmers based on the crop type on their agricultural land (Vermillion and Garcés-Restrepo, 1996).

2.5 Rice production

In the Saldaña and Coello irrigation districts, the most important and main crop type is rice. World rice production must increase annually by approximately 1 percent to meet the growing demand for food, which results from population growth and economic growth. This demand must come from higher yields on existing croplands (Peng & Otros, 2004). Air temperature and water supply are the main factors that can limit the cultivation of rice. After research on irrigated rice fields at the International Rice Research Institute Farm in 1992-2003, Peng & Otros (2004) described that the grain yield decreases by 10% for each 1°C increase in minimum temperature in the dry growing season. In contrast the effect of maximum temperature on crop yield was insignificant (Peng & Otros, 2004). Since irrigated rice is grown under flooded condition during most of the growing cycle, the evapotranspiration for rice is nearly equal to the potential evaporation at a given location, so there is a minimum of water supply equal to the sum of potential seasonal evaporation, plus the water loss during land preparation and water loss during percolation (Horie et al., 2000). Biomass production of rice increases by elevated CO_2, and this has the potential to increase the yield of the rice.

Rice is usually grown in puddled fields, i.e. a layer of 0-0.10 m ponded water, a puddled, muddy topsoil, and undisturbed subsoil (Bouman et al., 2007). The growing cycle duration is location dependent, but ranges from just 90 days in tropical environments to 180 days for subtropical/temperate environments. Rice requires much water because of the high amount of outflow from the field by seepage, percolation, evaporation and transpiration. Typical percolation rates vary from 1-5 mm/day for heavy clay soils to 25-30 mm/day for sandy soils (Bouman et al., 2007). Leaf and canopy expansion reduce soon after the soil dries below saturation, and causing significal yield losses. Usually, rice yield is expressed as dry rice with 14 percent moisture. Under continuously flooded conditions, tropical cultivars can yield 8-10 ton/ha of rice in the dry season and 6-8 ton/ha in the wet season (Bouman et al., 2007). Other common crops in the irrigation districts are Maize and Sorghum. Maize has a typical growing cycle of 120 to 135 days, the evapotranspiration is high for maize, and the crop yield is about 10 ton/ha. Sorghum has a growing cycle of around 90 to 110 days, and the evapotranspiration is a bit lower than that of maize. The crop yield under irrigation is around 5-7 ton/ha (Bouman et al., 2007).

In Colombia, there is a large difference in climate variability and the irrigated rice in the centre of Colombia all have different adaptations. The variability results in a large difference in yield and financial costs of rice (Gómez Higuera & Peluha Monroy, 2015). The majority of the rice sector is small businesses, and they require subsidies, insurance and agricultural loans by the government as the variability of investment costs are consistently high although the crop yield is not constant (Gómez Higuera & Peluha Monroy, 2015).

In Tolima, there are two semesters in which they plant and harvest rice. The second semester's minimum and maximum temperature is higher than the temperatures of the first semester (Figure 2).

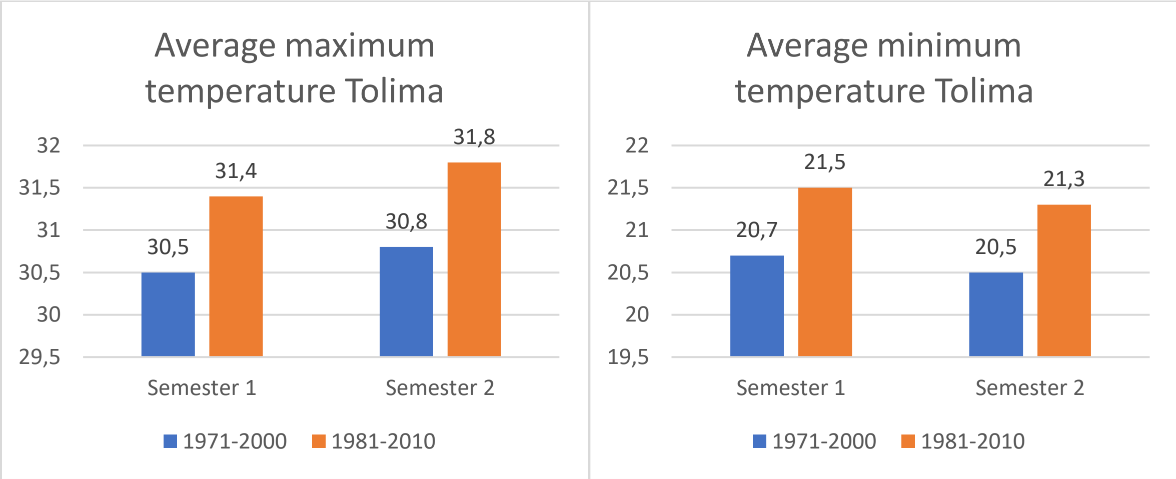


Figure 2 Change in maximum (left) and minimum temperature (right) for two growing semesters in Tolima, Colombia (IDEAM, 2020)

The average maximum temperature is increasing when comparing 1971-2000 and 1981-2010, while the average minimum temperature is decreasing somewhat for the same period (Figure 2). It is estimated that by every 1% increase in temperature, the yield of rice will decrease by 1,05% in central Colombia, and during the dry season this can be up to 10 percent for every degree increase (Gómez Higuera & Peluha Monroy, 2015). In Tolima, the average maximum has been above 34 °C, which has decreased the yields due to pollen sterility, while the average minimum temperature has been around 22 °C, which carries less grain weight, and of course lower yields per hectare (Fedearroz, 2010). The costs of rice production are increasing year by year, though the costs for the different semesters are almost equal. The average production in the Tolima district is 7.1 ton/ha, and for Saldaña, this is 6.9 ton/ha, in the second semester in 2016 (minagricultura, 2020).

3. Methodology

3.1 Overview

This section is based on the objectives, as described in the introduction. Figure 3 shows the methodology. First, the quantification of the drought periods in the Coello and Saldaña irrigation districts and the correlation with the ENSO driven droughts will be described. This corresponds with the first objective. For the second objective, a description of the AquaCrop model and the required input for the model are given, followed by the cropping areas' soil properties. With the questionnaire during the fieldwork, analyzation of the existing irrigation schedules, and creating possible irrigation schedules that can cope with periods of drought, the last two objectives are reached.

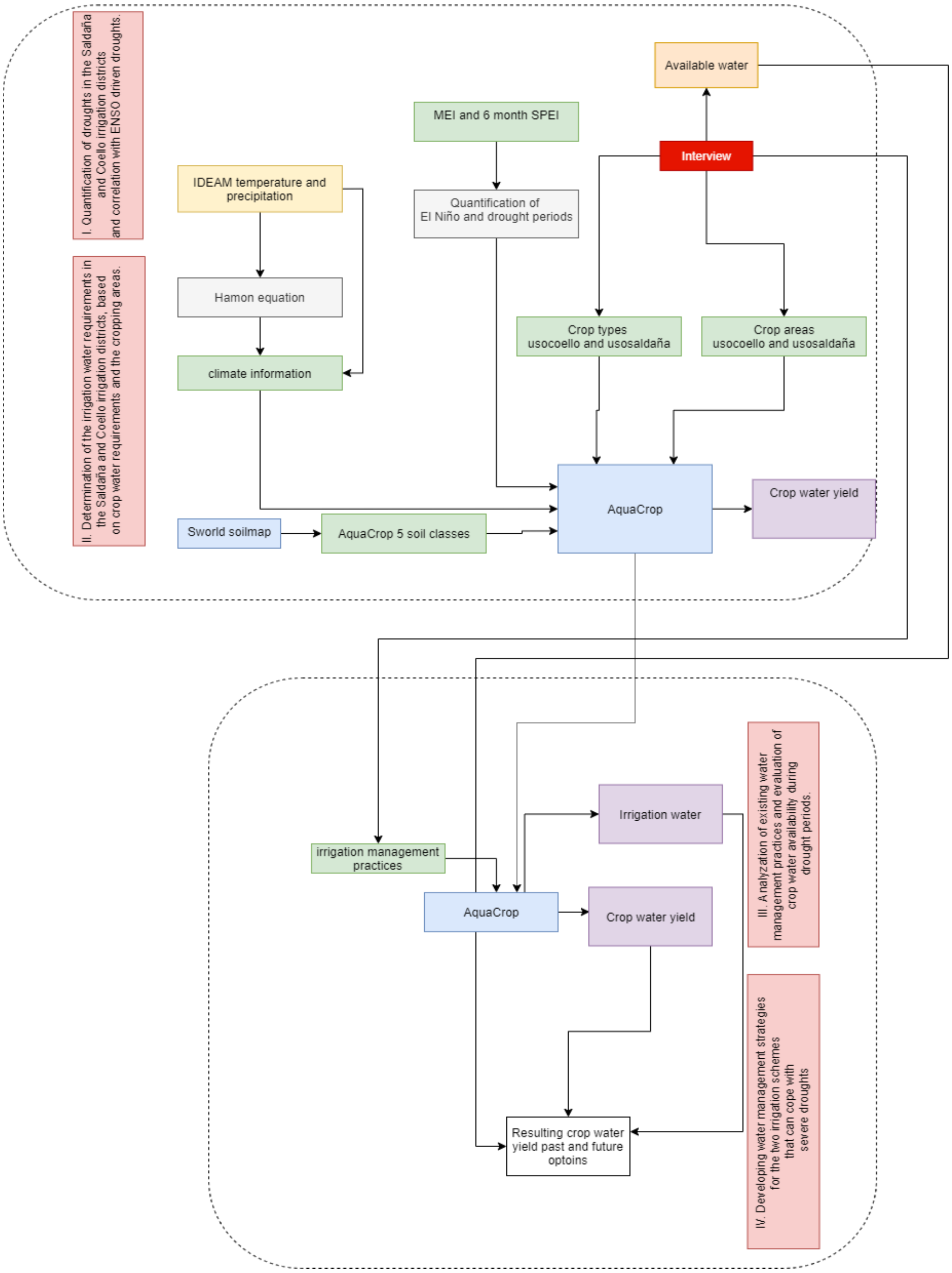


Figure 3 Workflow of this study. With objectives (light-red), input data for AquaCrop (green) IDEAM (yellow), models (blue), interview (red), output (grey, orange and purple) and final results (white).

3.2 Drought analysis

3.2.1 SPEI

The periods of drought were classified with the 6-month SPEI for the two irrigation districts. As stated by Grootveld (2019), the SPEI is the best drought indicator in the Magdalena River basin. The SPEI is a meteorological drought index based on precipitation and potential evapotranspiration data and can include the effects of temperature variability on drought assessment (Vicente-Serrano et al., 2010). It also includes a climatic water balance and the accumulation or deficit at different time scales, which is essential in analysing droughts. The difference between the precipitation (*Pi* in mm) and the potential evapotranspiration (*PETi* in mm) per month (*i*) is calculated first (Vicente-Serrano et al., 2010):

$$Di = Pi - PETi \quad (Eq. 1)$$

Where, *Di* (mm) is the water deficit or surplus per month. The accumulated precipitation is transformed into probabilities, which are converted to the standard normal distribution to create drought index values (Stagge et al., 2015). The SPEI represents the number of standard deviations from the typical climatic water balance at a given location and time (Stagge et al., 2015). The calibration period is 1950 to 2010. Negative values of the SPEI are associated with relative dry periods.

The SPEI can measure drought severity according to its intensity and duration, and it can identify the onset and end of drought episodes. In this study, the SPEI was calculated with the SPEI global drought monitor (SPEI, 2019), using the coordinates 3.75 latitude and -75.25 longitude for Saldaña district, and 4.25 latitude and -74.75 longitude for Coello district.

3.2.2 Correlation ENSO driven droughts

After classification of the historical droughts in the two districts, these periods were compared with the ENSO driven drought periods. The ENSO remains the most important coupled ocean-atmosphere phenomenon in global climate variability on a seasonal and inter-annual scale (Wolter and Timlin, 2011). There are different indices to study ENSO events. The Multivariate ENSO Index (MEI) provides a more complete and flexible description of the ENSO phenomenon than single variable ENSO indices such as the Southern Oscillation Index (SOI) (Wolter and Timlin, 2011). The MEI includes six atmospheric and oceanographic parameters. These parameters are sea level pressure, zonal and meridional surface wind components, sea surface temperature, near-surface air temperatures and total cloudiness (Wolter and Timlin, 1998). It is re-computed every month to monitor the strength of the ENSO conditions for the previous two months. The data for the MEI were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2019). El Niño events are associated with positive values of the MEI. In general, an El Niño event is the strongest at the end of the autumn until the beginning of the spring. The strongest El Niño events occurred in the winters of 1982-1983 and 1997-1998.

As stated by Grootveld (2019), the MEI and the 6-month SPEI have a strong correlation in the Magdalena River basin. The MEI and the droughts classified by the SPEI were compared on the occurrence and the spearman correlation for the two irrigation districts was used to compare the indices.

3.3 AquaCrop

3.3.1 AquaCrop model

AquaCrop is a low-input crop growth and water productivity model developed by the FAO. The AquaCrop model was developed to address food security, hereby considering the effects of the environment and management on crop production (Steduto et al., 2012). AquaCrop is particularly well suited to conditions in which water is a key limiting factor in crop production. The AquaCrop model can simulate the daily soil water balance, crop development, and the total attainable crop yield (Steduto et al., 2012). AquaCrop is often used as a planning tool or to assist in making management decisions and irrigation planning. AquaCrop simulates the final crop yield in four steps, which are calculated in series in each daily time step. The steps are (FAO, 2019):

1. Development of green **canopy cover (CC).** CC is the fraction of soil surface covered by the canopy. At sowing, CC is 0, and CC is at maximum 1 at mid-season when full canopy cover is reached. By determining the water content in the soil profile each day, AquaCrop keeps track of water stress, which can affect the maximum canopy cover.
2. **Crop transpiration (Tr).** Crop transpiration is calculated by multiplying the reference evapotranspiration (ETo) with a crop coefficient (Kc). KcTr is proportional to CC, therefore it varies throughout the life cycle of the crop. Water stress can not only affect the canopy development, but it can also induce stomata closure and thereby directly affect crop transpiration.
3. **Above-ground biomass (B).** The amount of biomass produced is proportional to the cumulative amount of crop transpiration (∑Tr), with a proportional factor for biomass water productivity.
4. **Crop yield (Y).** Crop yield is obtained from B by using a harvest index (HI), HI is the fraction of B that is the harvestable product.

HI and Y are dependent on environmental conditions and stresses on them. Figure 4 gives an overview of the functional relationship between the different model components. In the AquaCrop model, water stress effects on productivity and water use processes are simulated by impacts on canopy growth, stomatal conductance, canopy senescence, root deepening and harvest index.

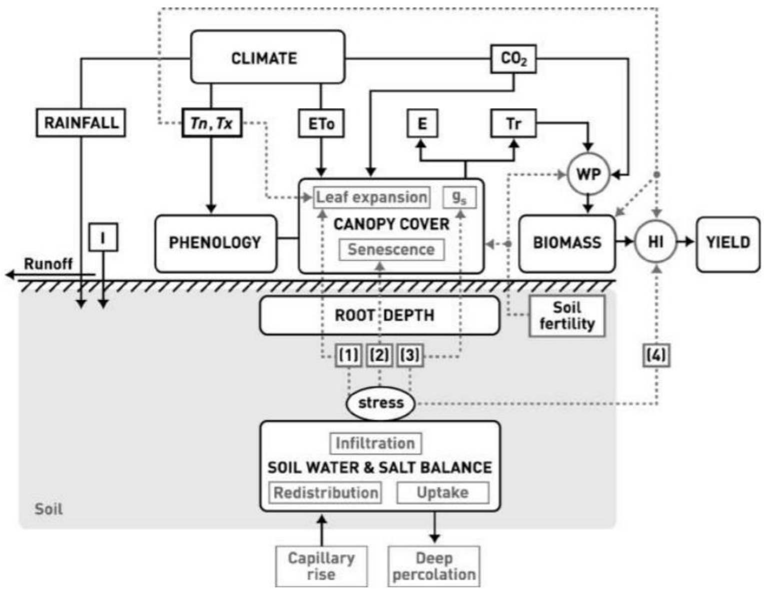


Figure 4 Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum, with water stress response functions for leaf expansion (1), senescence (2), stomatal conductance (3) and harvest index (4).

The root zone can be considered as a reservoir. The model keeps track of the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water fluxes. In the AquaCrop model, the soil evaporation and crop transpiration are separated. The amount of water can be calculated at any moment of the season; this is done by the soil water balance daily. The fluxes show the steps taken to come to the total output of the crop yield. The effect of water stress is described by stress coefficients (Ks) (Figure 5). Above an upper threshold of root zone depletion, the process is not affected, but if the soil water in the root zone drops below an upper threshold level, the crops are affected. Below the lower threshold, the water stress is at its maximum (Ks=0). Between the lower and upper threshold, the Ks-curve determines the magnitude of water stress on the crop development. In Figure 5, the Total Available soil Water (TAW) describes the difference between the water content at field capacity and permanent wilting point.

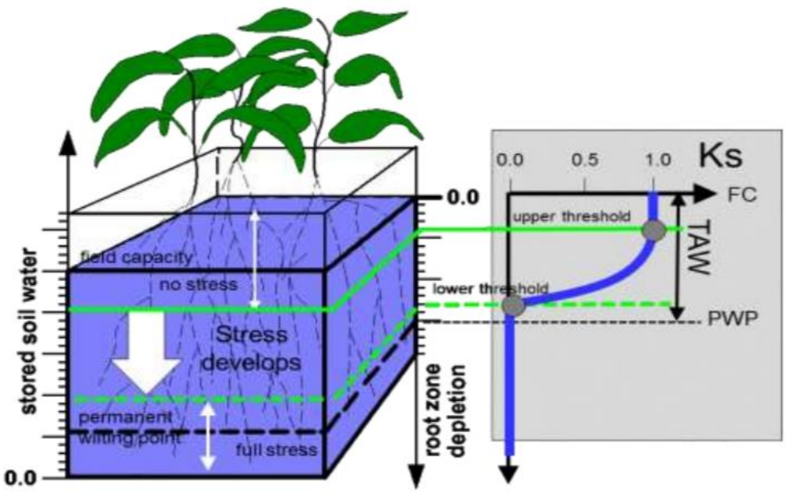


Figure 5 The water stress coefficient (Ks) for various degrees of root zone depletion, with field capacity (FC), permanent wilting point (PWP) and the resulting total available water (TAW)

The input of climate characteristics requires input files for daily maximum and minimum temperature, precipitation, reference evapotranspiration and the CO_2 concentration. The CO_2 concentration is measured by the Mauna Loa Observatory (FAO, 2019). The soil properties need to be specified for the soil profile, consisting of 3 soil horizons. The irrigation management practices consist of the irrigation method and the application depth and time of irrigation events. By dynamically simulating the yield response to different amounts of applied water (rainfall and irrigation) under a specific set of agronomic conditions, AquaCrop gives a realistic range of results (Steduto et al., 2012; Steduto et al., 2009).

3.3.2 Model set-up

In this study, there are three different crops modelled. Rice, maize and sorghum are analysed on the crop production, irrigation water, evapotranspiration reduced water use. There are soil bunds for irrigated rice, which are specified in the field management option in AquaCrop. In this model, the soil bunds have a height of 25 centimetres to prevent surface runoff during rice irrigation. The irrigation of rice is done by surface water supply. During the growing cycle, there needs to be a layer of water on top of the surface to prevent the occurrence of water stress. The growing cycle of rice is 100-110 days, depending on growing degree-days (GDD); the GDD of rice is 1900. The GDD of maize is 1700, which corresponds to a growing cycle of 90-100 days. Moreover the GDD of sorghum is 1760, which corresponds to a growing cycle of 94-104 days.

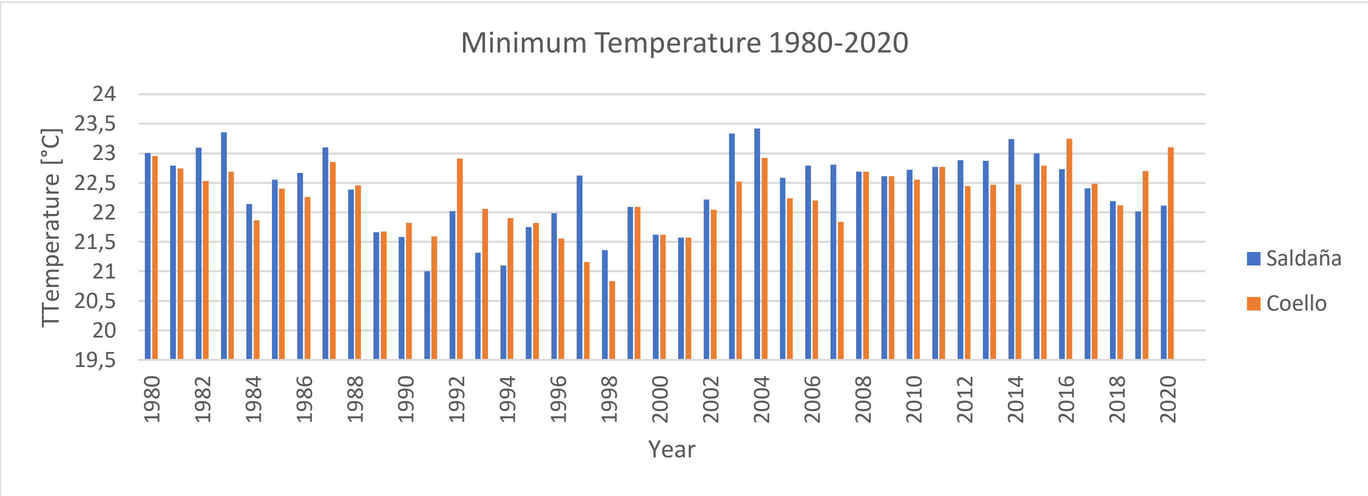
The amount of irrigation water is specified on a daily time step and is given in an irrigation schedule with the irrigation depth at each day of the growing cycle or it is calculated by AquaCrop if the water layer on top of the surface is below a certain threshold. There were six different irrigation schedules created, for the irrigation of rice, based on the fieldwork survey and the possible reduced irrigation schedules in AquaCrop. For the irrigation of maize and sorghum, the AquaCrop model can determine the net irrigation water requirements. This is done by the allowable root zone depletion (RAW) (Figure 5). The RAW is the difference between the field capacity and the threshold stomatal closure. The threshold stomatal closure is reached at 100% RAW and is this is less deep than the PWP. In this study, maize and sorghum are irrigated if the RAW drops below 50 percent in the AquaCrop model. The soils that are suited for rice cultivation, are rice cultivated and the soils that are unsuitable for the cultivation of rice are cultivated with sorghum and maize.

3.4 Data for AquaCrop Modelling

3.4.1 Precipitation and Temperature

The AquaCrop modelling of the two irrigation districts was done for the period of 1-1-1980 to 19-2-2020. The in-situ daily data of precipitation, minimum temperature (Tmin) and maximum temperature (Tmax) was available on the website of the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM).

For the Saldaña district, the station that provides data for Tmax and Tmin is Jabalcon, located on an altitude of 332 meters. For the Coello district, the station that provides data for Tmax and Tmin is Chicoral, located on an altitude of 409 m. Missing data of the Jabalcon and the Chicoral station were completed with other station's data or by data of the Guamo station, which is at an altitude of 360 meters, and is located in between the two stations. The average minimum and maximum temperatures for Saldana are 22.4 °C and 33.1 °C. For the Coello district, the average minimum and maximum temperatures are 22.3 °C and 32.4 °C. Figure 6 shows the average annual Tmax and Tmin for both irrigation districts. In general, there is an increase in the maximum temperature over the past 40 years, while in minimum temperature, the increase is slightly lower. This is the same pattern, as seen in section 2.5.



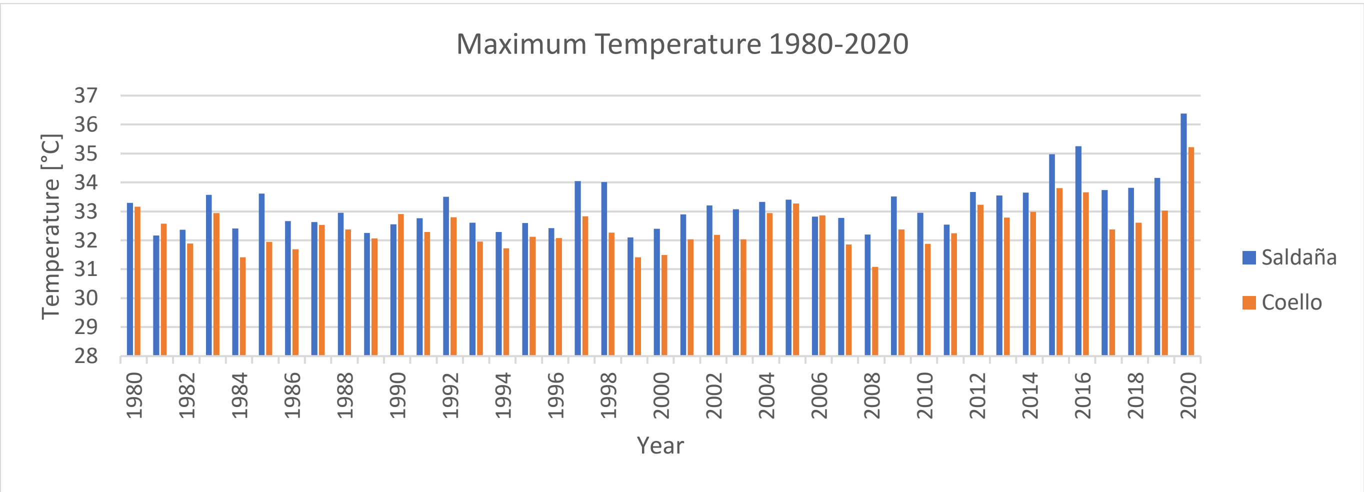


Figure 6 Yearly minimum and maximum temperatures from 1980 to 2020 in the Saldaña and Coello irrigation districts, Magdalena river basin, Colombia

The daily precipitation data were obtained from the same stations (Jabalcon and Chicoral) for the Saldaña and Coello districts. The average annual precipitation of the Saldaña district was 1410 mm over the past 40 years. In the Coello district, this was 1385 mm. Figure 7 shows the annual precipitation rates for both irrigation districts.

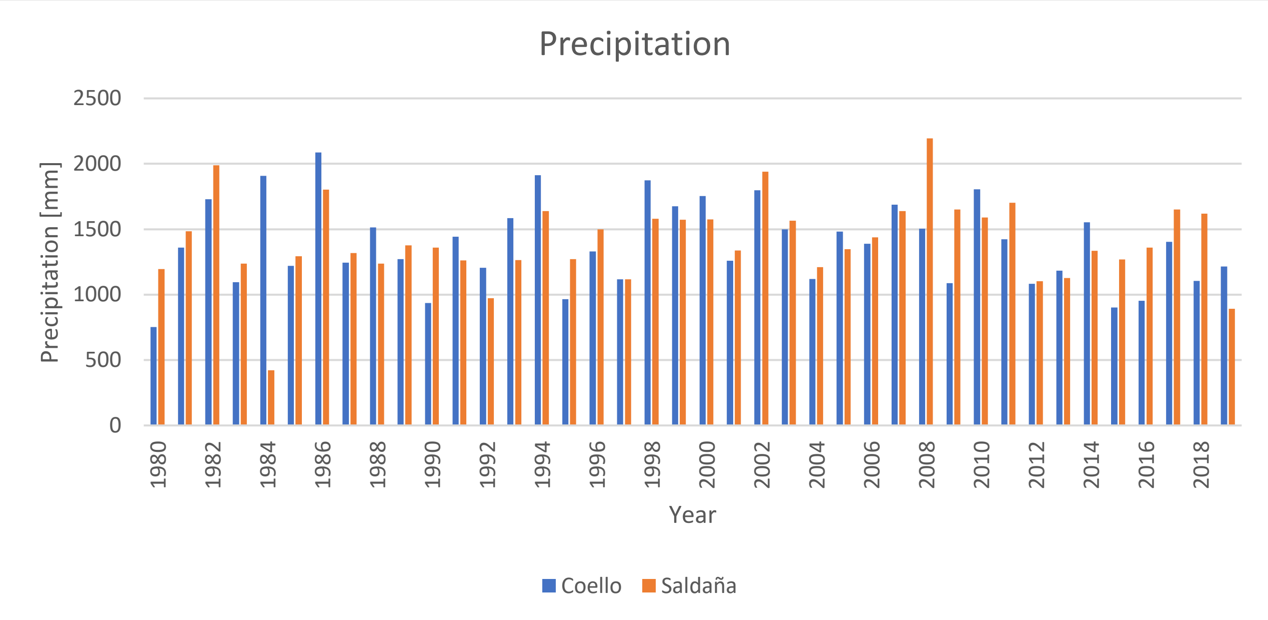


Figure 7 Yearly precipitation rates from 1980 to 2020 in the Saldaña and Coello irrigation districts, Magdalena river basin, Colombia

There are some periods with a lack of precipitation data, e.g. in 1983 and 1984 there are 122 and 185 days missing, respectively, although most of them are not in the periods of the analysed droughts. The missing data was completed with data of the nearest station for two periods, 30-11-1980 to 1-1-1981 and 31-8-1982 to 2-11-1982, as these are in the periods of drought. Other periods with missing data are not completed as these are not analysed; as a result of the parts with missing data, the average annual precipitation is slightly lower in this report.

3.4.2 Evapotranspiration

Potential evapotranspiration (*PET*) is a critical variable for understanding regional biological processes. Lu et al. (2005) compared six potential evaporation methods for regional use. In this report, the temperature based Hamon method is used for calculating the *PET*. The Hamon method was chosen as the daily climatic data of precipitation and temperature were the only variables that were complete for the past 40 years. The *PET* is calculated as follows:

$$PET = k * 0.165 * 216.7 * N * \left(\frac{es}{T+273.5}\right) \qquad \text{(eq. 2)}$$

Where, PET = potential evapotranspiration [mm day^{-1}], k = proportionality coefficient (= 1 [-]), N=daytime length [x/12 hours], es = saturation vapor pressure [mbar], T= mean temperature [^{o}C].

The daytime length of each day was calculated for the location of Bogota (Time and data, 2020). The saturation vapour pressure (es) is calculated by:

$$es = 6.108e^{\left(\frac{17.27T}{T+237.3}\right)} \qquad \text{(eq. 3)}$$

3.4.3 S-World data set

For each horizon, the soil water content at saturation, field capacity, permanent wilting point, and the saturated hydraulic conductivity is needed. Balland et al. (2008) estimated soil hydraulic properties, such as the saturated hydraulic conductivity, field capacity and permanent wilting point with point pedotransfer functions (PTFs). These soil hydraulic properties were estimated from soil composition and for a wide range of soil types and conditions. With these PTFs, the soil textures were determined in the S-world database (Stoorvogel et al., 2014). Figure 8 shows the average hydraulic conductivity of the top layer as an example of the estimated maps by Balland et al., 2008.

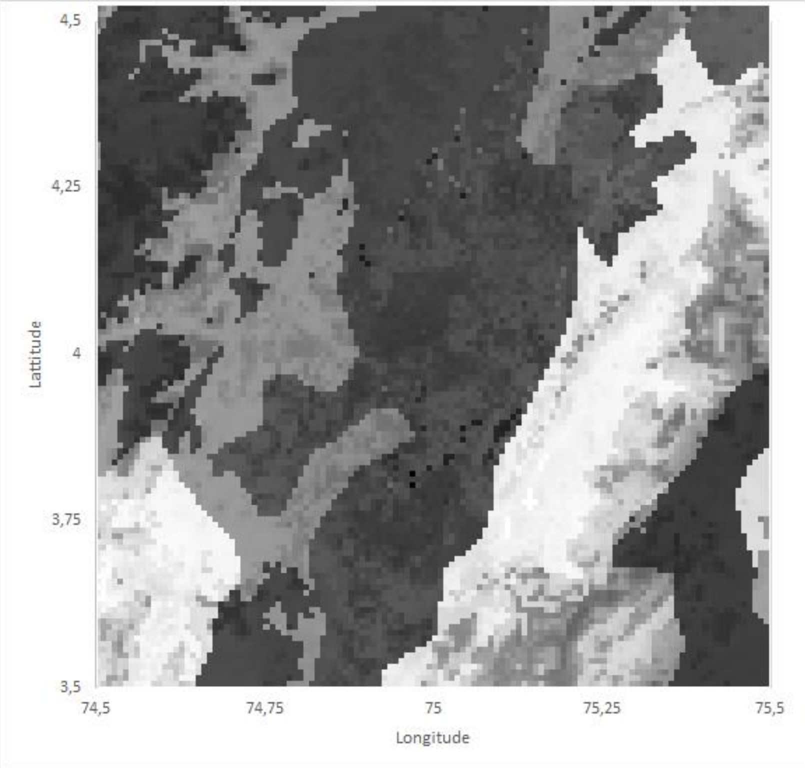
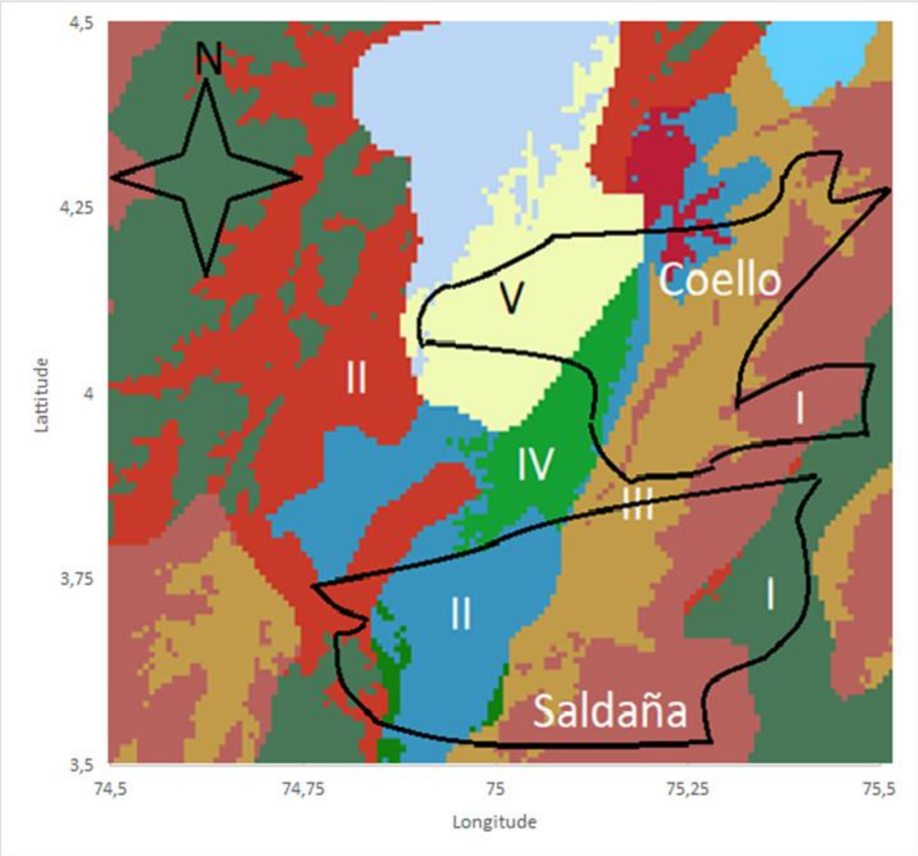


Figure 8 Average Hydraulic conductivity values of the top layer, estimated by Balland et al. (2008) for the Saldaña and Coello irrigation districts, Colombia

S-world (Soils of the World) is a high resolution (30 arc-second, roughly 1 km at the equator), global soil property map available for modelling purposes (Stoorvogel et al., 2014). The model is a novel methodology that combines recently developed innovation in digital soil mapping and includes the use of legacy and additional data sets. The S-world soil classification is based on the FAO classification of soils which includes 148 different soil types. Figure 9 shows the FAO soil classes and the five main different soil types. The S-world soil classification is used for both irrigation districts with three different horizons.



Number	FAO name
I	Dystric Leptosols
II	Ferric Podzols
III	Umbric Andosols
IV	Eutric Gleysols
V	Haplic Luvisols

Figure 9 S-world map with soil types and soil classification by the FAO of the Saldaña and Coello irrigation district, Colombia

3.4.4 Soil properties

The website of the Food and Agriculture Organization of the United Nations (FAO.org) gives a complete description of the soil classification. In this report the soil properties of the different soils are described with for each FAO soil type an average value of the following soil properties as estimated by Balland et al. (2008): Hydraulic conductivity (Ksat) (Figure 8), Field Capacity (FC), Permanent Wilting Point (PWP), Saturation Point (Sat) and the fractions of sand, clay, and silt. These soil properties are provided for three different soil horizons. The first layer is up to a depth of 30 cm (top layer), the second up to a depth of 75 cm (middle layer) and the third layer to a depth of 150 cm (bottom layer).

The average hydraulic characteristics of the S-world map (Figure 9) were determined for each soil class. Of these soil classes, the average hydraulic characteristics were calculated with zonal statistics in QGIS. First, the soil properties were calculated, followed by a calculation of the average soil textures.

Table 1 shows the result of the average hydraulic characteristics of the five areas. The soil texture was calculated by the soil texture calculator of the Natural Resources Conservation Service (NRCS, 2020).

Table 1 Soil properties as calculated from the S-world map of the Coello and Saldaña irrigation districts, Colombia

#soil class	FAO name	layer	% sand	% clay	% silt	soil type	% PWP	% FC	% Sat	Ksat [mm/d]
I	Dystric Leptosols	top layer	50	24	24	sandy clay loam	13	29	43	578
I		middle layer	51	24	24	sandy clay loam	10	21	35	189
I		bottom layer	51	23	25	sandy clay loam	9	18	31	91
II	Ferric Podzols	top layer	26	47	23	clay	22	46	55	480
II		middle layer	27	46	24	clay	15	31	36	59
II		bottom layer	28	44	24	clay	13	24	31	23
III	Umbric Andosols	top layer	15	29	39	silty clay loam	22	55	69	730
III		middle layer	17	32	43	silty clay loam	18	43	54	260
III		bottom layer	17	33	44	silty clay loam	16	38	48	140
IV	Eutric Gleysols	top layer	8	58	30	clay	22	40	45	74
IV		middle layer	8	59	30	clay	15	28	31	8
IV		bottom layer	8	59	30	clay	14	25	29	5
V	Haplic Luvisols	top layer	11	40	46	silty clay	19	37	45	170
V		middle layer	11	41	47	silty clay	13	25	31	49
V		bottom layer	11	41	47	silty clay	13	23	29	40

The soil types sandy clay loam and silty clay loam (soil class I and II) are not well suited for the cultivation of rice, due to the very high infiltration rates of these soils, as a result in the analysis in this report the other crops maize and sorghum are cultivated here. Soil class V is suited for the cultivation of rice, sorghum, and maize. Figure 10 shows the total areas of each soil class, as shown in Table 1. As the figure shows, the soil class V is not in the Saldaña irrigation district. Further all soil classes are represented in both irrigation districts.

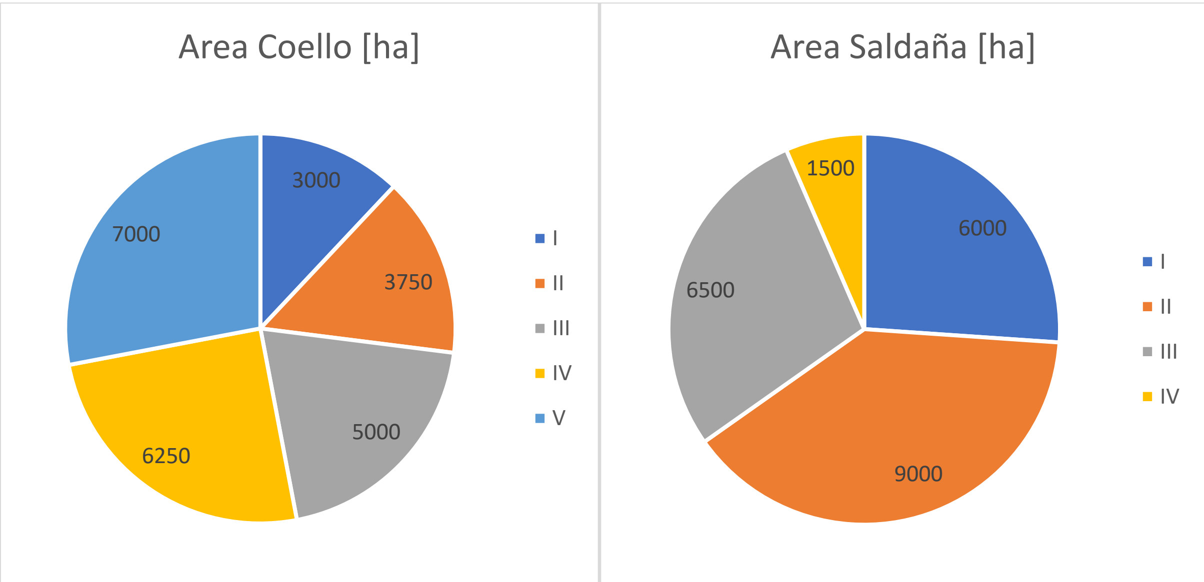


Figure 10 Soil areas of the Coello and Saldaña irrigation districts for the soil class properties in Table 1

3.5 Analyse and optimize irrigation schedules

3.5.1 Fieldwork and irrigation scenarios

In the field, the real situation of water management and the irrigation diversion scheme was investigated. The irrigation schemes of the different crops were determined during the fieldwork visit. And responses to periods of droughts of the water managers and the farmers have been studied. This was done by interviewing the water managers and the farmers in the irrigation districts. The two questionnaires used for the water managers and farmers in English and Spanish are given in Appendix 1. The results of the periods of drought and the correlation with the ENSO driven droughts are combined with the results of the fieldwork survey. Hereby obtaining the irrigation schedules of the crops during the periods of drought. The irrigation schedules, as obtained during the fieldwork visit and four other irrigation schedules, were created to model the rice yield and water use during the growing cycle of rice on different soils. For each scenario and the whole are of both districts, the total amount of irrigation water was calculated. Combining all the results and the most severe droughts, a water deficit irrigation schedule was created to cope with future droughts.

3.5.2 Water use

For each situation and each drought, the total irrigation water is calculated. This is done by:

$$TotI = \sum_{i=2,4,5} Si * Ii \quad (eq. 4)$$

Where, *TotI* = the total amount of irrigation water for a particular irrigation scenario and drought [m^3], *S*= the area of soil *i* in [m^2], and I2 = total irrigation water for soil *i*.

Equation 5 is used to calculate the average irrigation water supply *Q* [m^3/s] divided by the total time in seconds:

$$Q = \frac{TotI}{x * 3600s * 24h} \, (eq. 5)$$

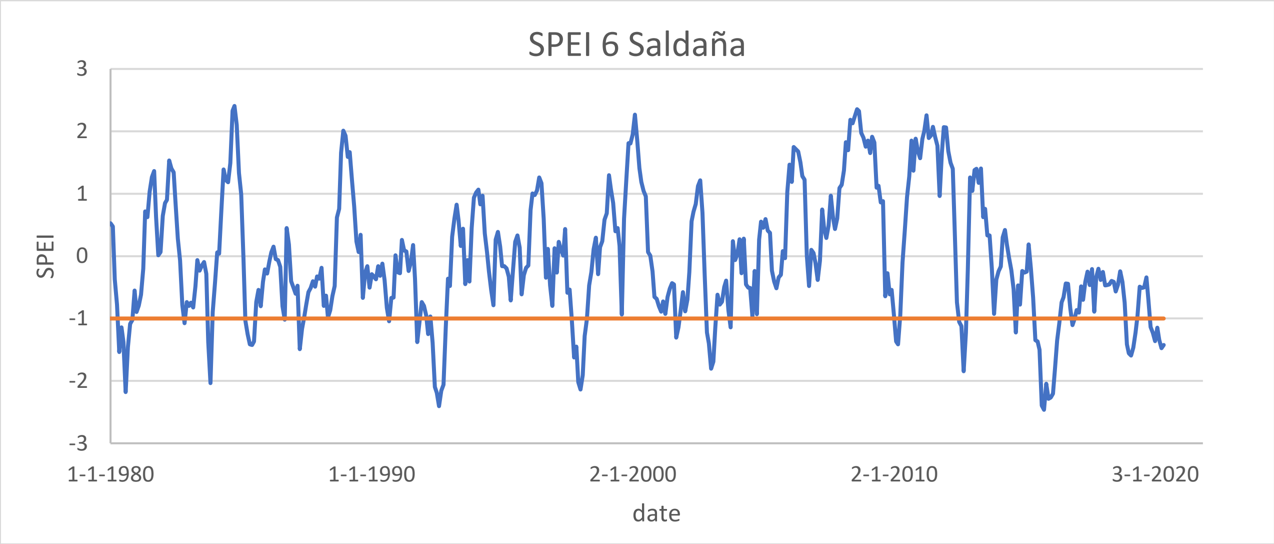
Where, *x* = length of growing cycle [days].

4. Results

4.1 Drought analysis

4.1.1 SPEI

The 6-month SPEI was obtained from the drought monitor. Values below 0 indicate a period with water deficits. Figure 11 shows the graphs of the monthly values of the 6-month SPEI drought index. If the SPEI6 is lower than -1 for more than three months, the period is classified as a severe drought, and these droughts are summarized in Table 2.



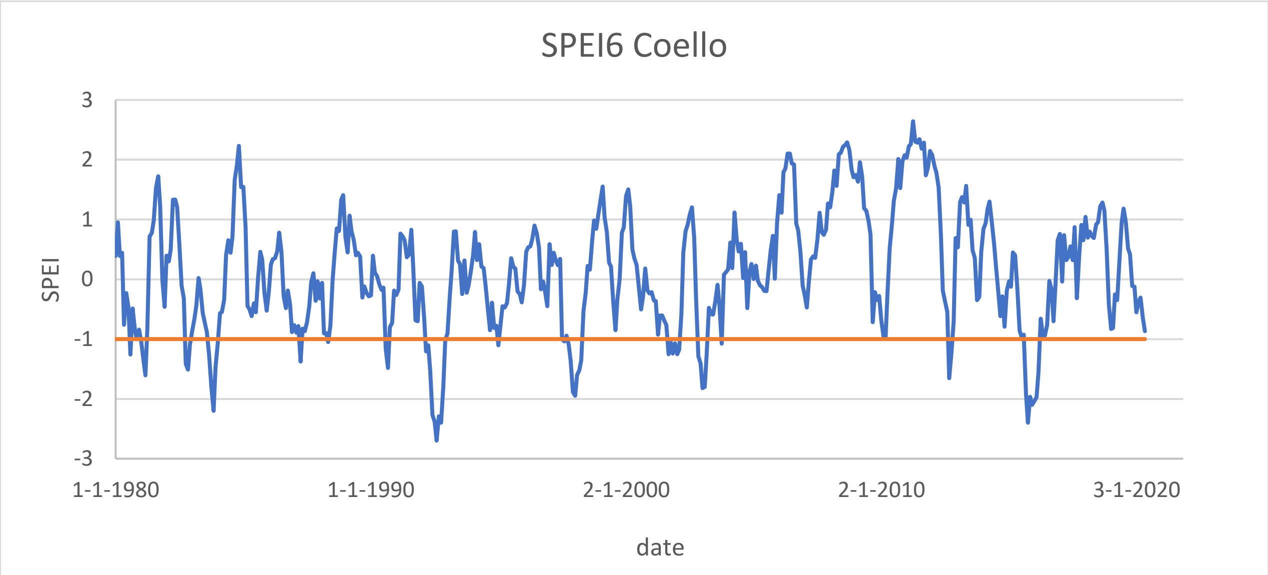


Figure 11 6-month SPEI for the Saldaña and Coello districts, Colombia. The orange line of -1 classifies the criterium for periods of drought

Table 2 SPEI6 Droughts classification for the Coello and Saldaña irrigation district with the duration of the drought in months *=not in the period of cultivation

	SPEI6 Saldaña					SPEI6 Coello			
Drought#	start	end	months		Drought#	start	end	months	
1	1-5-1980	1-12-1980	7		1	1-11-1980	1-4-1981	5	
2	1-10-1983	1-1-1984	3	*	2	1-10-1982	1-1-1983	3	*
3	1-3-1985	1-8-1985	5		3	1-8-1983	1-2-1984	6	
4	1-3-1992	1-7-1992	4		4	1-3-1992	1-8-1992	5	
5	1-7-1992	1-12-1992	5		5	1-8-1992	1-1-1993	5	
6	1-9-1997	1-1-1998	4		6	1-7-1997	1-12-1997	5	
7	1-1-1998	1-5-1998	4		7	1-12-1997	1-5-1998	5	
8	1-11-2002	1-4-2003	5		8	1-9-2001	1-3-2002	6	
9	1-1-2010	1-4-2010	3		9	1-11-2002	1-4-2003	5	
10	1-7-2012	1-11-2012	4		10	1-8-2012	1-11-2012	3	
11	1-6-2015	1-12-2015	6		11	1-9-2015	1-3-2016	6	
12	1-12-2015	1-5-2016	5						
13	1-12-2018	1-5-2019	5						

In Saldaña the droughts that occurred in 1992, 1997/1998 and 2015 are droughts that are in both growing semesters and considered as two droughts in this report. As well in Coello, the droughts that occurred in 1992 and 1997/1998 are droughts that are in both growing semesters and divided into 4 droughts.

4.1.2 Correlation droughts and ENSO

The principal droughts of the two districts and the world-wide ENSO driven droughts that are calculated with the MEI are compared (Figure 12). The positive MEI values would result in dryer periods in central Colombia.

The resulting droughts that occurred in both districts at the same time are commonly associated with positive MEI values, where the MEI positive values start earlier, resulting in dryer periods in the Coello and Saldaña districts. The El Niño events of 1991-1992, 1997-1998, and 2015-2016 are all correlated to droughts in both irrigation districts. The El Niño event of 1982-1983 is only related to a drought in the Coello district, and no primary drought occurred in the Saldaña district. The El Niño event of 1986-1987 did not result in a drought in one of the districts. The drought that occurred in the last months of 1983 could be correlated to an ENSO driven drought but occurred later than the El Niño event. The droughts of 1985, 2001, and 2002 are not associated with positive MEI values. Therefore these droughts cannot be correlated to the ENSO driven drought. This coincides with the findings of Vega-Viviescas (2019) that these droughts indicate that other climatic phenomena as strong as ENSO can generate droughts in the Magdalena Cauca-Basin. The Spearman correlation for the MEI and the 6-month SPEI of Coello has a correlation of -0,56, and the MEI and the 6-month SPEI of Saldaña have a correlation of -0,53.

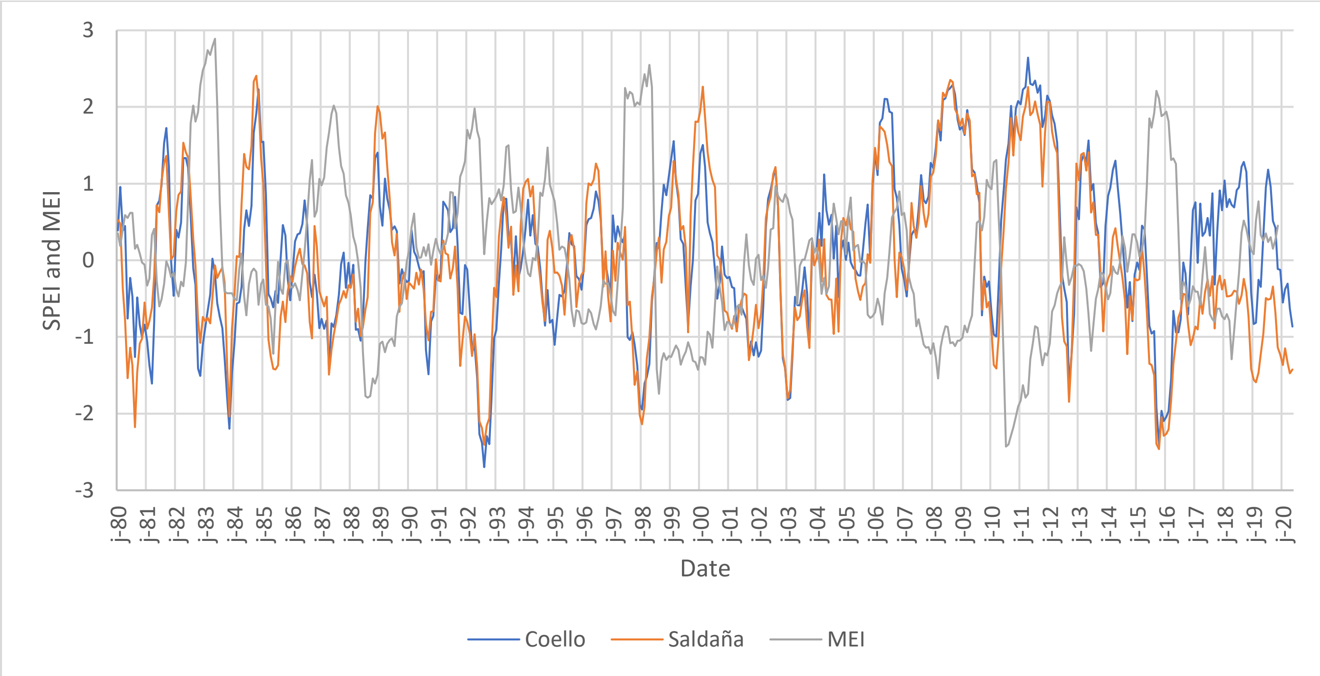


Figure 12 Monthly averaged series for the MEI and the 6-month SPEI for the Coello and Saldaña irrigation districts, Colombia

4.2 Fieldwork survey and irrigation scenarios

During the fieldwork visit of the two districts, the water managers of both districts were questioned about the management throughout a year, and the management of the districts during periods of droughts in the past.

4.2.1 Summary survey

In Coello, the number of users depends on year and period during a year, but there is a maximum amount of 2100 users and a minimum of 1980 users. In the Coello district, 70 percent of the land is used for agriculture. The total area that can be irrigated is 25000 hectares, and is composed out of area A (11635 hectares) and area B (13365 hectares). During the first semester, rice is irrigated in area A. Currently, sorghum, fruit, and maize are cultivated in area B. The change of the areas depends on the river flow rate during the year, and the period of cultivation depends on the climatic factors each year. Year by year the sowing period is investigated by the water managers, which often starts at the beginning of February. In normal conditions, the months January and July are drier. Therefore the seeds are sown after these periods. Generally speaking, the rice is cultivated in the period February to June, and in the period August to December. In the first semester there is more rainfall in comparison to the second semester. This is also reflected in the cultivation of maize, as this is mostly cultivated in the second semester.

There are two inspectors per system, and there are four different zones per system, so in total eight different zones for cultivation. The first system has the Cocuana river with 10.91 m^3/s as streamflow inlet, and the second system has the Coello river with 9.64 m^3/s as streamflow inlet. Almost all the water of the two rivers can be used for agriculture, and the rest is mostly used for hydropower. The water depth on top of the surface is approximately 6 centimetres during the growing cycle.

The users pay for a minimum of 10000 m^3 of water per hectare and maximum for 18000 m^3 of water per hectare, and they pay 23.67 COP/m^3 (=€0.0054). During droughts, the price does not change. There is a fixed price that the users have to pay at the beginning of the season. Farmers that usually grow rice are obliged to pay for irrigation even when they do not sow that year. In contrast, farmers that grow maize are not forced to pay for water if they do not cultivate maize that year. The price of the yield is constant throughout the year. It also does not vary with droughts. Year by year, the price of rice varies due to inflation. In years with less harvest, the farmers pay the same price as in other years, so droughts are more a problem.

Rice can maximum be three days without water, stressing the importance of irrigation. The irrigation schedule is composed of 6 days of irrigation, alternated by 3 days of no irrigation. However, this can be rescheduled to 5 days of irrigation alternated by 4 days without irrigation in drier periods. In general, the crop yield of rice is 8 ton/ha in the Coello district.

In Saldaña, there are 1432 users of the system at this moment. In 2019 the total area was 23267 ha, of which 13912 ha was irrigated. The entire system is divided into 6 zones, of the total area the most is rice cultivated, but there are also areas with maize, plantain, fishing areas, cotton, and lime. The size of one parcel is minimal 0.5 ha and has a maximum of 79 ha. On average the size of a parcel is 5 ha.

Usually the inlet of the system has a discharge of 20.75 m^3/s, and in the last ten years, the minimum was 13.30 m^3/s, in May, and the maximum was 25 m3/s, during the dryer months. The irrigation water supply is 2.32 L/s during a session of irrigation.

The price of water in 2019 was 21.798 COP/m^3 (=€0.0049), and two times a year at the beginning of the growing cycle, the users pay a fixed price. The price during a year remains constant, also in periods of droughts. There is no maximum use of water. 16000 m^3/ha (1600mm) of water is the minimum of water they need to use to cultivate rice.

The water users make decisions for the day of sowing. In general, this is in January or February for the first season, although this depends on which year and they investigate when to sow beforehand. The second period is at the beginning of June or July.

Almost all irrigation water used is surface water. In Saldaña, they do not use groundwater for irrigation. They also make use of the percolated water that flows to the canals. For rice, there is a constant level of five centimetres on top of the surface. In Saldaña, the irrigation plan is four days with irrigation water supply alternated by three days without irrigation water supply. During periods of drought, the moment of sowing is later.

The yield of maize, plantain, lime, and rice is all approximately 7 ton/ha in the Saldaña district. For this 7 ton of rice, the farmers will receive 7.2 million COP and the cost in a typical year for them is 6.3 million COP. Their net gain is 900,000 COP (211 euros), this is for both semesters.

Table 3 shows the essential results and differences for both irrigation districts.

Table 3 Summary of the survey with water managers of the Coello and Saldaña irrigation districts, Colombia

	Coello	**Saldaña**
Total area [ha]	25000	23267
irrigated area rice	semester 1: 11635, semester 2: 13365	13912
water layer on top of surface for rice	6 cm	5 cm
minimum water use	10000 m3/ha	16000 m3/ha
maximum water use	18000 m3/ha	no
day of sowing	February and August	January/February and June/July
Normal irrigation schedule	6 days with irrigation alternated by 3 days without	4 days with irrigation alternated by 3 days without
Irrigation schedule droughts	5 days with irrigation alternated by 3 days without	no data

4.2.2 Streamflow

In the Coello district, the minimum amount of water that the users need to use during the growing cycle is 10,000 m^3 and the maximum 18,000 m^3/ha. In Saldaña, there is only a minimum use of 16,000m^3/ha and no maximum. In Coello, the two rivers together have an inlet discharge of 21 m^3/s, and during one session of irrigation the discharge is 2 L/s. In Saldaña, the average inlet discharge is low in the wetter months, on average 16 m^3/s, and can be up to 25 m^3/s in the dryer months, e.g. in July 2019 the discharge throughout the whole month was 25m^3/s, and in March the average discharge was 13.3 m^3/s (USOSALDANA). During one session of irrigation the water supply is 2.32 L/s.

4.2.3 Climate droughts

The daily potential evapotranspiration, calculated from Equation 2, resulted in an average daily PET of 4.37 mm day^{-1} for Coello and 4.48 mm day^{-1} for Saldaña. During the past 40 years, the PET was slightly lower in the Coello irrigation district than in the Saldaña irrigation district (Figure 13). The results also show a similar trend for both districts that the PET on average is highest in August and lowest in November.

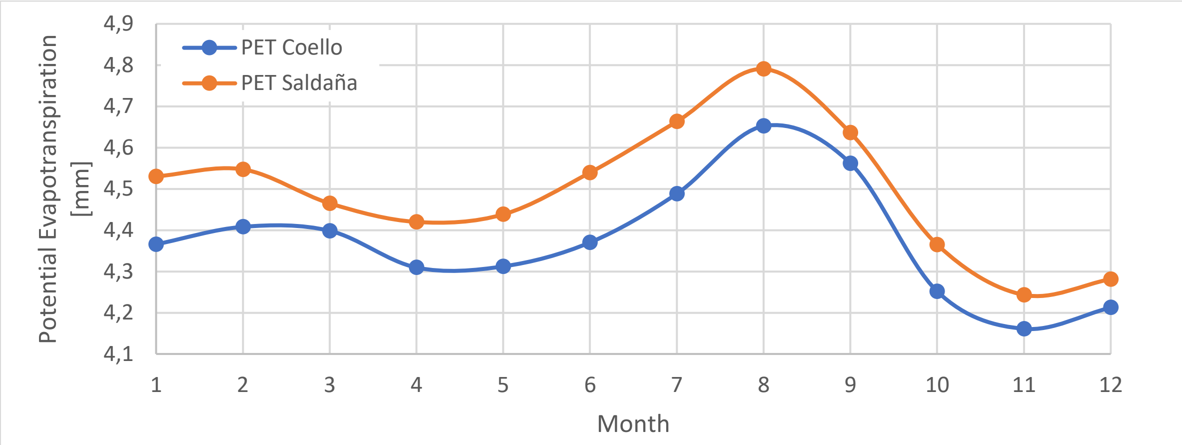


Figure 13 Average potential evapotranspiration for the period 1980-2020 in the Coello and Saldaña irrigation districts, Colombia

For each drought as classified by the 6-month, the onset of the growing cycle was calculated in AquaCrop. The start of the growing cycle is calculated by the sum of rainfall. The growing cycle begins if this sum is at least 20 mm in 4 days. For the Saldaña district, this is calculated for the first semester from the 15th of January to the 1st of March and for the second semester in the period from the 1st of June to the 15th of July. For the Coello district, this is calculated in the period of the 1st of February to the 15th of March and the 1st of August to the 15th of October, for the first and seconds semester, respectively. If this sum of 20mm is not reached in one of these periods, which was the case for some droughts in the Coello district, the 15th of August is taken as the starting date of the growing cycle. The second drought of both semesters is not studied because those are not in the periods of cultivation. Figure 14 shows the start of the growing cycle of each drought and the resulting cumulative rainfall in this period.

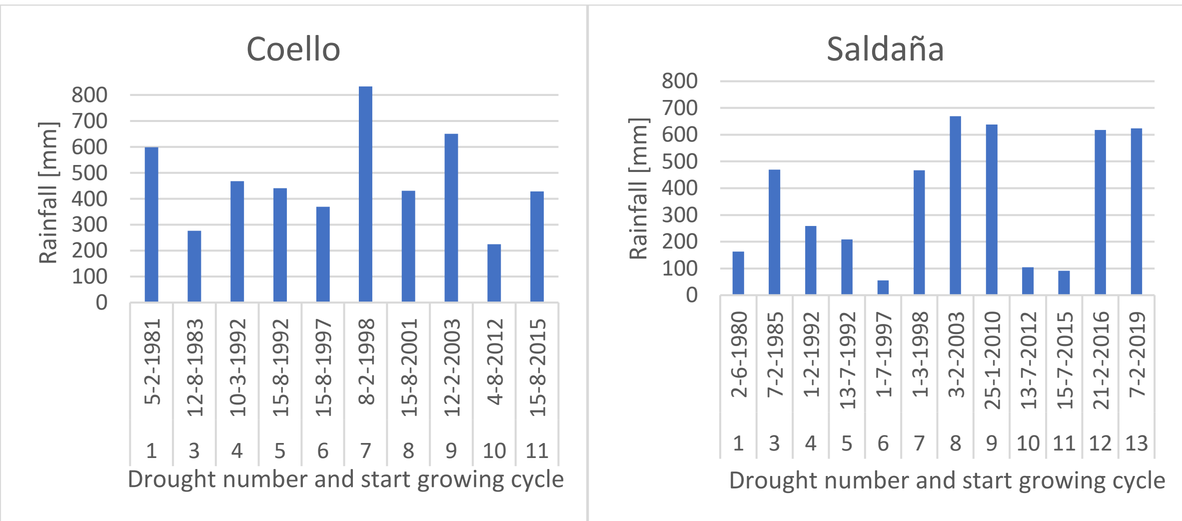
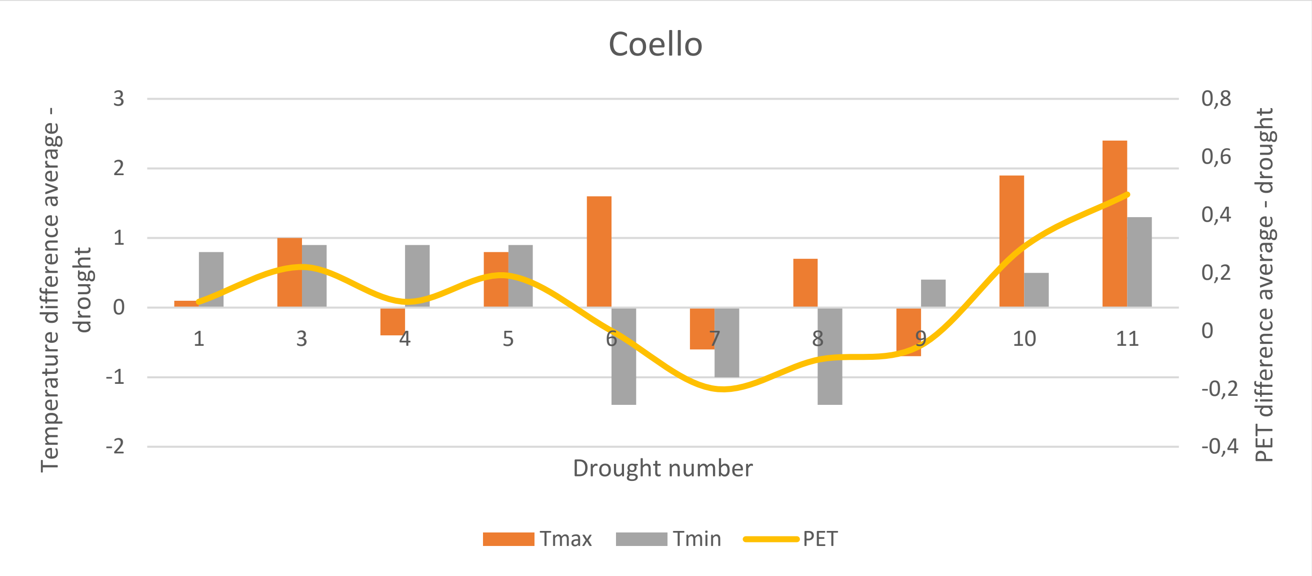


Figure 14 Cumulative rainfall during the growing cycle of each drought for the Coello and Saldaña irrigation districts, Colombia

For each growing cycle, the maximum temperature, the minimum temperature, and the potential evapotranspiration are calculated. The difference between the average during the growing cycle of a period of drought and the 40-year average of Tmin, Tmax and PET as given in given in Section 3.4 Data for AquaCrop Modelling is shown in Figure 15. In general, in Coello, the Tmax during droughts is 1°C higher, except for the droughts 4, 7, and 9. Further, the minimum temperatures are slightly higher during the periods of droughts except for the droughts 6, 7, and 8. In Saldaña, the maximum temperatures increased even more during droughts. During some droughts the average maximum temperature was 4°C higher than the 40-year average, also the minimum temperature was 1°C higher during most droughts (Figure 15). As a consequence the potential evapotranspiration was higher than average during most droughts.



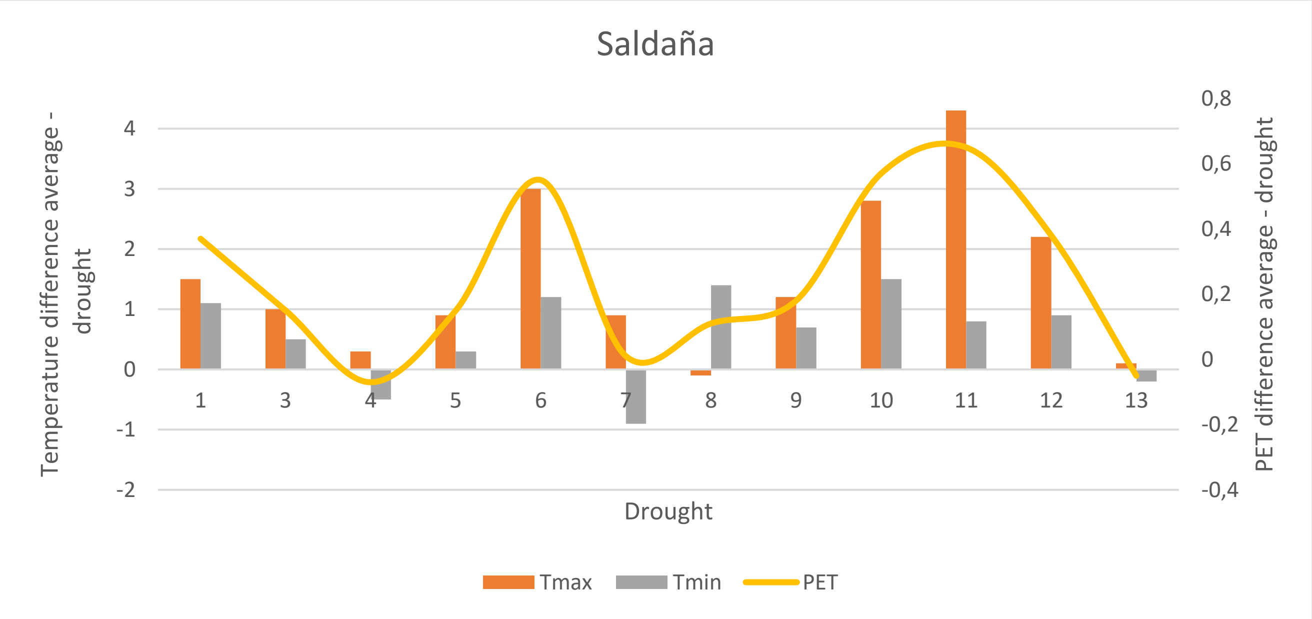


Figure 15 The difference between the average potential evapotranspiration (PET), minimum (Tmin) and maximum temperature (Tmax) and the PET, Tmin and Tmax during periods of drought in the Coello and Saldaña irrigation districts, Colombia

4.2.4 Irrigation schedules

The principal droughts are analysed, and an optimized irrigation schedule is created by trial and error. These runs showed that for each irrigation schedule of rice, the first 30 days do not demand an extra layer of water on top of the soil surface. Another result of these runs is that after 90 days, which is almost the end of the growing cycle, no extra added water is required, the dry crop yield of rice remains equal. Thus for each scenario after 90 days, no further irrigation water is supplied. For each drought, there are 6 different irrigation schedules to irrigate the rice crops. In Table 4, an overview of the irrigation scenarios is given for both districts.

Scenarios Coello *(Saldaña)**

1. **Normal** scenario. This is the scenario that is used during normal conditions. During this scenario, there is an irrigation water supply of 6 *(4)* days alternated by 3 days without irrigation water supply. In the first 30 days, if there is irrigation, the amount of water supplied is 10 mm. After 30 days, on the day of irrigation, this amount is 30 mm.
2. **Drought** scenario. This scenario is used in the case of a period of drought, this is 5 *(3)* days with irrigation water supply, alternated by 4 days without irrigation water supply. In this scenario, during the first 30 days, the amount of water supply is 10 mm, on days of irrigation. After day 30, this is 30 mm/day, on the days of irrigation.
3. Water supply if the water layer drops below **threshold #1.** During this scenario, there is a water layer of 30 mm applied to the surface, if the water layer on top of the soil is at the soil surface. On the 30^{th} day, the amount of irrigation water is 40 *(30)* mm on each day when the water layer on top of the surface is under 20 mm.
4. Water supply if the water layer drops below **threshold #2.** This scenario consists of the same 30 mm applied in the first 30 days. After these 30 days, the added water layer is 30 *(20)* mm for each time that the water layer on top of the surface is below 30 mm.
5. **Combination** threshold and **normal** scenario. During this scenario, there are 6 *(4)* days of irrigation, alternated by 3 days without irrigation. During irrigation events, a water supply of 10 mm is supplied, if the water layer is below the soil surface until the 30^{th} day. From the 30^{th} day onwards, the irrigation water supply is 40 *(30)* mm/day, if the surface water is below 20 mm and it is on a day of irrigation.
6. **Combination** threshold and **drought** scenario. This scenario consists of 5 *(3)* days of irrigation water supply of 10 mm, if the water layer is below the soil surface, alternated by 4 days without irrigation water supply. And then also from the 30^{th} day onwards, the irrigation water supply is 40 *(30)* mm/day if the surface water is below 20 mm, in the schedule of 5 *(3)* and 4 days.

* in between parentheses values for the Saldaña irrigation district

Table 4 Irrigation scenarios with the criterium and amounts of irrigation water for the irrigation of rice in the Coello and Saldaña irrigation districts

Irrigation scenario	valid from	mimum water layer on top of surface [mm]	irrigation depth [mm]	Days with irrigation	Days without irrigation
Coello					
Normal scenario	day 1	X	10	6	3
	day 30		30		
Drought scenario	day 1		10	5	4
	day 30		30		
Water supply up to threshold #1	day 1	0	30	X	
	day 30	20	40		
Water supply up to threshold #2	day 1	0	30		
	day 30	30	30		
Combination threshold and normal scenario	day 1	0	10	6	3
	day 30	20	40		
Combination threshold and drought scenario	day 1	0	10	5	4
	day 30	20	40		
Saldaña					
Normal scenario	day 1	X	10	4	3
	day 30		30		
Drought scenario	day 1		10	3	4
	day 30		30		
Water supply up to threshold #1	day 1	0	30	X	
	day 30	20	30		
Water supply up to threshold #2	day 1	0	30		
	day 30	30	20		
Combination threshold and normal scenario	day 1	0	10	4	3
	day 30	20	30		
Combination threshold and drought scenario	day 1	0	10	3	4
	day 30	20	30		

4.3 Irrigation scenarios

The 6 different irrigation scenarios, the principal droughts, and the soil classes for the Coello and Saldaña district are combined in each possible combination. For the irrigation of rice, three soils in Coello and two soils Saldaña are cultivated with rice, and here for the irrigation schedules of Section 4.3 are used. Soil 5 is cultivated with rice, sorghum, and maize. And soils 1 and 3 are cultivated with maize and sorghum. The dry yield, the amount of irrigation water supply, the total days of irrigation, and potentially the stresses on the rice crops are calculated with these runs. For the other crops, the irrigation water is determined by the AquaCrop model.

4.3.1 Rice irrigation water

Coello

The total applied water during the normal and drought scenario is constant for each drought and each soil. In the normal scenario, there are 60 irrigation events, supplying in total 1420 mm of water. For the drought scenario, this is 1160 mm in 50 irrigation events.

The irrigation water supply up to the threshold of 20 and 30 mm (scenario 3 and 4) is higher for the rice cultivated on soils 2 and 5 than the amount of irrigation water during the normal and drought scenarios (Figure 16). For soil 2, the average amount of irrigation water is almost equal with 2037 mm and 2040 mm for the irrigation scenarios 3 and 4. Still, the average amount of irrigation events increases from 56 for the third scenario to 68 for the fourth scenario. The rice cultivated on soil 4 shows a lower amount of irrigation water supply because the threshold value of the water layer below 20 or 30 mm is reached in fewer days, due to the lower infiltration rate. For soil 5, the amount of irrigation water supply is almost at the maximum for most droughts as the threshold value is reached during most days. As result during almost all days, irrigation was needed during these scenarios. Resulting in an average of 3033 mm and 2560 mm for scenarios 3 and 4, respectively.

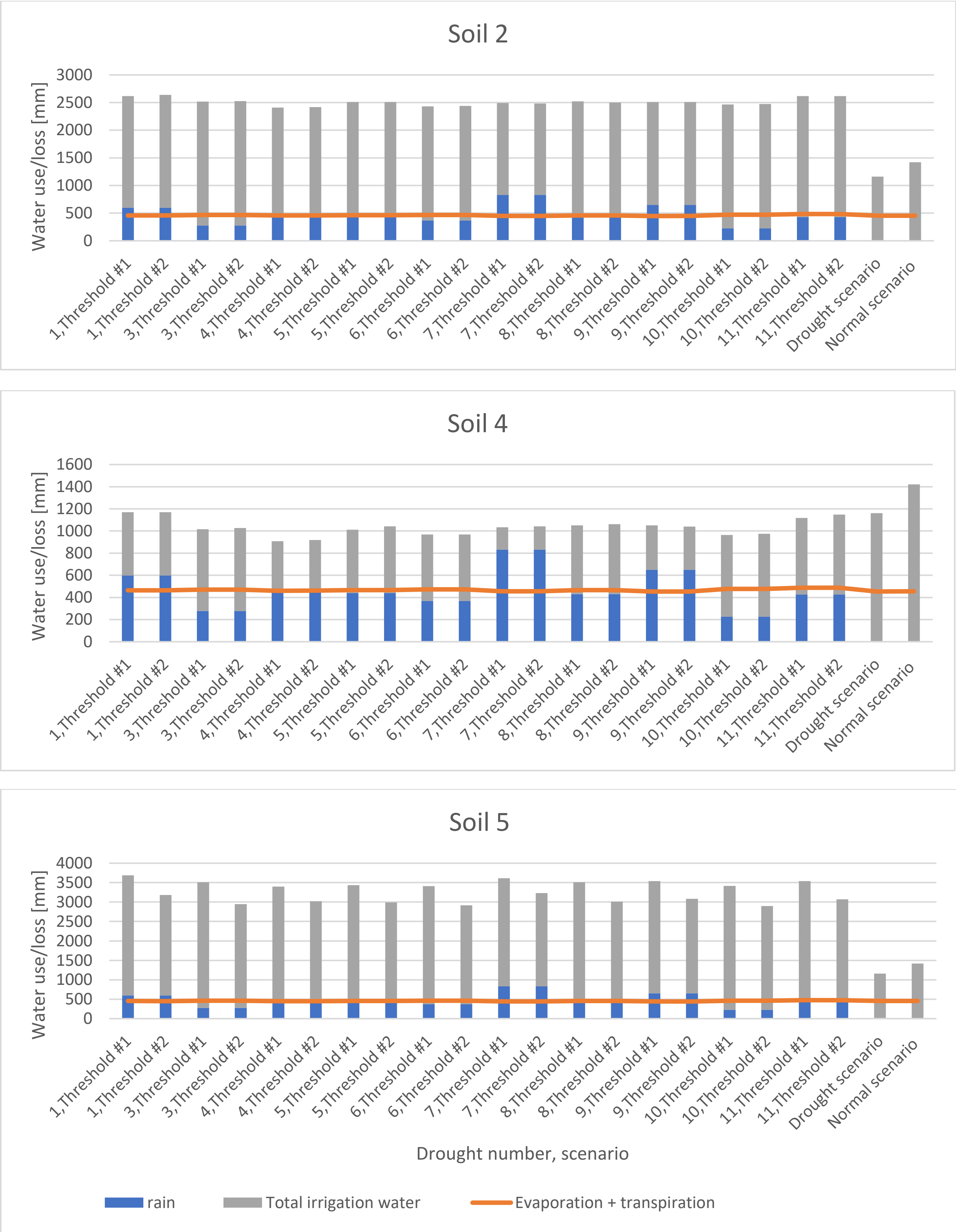
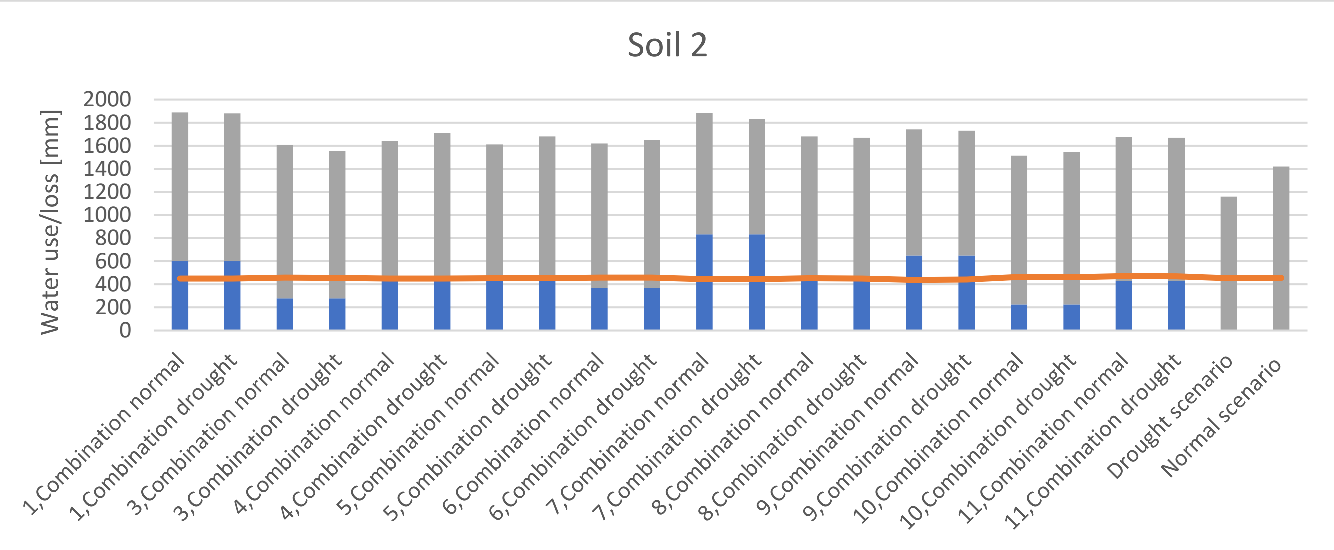
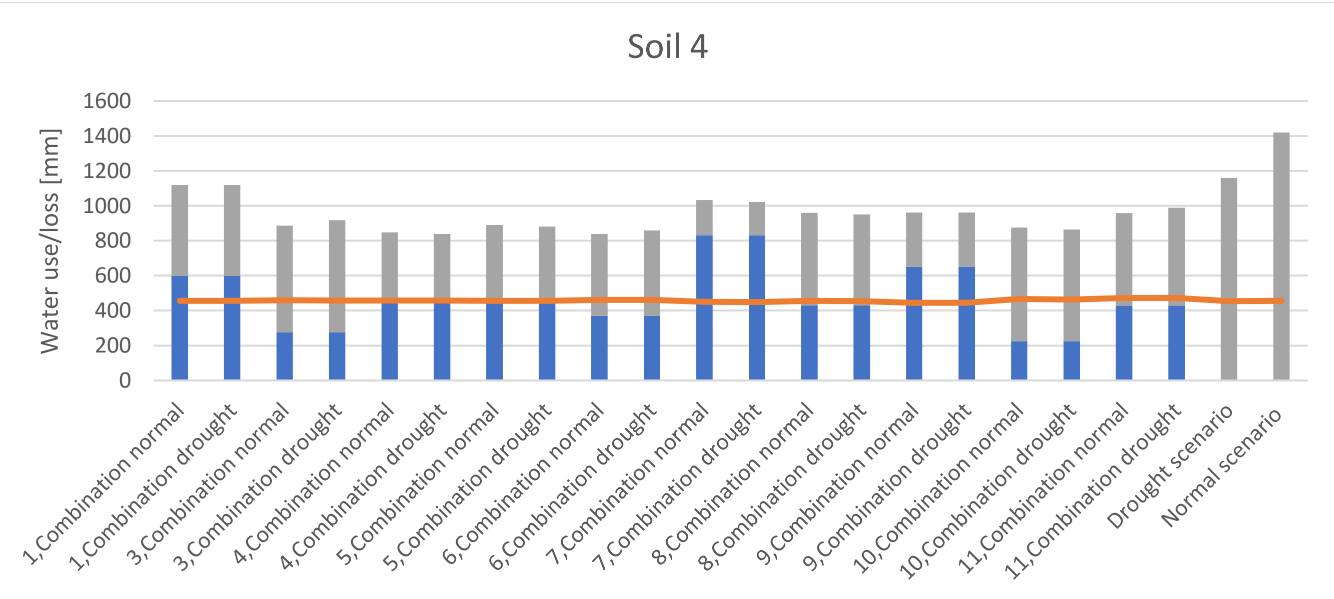


Figure 16 Amount of evapotranspiration, rainfall and irrigation water with irrigation scenarios 3 and 4 (Table 4), for rice cultivated on soils 2, 4 and 5 in the Coello irrigation district, Colombia

With irrigation scenarios 5 and 6 there are more fluctuations shown (Figure 17). Due to the combination with the irrigation schedules that has days with and days without irrigation water supply, the normal and drought scenario in the Coello district, and that there is only irrigation if the threshold value is reached, the total irrigation water supply is lower in all cases (Figure 16 and Figure 17). For soil 2, the irrigation water supply for the fifth scenario is mostly around 1250 mm, which is 200 mm lower than during the normal scenario. While the sixth scenario show slightly higher amounts of irrigation water, and the irrigation amounts are higher than during the drought scenario. The total irrigation events are almost equal for the combination scenarios. Figure 17 shows that the amount of irrigation water supply for soil 4 is slightly lower than during the threshold scenarios, but not much variation in irrigation amounts is shown here, only between the different drought events. For soil 5, the combination scenarios show lower amounts of irrigation water than the normal scenario but higher amounts than the drought scenario. Due to the lesser irrigation events, the total irrigation water amounts are lower for the combination drought than the combination normal scenario. Appendix 2 shows the result of all scenarios in one graph, separated for each soil.





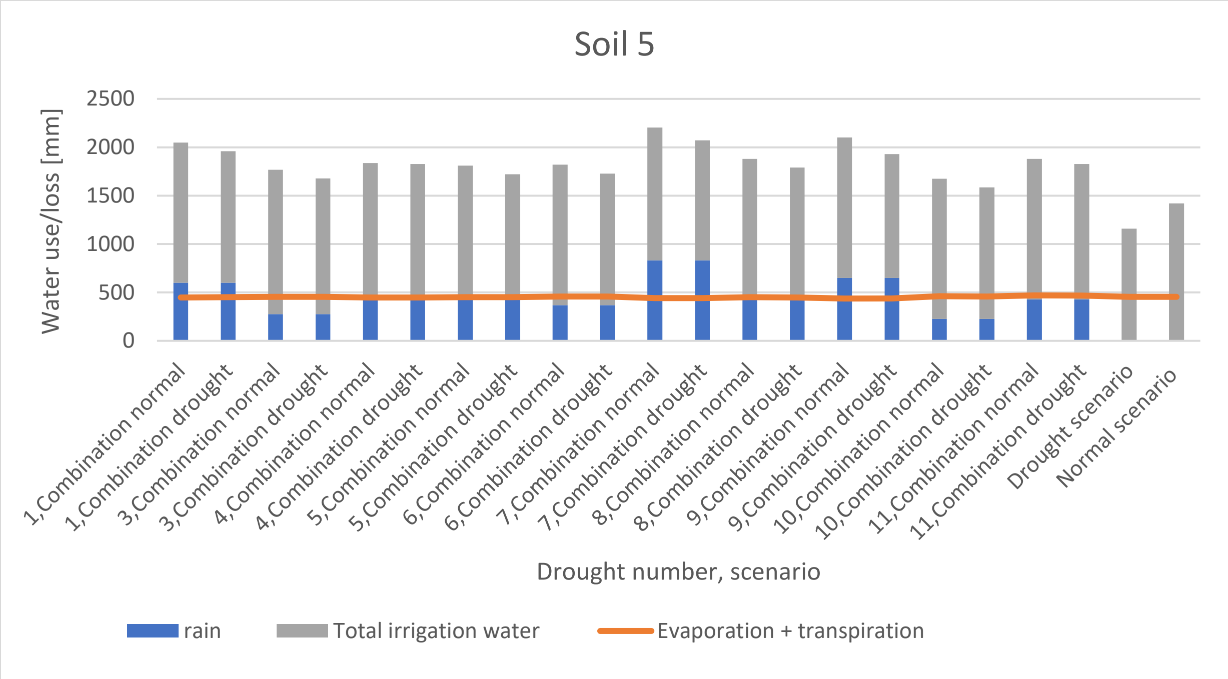


Figure 17 Amount of evapotranspiration, rainfall and irrigation water with irrigation scenarios 5 and 6 (Table 4), for rice cultivated on soils 2, 4 and 5 in the Coello irrigation district, Colombia

Saldaña

The scenarios of Saldaña are based on those in Coello only with some lower irrigation rates. In Saldaña, the rice irrigation is up to a water depth of 5 cm instead of 6 cm in Coello. The total applied water during the normal and drought scenario is also constant for each drought and each soil. In the normal scenario, there are 60 irrigation events, supplying in total 1420 mm of water. For the drought scenario, this is 1160 mm in 50 irrigation events.

The water supply up to the threshold of 20 and 30 mm (Table 4) show very high rates for the rice cultivated on soil 2 (Figure 18). During the most severe droughts, drought 6 and 11, the total amount of irrigation water was 2400 mm. There were 80 irrigation events needed to maintain the threshold of 20 mm on top of the surface. With the irrigation schedule up to the threshold 2, the maximum total irrigation was reached during the droughts of 6, 10, and 11. During other droughts the required irrigation water was high (Figure 18). For soil 4, the irrigation water supply was lower; on average the amount of irrigation water was almost equal for both threshold scenarios (Figure 18).

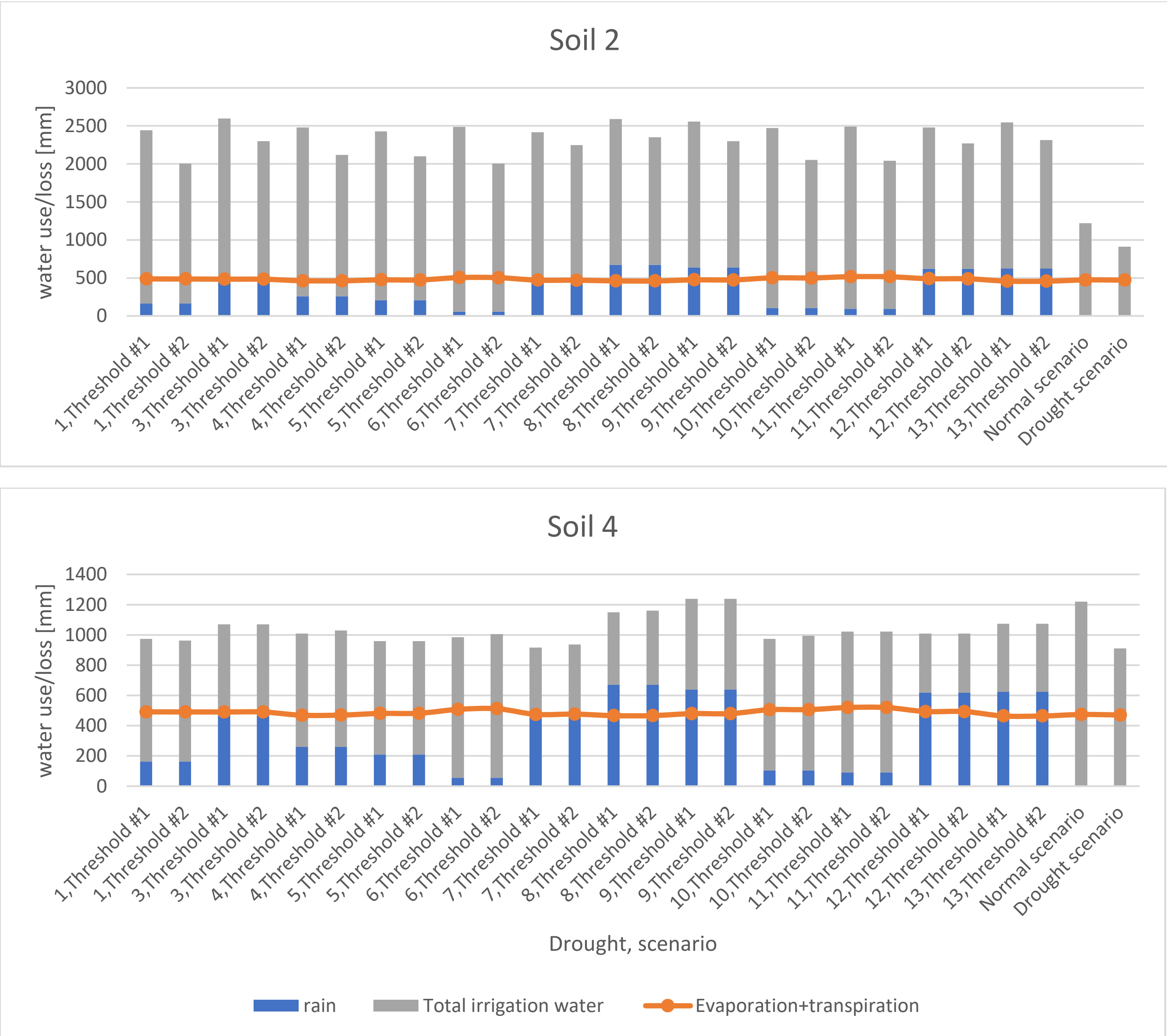


Figure 18 Amount of evapotranspiration, rainfall and irrigation water with irrigation scenarios 3 and 4 (Table 4), for rice cultivated on soils 2 and 4 in the Saldaña irrigation district, Colombia

For the irrigation schedules with the combination scenarios on soil 2, the threshold during the days of irrigation is often reached during most droughts (Figure 19). During droughts 7, 8, 9, 12, and 13, the amount of irrigation water with the combination scenarios the amount of irrigation water was lower. As result, during these droughts, water is conserved. For soil 4, the average amount of irrigation water was 550 mm for both combination scenarios. However, for the combination drought scenario the amount of irrigation was slightly lower due to the lesser days of irrigation water supply.

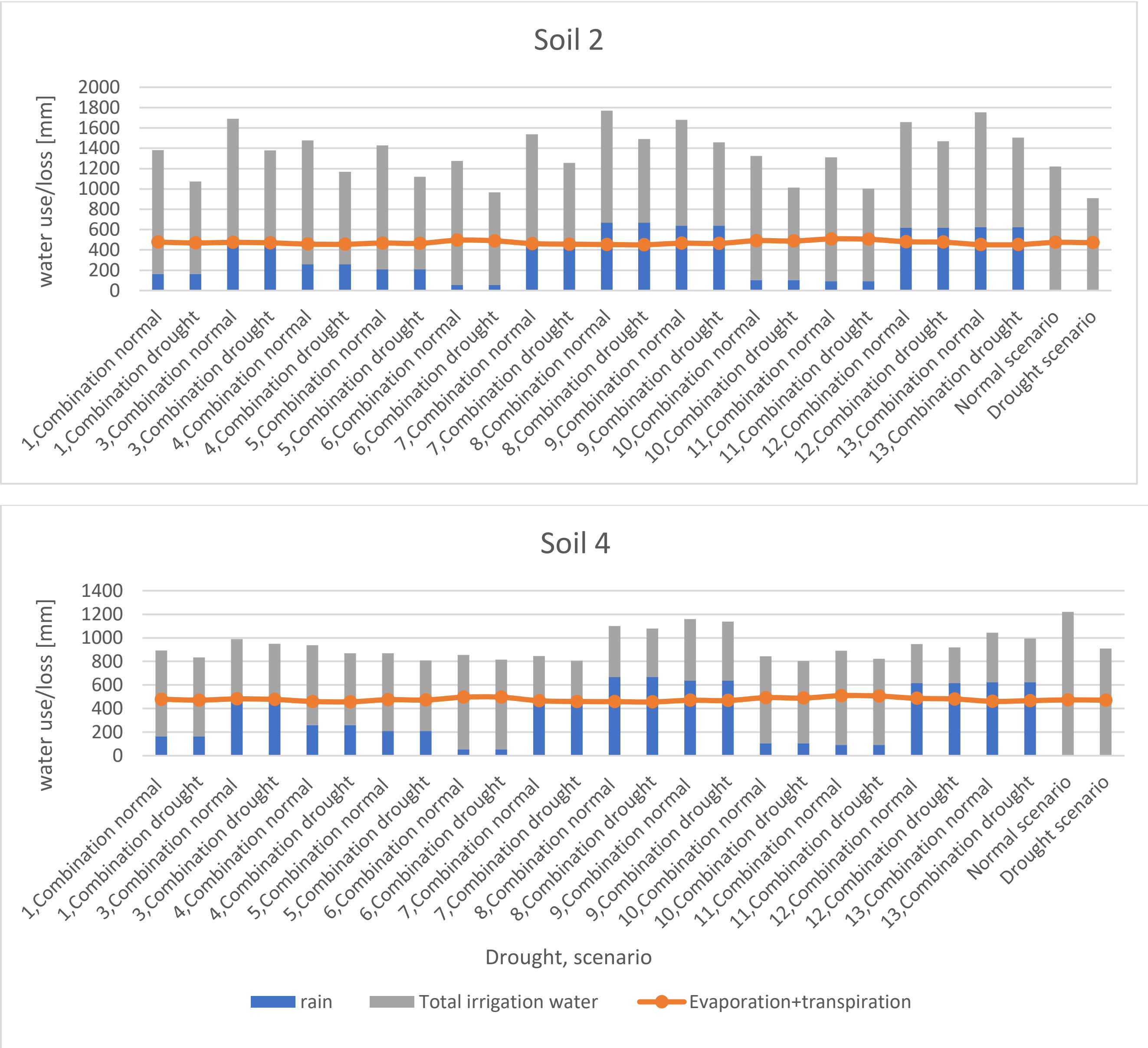
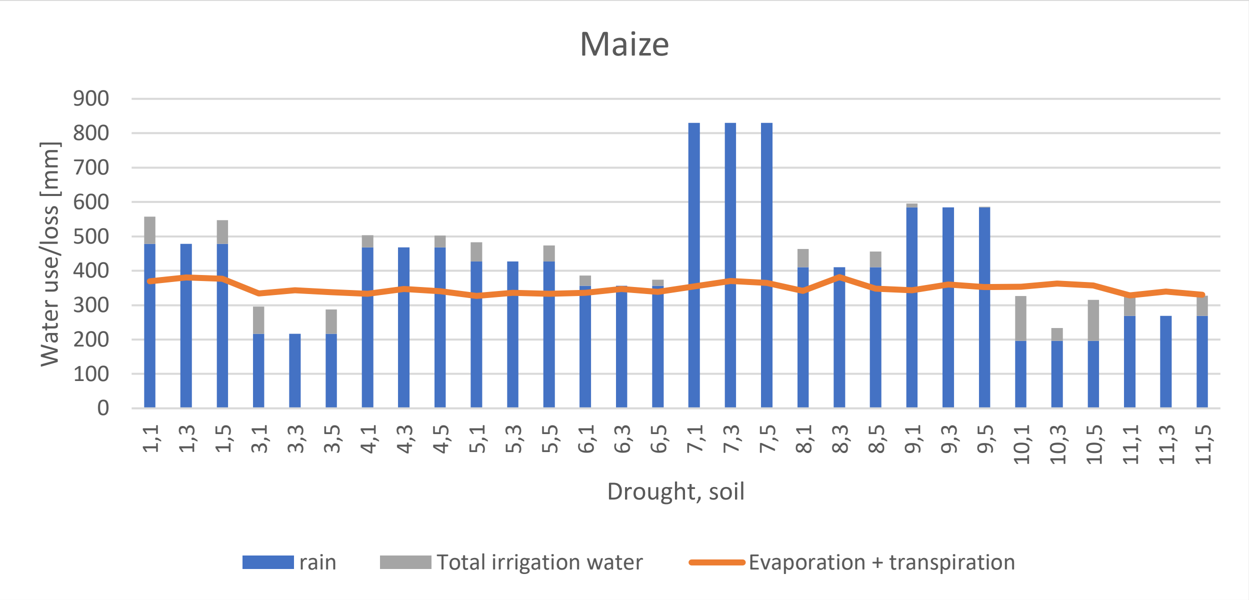


Figure 19 Amount of evapotranspiration, rainfall and irrigation water with irrigation scenarios 5 and 6 (Table 4), for rice cultivated on soils 2 and 4 in the Saldaña irrigation district, Colombia

4.3.2 Maize and Sorghum irrigation

Coello

The crops maize and sorghum do not require much irrigation water and are optimized with the irrigation requirements determined with AquaCrop. Figure 20 shows the amount of irrigation water requirements for each drought and the soils 1, 3, and 5 on which maize and sorghum are cultivated. Soil 3 does not require a lot of irrigation for maize and sorghum, during most drought no irrigation water was needed. Soil 1 requires slightly more irrigation water supply than soil 5, for both crops. During drought 7, no irrigation water was required and also during droughts 4 and 9 little irrigation water was needed. During droughts 1, 3, 5, 8, 10, and 11, more than 50 mm of irrigation water was required to compensate for the water losses due to evapotranspiration and percolation. The irrigation requirements for sorghum are mostly slightly higher than for maize, due to the extended growing cycle of sorghum.



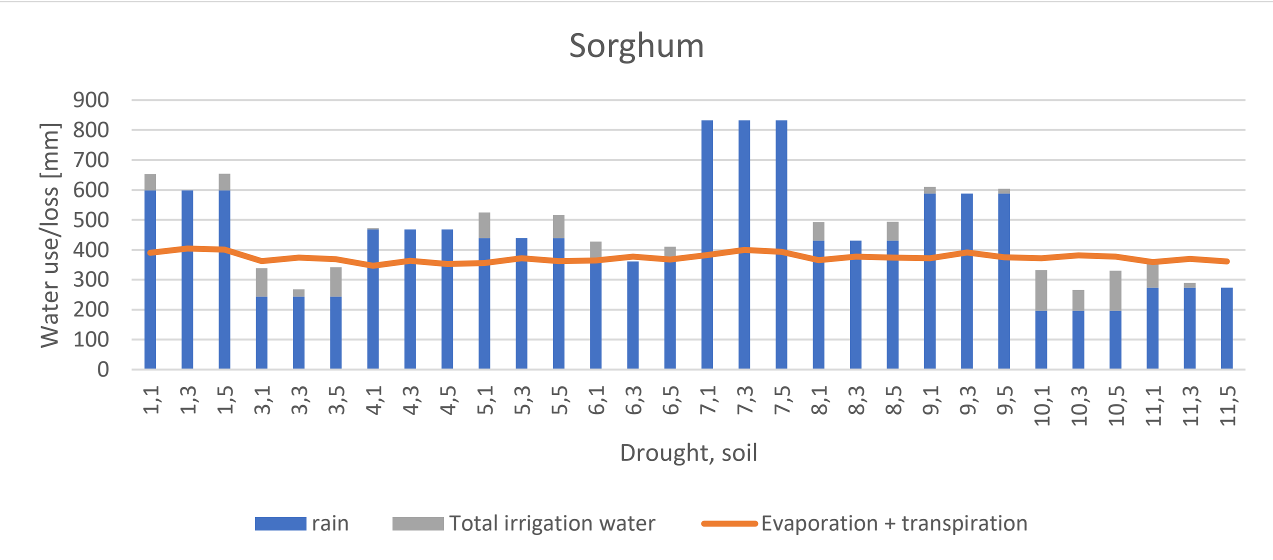
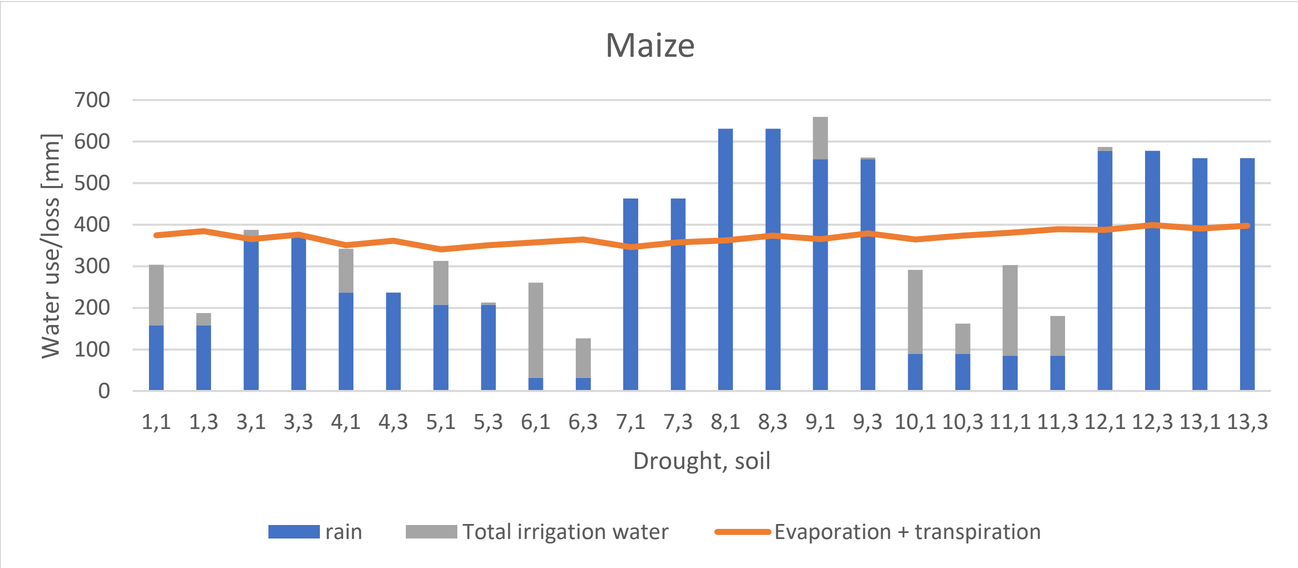


Figure 20 Amount of rainfall, irrigation, and evapotranspiration for maize and sorghum cultivated on soils 1, 3 and 5 during periods of drought in the Coello irrigation district, Colombia

Saldaña

Figure 21 shows the amount of irrigation water requirements for maize and sorghum cultivated on soils 1 and 3. As the results in Figure 20 showed as well, the amount of irrigation water requirements for soil 3 is low. But in the case of Saldaña, there are more severe droughts and more often, irrigation water is required for the cultivation of maize and sorghum on soil 3. For the cultivation of these crops during the droughts 7, 8, 12, and 13 almost no irrigation water was needed (Figure 21). During the droughts 1, 6, 10, and 11, the crops cultivated on soil 1 required more than 150 mm of irrigation water. In general, the evapotranspiration was increasing over time with the droughts, thereby increasing the irrigation demands for both crops. This is shown with the higher irrigation demands for soils 10 and 11 compared to soil 6, while the cumulative rainfall was lower for soil 6.



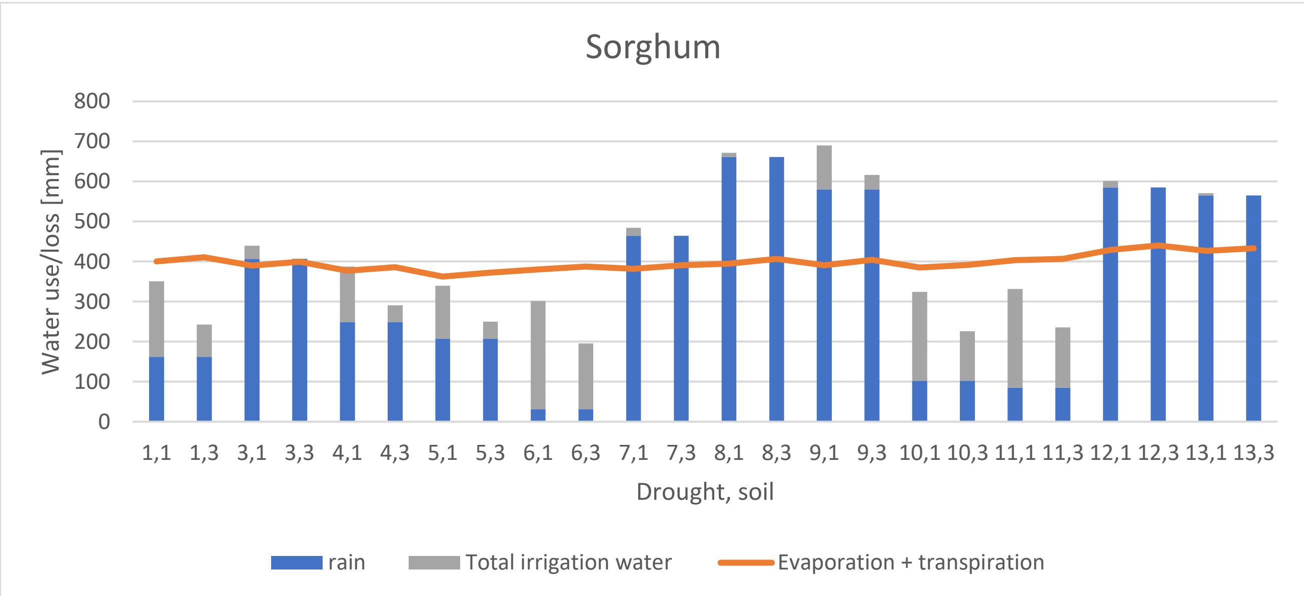


Figure 21 Amount of rainfall, irrigation, and evapotranspiration for maize and sorghum cultivated on soils 1, 3 and 5 during periods of drought in the Saldaña irrigation district, Colombia

4.3.3 Water use

Coello

In Coello, the irrigated area for rice in the first semester is 11635 ha, and in the second semester this is 13365 ha. The rest of the area is cultivated with maize and sorghum, this is mostly on the soils 1 and 3 and size depended per year for soil 5 (Table 5). Note, in this report, the cultivated areas maize and sorghum are considered to be equal.

Table 5 Crop areas per soil class and semester for the Coello irrigation district, Colombia

	soil	rice [ha]	sorghum [ha]	maize [ha]
	1	0	1500	1500
	2	3750	0	0
	3	0	2500	2500
	4	6250	0	0
semester 1	5	1635	2682	2683
semester 2	5	3365	1818	1818

The irrigation water supply for maize and sorghum are constant for each drought. This is due to the calculated determination of irrigation water in AquaCrop. The average irrigation water supply is calculated with Equations 4 and 5. Table 6 shows the average irrigation water supply during the average growing cycle for maize and sorghum, which is considered as 100 days.

Table 6 The average irrigation water supply [m3/s] during the growing cycle of maize and sorghum during periods of drought in Coello, Colombia

Drought	Irrigation water supply Q [m3/s]
1	0,62
3	0,73
4	0,17
5	0,51
6	0,31
7	0
8	0,43
9	0,11
10	1,30
11	0,57

The total water supply during the 90 days of irrigation for rice is calculated with the areas of irrigated rice of both semesters (Table 5) and the total irrigation water for the 6 scenarios during each drought, with Equation 5 the average irrigation water supply [m^3/s] is calculated. The results of the irrigation of maize and sorghum from Table 6 are added to this. Resulting in a boxplot with for all 6 scenarios the average water supply [m^3/s] (Figure 22). The average water supply is the amount of water the inlet should supply during the period of drought to irrigate the whole area, with a certain scenario. Appendix 3 shows the exact resulting average Q for the Coello district. The average water supply is constant for the drought and normal scenario, only differ per semester. During the first semester, the average water supply is 21.9 m^3/s during the normal scenario and 18.0 m^3/s during the drought scenario. In the second semester, more rice is irrigated. As a result, the average water supplies are higher with 24.4 and 20.0 m^3/s for the normal and drought scenario, respectively. The lower values (Figure 22) are the combination scenarios. The boxplots show the lower irrigation requirements during droughts 1, 4, 7, and 9, where the irrigation water supply for the threshold and combination scenarios is lower than the normal and drought scenario. And the boxplots with higher values are periods of drought with a higher irrigation water requirement, e.g., during drought 3 and 10 for each scenario, the average irrigation water supply is at least 18 m^3/s.

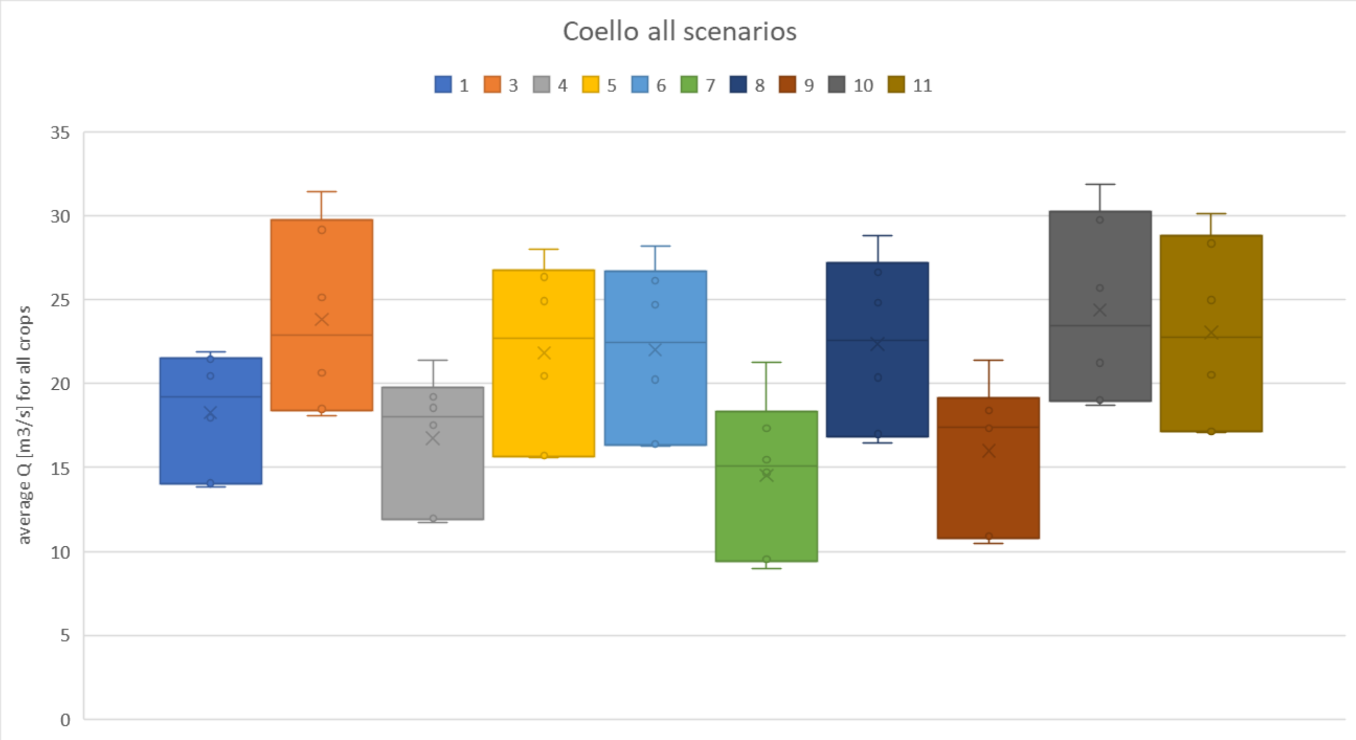


Figure 22 Boxplots of the average water supply for the whole Coello district, Colombia, for all periods of drought. Where, X denotes the average of the 6 scenarios, and in legend the numbers of the periods of drought.

Saldaña

In Saldaña, the irrigated area cultivated with rice and the areas cultivated with maize and sorghum is given in Table 7. And the calculated required average irrigation water supply for the growing cycle of maize and sorghum during the periods of drought is shown on the right (Table 7).

Table 7 Crop areas per soil class (left) and the average irrigation water supply [m3/s] during the growing cycle of maize and sorghum during periods of drought (right) for the Saldaña irrigation district, Colombia.

soil	rice [ha]	sorghum [ha]	maize [ha]
1	0	2500	2500
2	9000	0	0
3	0	2100	2100
4	4000	0	0

Drought	Irrigation water supply Q [m3/s]	Drought	Irrigation water supply Q [m3/s]
1	1,24	8	0,03
3	0,15	9	0,71
4	0,80	10	1,70
5	0,81	11	1,94
6	2,07	12	0,07
7	0,06	13	0,02

With the same calculations as for the Coello irrigation district the average irrigation water supply is calculated for Saldaña (Figure 23). Here the irrigated areas are equal for both semesters. The average water supply is 21.6 m^3/s during the normal scenario and 16.5 m^3/s during the drought scenario. The high average and the top values in the boxplots are mostly due to the threshold scenarios. The combination normal scenario on average show results of 17 m^3/s, and with the combination drought scenario this is 14 m^3/s on average. Appendix 3 shows all the exact values for the Saldaña irrigation district. During the more severe droughts, drought 1, 4, 6, 10 and 11, the variation in results increases due to the increase in water supply with the threshold scenarios. The most other droughts that occurred show a variety of 10 m^3/s between the combination drought and the threshold scenario.

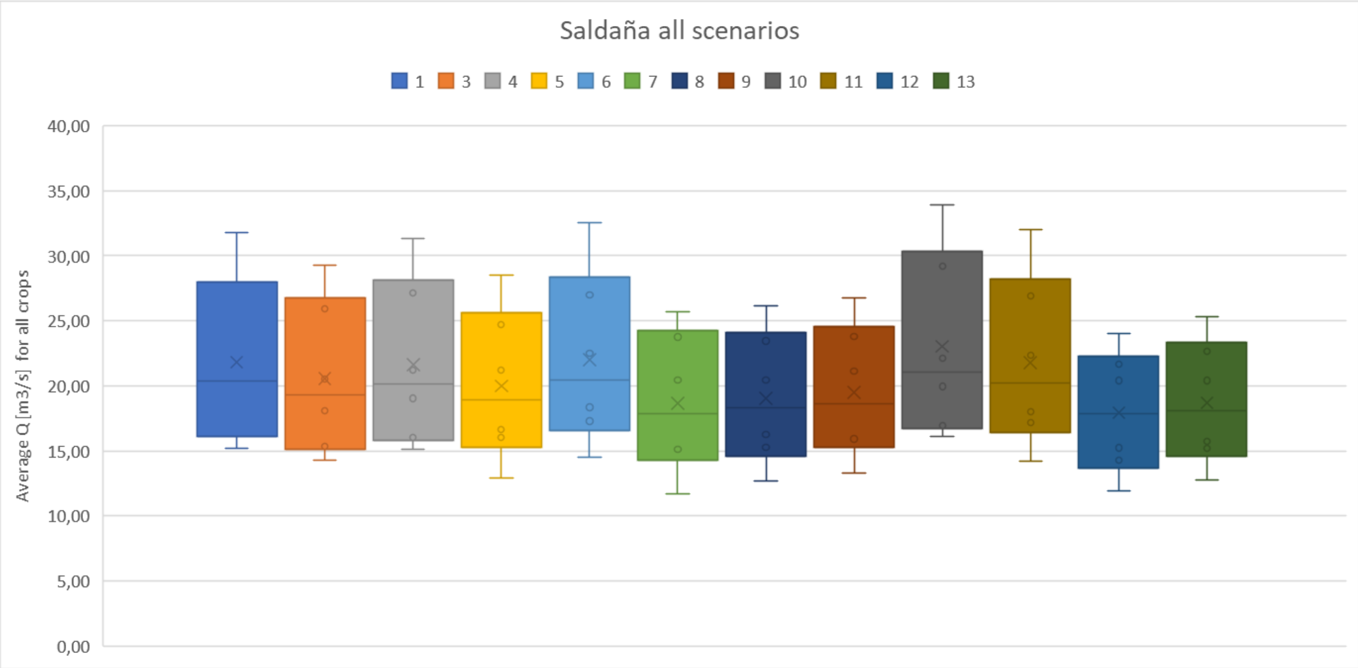
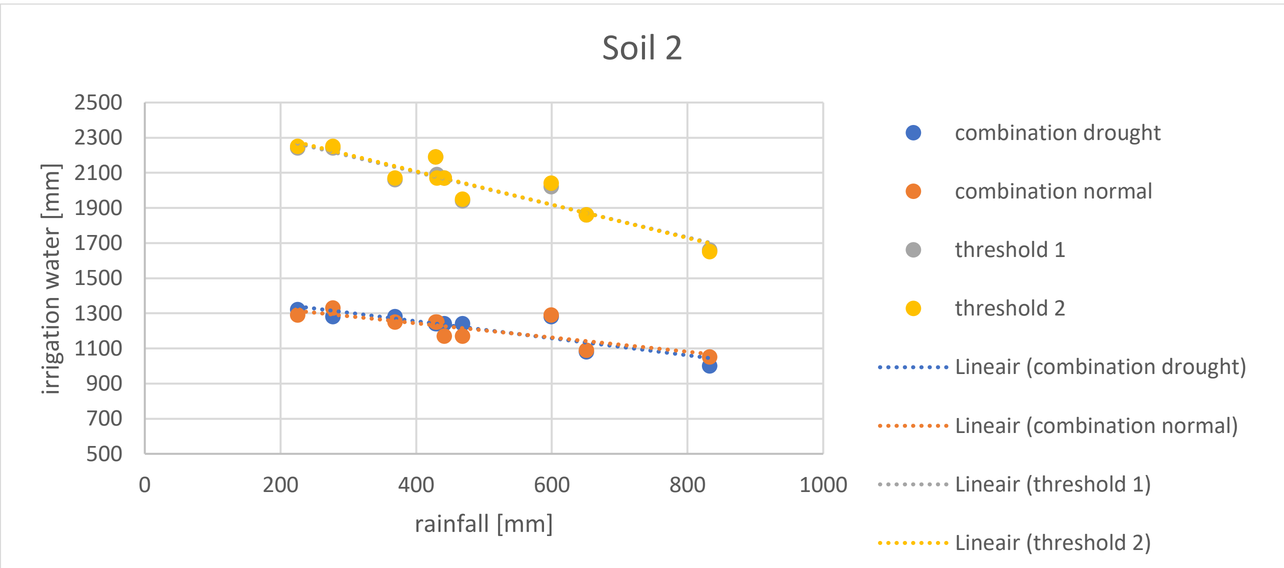


Figure 23 Boxplots of the average water supply for the whole Saldaña district, Colombia, for all periods of drought. Where, X denotes the average of the 6 scenarios, and in legend the numbers of the periods of drought.

4.3.4 Trend rainfall and irrigation

Coello

Figure 24 shows the amount of rainfall and the required irrigation for the same rice production during periods of drought, in Coello. If the amount of rainfall increases the amount of irrigation water slightly decreases. As shown in the previous sections, the amount of irrigation water supply is more with the threshold scenarios. However, the linear relationship is steeper for the threshold scenarios than for the combination scenarios. For soil 4, with more than 800 mm of rainfall the scenarios are almost equal.



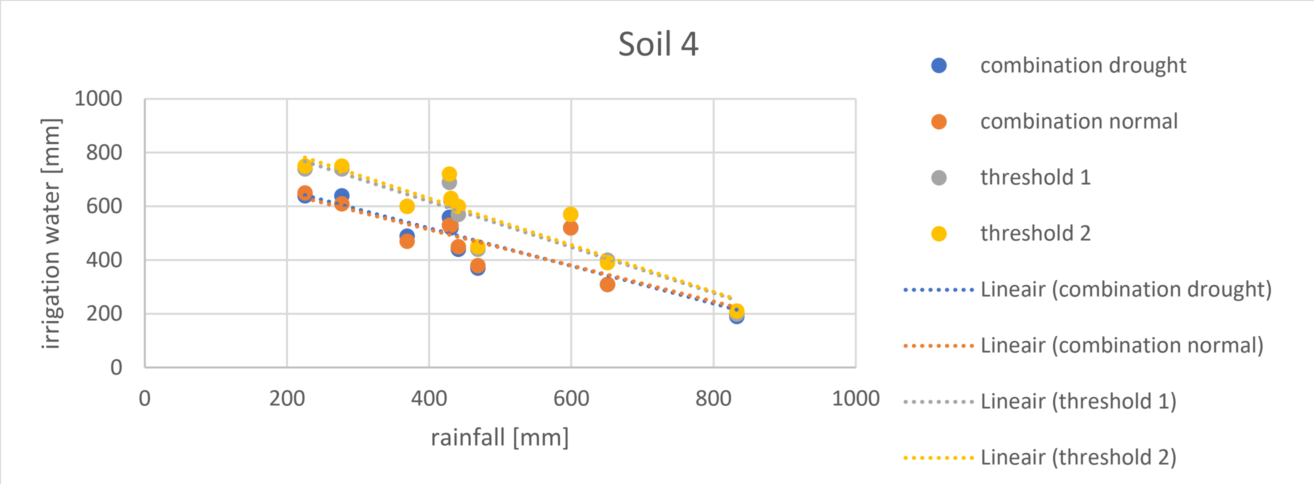
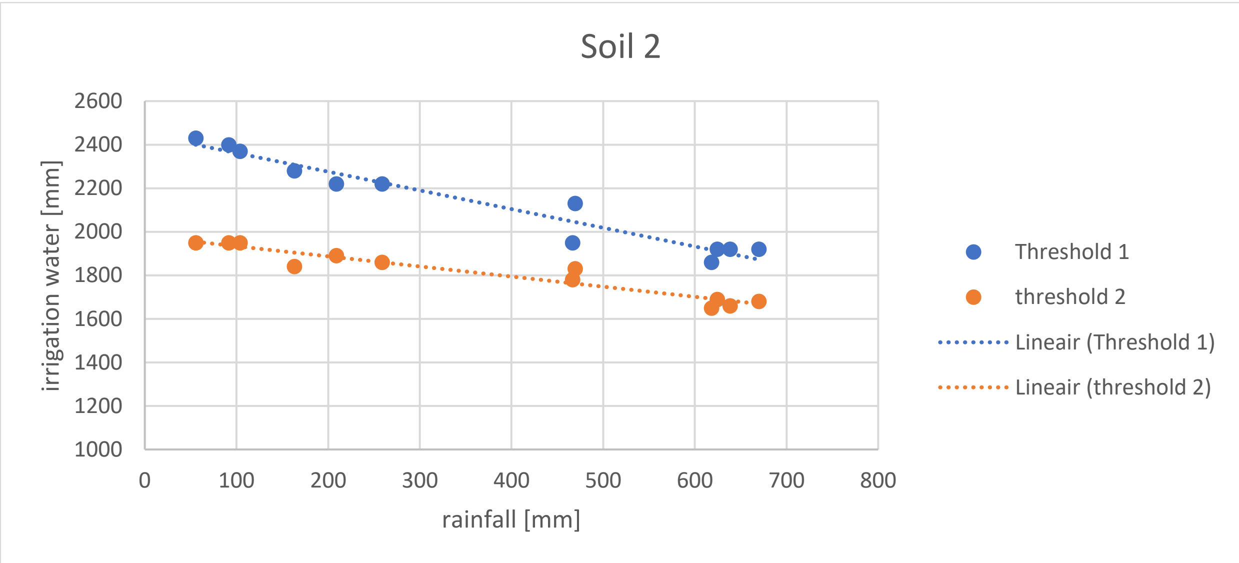


Figure 24 Trend in amount of rainfall and required irrigation water for cultivated rice on soils 2 and 4 in the Coello irrigation district, Colombia

Saldaña

In Saldaña, a similar decreasing trend is shown, but there is more difference between the drought and normal threshold scenarios (Figure 25). Due to the same values for the combination and threshold scenario on soil 2 the combination scenarios are neglected. On soil 2 the irrigation water with threshold 2 is almost equal, independent of the amount of rainfall. As the period of drought is less severe, the amount of irrigation water is almost equal for both soils. The decreasing trend for soil 4 is much steeper than for soil 2, showing the



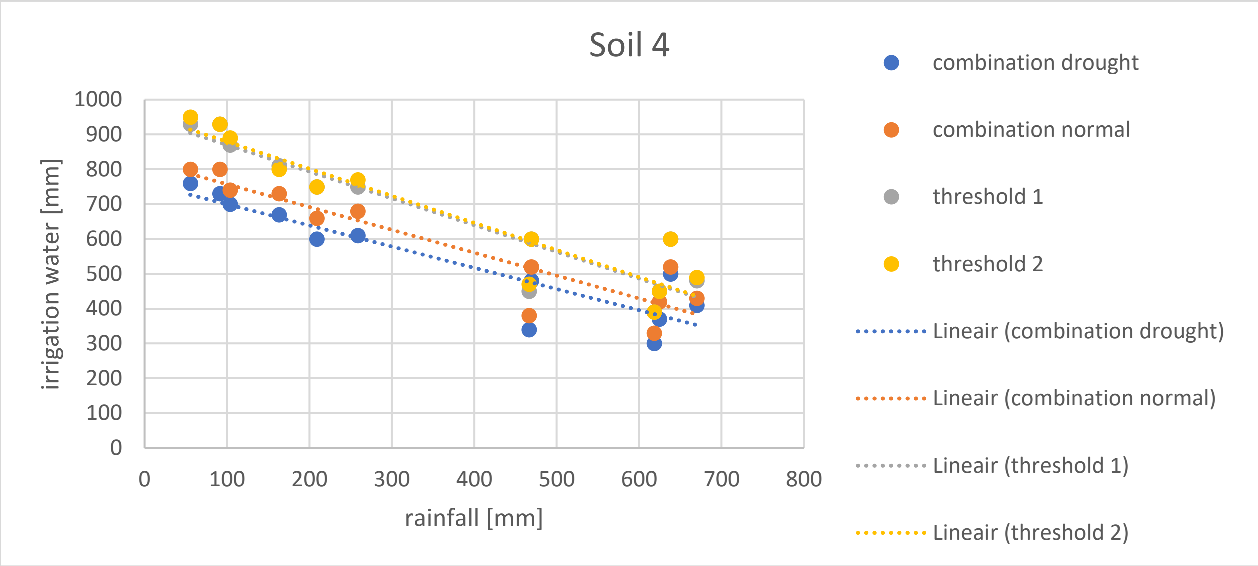


Figure 25 Trend in amount of rainfall and required irrigation water for cultivated rice on soils 2 and 4 in the Saldaña irrigation district, Colombia

4.3.5 Irrigation consequences and yield

Coello

Some irrigation scenarios were not suited for the cultivation of rice as these irrigation scenarios caused water stress. The normal irrigation scenario is sufficient for all soils and all droughts. Only for soil 5, the water level was below the field capacity during droughts 8 and 11, and this could cause some water stress. During the irrigation drought scenario the water levels were below field capacity for soil 5 with every drought and causing canopy stress. Also, for soil 2, the rice crops experienced water stress, during the more severe droughts.

In the threshold scenarios no water stress was observed for the rice crops. This is due to the very high irrigation rates during the whole growing cycle, with soil 5 often more than 80 irrigation events in the AquaCrop model.

The combination normal scenario causes periods of the water level below field capacity during most droughts for soil 5. During droughts 6, 10 and 11 also on soil 2, the water level drops below the field capacity in some periods. Due to the fewer irrigation water supply during the first 30 days, some canopy expansion stress was observed, mostly for soil 5, although during droughts 5, 6, 10 and 11, it was observed on all soils with cultivated rice. The combination drought scenario also caused the same water stress. Still, for soil 2, periods of the water level below field capacity during drought 6 and more often canopy expansion stress was found. Only during drought 7 no canopy expansion stress for all soils was observed, and for soil 4 only during 4 droughts, there was some water stress.

The dry yield of rice per scenario does not change much in the AquaCrop model. However, it does change per drought (Figure 26). Due to the canopy expansion stress, the dry yield does vary slightly. Also, the dry yield of rice per soil does not change significantly in the AquaCrop model. The dry yield of rice increases over time due to the increase in CO_2, and slightly due to the rise in temperature, there is an increasing trend in the dry yield in Coello. The drought periods 7 and 9 are somewhat under this trend due to the lower temperatures than during the other droughts.

During most droughts, the combination scenario resulted in marginally lower dry yield; the maximum decrease in dry yield is less than 2%.

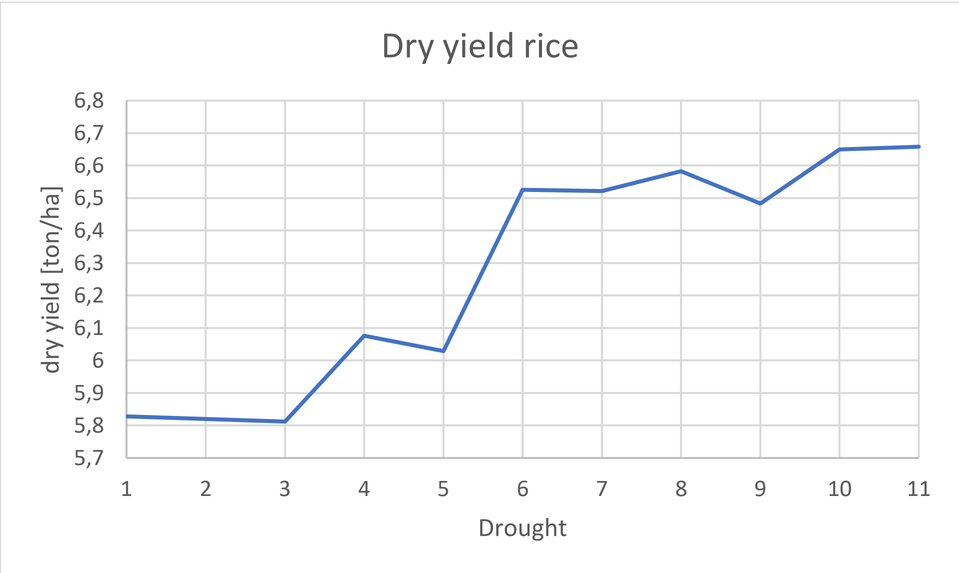


Figure 26 Dry yield of rice during periods of droughts in the Coello irrigation district, Colombia

The dry yield of maize and sorghum show an increasing trend during the periods of drought in the past 40 years (Figure 27) and decreases slightly during the last droughts. The dry yield of maize is mostly more on soil 3 than on the other soils. The dry yield of sorghum is also mostly more on soil 3 but varies more, even during drought 5, the dry yield is less than on other soils. During drought 7, when there is no irrigation, the yield on the different soils are equal.

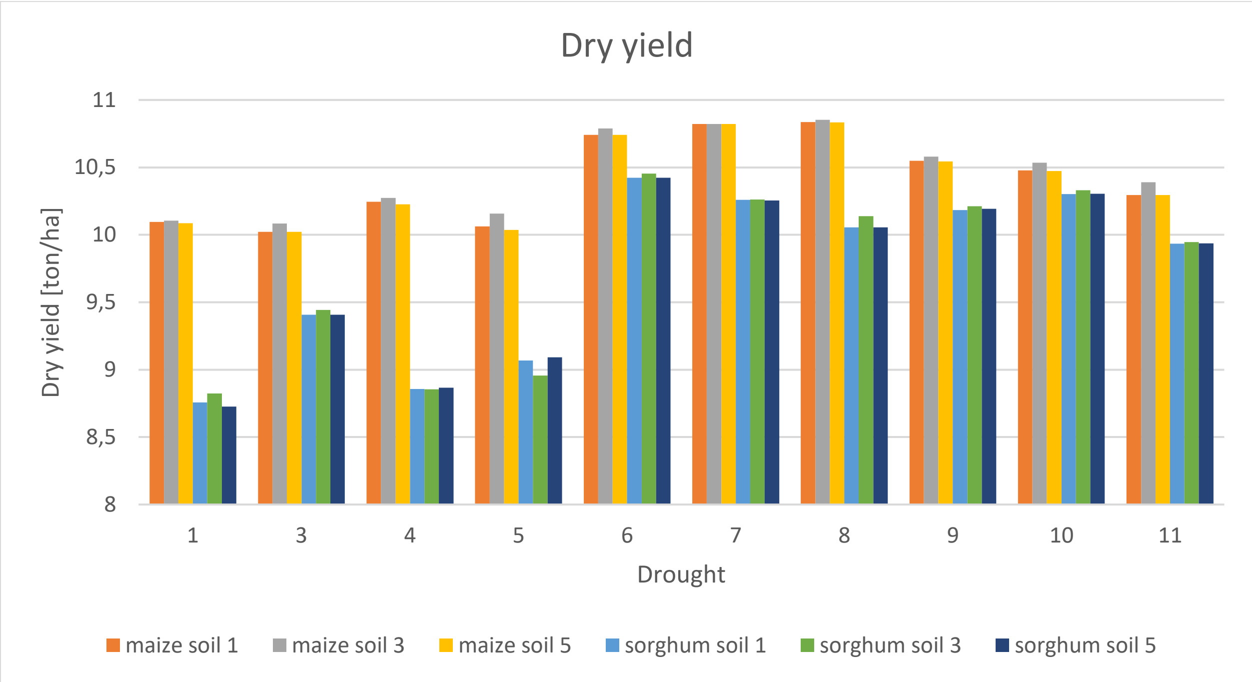


Figure 27 Dry yield of irrigated maize and sorghum during periods of droughts in the Coello irrigation district, Colombia

Saldaña

In Saldaña, the normal irrigation scenario is well suited for almost all droughts. However, during drought 6, 10 and 11, there was some canopy expansion stress observed. Due to the lower irrigation rates in the first 30 days. With the drought scenario the water level on soil 2 drops below field capacity during each drought and causing canopy expansion stress, while on soil 4 only during droughts 3, 5, 6, and 7 canopy expansion stress was observed.

During the periods of drought and the irrigation threshold scenarios there was no canopy expansion stress or periods of the water level under field capacity. The irrigation water supply is high for the rice cultivated on soil 2 during each drought. With the combination normal irrigation scenario there is canopy expansion stress during droughts 6, 10, and 11 for both soils. The combination drought scenario causes periods of the water level under field capacity during almost all droughts for rice cultivated on soil 2, except for droughts 7, 8, and 13, and during almost all scenarios there was canopy expansion stress on soil 2. For rice grown on soil 4, there was only during drought 6 a period of the water level under field capacity, but there were periods of canopy expansion stress during half of the periods of drought.

In Saldaña, the lower values are mostly shown with the combination drought and the drought scenario. Due to the extended days without irrigation water, which causes canopy expansion stress. There was slight difference between the dry yield on soil 2 and 4; the maximum difference that is observed is less than 1%. The dry yield on soils 2 and 4 for the cultivation of rice is shown in Figure 28. There is a general increase in the dry yield of rice observed, only for the rice cultivated during drought 11, the dry yield is more than 1 ton/ha less than for the other droughts.

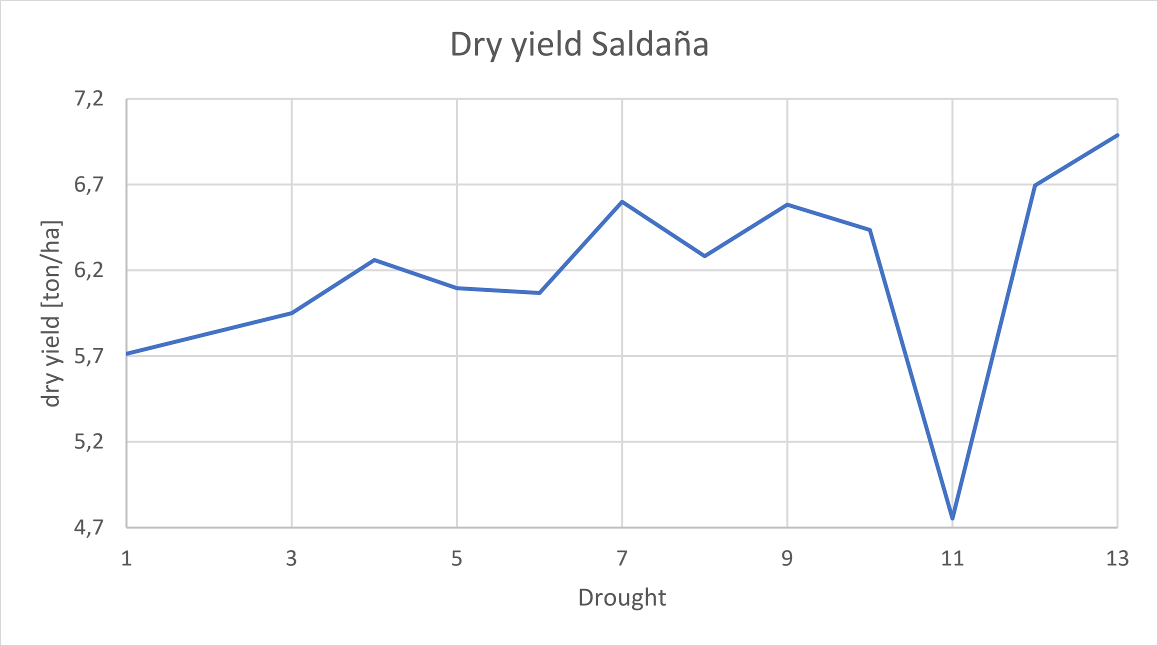


Figure 28 Dry yield of rice during periods of droughts in the Saldaña irrigation district, Colombia

In Saldaña also an increasing pattern in yield is observed during the first droughts, then after drought 7, a more constant pattern in dry yield is observed (Figure 29). Also, in Saldaña, the maize yield on soil 3 is often slightly more than on soil 1. The dry yield of sorghum is usually somewhat higher on soil 1 than on soil 3. Also, the dry yield on average is lower in the Saldaña district than in the Coello district, only during the first periods of drought, up to the year 1997, the dry yield is higher in Saldaña than is observed in Coello.

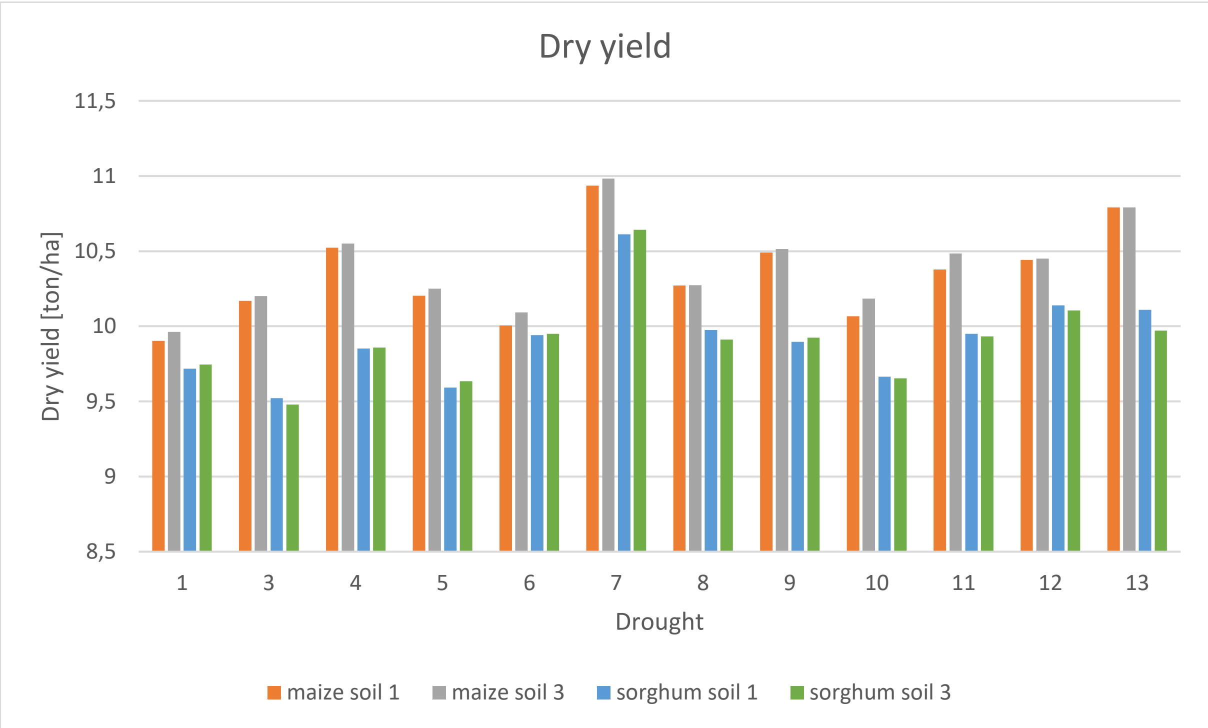


Figure 29 Dry yield of irrigated maize and sorghum during periods of droughts in the Coello irrigation district, Colombia

4.4 Irrigation schedule for future droughts

By optimizing the Coello and Saldaña irrigation schemes, an irrigation schedule is created that can be used for every drought. Based on the severe droughts of the past 40 years, this irrigation schedule could be used with future periods of drought. The droughts 3, 10, and 11 of Coello and the droughts 6, 10, and 11 of Saldaña were the more severe droughts. The results of the irrigation scenarios showed that too many days without irrigation water supply is not suited for the irrigation of rice. Due to the high evapotranspiration rate in the Coello and Saldaña irrigation district and also by percolation to the groundwater table. To prevent canopy expansion stress during the first 30 days of the growing cycle, the irrigation schedule starts with 2 days of irrigation alternated by 2 days without irrigation until day 30. Then the water layer on top of the surface is 5 centimetres after irrigation, the threshold value is 20 mm, and then 30 mm of irrigation water is supplied. This is done by the schedule of 2 days with irrigation, if the water layer is below the threshold value, alternated by 3 days without irrigation water supply. In this schedule the maximum irrigation water supply is 880 mm and supplied in 40 irrigation events, this is the case for the soils 2 and 4. With this schedule, the amount of irrigation water for soil 4 is less (Table 8). The average water supply in m^3/s is calculated as in section 4.3.3, the required amount of irrigation for maize and sorghum remained equal, and further the calculations are with 880 mm for both soils 2 and 5 and the irrigation water supply for soil 4 as in Table 8. As shown in the table, with this irrigation schedule, the average irrigation water supply is reduced during all severe droughts.

Table 8 The amount of irrigation water supply for rice cultivation on soil 4 and the average water supply [m3/s] during the most severe droughts in the Coello and Saldaña districts, Colombia.

	Drought	Total irrigation water soil 4	average Q for the whole area
Coello	3	610	13,68
	10	610	14,25
	11	520	12,80
Saldaña	6	760	16,17
	10	730	15,64
	11	760	16,04

5. Discussion

To perform the analysis and to optimize the irrigation districts, some assumptions and limitations were considered when the research was conducted, which are discussed in this section. Further, the drought analysis of the SPEI and MEI for the two irrigation districts over the past 40 years are analysed here, and the overall outcome of the AquaCrop model is described.

5.1 Data assumptions and limitations

Due to missing temperature data for both areas and the completed data with nearby stations, the temperature data is not entirely reliable. In the research, the temperature is considered constant for the whole Saldaña and Coello irrigation districts areas, while there are fluctuations in large areas. Furthermore, the limiting data of the precipitation, which is completed with nearby stations, has a high spatial variability that is not considered.

The evapotranspiration was calculated with the Hamon equation; this is a simplified equation. Considering the only available data series of temperature and precipitation over the past 40 years for these areas and their stations, this Hamon equation is chosen. Although in the tropics, the evapotranspiration is more complex with the clouds and the turbulent exchange of air, this will result in more fluctuations in the results of evapotranspiration.

The soil properties were calculated with the S-world map, due to the limited available data of soils in the Coello and Saldaña irrigation districts. The 30 arc-second resolution of this map and the 5 soil classes give a rough averaged soil profile, a rough representative of the situation. Due to the average results of each subsoil in each soil class, the sandy underground of the neighbouring soils, where no rice is cultivated, is also taken into consideration. Thus the resulting soil, in this report, contains a higher fraction of sand than there is in the districts. Also, Balland et al. (2008) state that the uncertainties in the PTFs calibrations have an RSME of 3% to 6%, and increasing with soil depth.

There are various sorts of rice worldwide, and in the Saldaña and Coello districts, the rice is a bit different from the modified rice, which is the input in the AquaCrop model. The supplied irrigation water in the AquaCrop model is supplied as one layer of water on top of the soil surface and a direct inflow of water, while in the field, the crops are irrigated during the whole day. Consequently, for the soils with a high infiltration rate in the AquaCrop model, there is almost no water on top of the surface after an irrigation event, while in the field, there will still be some water on top of the surface. Furthermore, the groundwater is chosen as a constant level of 3 meters, while in reality, this fluctuates a bit over time. This will not have a significant influence on the results of the amount of irrigation water supply.

5.2 Drought analysis

The six month SPEI droughts that are calculated for the two irrigation districts are calculated with a general drought calculator. These droughts all vary over time and intensity; it is calculated with a re-analyzation of global data, resulting in rough estimates of the SPEI. The calculation of SPEI is location specific, and in this report, the estimates with a 0.5 degrees spatial resolution will give slightly different results than calculation with the station-specific data, and with the drought monitor, the potential evapotranspiration is calculated with the Penman-Monteith equation. Nevertheless, the SPEI drought monitor consists of data of a more extended time range.

The droughts calculated with the MEI and the SPEI, correlate, with a lag time of approximately three months. The Spearman correlation in this report is lower than the calculations of Vega-Viviescas (2019), close to -0.70, with a lag of 3 months with the warm El Niño phase. This is in accordance with the correlation in this report, only the Spearman correlation is a bit better in the report of Vega-Viviescas (2019).

5.3 AquaCrop model performance

The AquaCrop model also has some limitation in modelling. The model can only model one growing cycle, the simulation is at a single field scale, and this is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics and in irrigation and field management practices (FAO, 2019). Furthermore, only the vertical incoming and outgoing water fluxes are considered, although the land surface of both irrigation district is rather flat, so the water loss due to runoff is small.

The potential evapotranspiration calculated with the Hamon equation, is roughly equal to the evapotranspiration as calculated in the AquaCrop for irrigated rice as there is a water layer on top of the soil surface. This is also shown in the average evapotranspiration in the growing cycle of rice that is a little less than 500 mm in each scenario.

The evapotranspiration of an irrigated clayey soil is less than that of a more a loamy irrigated soil and the crop yield of clayey soils is also less. In general, the water use efficiency, i.e., the evapotranspiration divided by the yield, is lower for the clay soil than for the loam soil (Katerji & Mastrorilli, 2019).

The determined irrigation water for the cultivation of maize and sorghum is also based on the field scale, and the AquaCrop model tends to underpredict the dry yield of maize under irrigation. The modelled dry yield with the average amount of seasonal water supply is close to the boundary function in Grassini et al., (2011), this shows that the optimal determined irrigation water in AquaCrop in combination with the soil properties do not give the most optimal dry yields as would be observed in the field (Grassini et al., 2011).

In the model, losses due to evaporation of surface water during irrigation are not considered, which would implement the average streamflow of the inlet should is higher than in this report. Also, the reuse of percolated water is not considered in this report, which would mean a higher availability of water.

The irrigation scenarios with threshold values are easy to model but in field-scale this is harder to reach as this needs to be measured daily and the moment on when to measure will result in different results. Due to more or less water will be infiltrated or evaporated, also in this scenario, the irrigation water requirements are too high, due to the sandier underground and due to no limitations in water supply in the model. The decrease in days of irrigation did not per definition show lower amounts of irrigation water supply. During most droughts, it was more important to irrigate the surface during more days than supplying the same amount of water in fewer days.

In the Coello irrigation district, the most severe droughts were drought 3, 6, 10, and 11. In Saldaña, the most severe droughts were the droughts 4, 6, 10, and 11. These droughts required more irrigation water, as showed with the threshold and combination scenarios. In Saldaña, the maximum irrigation water requirements were reached during these droughts with these irrigation scenarios. The water supply was not sufficient during these droughts and showing that the required amount of water with threshold scenarios and severe droughts is high. While this requirement is high, the available surface water for irrigation will be lower, due to the period of drought that occurred for several months. With this an irrigation schedule that could cope with these severe droughts and lower available water was created.

The created irrigation schedule that could cope with future droughts is specific for these soil conditions, and as described, the AquaCrop model is on field-scale. In the Coello and Saldaña irrigation districts, this schedule will be possible, but there need to be some changes; more measures in the field to obtain information on the threshold value is necessary. As these result in irrigation supply or not, if the threshold value is not reached. Furthermore, the irrigation reschedules of two and three days of irrigation and no irrigation costs more energy and effort than the schedule of six and three days that is currently used in Coello.

As discussed during the fieldwork, 95 percent of the streamflow water can be used to irrigate the crops, so the effects of water use on other sectors are not considered much in the report. The more severe droughts will have impacts on the streamflow for irrigation and other sections as hydropower. The more severe droughts are hydrological droughts and the streamflow is low with this drought; then the available water for irrigation of both districts is lower. Meteorological drought does not have an impact on irrigated crops, but hydrological droughts have major impacts on irrigated crops and can last for months to years with devastating impacts on crop production (Van Loon, 2015).

The dry crop yield is almost equal for each scenario of rice irrigation, also with water stress, there is only a slight difference in the dry yield. This is less than 2% and should be more as the dry yield of rice will decrease faster in the field. The yield of rice irrigated rice that is calculated in this report, agrees with the yields as discussed during the fieldwork visit and the report of Fedearroz (2010). The dry yield of the drought that occurred in this decade modelled with AquaCrop is in accordance with the dry yields in Fedearroz (2010). Thus, the model is quite accurate in modelling the dry yield during normal conditions, although with water deficit conditions, the model is less accurate.

In Saldaña the total area with rice is larger, but the total available water in general is more. Also the discharge at the inlet is more, this makes it easier to irrigate a larger area during one day. The potential evapotranspiration is higher for the Saldaña irrigation district so the water requirements independent on weather conditions will be higher. During the periods of drought the maximum and minimum temperature are also higher than the mean temperature of the past 40 years.

The boxplots show that the average discharge with some scenarios, during the more severe droughts, are too high for the inlet of the Coello and Saldaña irrigation districts. These scenarios are not realistic for the districts, especially during the droughts when the water availability is low. Still, these threshold scenarios show that the ideal irrigation water requirements are high. The combination scenarios show the lower average discharge during droughts and this is possibly the best scenario. Here for, some reservoirs could serve to supply irrigation water during periods of drought, and if the water layer on top of the surface is too low.

Of course the easiest way to decrease the total water use is only planting the crops maize and sorghum as rice requires a very high amount of water. But the main crop and income in both areas are from the rice crops, so in the report the soils that are suited for the cultivation of rice are rice cultivated.

6. Conclusion

The droughts in the Coello and Saldaña irrigation districts are classified with the 6-month SPEI for the period 1980-2020 and are classified as a drought is the SPEI value is below -1 for at least 3 months. In this period, there were 9 droughts in Coello and 10 droughts in Saldaña. In both districts, there are two growing cycles for the cultivation of rice, maize, and sorghum. In the Coello district, there were two droughts that were in both growing semesters, and in the Saldaña district, there were 3 droughts that extended in both semesters. The ENSO driven droughts are classified with the MEI and have a correlation of -0,56 and -0,53 with the 6-month SPEI of the Coello and Saldaña irrigation districts. The El Niño events of 1991-1992, 1997-1998 and 2015-2016 are in comparison to droughts in both irrigation districts, the El Niño event of 1982-1983 is correlated to a drought in the Coello district, while the El Niño that occurred in 1987-1988 did not cause any drought in both districts. The El Niño events start before the occurrence of drought in both districts, implementing the water managers could reschedule their irrigation schedule to cope with the periods of drought.

In combination with the soil areas and the soil properties, determined with the S-world map, the total irrigation water requirements were calculated in AquaCrop. The irrigation water requirements for rice are determined with 6 different irrigation scenarios for each drought and for both irrigation districts, which are based on the irrigation practices in the two districts as described by the water managers. Rice irrigation is only needed during the first 90 days of the growing cycle. In the first 30 days the irrigation requirements are lower, and then it is followed by a layer of surface water that is required on top of the surface for the cultivation of rice. The irrigation requirements for maize and sorghum are determined as the most optimal in AquaCrop. The Coello district consists of 25000 ha, of which more than 13000 ha is irrigated rice, and the Saldaña district has a total area of more than 23000 ha of which almost 14000 ha is irrigated rice.

The total water use for all droughts showed that in Coello, the most severe droughts occurred in 1983, 1997, 2012, and 2015. The cumulative amount of rainfall during periods of drought in Saldaña was significantly lower than in Coello, so the droughts that occurred in Saldaña were more severe than in Coello, these droughts occurred in 1992, 1997, 2012, and 2015. Almost all severe droughts in both districts are in agreement with the occurrence of the El Niño phenomenon.

The most severe droughts were used to create a universal irrigation schedule that could serve both districts in the future and could cope with low precipitation rates and low water levels. In this schedule, during the first 30 days of irrigation, 10 mm of surface water is supplied during two days, and this is alternated by two days without irrigation water supply. After 30 days the irrigation schedule consists of 2 days of 30 mm of irrigation water, if the water level on top of the soil drops below 20 mm, this is alternated by 3 days without irrigation water supply. For two soils, this irrigation schedule is 880 mm, and for the more clayey soil this irrigation schedule will result in less irrigation water supply. This irrigation schedule could supply sufficient water during the most severe drought in Coello with an average supply of 14 m^3/s. In Saldaña, this is 16 m^3/s for the growing cycle during the most severe droughts.

Future fieldwork should be used to optimize the model results to deal with the spatial variation, and the soil properties should be measured in the field. The streamflow at any moment in the past should be documented and taken into consideration because, in this report, the streamflow is considered to be constant. However, during hydrological droughts the water availability will be lower than is considered during this study. This also shows the importance of water conservation during periods of drought. Other drought indices that measure hydrological droughts could be used with more available data; this could show the deficit volume for irrigation during severe droughts.

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Appendices

Appendix 1 – Fieldwork survey

Interview English and Spanish version

Survey (English)

Water managers

1. How many users does your system serve?
2. How many acres are irrigated?
3. The main crop type is rice, how much of the total area is cultivated by rice? What other crop types are and is the total area used for agriculture?
4. How much water do you deliver on average at dry season and wet season?
5. What influence do water managers have on the farmers, do they have influence on the cropping season (day of transplanting, harvesting etc.)?
6. What is the price of one m^3 for the water users? Are there difference during periods of droughts?
7. How do the groundwater levels change during a year? Are there observation of the past 40 years?
8. What influence do the water managers have on the water users? For example, do the water users have influence on the timing of planting and the time of harvest?
9. How is the water distributed during normal periods and during periods of droughts?
10. In general, is all the water taken at the inlet used for irrigation or are there also some other purposes?
11. Is all the water that is used for irrigation of surface water or is there also use of groundwater? Is there some wastewater reused?
12. In periods of drought, are there changes in the cost of water and what is the water availability for farmers during these periods?
13. In periods of droughts, are there periods with a lot of water deficit and how do the water managers deal with this?
14. During droughts, how is the distribution of water for the agricultural sector?
15. In periods of drought, when the water availability is lower, are there less possibilities of irrigation or is there an increase in the water price?
16. Are there some primary concerns pertaining to the future of your water delivery and use?
17. Are there future solutions/ideas on when there are more intense droughts/next ENSO driven drought; how do you want to deal with droughts in the future?
18. If in the future on short or long term, there is less water available, what will you change in the system?

Fieldwork survey

Water users for agriculture

1. How much area of agricultural land do you have?
2. How much of this agricultural area is irrigated?
3. The main crop is rice in the area, but what percentage of the total land is cropland? What crops do you have next to rice fields?
4. During a normal year what is the day of sowing/transplanting of rice, growing cycle crops and the day of harvest.
5. How much is the biomass production and the yield during a cropping season? How much do you earn for 1 ton of rice?
6. How much yield is there from rainfed agriculture and irrigated agriculture?
7. How is the irrigation schedule, in which days is the water applied to the crops?
8. What is the average amount of water used during one irrigation session and during the growing season?
9. How is the field management in the period between harvest and sowing?
10. Is there an approximately constant level of water on top of the surface during the growing stage of the rice?
11. What is the irrigation schedule during periods of droughts?
12. During droughts, what solutions do you have to sustain approximately at the same production level, e.g. do the crops change or are you reducing the irrigated area?
13. When the biomass production does change, does the price of 1 ton of rice also change or will it just be less income for the farmers?
14. How much is the biomass production approximately in this period?
15. The cost of water is increasing, how would you adapt to this/be more secure with the water use?
16. Are there future solutions/ideas on when there are more intense droughts/next ENSO driven drought; how do you want to deal with droughts in the future?

Encuesta (Spanish)

Administradores de agua

1. ¿A cuántos usuarios atiende el distrito de riego?
2. ¿Cuál es el área irrigada?
3. El principal cultivo es el arroz, qué área de total está actualmente plantada en arroz? Qué otros cultivos existen? Qué áreas ocupan?
4. ¿Cuál es el caudal promedio que suministra el distrito de riego en época seca y en época húmeda?
5. ¿Existe una planeación de largo plazo para el área cultivada? Cómo se realiza esta planeación?
6. ¿Cual es el precio promedio por m3 que carga el distrito a los diferentes usuarios? Existen diferencias en el precio en época de sequía?
7. ¿Cómo cambia el nivel freático a lo largo del año? Existen observaciones que pudieran compartir?
8. ¿Qué influencia tienen los administradores del Distrito en las decisiones de los agricultores? Tienen ellos influencia por ejemplo en la definición de épocas de plantado, cosecha etc?
9. ¿Cómo se distribuye el agua para los diferentes predios tanto en épocas húmedas como en épocas secas?
10. ¿En general toda el agua captada en la bocatoma se utiliza para riego de predios? ¿A donde va el drenaje de predios y a qué porentanje del agua captada corresponde?
11. ¿El agua usada para riego es enteramente agua superficial o incluye agua subterránea también? Existe reuso de agua?
12. ¿En períodos de sequía existen algunos cambios en la operación del Distrito: costos del agua, disponibilidad de agua para agricultores?
13. ¿Durante los períodos de sequía con deficit de agua (si existen) como el Distrito de Riego los enfrenta?
14. ¿Durante periodos de sequías, cómo es la distribucción del agua para los agricultores?
15. ¿Durante periodos de sequías, cuando hay menos agua, hay menos periodos de irrigación o hay un incremento en el precio del agua?
16. ¿Existen preocupaciones a futuro relacionadas con la distribucción del agua durante periodos de sequías?
17. A futuro, cuando haya periodos de sequías más intensos, ¿que hara usted frente a los eventos de sequía mas intensos en el futuro?
18. Si en el futuro medio o largo usted trendra menos agua para realizar su actividad productiva, ¿qué va hacer usted al respecto?

Encuesta (Spanish)

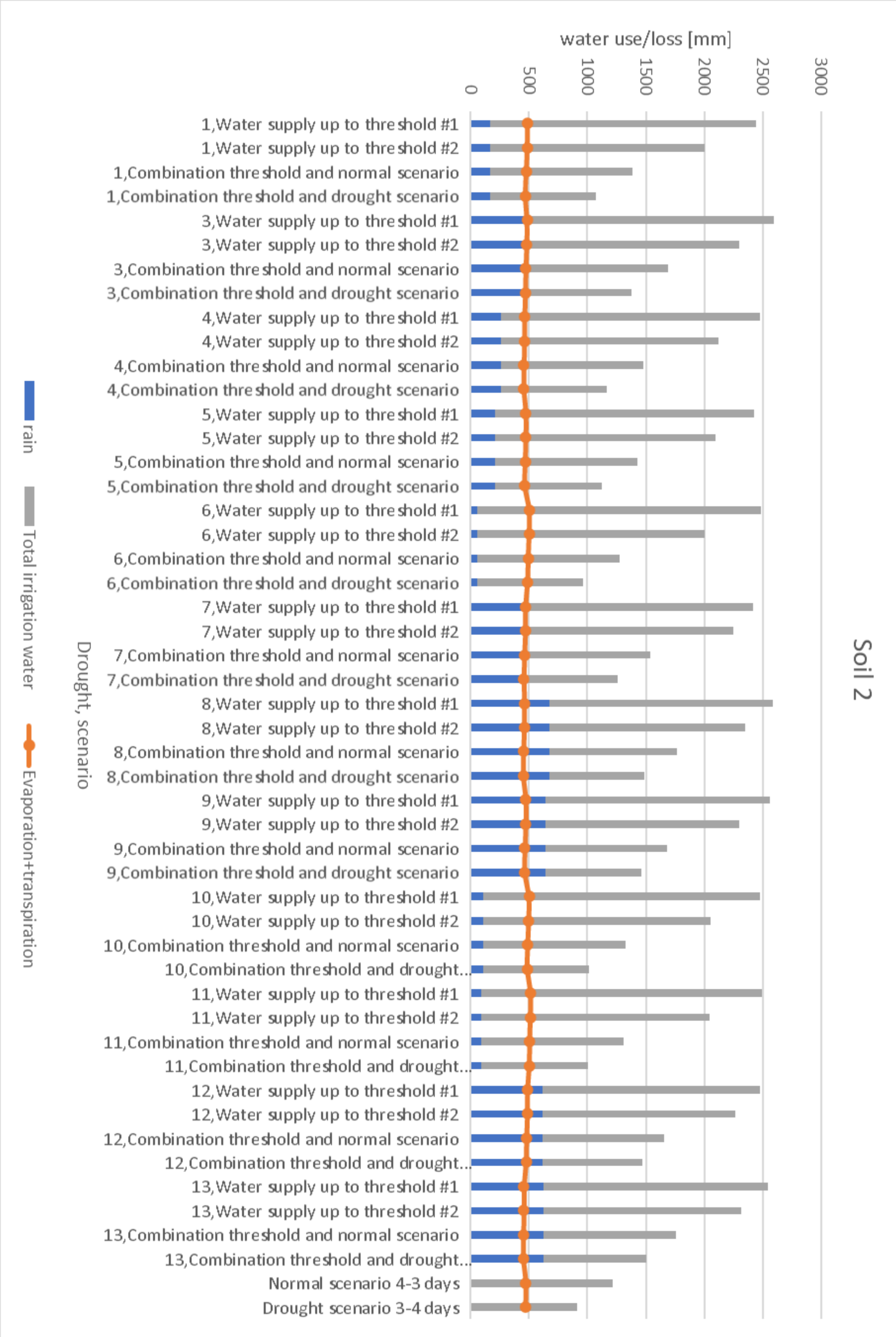
Agricultores

1. ¿Cuántas hectáreas de cultivo tiene?
2. ¿Cuál es el área irrigada?
3. El principal cultivo es el arroz, que área del total está actualmente plantada en arroz? Qué otros cultivos tiene? Qué áreas ocupan?
4. Normalmente, durante un año, ¿cual es el día de siembra de arroz? Y también, ¿cual es el día de cosecha?
5. ¿Cuánta es la producción y el rendimiento de la biomasa? ¿Cuánto dinero ganan por 1 tonelada de arroz durante un periodo de cosecha?
6. ¿Cuánto rendimiento hay de la agricultura con y sin riego?
7. ¿Cómo es el calendario de riego, cada cuantos días hay riego?
8. ¿Cuantos m3 de agua utiliza durante una sesión de riego normalmente, y cuantos en periodos de sequías?
9. ¿Cómo es el manejo del campo en el período comprendido entre la cosecha y la siembra?
10. Durante el período de cultivo, ¿hay un nivel del agua constante encima de la tierra? ¿Y cuántos centímetros son?
11. ¿Cual es el calendario de riego durante periodos de sequías?
12. ¿Durante periodos de sequías, cuales son las soluciones existentes para mantener la misma producción de biomasa que un periodo humedo?
13. ¿Cuando la producción de biomasa cambia, también lo hacen los precios del mercado por tonelada de arroz producida o se generan menores ingresos para los agricultores?
14. Durante periodos de sequía ¿cuánta es la producción de arroz en comparación con las condiciones durante otro periodos?
15. El precio del agua esta aumentando, ¿cómo usted se está adaptando a esto?
16. A futuro, cuando hay periodos de sequías más intensos, ¿qué haria usted frente a los eventos de sequía más intensos en el futuro?

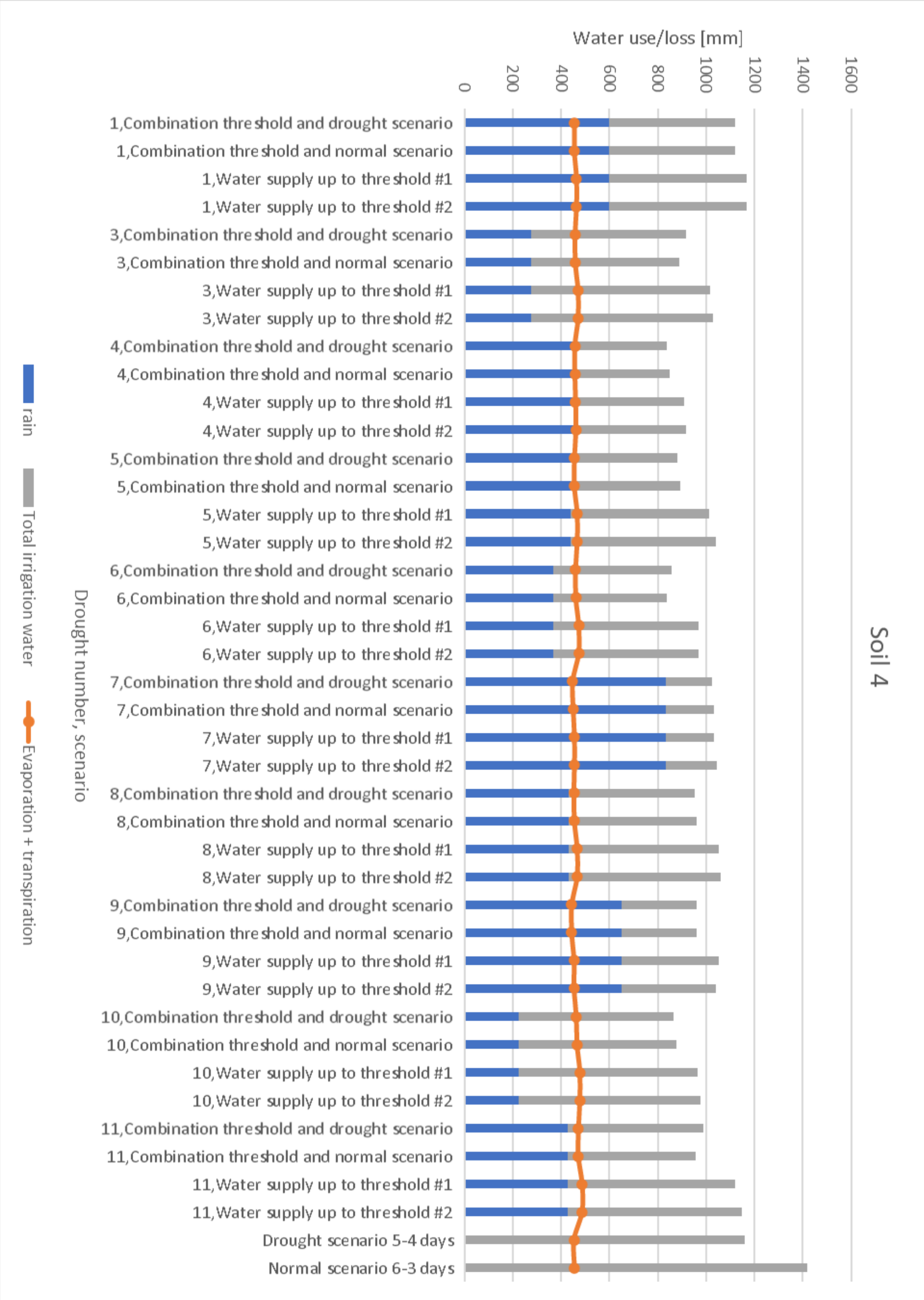
Appendix 2 – Total water use and loss rice irrigation

Coello

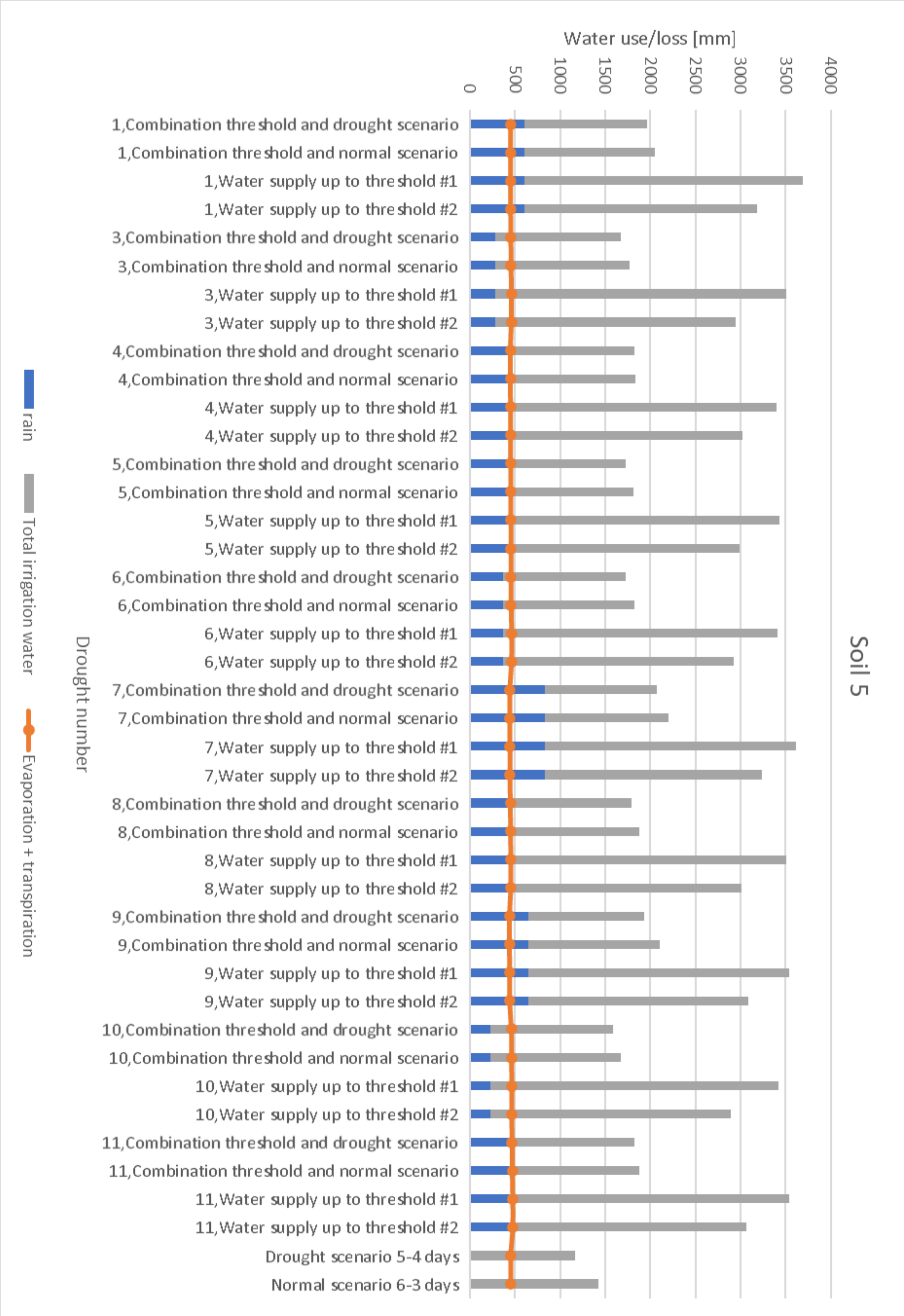
Total water use and loss soil 2



Total water use and loss soil 4

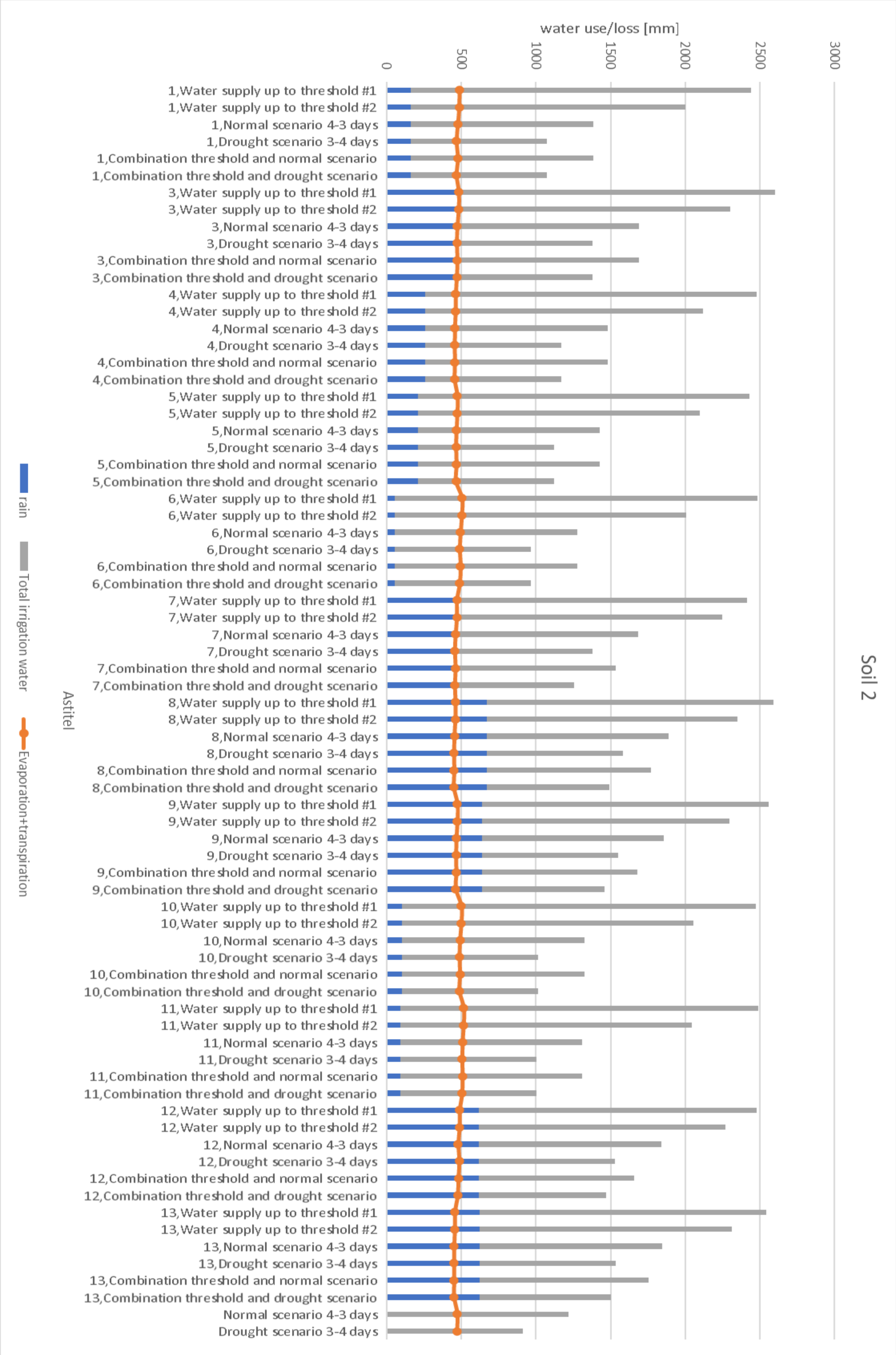


Total water use and loss soil 5

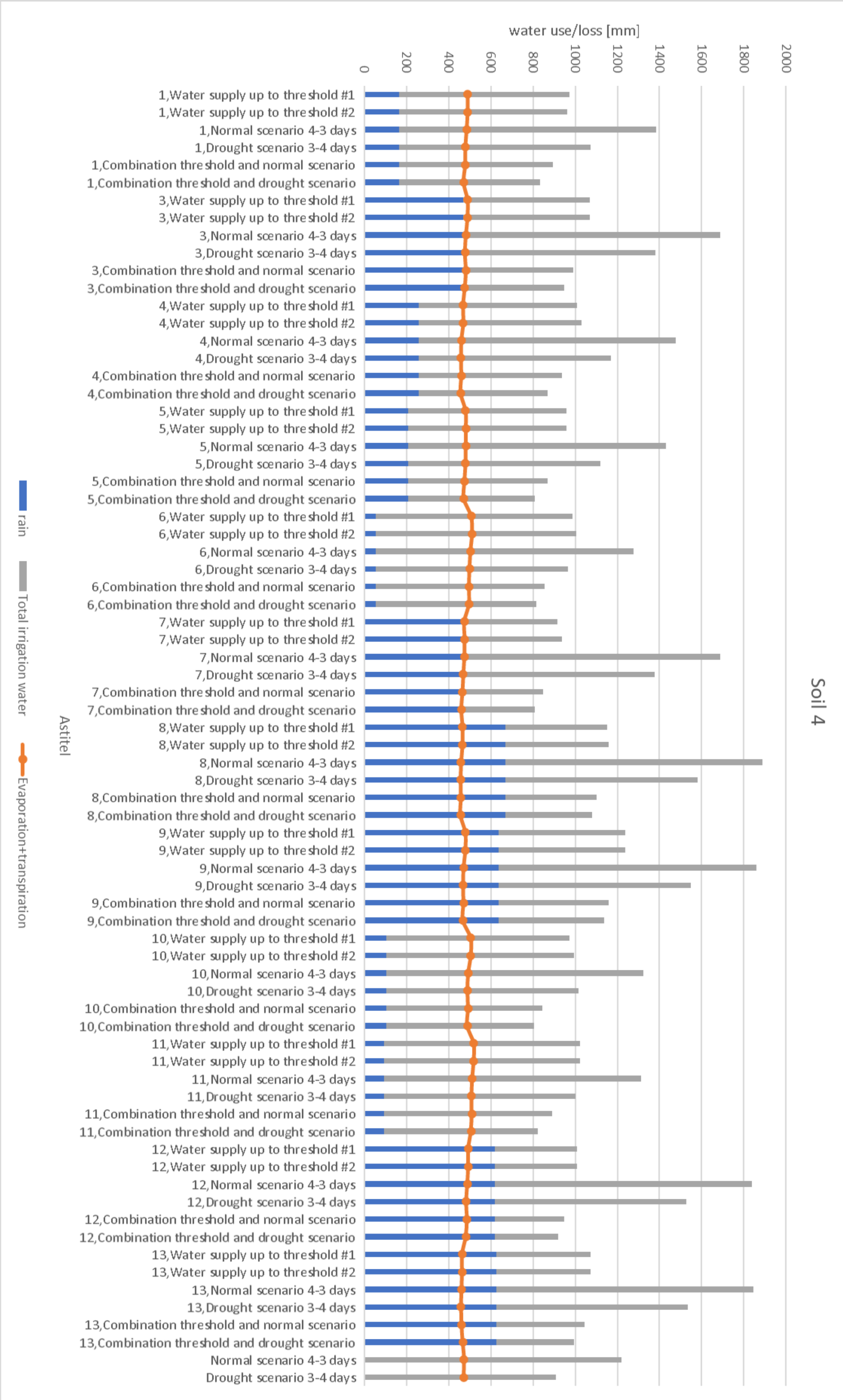


Saldaña

Total water use and loss soil 2

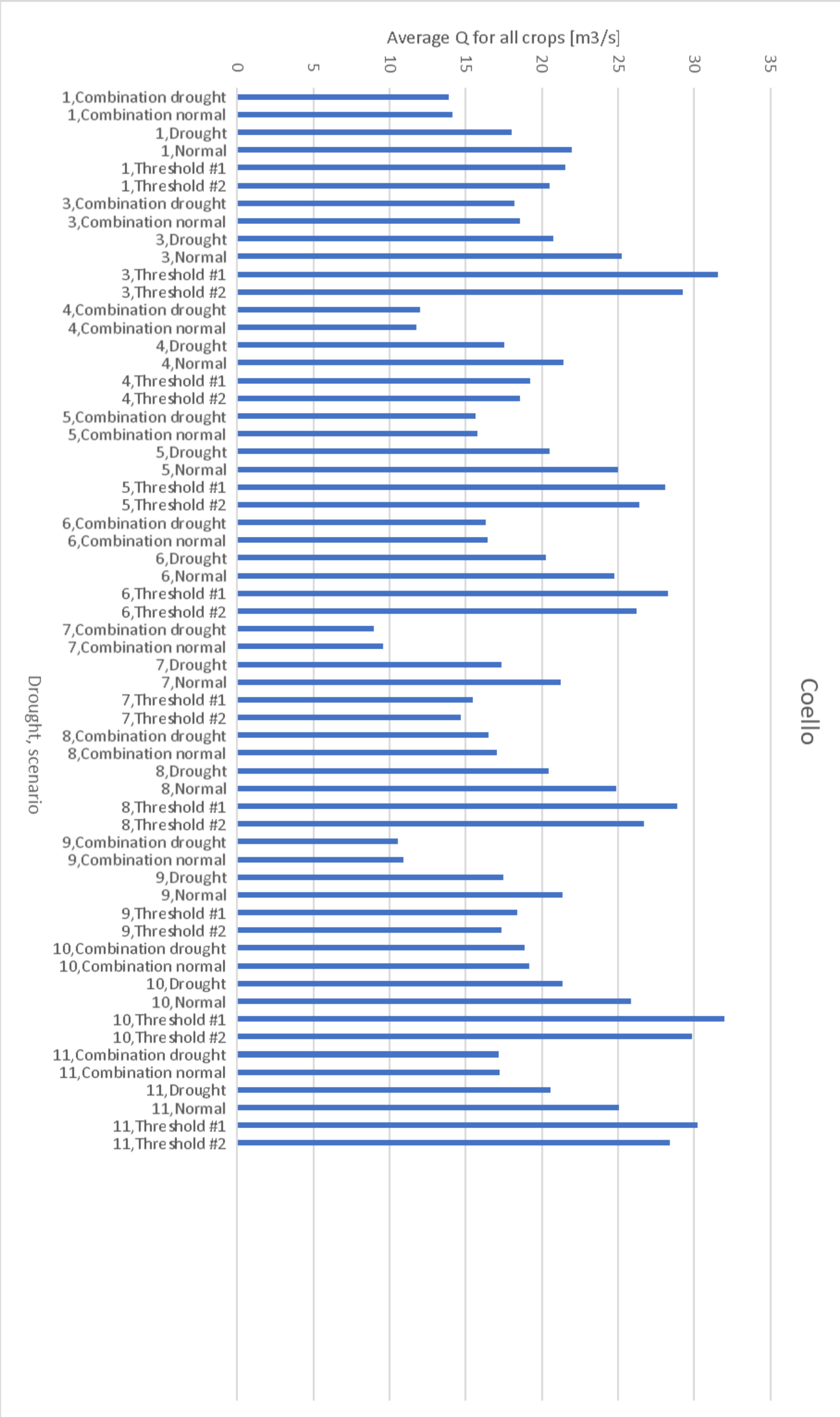


Total water use and loss soil 4



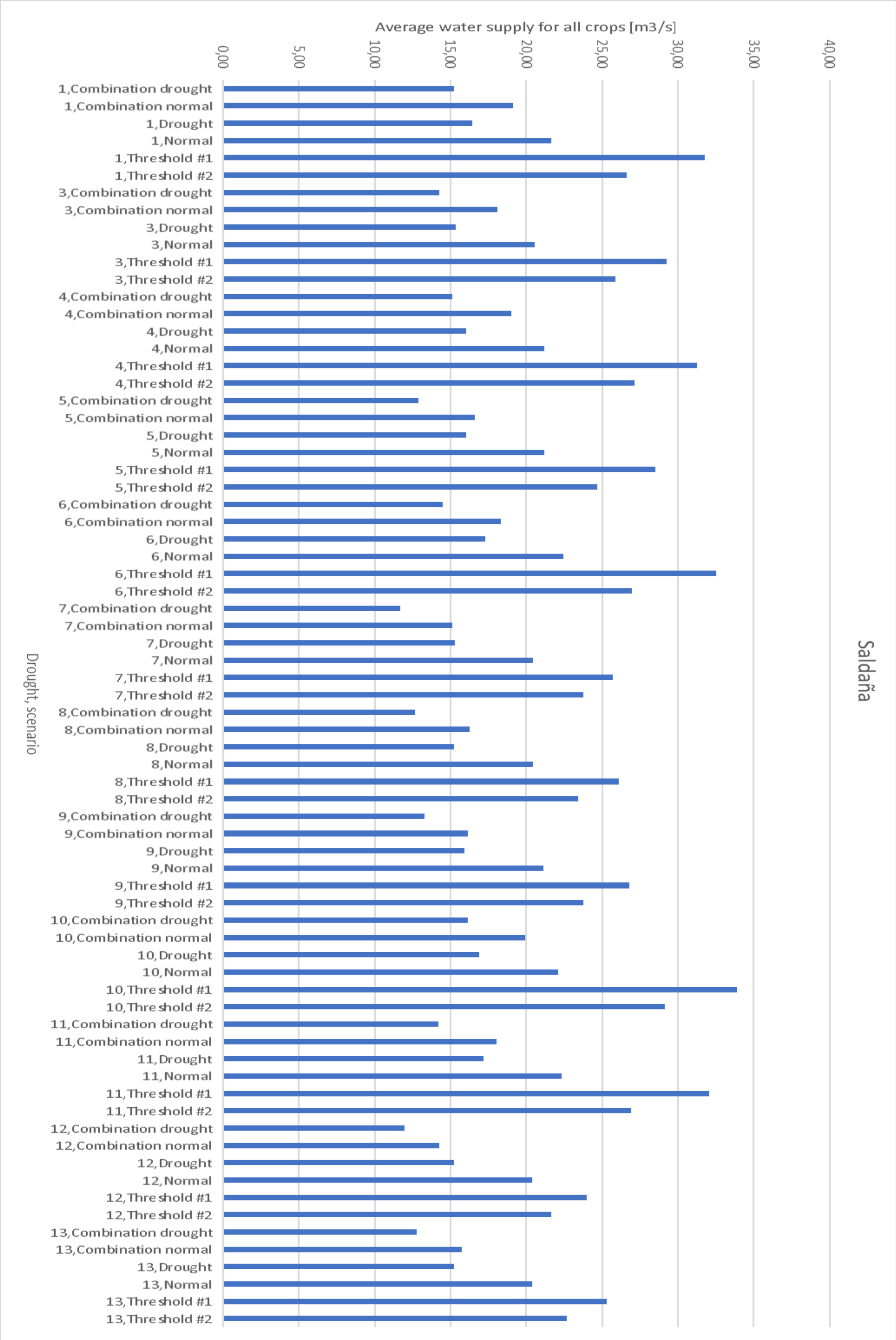
Appendix 3 – Average water supply

Coello



drought, scenario	Total water supply rice [km3]	average Q [m3/s] for all crops
1,Combination drought	0,103	13,83
1,Combination normal	0,105	14,07
1,Drought	0,135	17,97
1,Normal	0,165	21,86
1,Threshold #1	0,162	21,44
1,Threshold #2	0,154	20,46
3,Combination drought	0,135	18,10
3,Combination normal	0,138	18,49
3,Drought	0,155	20,66
3,Normal	0,190	25,13
3,Threshold #1	0,239	31,45
3,Threshold #2	0,221	29,16
4,Combination drought	0,092	11,99
4,Combination normal	0,090	11,75
4,Drought	0,135	17,53
4,Normal	0,165	21,42
4,Threshold #1	0,148	19,23
4,Threshold #2	0,143	18,56
5,Combination drought	0,117	15,56
5,Combination normal	0,118	15,70
5,Drought	0,155	20,45
5,Normal	0,190	24,91
5,Threshold #1	0,214	28,01
5,Threshold #2	0,201	26,35
6,Combination drought	0,124	16,30
6,Combination normal	0,125	16,39
6,Drought	0,155	20,24
6,Normal	0,190	24,71
6,Threshold #1	0,217	28,22
6,Threshold #2	0,201	26,15
7,Combination drought	0,070	8,96
7,Combination normal	0,074	9,55
7,Drought	0,135	17,36
7,Normal	0,165	21,25
7,Threshold #1	0,120	15,46
7,Threshold #2	0,114	14,69
8,Combination drought	0,125	16,47
8,Combination normal	0,129	16,99
8,Drought	0,155	20,37
8,Normal	0,190	24,84
8,Threshold #1	0,221	28,82
8,Threshold #2	0,204	26,64
9,Combination drought	0,081	10,51
9,Combination normal	0,084	10,91
9,Drought	0,135	17,47
9,Normal	0,165	21,36
9,Threshold #1	0,142	18,38
9,Threshold #2	0,134	17,33
10,Combination drought	0,135	18,69
10,Combination normal	0,138	19,02
10,Drought	0,155	21,24
10,Normal	0,190	25,71
10,Threshold #1	0,238	31,85
10,Threshold #2	0,221	29,73
11,Combination drought	0,129	17,11
11,Combination normal	0,129	17,13
11,Drought	0,155	20,51
11,Normal	0,190	24,98
11,Threshold #1	0,230	30,14
11,Threshold #2	0,216	28,34

Saldaña



Average water supply for all crops [m3/s]
0,00
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00
Drought, scenario
Saldaña
1,Combination drought
1,Combination normal
1,Drought
1,Normal
1,Threshold #1
1,Threshold #2
3,Combination drought
3,Combination normal
3,Drought
3,Normal
3,Threshold #1
3,Threshold #2
4,Combination drought
4,Combination normal
4,Drought
4,Normal
4,Threshold #1
4,Threshold #2
5,Combination drought
5,Combination normal
5,Drought
5,Normal
5,Threshold #1
5,Threshold #2
6,Combination drought
6,Combination normal
6,Drought
6,Normal
6,Threshold #1
6,Threshold #2
7,Combination drought
7,Combination normal
7,Drought
7,Normal
7,Threshold #1
7,Threshold #2
8,Combination drought
8,Combination normal
8,Drought
8,Normal
8,Threshold #1
8,Threshold #2
9,Combination drought
9,Combination normal
9,Drought
9,Normal
9,Threshold #1
9,Threshold #2
10,Combination drought
10,Combination normal
10,Drought
10,Normal
10,Threshold #1
10,Threshold #2
11,Combination drought
11,Combination normal
11,Drought
11,Normal
11,Threshold #1
11,Threshold #2
12,Combination drought
12,Combination normal
12,Drought
12,Normal
12,Threshold #1
12,Threshold #2
13,Combination drought
13,Combination normal
13,Drought
13,Normal
13,Threshold #1
13,Threshold #2

drought, scenario	Total water supply rice [km3]	average Q [m3/s] for all crops
1,Combination drought	0,1087	15,22
1,Combination normal	0,139	19,11
1,Drought	0,1183	16,45
1,Normal	0,1586	21,64
1,Threshold #1	0,2376	31,79
1,Threshold #2	0,1976	26,65
3,Combination drought	0,1099	14,28
3,Combination normal	0,1394	18,07
3,Drought	0,1183	15,36
3,Normal	0,1586	20,54
3,Threshold #1	0,2265	29,27
3,Threshold #2	0,2003	25,90
4,Combination drought	0,1111	15,09
4,Combination normal	0,1418	19,04
4,Drought	0,1183	16,02
4,Normal	0,1586	21,20
4,Threshold #1	0,237	31,28
4,Threshold #2	0,2046	27,12
5,Combination drought	0,0939	12,88
5,Combination normal	0,123	16,62
5,Drought	0,1183	16,02
5,Normal	0,1586	21,20
5,Threshold #1	0,2154	28,51
5,Threshold #2	0,1857	24,69
6,Combination drought	0,0967	14,51
6,Combination normal	0,1266	18,35
6,Drought	0,1183	17,28
6,Normal	0,1586	22,47
6,Threshold #1	0,2367	32,51
6,Threshold #2	0,1935	26,96
7,Combination drought	0,0903	11,67
7,Combination normal	0,1171	15,12
7,Drought	0,1183	15,27
7,Normal	0,1586	20,45
7,Threshold #1	0,1995	25,71
7,Threshold #2	0,1842	23,75
8,Combination drought	0,0982	12,66
8,Combination normal	0,1262	16,26
8,Drought	0,1183	15,24
8,Normal	0,1586	20,43
8,Threshold #1	0,2028	26,11
8,Threshold #2	0,182	23,44
9,Combination drought	0,0978	13,28
9,Combination normal	0,12	16,14
9,Drought	0,1183	15,92
9,Normal	0,1586	21,10
9,Threshold #1	0,2028	26,79
9,Threshold #2	0,1794	23,78
10,Combination drought	0,1123	16,14
10,Combination normal	0,1418	19,94
10,Drought	0,1183	16,92
10,Normal	0,1586	22,10
10,Threshold #1	0,2505	33,92
10,Threshold #2	0,2135	29,16
11,Combination drought	0,0955	14,22
11,Combination normal	0,125	18,02
11,Drought	0,1183	17,16
11,Normal	0,1586	22,34
11,Threshold #1	0,234	32,04
11,Threshold #2	0,1943	26,93
12,Combination drought	0,0929	11,96
12,Combination normal	0,1108	14,27
12,Drought	0,1183	15,23
12,Normal	0,1586	20,41
12,Threshold #1	0,1866	24,01
12,Threshold #2	0,1681	21,63
13,Combination drought	0,0992	12,76
13,Combination normal	0,1225	15,75
13,Drought	0,1183	15,21
13,Normal	0,1586	20,40
13,Threshold #1	0,1968	25,31
13,Threshold #2	0,1761	22,65