CRANFIELD UNIVERSITY

THOMAS MEDORI

MODELLING THE IMPACT OF CLIMATE CHANGE ON AVOCADOS’ FUTURE IRRIGATION REQUIREMENTS IN SOUTH AFRICA

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
Environmental Engineering

MSc
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This thesis is submitted in partial fulfilment of the requirements for the degree of Environmental Engineering MSc.

ABSTRACT

Climate change will affect worldwide weather and crop development. Agriculture is a major concern around Groot Letaba catchment (South Africa), and future irrigation supply for avocado crops is at risk but remains unclear. This research focused on the impact of climate change on future irrigation demand of avocados, with a case study in Limpopo province, South Africa. The objective was to compare water demand between the baseline data (1982-2010) and projections for 2050 and 2080 and determine the potential effect of climate change on avocados' irrigation requirements in the future. First, a weather generator was used to create 1000 future daily time-series of rainfall and temperature, following nineteen different General Climate Models, for two emissions scenarios. The outputs were used in a soil-water balance model to simulate irrigation requirements of avocados according to the different scenarios and years studied. Models' average irrigation demand was found to increase by at least 8.7% by 2050, and up to 17.4% by 2080, with a notable dispersion of values and few models predicting a decrease. The frequency of exceeding annual irrigation capacity could reach 45% with mitigation and 58% without mitigation by 2080. Farmers are expected to have more difficulties providing sufficient irrigation to avocados trees and facing possible multi-year droughts. Mitigation appeared as essential to ensure the sustainability of avocado business.

Keywords:
Groot Letaba, LARS WG, Wasim, mitigation scenarios, climate model

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GCM	General Circulation Models
RCM	Regional Climate Models
ET	Crop Evapotranspiration
RCP	Representative Concentration Pathway
CO_2	Carbon Dioxide

1 INTRODUCTION

1.1 Background

The Limpopo province is known in South Africa for agriculture. A big variety of products (fruits, vegetables, cereals…) can grow there thanks to different climates (arid, semi-arid, and humid). Limpopo is producing tropical fruits such as mangoes and avocados, because of warm subtropical conditions. The southern regions of South Africa have cooler climate not ideal for this industry.

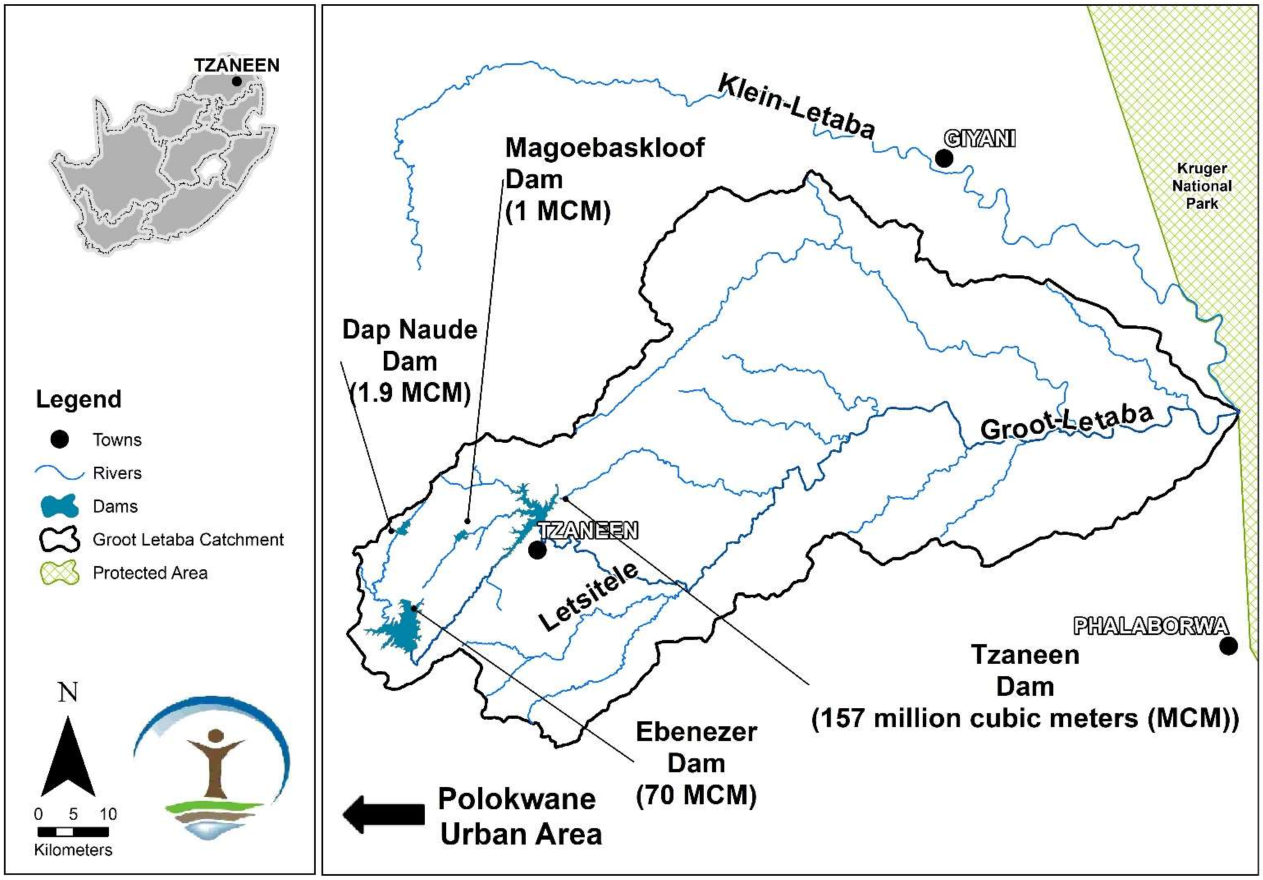

Figure 1: Map of South Africa with Limpopo (Source: INR (Pers. Com.))

Avocado has worldwide become a very popular product, especially in Europe and North America. The value of a ton of South African avocados has been multiplied by nearly 3 in the last decade as a consequence of its attractiveness (FAOSTAT, 2021).

Avocado crops, highly water-demanding (Hoffman and Du Plessis, 1999; Moreno-Ortega *et al.*, 2019; Silber *et al.*, 2019), are particularly vulnerable to irrigation changes. They can not only be rain-fed: a part from the water used by crops comes from rain, and rainfall variability affect the amount of water brought artificially by irrigation. The total water volume dedicated to agriculture is defined each year by authorities considering recharge of the Groot Letaba catchment area.

Important shortage in water can lead to diseases and death of avocados, smaller deficits can affect the number of fruits, and their size/weight (Silber *et al.*, 2019). It is a challenge to maintain high yields, while being constrained on water availability. Trees respond better to a constant regulated hydric stress than a partial water deficit on a defined period of time (Silber *et al.*, 2019).

Modification of climate is likely to have an effect on avocados. The Climate Convention established requirements for every country to realise a climate change risk assessment (IPCC, 2018). Following this guidance, multiple reports have been written by South African government to adapt to climate change consequences (DEA, 2016; DEFF, 2019). As the first effects of climate change already appeared during the last decades (drought likelihood increase and water related issues), it is a major concern for the country and national strategies are essential to face it. In addition, several studies realised general risk assessments for the country (Van Jaarsveld and Chown, 2001), suggested adaptation responses (Mwenge Kahinda, Taigbenu and Boroto, 2010; Vogel and van Zyl, 2016), others focused more deeply on climate change impact on water management (Mukheibir and Sparks, 2003), and agriculture (Gbetibouo and Hassan, 2005; Calzadilla *et al.*, 2014).

In South Africa, water scarcity due to climate change could disturb numerous sectors, and mostly water availability for people, agriculture (and by the same mean food production and security), and industry. Drought periods combined with rainfall diminution can cause multiple problems for water catchment areas, making difficult the allocation of sufficient amount of water for all human activity when water availability diminishes. The Groot Letaba catchment area in

Limpopo province is notably affected by water availability issues (Kanjere, Thaba and Lekoana, 2014).

When doing a climate change impact assessment, it is essential to consider local conditions and parameters. Studies were made in other parts of the world (Howden, Newett and Deuter, 2005) or on larger scales (Tubiello and Fischer, 2007), but their use is not recommended for a study in a specific location. It is imperative to work with models and scenarios that can be locally used for the region concerned.

Climate change scenarios have been realised for decades, with the will to predict climate evolution considering the extent of mitigation efforts worldwide (McGinnis *et al.*, 1973; Hulme *et al.*, 1999). It is not possible anymore to rely on historical data only for future climate projections, as the current and expected changes have never been seen in such proportions. Thus, developing strong models, to help understand what to expect and plan future actions, is decisive.

Nowadays, four different mitigation scenarios are generally accepted by the scientific community and form the baseline of any climate-related study. These scenarios are the RCPs (Representative Concentration Pathway) representing worldwide efforts to stabilize or not radiating forcing to sustainable rates by 2100: they range from 2.6 W/m^2 (intense mitigation) to 8.5 W/m^2 (no mitigation) (The Core Writing Team IPCC, 2015). For the best-case scenario, temperature increase in Tzaneen, Limpopo would be limited below 1.6°C by 2100 (Pearce and Hausfather, 2018). If no mitigation is planned, the average temperature rise could reach 5.5°C by 2100 there (Pearce and Hausfather, 2018).

As part of climate change, drought episodes and rainfall diminution could put in danger crop irrigation and create water deficit, as already observed over the last years (Wiid and Ziervogel, 2012). Temperature variability can modify crop development, by reducing the fruits' final size, causing an early or late maturity (Howden, Newett and Deuter, 2005), and increase crop evapotranspiration (ET), which implies bigger irrigation requirements. Rainfall diminution would increase irrigation requirements, but water allocation is already constrained. In addition, carbon dioxide rates in the atmosphere can also affect ET, as air composition has a role in water exchanges between air and crop (Kimball and Idso, 1983; Pan *et al.*, 2015).

South African agriculture is at risk with climate change (Muller *et al.*, 2011; Calzadilla *et al.*, 2014), but the impact on avocados' future water demand remains unclear. Therefore, it is important for everyone, especially farmers to understand how avocado crops and their irrigation requirements could be affected. Many farmers understood the risk, expect changes for crop irrigation, but don't know yet the scale of these changes (Wiid and Ziervogel, 2012).

Climate change impact assessments require the use of climate models as tools for the generation of future data. Climate models, also called General / Regional Circulation Models (GCMs / RCMs) are based on physics and equations to simulate interactions defining Earth's climate at large spatial and temporal scales. They are used as an interpretation of energy and matter exchanges between and inside the different layers of the planet. Each climate model interprets the RCPs to develop a range of predictions on future climate.

Using raw climate data directly from GCMs for local analysis is not encouraged because these models reflect large spatial or time scale variation, and local data generated would rely on a lot of assumptions, that are unclear and not always defined or explained to the user, limiting the results. It is advised to extract large-scale data, with high reliability, and then treat the data with adapted techniques (Trzaska and Schnarr, 2014). Dynamic and statistical downscaling are two different ways to realise this: these techniques increase precision and reduce uncertainty. They enable to obtain a better resolution than the GCMs for which "the spatial scale can't be finer than 100km*100km" (Trzaska and Schnarr, 2014).

Both methods require reliable GCMs simulations and data. Dynamic downscaling is often used for regional or national applications, which is not the case in this study. Even though it is a very precise technique, dynamic downscaling requires significant resources (computing, data) and a high level of expertise and is not implementable at this level. Statistical downscaling appears as a more adapted method for local climate modelling, as it is easy to do, it requires medium to low data amount and can be used at very local scales (further comparison in Table A-1 of Appendix A).

3 main statistical downscaling solutions exist: linear methods, weather classification, and weather generators. Linear methods such as the change factor are interesting when a proportionality relationship can be established between past and future data but is not usable when it comes to non-normally distributed variables such as daily rainfall. The second one, weather classification, can deal with normally and non-normally distributed data. Nevertheless, it requires a better computation capacity and big data amount and is not able to predict new values outside of the historical data intervals. The last one, the weather generator, can provide large numbers of daily time-series (which helps reducing uncertainty), with a decent amount of data, for every type of variable. The main disadvantage is the sensitivity to inaccurate historical data.

1.2 Area of study

This study focuses on a commercial avocado farm in Tzaneen, Limpopo, South Africa (23° 45’ 15’’ S, 30° 07’ 43’’ E). Limpopo province is the leading avocado producer in the country, accounting for 58% of the national business (The South African Avocado Growers’ Association, 2020).

The focus is made on the Hass variety of avocado, as it is the predominant one (80% of the area planted among avocado varieties).

The avocado business in Limpopo relies partly on the Groot Letaba catchment area, providing water for irrigation. This catchment area suffered from hydric stress during the last few years, and as a consequence, could not entirely supply all water demanding human activities, as avocado growth. Recently, river dams in South Africa experienced all-time lows, the likelihood of dry years has increased (Mahlalela *et al.*, 2020), and climate change is expected to amplify drought risk and hydric stress on agriculture (Pascale *et al.*, 2020).

1.3 Aim and Objectives

The aim of this thesis is to assess the impact of climate change on avocados' future irrigation demand in the Groot Letaba catchment following 2 major predictive scenarios, in order to inform adaptation strategies.

The different objectives are:

1. To generate the possible scenarios for the future climate in the Groot Letaba catchment, especially rainfall and temperature.
2. To model the current and future irrigation water demand of avocados in the Groot Letaba catchment for all scenarios studied.
3. To establish a probabilistic model of future irrigation water demand of avocados.

2 METHODOLOGY

Figure 2 summarizes the methodology of this study.

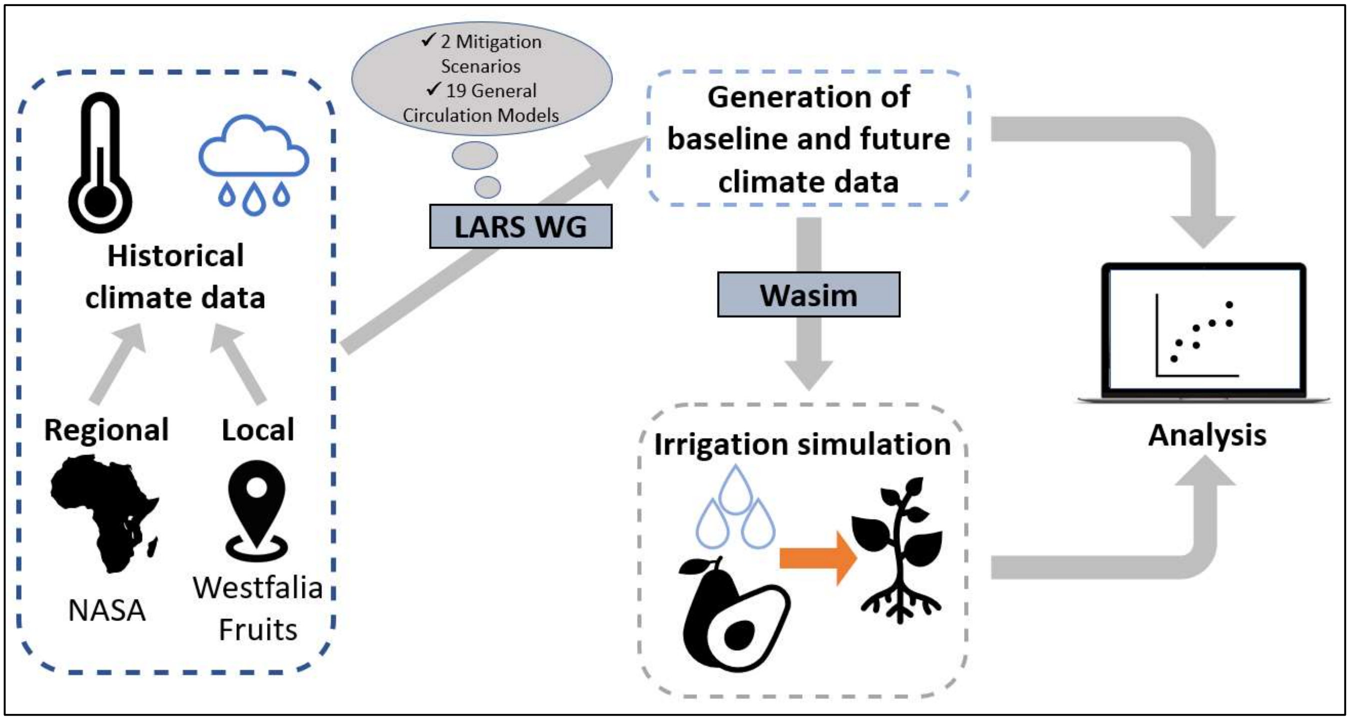

Figure 2: Diagram summarizing the methodology chosen and its different steps

2.1 Climate data

2.1.1 Production of a baseline climate dataset

The first step was to obtain a baseline climate set of data, as historical daily weather information (rainfall, minimum and maximum temperature) was required as input in the modelling part (between 20 and 30 years of data for calibration). The primary data source was Westfalia Fruits: one of the biggest South-African avocado producing companies located in Tzaneen, contributing information on crops, irrigation techniques, and local climate. Westfalia Fruits has provided monthly rainfall data in Tzaneen since 1978. As daily datasets are required, the NASA database was used to complete it (LaRC Power Project, 2021). It provided daily historical information on rainfall, minimum and maximum temperature since 1982. The Groot Letaba region has a strong rainfall gradient. Annual rainfall values can go from 200mm to 1400mm between the low and high-altitude sites. NASA rainfall information is average values of a grid-cell (0.5° latitude by 0.5° longitude), and can't guarantee high precision, but it is possible to know the monthly average difference from Tzaneen thanks to Westfalia Fruits.

The annual rainfall distribution provided by NASA was combined with monthly rainfall values given by Westfalia Fruits to generate daily time-series of rainfall from 01/01/1982 to 31/12/2010 (29 years), to have enough historical data as input for the modelling part. This step was not necessary for minimum and maximum temperature, as temperature gradient is less important than the rainfall one within a grid-cell, and temperature data from NASA can be used.

2.1.2 Use of LARS WG to generate baseline climate datasets

In this study, a weather generator was chosen for several reasons. First, the mix of local (Westfalia Fruits) and global (NASA) data sources increases the confidence in data quality. Then, as explained in section **1.1**, among statistical downscaling methods, linear ones are not adapted to non-linear variables such as rainfall, and a weather classification is not capable of predicting values out of the historical range, limiting its relevance regarding climate change. A weather generator is able to generate a large amount of daily time-series, required in this study. The purpose is to generate a thousand years of daily time-series of rainfall, minimum and maximum temperature, as it is necessary for the second modelling part (section **2.2**).

The stochastic weather generator chosen here is Long Ashton Research Station Weather Generator (LARS WG) (SEMENOV and BARROW, 1997). LARS WG uses climate models and historical data to simulate multiple single-year time series of local daily weather representing 20-year periods, from 2011-2030 to 2081-2100.

LARS WG has been widely used to obtain time series of rainfall and temperature (Chen *et al.*, 2013; Hassan, Shamsudin and Harun, 2014; Sha, Li and Wang, 2019), because it can work with as little as a single year of historical data. 20 to 30-year record data is still advised to better calibrate LARS WG, and for this study, the baseline was 1982-2010.

Before any result generation, LARS WG realised a calibration by performing a site analysis of the data record given as input. Then, to ensure that the differences observed between the results are only due to climate change, a thousand years of time-series of baseline data were generated and considered as the baseline for the results. The baseline data was used on the one hand, for comparison with generated future climate data and on the other hand, as input for the second modelling part. It was important to work only with LARS WG outputs, to give more confidence on the hypothesis that the evolutions observed are due to climate change and not a systematic software error. It relied on the hypothesis that the systematic error due to LARS WG is the same for historical and future data.

2.1.3 Analysis of LARS WG performances

Then, LARS WG realised statistical analysis of generated rainfall, minimum and maximum temperature historical data. For each of them, observed and LARS WG generated monthly means were compared, with 2 statistical tests: the t-test (to show any significant difference between mean values) and the f-test (differences in standard deviation). Each test result was given with an associated p-value, “the probability that the observed and synthetic mean values are derived from the same population” (Semenov and Barrow, 2002). P-values would then validate or not the hypothesis that LARS WG generated historical data reflects the observed historical data. To be significant, p-values have to be above 0.05 according to Semenov and Barrow (2002).

It is important to notice here that LARS WG is not a predictive tool, but a way to produce daily time-series likely to happen in the future.

2.1.4 Future climate: years, RCPs and models

19 General Circulation Models, from the CMIP5 ensemble of the IPCC Fifth Assessment Report (2018), are included in LARS WG, helping models uncertainty management, and work for multiple RCP scenarios (2.6 to 8.5) (list

of models in Table B-1 of Appendix B). All models cover RCP 4.5 and 8.5, only 6 of them for RCP 2.6, and none for RCP 6.5. In addition, it would not have been relevant to focus on the four of them, because of the uncertainty existing on each model. For example, the uncertainty on RCP 6.5 overlaps both RCPs 4.5 and 8.5. The choice was made to focus on RCPs 4.5 and 8.5, with a thousand years of simulated weather per model and per RCP.

Two years were chosen: 2050 (period 2041-2060), which corresponds to the middle of the century and is often used in climate change projections, and 2080 (period 2071-2090), which is close to the end of the century.

In addition to the baseline, the four scenarios mentioned in the results are:

- Scenario n°1: RCP 4.5, by 2050
- Scenario n°2: RCP 8.5, by 2050
- Scenario n°3: RCP 4.5, by 2080
- Scenario n°4: RCP 8.5, by 2080

2.1.5 Generation of future climate datasets and analysis

For the 19 models and the two RCPs chosen, a thousand years of daily time-series of rainfall, minimum and maximum temperatures were generated using LARS WG. This data was used as an input for the second modelling part (section **112.2**). LARS WG outputs were also analysed using a python code, to summarize weather information (rainfall and temperature) from LARS WG, for future and LARS WG-generated historical data. The python files results were then interpreted to observe trends and magnitude of changes and distribution of extreme values.

The first analysis was a general comparison between future and historical weather conditions, realised looking at the average rainfall and temperature differences between each model and baseline, for all four scenarios. The averages for baseline and each model were made on the 1000 years of simulated climate.

In a second time, precipitation distribution per trimester was studied, to highlight any modification in rainfall dispersion throughout the year, in addition to the focus on the average values before.

The third part focused on dry years. Dry year occurrences are critical because they require careful management and bigger irrigation supply, and water availability can become a problem. In this study, a year was considered dry if its precipitation amount was below the 20th percentile of baseline rainfall. The objective was to calculate the frequency of dry years expected in the future according to the four scenarios, doing an average with each model's dry years frequency (19 values, one per model).

2.2 Wasim model

According to Hess and Counsell, (2000), Wasim model is a "one-dimensional daily soil water balance model", able to replicate modifications between soil layers. It was used in previous studies for its capacity to model groundwater table (Hirekhan, Gupta and Mishra, 2007), roots interactions with soil (Uprety *et al.*, 2019) and soil water recharge (Holman, Tascone and Hess, 2009). It helps multi-years planning.

Wasim was used in this study to simulate net irrigation requirements for baseline and the 19 models for the four scenarios. The objective was to compare results of future scenarios to the baseline 1982-2010 following the same irrigation scheme. Irrigation requirements are likely to be affected by external variables such as temperature, ET and rainfall, and water management made by farmers.

2.2.1 Parameterisation of Wasim

2.2.1.1 Soil and crop parameterisation

Wasim was not by default parameterised for avocado. Parameterisation was realised using data from Westfalia and external sources. It was assumed that soil, cultivar, and crop management remained the same for all the simulations. Table 1 summarises all the values chosen for Wasim parameterisation.

Table 1: Parameterisation of Wasim

Variable	Value(s) chosen	Comments
Soil type	Clay Loam	The soil type of Westfalia Fruits' farms
Curve Number	82	(USACE Hydrologic Engineering Center, 2021) Value corresponding to agricultural lands in a fair hydrologic condition, for clay soil
Depth of soil	6m	With Wasim, the depth of soil is not important if the value is bigger than max root depth, it is only useful for Wasim salinity modules.
Hydraulic conductivity	0.2 m/d	Default value for clay loam soil
Planting date	Jan 1st	The crop calendar was not realised considering the fruit, but the avocado tree, which is here all year long.
Emergence date	Jan 1st	
20% cover	Jan 1st	
Full cover	Jan 1st	
Maturity	Dec 31st	
Harvest	Dec 31st	
Max root depth	Jan 1st	
Max cover (%)	100%	
Mulch cover (%)	0%	
Reference evapotranspiration ET_0	Equation 1	
Crop evapotranspiration ET	$ET = ET_0 * Kc$	Seasonal values of Kc (crop factor) from Mazhawu *et al.* (2018)

Crop coefficient at full cover (%)	100%	
Max root depth	3m	
Planting depth	0.1m	
Max ponding depth (cm)	0	No ponding happening.

Equation 1: Calculation of daily reference evapotranspiration

$$ET0 = 0.0135 * Krs * (Tmax - Tmin)^{0.5} * (Tmax - Tmin + 17.8) * \frac{Ra}{\lambda}$$

With K_{rs} = 0.17 $°C^{-0.5}$ and λ = 2.45 M.J/kg (Paredes *et al.*, 2020); T_{max} and T_{min} from LARS WG outputs; Ra from Allen, R. G., Pereira, L. S., Raes, D. and Smith (1998)

2.2.1.2 Irrigation scheduling

Irrigation was realised at fixed depletion (50% of Total Available Moisture), with a fixed amount of 10mm. According to Allen, R. G. *et al.*, (1998), the depletion fraction (i.e. the fraction of water deficit a crop can allow without any impact on its growth) for avocados is 70%, nevertheless, it was safer to set the depletion fraction at 50% to avoid any water lack. The fixed amount was set to favour regular irrigation of small quantities rather than big quantities at one time, and this for two reasons. First, it matched the irrigation systems and it is easier for farmers to provide small water volumes to the entire orchard at the same time. Second, if precipitations occurred the following days, rainfall water was lost as big volumes of water were already brought the days before. Small quantities help reducing water depletion and optimise rainfall use.

2.2.2 Simulation of irrigation requirements for baseline and climate change scenarios, and analysis

Once Wasim was parameterised, irrigation simulation was performed for generated historical data and all models for the four future scenarios.

A python code was also used to summarise irrigation results from Wasim outputs, for future and baseline data.

The first results were a comparison of the evolution between baseline and the four scenarios on annual irrigation average (trends and magnitude). For each scenario, the irrigation average was calculated considering the 19 models and their 1000 instances each, and model uncertainty is given as a 95% confidence interval on the average values of the 19 models. Then, a further analysis was made looking at the trimestral distribution of irrigation (calculated with the monthly averages of the 19 models).

Finally, the likelihood of years exceeding design irrigation was studied in more depth. The frequency of ‘design years’ is an indicator representing the probability that irrigation demand in any year exceeds the design value of irrigation systems. Irrigation systems are often designed for a 20% probability of exceedance (Knox *et al.*, 2010), meaning that in 1 year in 5, farmers won’t be able to fully supply irrigation demand. This analysis was realised focusing on the expected frequency of exceeding design value for the four future scenarios. Box diagrams were chosen to represent models’ uncertainty and variability, and include the value of the variable studied of each model.

3 RESULTS

3.1 Analysis of LARS WG generated historical and future climate datasets

3.1.1 P-values of t-test and f-test realised on LARS WG generated baseline climate data

Table 2 compiles results of the t-tests and f-tests performed on the three output variables from LARS WG calibration: rainfall, minimum and maximum temperature. The green boxes are values greater than 0.05 (successful test), the red boxes are values below 0.05 (unsuccessful test).

Table 2: P-values of t-test and f-test, for rainfall, minimum and maximum temperature of LARS WG generated baseline climate

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Rain	t-test	0.448	0.780	0.867	0.981	0.623	0.195	0.567	0.277	0.296	0.802	0.508	0.924
	f-test	0.000	0.000	0.058	0.000	0.211	0.423	0.745	0.029	0.542	0.942	0.004	0.005
Min Temp	t-test	0.911	0.046	0.876	0.538	0.279	0.164	0.633	0.917	0.046	0.853	0.446	0.786
	f-test	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Max Temp	t-test	0.748	0.875	0.613	0.825	0.813	0.327	0.959	0.474	0.180	0.133	0.843	0.422
	f-test	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.006	0.540	0.044	0.077	0.000

For nearly all t-tests on rainfall and maximum temperature and 10/12 for minimum temperature, p-values are above 0.05, suggesting that LARS WG reflects well average values of the variables. Nevertheless, it is important to notice that it is not proof, but only a statistical tool.

For rainfall f-tests, 7/12 results are greater than 0.05. Respectively 12/12 and 10/12 of the f-tests p-values are below the limit for minimum and maximum temperatures. LARS WG-generated historical data is not a completely accurate representation of the real historical data.

The results imply that the average values of the variables are likely to be correctly represented, but the statistical distributions are expected not to be the same.

3.1.2 Weather conditions in the future

Figure 3 combines four graphs, one per scenario. Each graph shows, for the scenario considered, annual average rainfall difference from baseline in percentage (horizontal axis) and annual average temperature difference from baseline in Celsius degrees (vertical axis) for each model. The pink cross is the average of all models.

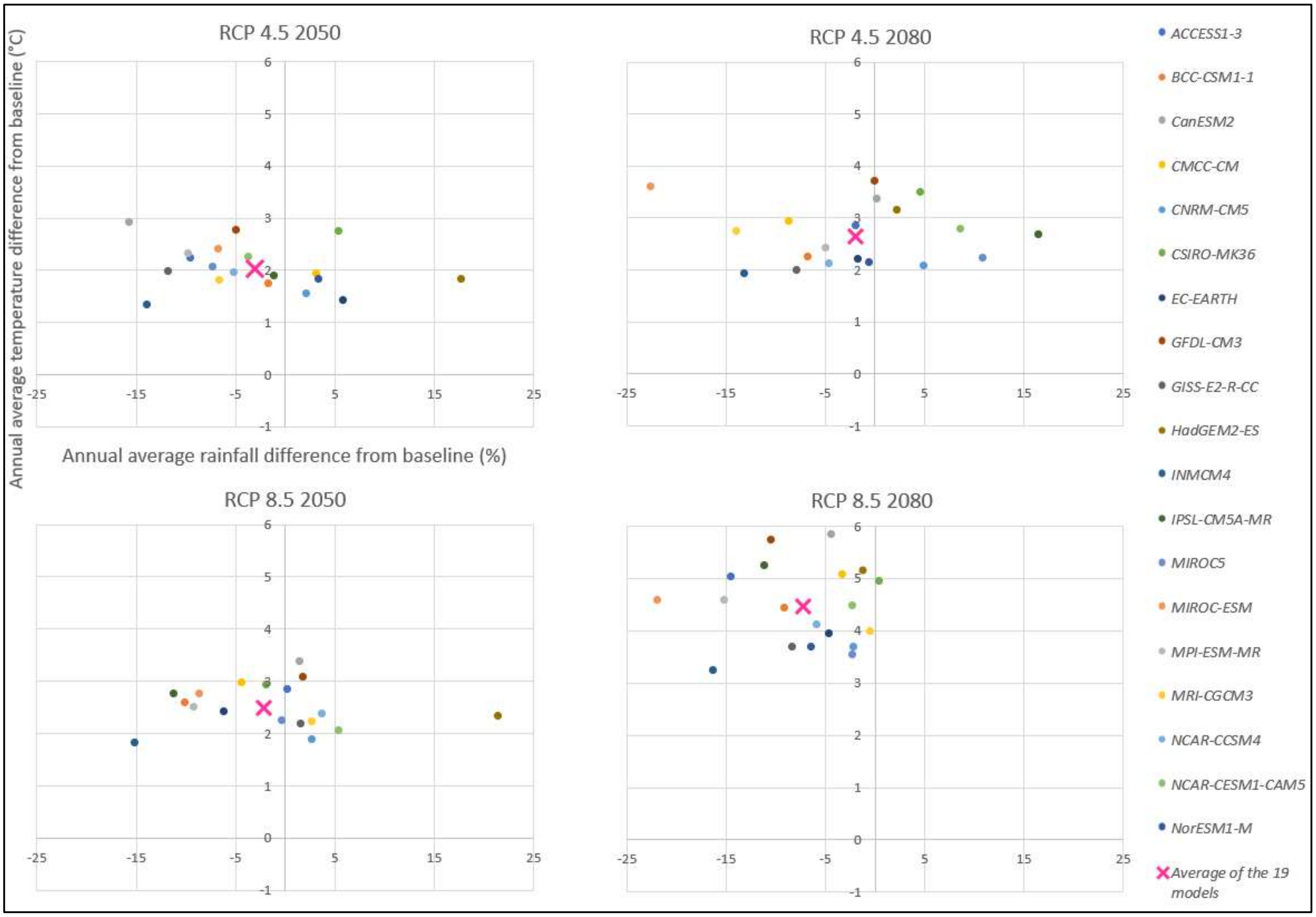

Figure 3: Annual average temperature (°C) and rainfall (%) differences between LARS WG generated baseline data and each model, for the four future scenarios

Temperature :

There is a notable trend in temperature evolution: all models for all RCPs expect an increase of at least 1.3°C. The magnitude of changes intensifies over time and from RCP 4.5 to 8.5, with the fourth scenario anticipating a temperature increase higher than 5°C for 6 out of 19 models. This is the only one projecting more than 4°C difference with baseline in average.

Rainfall :

Rainfall evolution is unclear: there is an important disparity in the values obtained according to the models. A clear tendency is noticeable for RCP 8.5 with nearly all the annual precipitation values decreasing compared to baseline

(18/19 models). By 2080, for both RCPs, some models predict more than 20% diminution compare to the historical value. The situation of RCP 4.5 is globally uncertain: for 2050 and 2080, the models are well spread around the vertical axis, without a perceptible trend. For all 4 scenarios, the average precipitation amount decreases.

For Figures 4 and 6, the year is divided into four trimesters according to the calendar. Figure 4 represents the evolution of average annual precipitation distribution by trimester, considering the averages of all instances of the 19 models for each scenario.

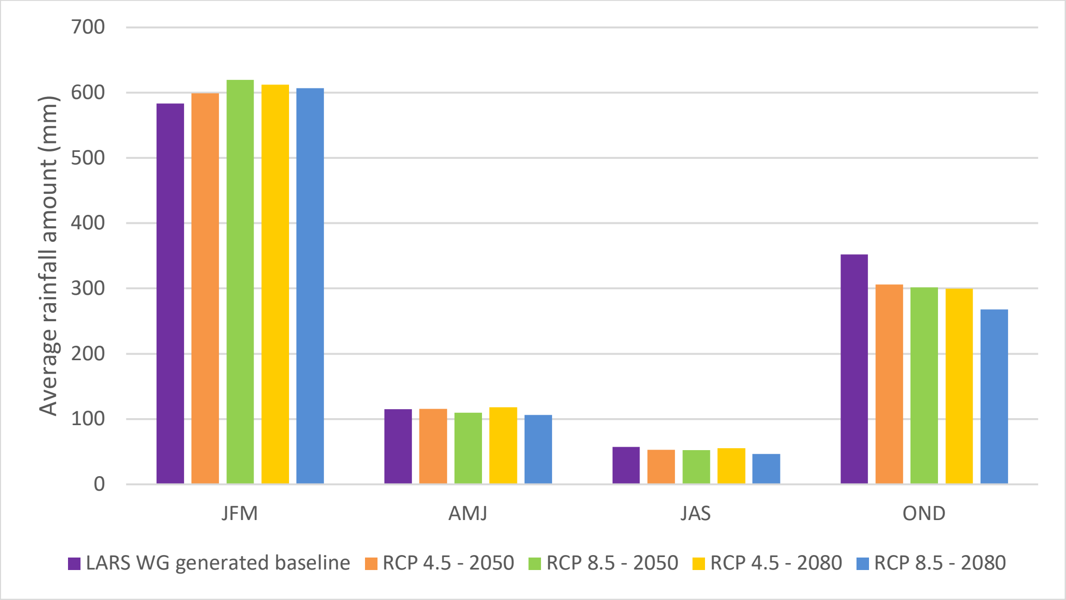

Figure 4: Comparison of average precipitations (mm) per trimester demand between LARS WG generated baseline data and the four future scenarios

There are two different trends in evolution. The first one is a small precipitation rise (between 19 to 36mm according to the scenario) for the four scenarios during the first trimester, in comparison to baseline. These increases happen during a wet period of the year, so are less notable. On the opposite, during the last trimester, there is a marked decrease for all four scenarios compared to baseline: at least 46mm for scenario n°1, up to 84 mm for scenario n°4. It occurs at the beginning of the wet season in South Africa, when rainfall is not as heavy as during the first trimester, so the evolution is more visible.

3.1.3 Extreme years likelihood evolution

For Figures 5,7 and 8, box diagrams are realised using 19 values: each model average of the variable studied, calculated with its thousand instances. The middle line corresponds to the median of the 19 models and the cross is their average value. The top and bottom of the box are respectively the 25th and 75th percentiles, and the top and bottom lines are the extreme values. The values out of the boxes are outliers points according to Microsoft Excel. Future scenarios' uncertainty is due to statistical distribution between the 19 models.

Figure 5 is a box diagram showing the frequency of dry years for baseline and the four future scenarios. A dry year has an annual rainfall below the 20th percentile of LARS WG generated baseline rainfall (cf section **2.1.5**).

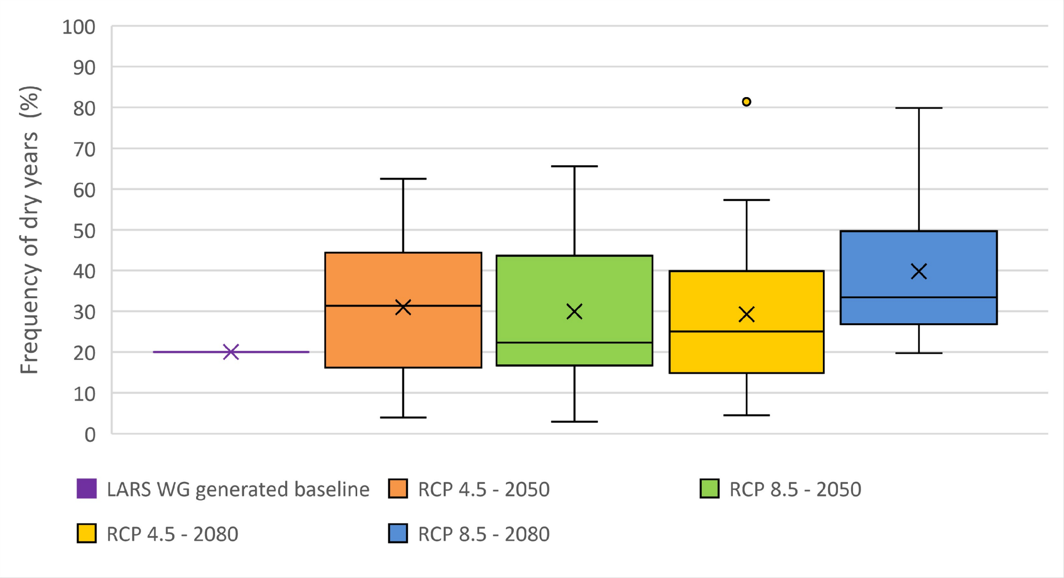

Figure 5: Frequency of dry years for LARS WG generated baseline data and the four future scenarios

The frequency of dry years is predicted to be respectively 31% and 29% by 2050 and 2080 with RCP 4.5. For RCP 8.5, the likelihoods are 30% by 2050 and 40% by 2080. Some models anticipate up to 80% of dry years by 2080, in the case of RCP 8.5.

3.2 Irrigation requirements evolution

3.2.1 Irrigation evolution in average

Table 3 shows the absolute and relative difference between baseline and the future scenarios regarding future annual irrigation averages, with a 95% confidence interval corresponding to models' variability.

Table 3: Average annual irrigation requirements and 95% confidence interval for baseline and the four scenarios

Scenario	Baseline	2050		2080	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Annual average irrigation demand (mm)	518 mm	570 ± 26 mm	563 ± 27 mm	574 ± 33 mm	608 ± 21 mm
Average difference from baseline (%)	/	+ 10.1%	+ 8.7 %	+ 10.8%	+ 17.4%

The four future scenarios expect on average an increase in irrigation demand compared to baseline, but in case of RCP 8.5, models suggest a big difference between 2050 and 2080 (from 563mm to 608mm), whereas it is stable after these 30 years for RCP 4.5. The results per model are summarised in Table C-1 and C-2 in Appendix C. The uncertainty highlights a significant dispersion of values, but even with a large statistical distribution, in all situations, the lower end of the confidence interval is greater than the baseline value.

3.2.2 Irrigation distribution evolution

Figure 6 represents the evolution of average irrigation distribution by trimester, calculated realising the average of all instances of the 19 models.

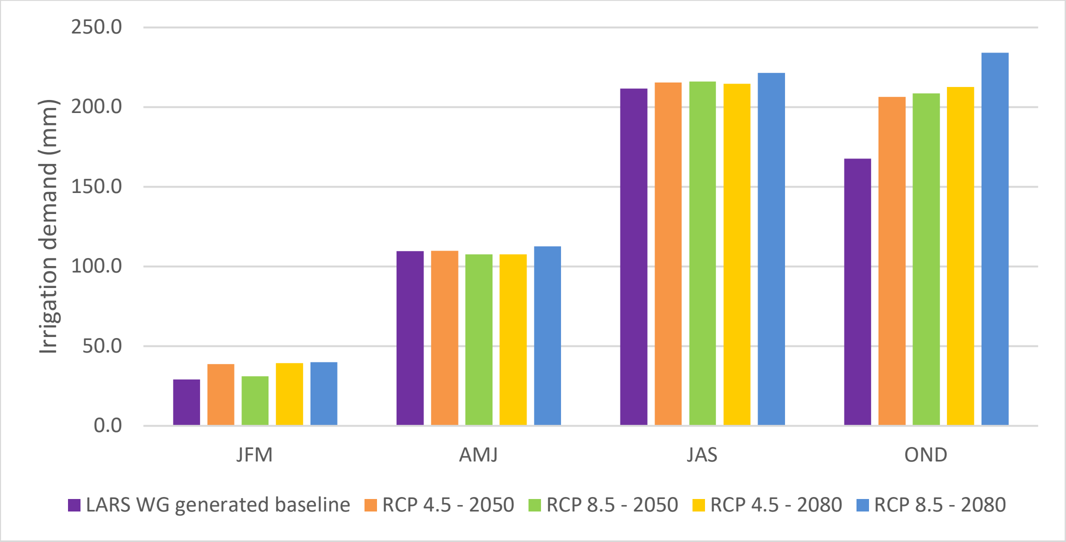

Figure 6: Comparison of average irrigation demand (mm) per trimester between LARS WG generated baseline data and the four future scenarios

The main difference in irrigation distribution is occurring during the last trimester: irrigation difference from baseline is respectively 39mm, 41mm, 45mm, and 66mm for scenarios n°1 to 4. During the other part of the year, average irrigation demand remains close to baseline for the first three scenarios. It is with RCP 8.5 by 2080 that the irrigation difference is the most visible throughout the year.

As seen in Table 3, for all four scenarios, average irrigation is increasing, from 8.7% to 17.4% compared to baseline. Even if annual average precipitation is not changing significantly from baseline in case of scenarios n°1 to 3 (between -2% and -3.1%), and decreasing more notably for scenario n°4 (-7.3%), the main difference is its annual distribution: it is evolving and rainfall is spread differently throughout the year (Figure 4). The small precipitation augmentation observed during the first three months of the year for all four scenarios (between +2.7% and +6.2% compared to baseline) occurs during a wet period when artificial irrigation demand is very low and trees are mainly rainfed. But even with a small precipitation rise, the irrigation is not diminishing: this is probably due to temperature rise causing higher ET, not compensated by slightly more precipitation. On the opposite, the average precipitation diminution during the last trimester of the year coincides with irrigation demand increasing at the same period of the year. During this trimester, rainfall diminution from baseline for the four scenarios is bigger and occurs simultaneously with a period of the year when significant irrigation is required for avocado trees. In the end, the rainfall increase at the beginning of the year does not balance the precipitation diminution during October-November-December in terms of water requirements for the avocado trees, and in total, average irrigation increases for all 4 scenarios.

3.2.3 Design years irrigation

Figure 7 compares the 80th percentile value of annual irrigation demand for the 5 cases studied.

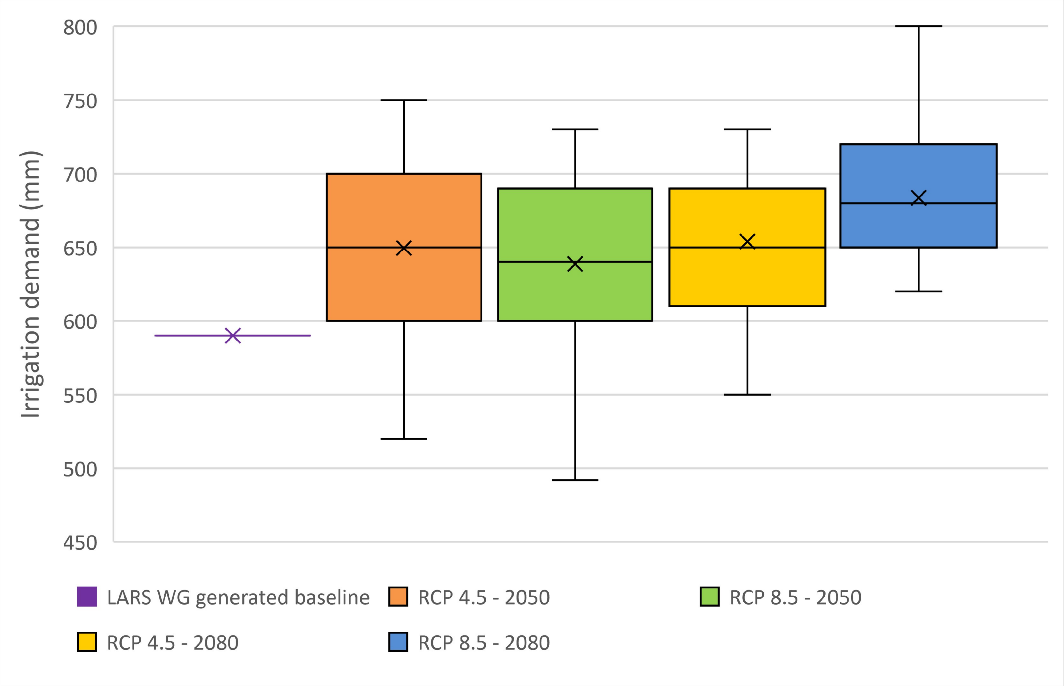

Figure 7: Box diagram of the 80th percentile of average annual irrigation demand (mm), for baseline and the four future scenarios

In all situations, average irrigation requirements for the 80th percentile is expected to rise, of at least 49mm by 2050 and up to 194 mm annually by 2080. As for rainfall, some models anticipate an irrigation diminution, but the general trend is an increase, and all models converge to this conclusion for RCP 8.5 by 2080.

Figure 8 displays the average expected frequency of design years, for baseline and the four scenarios.

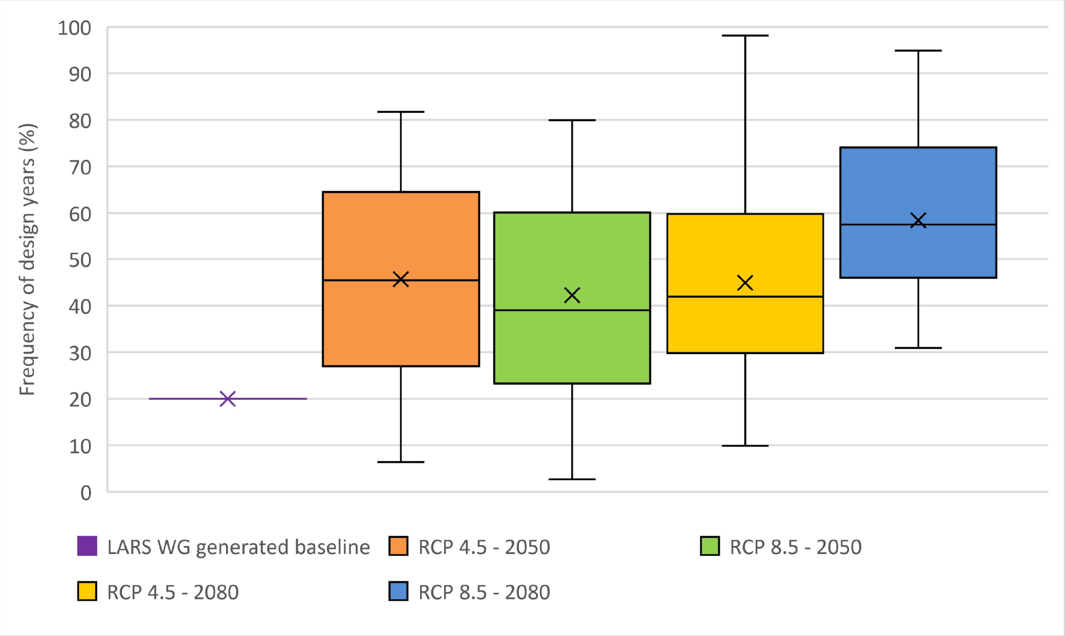

Figure 8: Frequency of exceeding design irrigation value, for baseline and the four future scenarios

Figure 8 shows that the frequency of design years is on average decreasing for all scenarios. For the first three future scenarios, the majority of models predict a rise (16 out of 19 models for each of them) in comparison to baseline, and for scenario n°4, none of them suggest a diminution. For baseline, 590mm of water was enough in 80% of the cases to ensure proper irrigation all along the year. The same 590mm are predicted to be able to supply respectively 54%, 58%, 55%, and 42% of the situations for scenarios n°1 to 4. Design years are likely to happen more often and the resilience of farmers will be challenged, as design years could happen in a row and impact the avocado business on a medium to long term basis. A future average year is likely to be close to a current design year regarding irrigation requirements, and current irrigation designs would not fit in nearly 1 year out of 2 on average.

4 DISCUSSION

4.1 Implications of the results

4.1.1 Comparison of the average irrigation results with similar studies

In this study, the annual average rainfall is found to be respectively 1108mm, 1074mm, 1084mm, 1086mm, and 1028mm for baseline and scenarios 1 to 4. The four future scenarios predict in average an increase in net annual irrigation demand compared to baseline (518mm): respectively 570, 563, 574 and 608mm are expected for scenarios 1 to 4.

Hoffman and Du Plessis (1999) previously studied Hass avocados' water requirements and hydric stress effect on fruit development in South Africa. Assuming that micro-sprinkler irrigation is 80% efficient, they found an annual average net irrigation demand of 712mm, notably greater than all the results mentioned above. The differences from the values obtained in this study can be explained by the gap between the average precipitations of the 2 studies. Hoffman and Du Plessis measured 961mm of annual rainfall, significantly lower than the amounts obtained in this study. Lower rainfall implies more irrigation, and the irrigation difference between the studies (between 104mm and 194mm) is of the same range of values as the rainfall gap (between 66mm and 147mm).

In Chile, Holzapfel *et al. (*2017) also focused on avocados and obtained an average of 667mm of net irrigation demand. There is a big rainfall gap between the two studies: at least 417mm and up to 498mm more in simulations in South Africa than the observations in Chile. But at the same time, the gap between irrigation demand is not that distinct: between 2 and 98mm greater in Chile than what was found in this study. The magnitude contrast between rainfall and irrigation differences can be explained by the variation of average temperature for the 2 experiments: in Chile, it was 14°C, far from 21.3°C, 23.1°C, 23.5°C, 23.7 and 25.5 for respectively baseline and scenarios 1 to 4. Lower temperatures are likely to decrease notably ET, so even with considerably less rainfall, irrigation would not increasing a lot.

4.1.2 Irrigation evolution according to the RCPs

RCP 4.5:

Between baseline and 2050, the temperature rise is correlated to irrigation increase. The climate in 2080 is close to the one in 2050, with lower temperature rise and still uncertain rainfall evolution, with the same range of values. It can be explained by the definition of this scenario: important mitigation efforts are anticipated, limiting radiative forcing and global warming (The Core Writing Team IPCC, 2015). Parallelly, irrigation demand is on average very close: 570mm by 2050, 574mm by 2080. The equilibrium happening to climate between 2050 and 2080 stabilises ET and rainfall, and at the end, balance is also happening for water requirements of crops and irrigation is only slightly bigger by 2080.

RCP 8.5:

RCP 8.5 is defined by low mitigation efforts and the radiative forcing remaining high (The Core Writing Team IPCC, 2015). Consequently, the temperature rise is not attenuated: no balance in climate appears for RCP 8.5 over time. Temperature increases notably twice, for baseline-2050, and 2050-2080, and rainfall decreases for 18 out of 19 models by 2080. The new climatic conditions put pressure on avocado trees: higher temperatures leading to more ET, but at the same time, less water is provided by rainfall. As a consequence, irrigation demand increases in considerable proportions: +8.7% by 2050, and +17.4% by 2080. This is particularly happening during the last trimester of the year, which is the beginning of the wet season, and when the precipitations are predicted to decrease.

Climate change impact on crops in the eastern part of South Africa was previously studied by Knox *et al.*, (2010), and Jones, Singels and Ruane, (2015). Both studies focused on sugarcane irrigation and yields in Swaziland using a similar methodology, and following scenario A2, from previous IPCC reports and close to RCP 8.5. Knox *et al.* (2010) found a 26% average irrigation increase, by 2050, compared to 9% obtained for RCP 8.5 by 2050 here.

Similarly, Jones, Singels and Ruan (2014) calculated that average annual irrigation would increase by 11% by 2070-2100, which is greater than the 17% found in this study for scenario n°4. Both studies expect

For both studies, the results differences with this study can be explained by the selection of climate models and scenarios. Scenario A2 is not exactly the same as RCP 8.5, and Knox *et al.* (2010) and Jones, Singels and Ruane (2015) worked respectively on one and three GCMs, whereas 19 were used in this study.

Fischer *et al.* (2007) studied global trends in irrigation and agricultural water withdrawals. They compared the effect of mitigated and unmitigated climate change, which could correspond to a comparison between RCPs 4.5 and 8.5. They suggested that by 2080, in Africa, mitigation would reduce the impact of climate change on irrigation by 28%, close to the 37% found in this study. Even though Fischer *et al.* (2007) provided a regional trend and climate change effects defer within the regional scale, their study gives a trend of future evolution, and the range of values is the same as in this study.

4.1.3 Design years frequency

In this study, the frequency of design years is respectively 46%, 42%, 45% and 58% for scenarios 1 to 4. Knox *et al.* (2010), in their study on climate change's effect on sugarcane irrigation and yields in South Africa, and mentioned future irrigation requirements that 'could well exceed current design criteria'. They obtained a 50% frequency of design years by 2050 for scenario A2 (similar to RCP 8.5), also considering the baseline value is 20%. As for irrigation averages, their value is greater than the one in this study (42%), the difference is likely to come from the use of a single climate model in their study, and small variations between climate scenario A2 and RCP 8.5.

4.2 Dealing with uncertainty

In this study, there are multiple sources of uncertainty to manage:

- Scenario uncertainty: climate and CO_2 concentration evolutions depend on future human behaviours and activities, yet this is not predictable. The RCPs are solid tools developed by scientists and accepted by many nowadays. Using two very different robust scenarios, RCPs 4.5 (mitigation) and 8.5 (no mitigation), enable to cover more possibilities and understand the potential futures. The uncertainty on their concrete interpretation is then dealt with by models.
- Model uncertainty: all the models are based on the same equations and physic principles, but each of them has its own hypotheses and interpretations. General Circulation Models are very complex tools and need numerous years and scientists to be built. Using 19 different models, cited in IPCC reports, and working on the averages of these 19 tools helps managing model uncertainty.
- Climate uncertainty: climate evolution is uncertain. For each combination of one model and one RCP, the generation of a thousand instances of annual weather allowed having a large statistical distribution that would cover many possible weather scenarios (dry and wet extremes) and cover the aleatory aspect of weather. Considering fewer instances of simulation would add a risk of having non-representative climate samples, whichever the year. With 1000 instances, a year with outlier values has then less weight and doesn’t alter too much the final results.

4.3 Limitations

4.3.1 LARS WG performances: p-values as an indicator

The performances of LARS WG have to be put into perspective because of the results of the f-tests (Table 2). Average rainfall, temperature, and irrigation results are not likely to be affected, as t-tests results showed good performances of LARS WG to reflect average values. Nevertheless, f-tests results suggest that the variances of variables are not correctly represented.

The analyses regarding the 80th percentile of irrigation, dry years and design years frequencies have to be considered carefully, as the calculations are realised on the statistical distribution of rainfall and irrigation. It is recommended to work with the relative trends of the results, that are likely to be more significant than the absolute values.

4.3.2 Atmospheric CO_2 concentration

For all RCPs, atmospheric carbon dioxide concentration rises, and higher CO_2 rates are expected to decrease ET (Pan *et al.*, 2015). Higher carbon dioxide concentrations diminish the crops' stomatal conductance, which means less ET takes place. The evolution of ET is unclear because higher temperatures will increase ET contrary to carbon dioxide.

Pan *et al.* (2015) studied the response of global terrestrial ET to climate change and increased CO_2 concentrations, working on scenarios A2 (similar to RCP 8.5) and B1 (close to RCP 4.5), with and without considering the CO_2 effect. They suggested that for low-latitude countries like South Africa, a carbon dioxide concentration increase would not counterbalance temperature rise. It would still reduce the average ET increase by 46% and 66% for respectively B1 and A2 scenarios, by 2090. The decrease of ET due only to CO_2 would be 2% for B1 and 8% for A2 by 2090, not enough to counterbalance temperature increase consequences.

Yet, even if carbon dioxide rates partly compensate temperature effects on ET, and reduce total water demand augmentation (rainfall and irrigation) because of lower ET, in this study average precipitations are expected to diminish for all four scenarios, so irrigation would still increase, but in reduced proportions. Thus, it is likely in this study that the irrigation increase was overestimated, especially for RCP 8.5 for which the carbon concentrations are the highest and the CO_2 impact on ET would be the most important. Nevertheless, average irrigation would still have increased, in lower proportions, as well as design years frequency.

5 CONCLUSION

Climate change impact on avocados' future irrigation demand was assessed. A thousand instance of annual future climate data was generated for multiple models and two mitigation scenarios and then net irrigation requirements were simulated. Compared to baseline, the results all showed a rise in average temperature and an average rainfall diminution which is expected to be low in 3 of the 4 scenarios. The scenarios chosen have all predicted an increase in the annual average irrigation demand of avocado trees of at least 9% by 2050 and up to 17% by 2080. The frequency design will rise, with direct impacts on the avocado business.

Climate change will increase water requirements from crops, and put more hydric stress on the Groot Letaba catchment. Groot Letaba river is already under pressure because of 'high demand of water and limited availability', and its flow is expected to decrease by 30% by 2050 (Querner *et al.*, 2016). Thus water competition will happen between the different activities. Careful management of water allocation and long-term planning are necessary to ensure the sustainability of businesses relying on irrigation water from Groot Letaba river.

The general approach chosen here can be used in similar studies, for other regions of the world or different crops, as downscaling methods and selection of multiple climate models give robustness to the method.

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APPENDICES

Appendix A : Downscaling Methods

Appendix A-1 summarises the positive and negative aspect of statistical and dynamic downscaling.

Table A-1: Comparison between dynamic and statistical downscaling

	Statistical downscaling	**Dynamic downscaling**
Pros	Any scale up to site-specific Medium to low data requirements Based on observations (historical trends as a baseline to support forecasts) Easy to implement, flexible methods Weather generator method includes daily time series and scenarios for extreme wet / dry events	20 to 50km grid information Based on physics, no need of observational data (so less uncertainty linked to data collection) Daily time-series for all methods Includes extreme wet and dry events
Cons	Requires good quality historical data (about 30 years), and sensitive to erroneous data Assumption that relationships between large and local-scale processes will remain the same in the future	High computation capacity and knowledge level required Very big data amount as input Relies only on the General or Regional Climate Models (GCM / RCM) simulations RCMs are not available in all parts of the world

Source: (Trzaska and Schnarr, 2014)

Appendix B : Methodology

Table B-1 lists the 19 General Circulation Models, from the CMIP5 ensemble of the IPCC Fifth Assessment Report (2018), included in LARS WG, and their origin.

Table B-1: List of General Circulation Models chosen and their country of origin

Model Name	Origin
ACCESS1-3	Australia
BCC-CSM1-1	China
CanESM2	Canada
CMCC-CM	Italy
CNRM-CM5	France
CSIRO-MK36	Australia
EC-EARTH	Europe
GFDL-CM3	United States of America
GISS-E2-R-CC	United States of America
HadGEM2-ES	United Kingdom
INM-CM4	Russia
IPSL-CM5A-MR	France
MIROC5	Japan
MIROC-ESM	Japan
MPI-ESM-MR	Germany
MRI-CGCM3	Japan
NCAR-CCSM4	United States of America
NCAR-CESM1-CAM5	United States of America
NorESM1-M	Norway

Appendix C : Results

Table C-1 explains the colour code used in Table C-2, which displays the irrigation difference from baseline for each of the 19 models

Table C-1: Colour code for Table C-2

X ≤ -10%	-10% < X ≤ 0%	0% < X ≤ 10%	10% < X ≤ 20%	20% < X

Table C-2 : Average annual irrigation difference from baseline per model, for the four scenarios

General Circulation Model	Average irrigation difference from baseline (%)			
	2050		2080	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
ACCESS1-3	+ 11	+ 1	+ 5	+ 20
BCC-CSM1-1	+ 5	+ 18	+ 7	+ 17
CanESM2	+ 29	+ 8	+ 9	+ 17
CMCC-CM	+ 2	+ 11	+ 16	+ 14
CNRM-CM5	- 2	- 1	- 5	+ 6
CSIRO-MK36	- 3	+ 7	+ 8	+ 5
EC-EARTH	- 6	+ 8	+ 2	+ 8
GFDL-CM3	+ 19	+ 12	+ 21	+ 27
GISS-E2-R-CC	+ 20	- 3	+ 13	+ 13
HadGEM2-ES	- 14	-17	+ 5	+ 19
INMCM4	+ 19	+ 21	+ 18	+ 13
IPSL-CM5A-MR	+ 11	+ 24	- 10	+ 24

MIROC5	+ 19	+ 7	- 6	+ 16
MIROC-ESM	+ 23	+ 27	+ 55	+ 41
MPI-ESM-MR	+ 20	+ 17	+ 26	+ 27
MRI-CGCM3	+ 15	+ 26	+ 17	+ 16
NCAR-CCSM4	+ 9	- 4	+ 10	+ 11
NCAR-CESM1-CAM5	+ 9	+ 1	0	+ 9
NorESM1-M	+ 7	+ 2	+ 17	+ 28