José Benito de Andrade Vieira

Adaptation to climate change in irrigated agriculture: An evolutive water footprint approach.

Campina Grande - PB

February, 2020

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Dissertation presented to the Graduate Program in Civil and Environmental Engineering in compliance with the requirements to obtain the Master's Degree.

Federal University of Campina Grande - UFCG

Graduate Program in Civil and Environmental Engineering

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"isso de querer
ser exatamente aquilo
que a gente é
ainda vai
nos levar além"
(Paulo Leminski)

Resumo

Em um cenário global em constante alteração devido às mudanças climáticas, surge a necessidade de se melhorar a maneira como usamos os nossos cada vez mais escassos recursos naturais. Como a agricultura é o setor produtivo que consome mais água no mundo, esta torna-se um foco prioritário destes esforços. Muitos trabalhos já apontaram quais seriam as melhores medidas de adaptação aos impactos das mudanças climáticas na agricultura, porém pouco se sabe sobre quais são as melhores maneiras de implementar essas medidas, especialmente quando se inclui nesta problemática variáveis como: limitações financeiras, disparidades de poder entre grandes e pequenos agricultores, e perdas de produtividade devido à diminuição da disponibilidade de água. Este trabalho objetivou desenvolver uma metodologia para determinar estratégias ótimas de adaptação para o uso da água na agricultura irrigada, utilizando a pegada hídrica como indicador de eficiência/sustentabilidade para guiar o processo. O SPEA2, um algoritmo evolutivo de segunda geração, foi usado para encontrar soluções ótimas, enquanto o software Aquacrop OS foi usado para estimar a pegada hídrica de cada agricultor. Com isso, é possível determinar um conjunto de soluções ótimas de Pareto, a partir dos dois principais objetivos deste processo de adaptação: aumentar a eficiência/sustentabilidade do uso da água e minimizar o custo para fazer isso. A estratégia de adaptação, segundo a metodologia proposta, é gerada em várias etapas, de maneira que a mesma importância é dada aos estágios intermediários e ao resultado final do processo. Com o objetivo de testar a metodologia desenvolvida, um caso de estudo prático foi realizado, utilizando como exemplo a Bacia do Rio Mamuaba (uma sub bacia da bacia do Rio Gramame), localizada no estado da Paraíba, nordeste do Brasil. Para o caso de estudo, observando-se todas as fronteiras de Pareto obtidas no processo, algumas recomendações gerais puderam ser extraídas para os agricultores. Nas primeiras décadas, até um certo custo, a redução na pegada hídrica por unidade de dinheiro investida é mais proveitosa do que além desse ponto, enquanto no final do período de adaptação é melhor escolher medidas mais baratas. Também foi sugerido fazer mais alterações que aprimoram a eficiência do sistema do que alterações que substituem diferentes tipos de culturas. Pequenos agricultores foram priorizados no processo de adaptação, tornando a abordagem mais holística. Também foram sugeridos valores de referência de Pegada Hídrica com o objetivo de servir como metas de redução para orientar e ajudar a monitorar o processo de implementação da estratégia de adaptação no campo.

Palavras-chave: otimização sequencial; equidade; gestão adaptativa.

Abstract

In a rapidly changing global scenario due to climate change, there is a need to improve the way we treat our increasingly scarce natural resources. As agriculture is the most water-consuming productive sector in the world, it becomes a priority focus on these efforts. A lot of works had pointed out what are the best adaptation measures to climate change impacts on agriculture, however little is known about what are the best ways to implement these measures, especially when are included in the problem variables such: financial limitations, power gaps between large and smallholder farmers, and losses in productivity due to decreases in water availability. This work aims to develop a methodology to determine optimal adaptation strategies for water use in irrigated agriculture using the water footprint as an efficiency/sustainability indicator to guide the process. SPEA2, a second-generation evolutionary algorithm, was used to find optimal solutions, and Aquacrop OS was used to estimate the farmer's water footprint. Through this, it is possible to determine a set of Pareto solutions with the two main objectives of the adaptation process: increase water use efficiency/sustainability and minimize the cost to do so. The adaptation strategy is generated in several steps, in a way that the same importance is given to the mid rages and the final result of the process. To test the develop methodology, a practical study case was simulated using River Mamuaba basin (a sub basin from River Gramame basin), located in the Paraiba state in northeast Brazil. For the study case, observing the Pareto frontiers for all decades, some general recommendations could be extracted to the farmers. For the firsts decades, until a certain cost, the reduction in water footprint per unit of money invested is more gainfull than beyond that point, while at the end of the adaptation period, it is better to choose cheaper measures. It was also suggested to make more changes that enhance the system's efficiency than changes that replace different kinds of crops. Very small and small farmers were prioritized in the adaptation process, making the approach more holistic. Water Footprint benchmarks are also suggested to serve as reduction targets to guide and helps to monitor the adaptation strategy implementation process on the ground.

Keywords: sequential optimization; equity; adaptative management

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1 Introduction

1.1 Problem

Climate change has been cited by **??**) as a phenomenon of relevant importance in short and long term projections. Projected variations are mainly associated with an increase in temperatures and a decrease in average rainfall. In addition, there is also a high probability of intensification of extreme events, such droughts. This conjuncture emphasizes the need to take measures to address the risks related to climate change, taking into account the scale of the analysis and the local particularities (**??**).

In recent decades, a large number of studies have indicated that rural areas are particularly vulnerable to climate change, that is because plant growth can be severely affected by rising temperatures and decreasing rainfall, compromising agricultural production and food security both globally and locally (**??**). According to **??**), for each degree increased in the historical average temperature, a decrease of 5 % in agricultural production is expected. Still according to the same authors, crops that have undergone some measure of adaptation to climate change have a yield about 7 % higher than non-adapted ones. For this reason, maintaining the sustainability of this sector in an ever-changing scenario has become a staple on the agenda of farmers, politicians, and government agencies (**????**).

Householders farmers living in underdeveloped countries are the most vulnerable to these impacts. For this group, even small changes in climate can result in disastrous impacts on their lives and livelihoods. The main aggravating factors are: unfavorable geographical positions, low income, high dependence on agriculture for subsistence, and limited ability to look for alternative forms of livelihood (**??**). In this context, considerable effort has been made to determine what are the best ways to adapt to future climate conditions, taking into account all uncertainties associated with climate projections (**????**). Speaking of agriculture in particular, several adaptation strategies have been proposed by several authors, among them: increase water use efficiency, increase soil water retention capacity, and biodiversity (**??????????**).

In addition to these, more specific strategies have been proposed. **??**) studied the main crops of Central Europe and suggested better agricultural management and genetic improvement as ways to confront climate change. **??**) used a multi-purpose genetic algorithm to generate climate resilient land use compositions. **??**) has created a three-step adaptation strategy for an agricultural area in sub-Saharan Africa, where for each location and each time period one type of adaptive measure would be most appropriate. **??**) studied the relationship between adaptation strategies, food security, agricultural production and

the type of production (subsistence, diversified, extensive or intensive). The conclusion was that, depending on the type and size of the producer, different adaptation strategies are more appropriate.

After analyzing several papers related to this theme (including those already mentioned above), it was possible to realize that the main focus of these is, in the vast majority of cases, the determination of what measures can be taken to make a region less vulnerable to the effects of climate change, hence little was said about how these measures would be implemented (the transition process) on the ground. Taking into account the information mentioned above, one of the innovations that this work aims to present refers to the focus that is given to the elaboration of an optimized transition process between the current state of a given region and the so-called ideal state (a state that is adapted to the impacts of climate change), caring about the transition process as much as its the end result. Besides that, when looking for the best ways to adapt, the factors listed below are taken into account:

- Budgetary limitations, which indirectly dictate what action can be taken and the speed with which it will happen.

- Mixed groups of farmers, ranging from small families who see agriculture as their livelihood to large intensive farming, where a clear power difference can be identified between the parties.

- Loss in production due to decreased water availability coupled with the impossibility of applying an adaptive measure in a timely manner.

Thus, this work proposes to answer the following questions: What must be done so that the adaptation process occur as best as possible, considering local financial constraints? Is it possible to maintain equity during this whole process since there are such power asymmetry involved? What is the most appropriate (cost-effective) adaptation strategy that compensates for the reduction in water availability (over a certain period of time) and does not undermine farmer's production? What goals can be set to assess whether adequate effort is being employed in adopting such measures over time?

It is critical to be concerned about the applicability of the adaptation measures from the point of view of those who will apply them if they are ever expected to come out of paper and become a reality, as the negative impacts of climate change are already occurring.

1.2 Proposed Solution

There are two main ways to deal with decreasing water availability. The first would be to reduce cultivated area, which would not require any other measure, but which, on the other hand, would reduce food production, a fact that should be avoided as much as possible. The second way would be to increase water use efficiency, which would not require a reduction in the cultivated area, but which, on the other hand, would incur extra costs for the farmer, who would have to modernize his irrigation and soil management system. It is also possible to employ both strategies together.

What will determine in practice which strategy is going to be employed is the amount of money available to invest. In an utopian scenario with unlimited funding and unlimited technology, no reduction in productivity would be required and all adaptation would be done by increasing system's efficiency. In a real scenario, where funding and technology is limited, especially in developing countries like Brazil, it is not always possible to do this.

Therefore, it is essential to optimize the decision-making process so that the limited money is spent in order to produce the best outcome, so that the impact of climate change on agricultural production is minimal. Besides cost and productivity, it is essential to consider the social aspect as well. The adaptation strategy should, in addition to fulfilling the objectives mentioned above, favor the adaptation of small farmers, because, as we have seen, they are the most vulnerable.

Assuming that the available budget for adaptation is finite and renewable over time and knowing that climate change is a dynamic phenomenon and will continue to affect the planet's climate for several decades, the adaptation strategy has been subdivided into several stages (or steps), each step is product of an independent optimization process, so that the adaptation strategy can change over time, adjusting to the dynamic aspect of the process. The evolutionary approach of the adaptation strategy proposed by the suggested methodology can be seen as another innovation of this research, since none of the papers researched in this works presented an approach similar to what was done in this work. Due to the progressive aspect of the adaptation strategy, it will be possible to establish sustainability goals to be achieved over time. These goals will serve as a means of monitoring and evaluating if the adaptation strategy is being effectively implemented on the ground. It is necessary to make it clear that the main objective of this work is to propose a generic methodology for the generation of adaptation strategies for different cases and locations around the world. At the end of the work, the methodology developed was applied to a local case study, with the aim of demonstrating the performance of the method in concrete case.

To guide the optimization process it is necessary to quantify the sustainability/ef-

ficiency of the system, in order to aim for the highest efficiency increases at the lowest costs. In the literature there are a large number of indicators that could serve to this purpose, among them, this research proposes to use the water footprint, due to its use in other works as an aid in the decision making process (**??**) and as a tool to encourage the replacement of less efficient methods by more efficient ones (**??**).

The optimization method used in this work was a type of evolutionary algorithm known as genetic algorithm. This method was chosen due to several factors. In general, these algorithms can work very well together with other models, since they use only objective function's information and suitability of the solutions; They are also highly capable of optimizing objective functions with complex surfaces, reducing problems related to convergence to local minimum points, are less susceptible to the shape or continuity of the Pareto Frontier, and are simpler to impose qualitative constraints (**??**).

The genetic algorithm, like most multiobjective methods, uses Pareto's dominance concept, which is the search not only for a single optimal solution but for a set of favorable solutions for all goals. According to **??**) Pareto's optimal solutions are those in which one goal can only be improved by causing a simultaneous worsening to another, and that are better than the others in at least one goal. Through the Pareto optimality concept a set of optimized solutions can be determined, which can serve as scenario options. This opens the possibility of having a meeting between the farmers participants in the process to define, in a participatory way, which option is the most advantageous for the group. Since all options results from a optimization process, they are all able to solve the adaptation problem in different ways.

2 Objectives

2.1 General Objective

Determine medium to long-term adaptation strategies for increasing water use sustainability of a group of farmers that shares the same water source.

2.2 Specific Objectives

- Assess whether that strategies contribute positively or negatively to mitigate the power and opportunity differences that exist between small and large farmers.
- Identify through the adaptation strategies general recommendations to be followed by the farmers
- Set sustainability goals based on local characteristics, which could serve for monitoring and evaluating the implementation of adaptation strategies on the ground.

3 Literature Review

3.1 The History of Environmental Issues and the Decision Making Process in Environmental Management

Since the 1960s, environmental issues were evident and caused concern among state leaders and the scientific community. In the following years, this concern only increased due an increasing number of disasters and the worsening of environmental imbalances. This fear for the worrisome future of the planet motivated the first global environmental conference, known as the Stockholm Conference, held in 1972 in Stockholm, Sweden. It was considered an international political milestone, as it has played a decisive role in directing the world's eyes to environmental issues and, consequently, enabling the emergence of environmental management policies (**??**).

In 1974 a meeting between UNCTAD (United Nations Conferences on Trade-Development) and UNEP (United Nations Environment Program) resulted in Cocoyok's statement, which contributed to the discussion about the relationship between the level of development of countries and the environment. Among the conclusions of this meeting there as: 1) Environmental destruction is caused, among other factors, by poverty, which leads the needy population to overuse the soil and native vegetation; 2) There is not only a minimum of resources necessary for the welfare of an person; there is also a maximum (**??**).

In 1975, the final report of a Dag-Hammarskjöld Foundation project involving researchers and politicians from 48 countries was presented, reinforcing and deepening the points presented at Cocoyok. This report shows the relationship between power abuse and ecological degradation. In it is possible to see how the colonial system concentrated the most suitable soils for agriculture in the hands of a social minority, while the large mass of the original population was expelled, marginalized and forced to use lower quality lands. This has devastated many landscapes in South Africa, Morocco, and many other locations (**??**).

Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This concept of sustainable development was first introduced to the world in 1987 with the publication of "Our Common Future Report" by the World Commission on Environment and Development(WCED) (**??**).

In 1992, in Rio de Janeiro took place the Earth Conference, also known as Eco-92,

where sustainable development was recognized as a goal to be pursued by all nations. This conference gave rise to Agenda 21, a document that systematizes an action plan that has been helping many country to achieve a more sustainable development and to improve environmental and life quality of the population (**??**).

After these, other meetings were held and other environmental documents were published to discuss and reaffirm the commitment to sustainable development. These include the Earth Charter (in Paris in 2000), the Johannesburg Declaration (in South Africa in 2002) and the Rio +20 (in Rio de Janeiro in 2012).

It is important to present this background to show how the concern with sustainability and sustainable development has grown and become more relevant to national leaders over the years. It is important to mention as well, however, that the decision-making process in environmental management is complex, interdisciplinary and fraught with uncertainty, especially when considering climate change scenarios (**??**).

To deal with these complexities and uncertainties, it is important that the approaches developed to assist in the decision-making process are multidisciplinary and allow the participation of all parties involved (**??**). According to **??**), social participation is essential for solving unstructured (climate change and adaptation) or moderately structured problems, although less necessary for well-structured problems.

??) recognizes that the lack of articulation between stakeholders is still a reality in natural resources management, constituting the biggest obstacle for sustainable development. The same author also points out that collaborative management is essential to deal with complex problems.

Organizations must adapt to cope with change, since this changes can become a serious problem if not addressed properly. Many organizations are unable to adapt efficiently or quickly enough due to its stifled standards, institutional arrangement and governance. **??**) presents the concept of adaptive governance, which aims to increase an organization's ability to adapt to change. Adaptive governance strategies include utilizing internal and external resources, decentralizing the decision-making process, and seeking to convey decision-making information bottom-up.

3.2 Climate Change and its Implications for Water Availability

Global warming continues to dominate the global political and scientific agenda, mainly due to the changes it is causing in the behavior of the various planet's ecosystems. Water's vapor saturation pressure in the atmosphere is highly sensitive to temperature, so it can be said that the warming of the planet causes changes in the water cycle. Imbalances in the hydrological cycle will reflect in rainfall and river flow on many parts of the world,

where will be expected an increase in some places and decrease in others (**??**).

A key concern is the impact of climate change on global water availability. Studies such as **??**) already pointed, a few decades ago, that a significant portion of the population was already living in areas where there was water deficit and that this situation would only worsen in the future, mainly due to global warming and increasing water demands.

According to **??**), between 1.6 and 2.4 billion people currently live in river basins that suffer from water scarcity. According to these authors, by 2050, it is estimated that this range will increase to between 0.5 and 3.1 billion due to climate change. Another important conclusion from this study is that in the future the world will see more areas entering in water scarcity scenarios than getting out of them.

Other studies also reveals that climate change will cause an increase in the demand for water, especially in the agricultural sector. As irrigation accounts for the biggest part of the global water consumption, an increase in the water demand of this sector can cause severe stress on water resources. Just proper management of the water sources will not be enough to adapt to this new reality, water management on the demand-side is also needed in order to adapt to this new uncertain and constantly changing environment (**??**).

??) shows the consequences that global warming will provoke on irrigated agriculture. According to them, in some regions of the United States, China and Asia, it will be necessary to convert between $20 - 60 Mha$ from irrigated crops to rainfed crops by the end of the century. This will represent a loss of between $600 - 2900 Pcal$ [1] in agricultural production.

In China, over the past decade, global warming is estimated to have caused a loss of about 820 million in the maize and soybean sectors. In addition, the production of these two sectors are expected to fall between $3 - 12$ % and $7 - 19$ %, respectively, by the year of 2100, for the same reason (**??**).

3.3 Climate Change Adaptation

There are two main ways for society to respond to the consequences of climate change: Mitigation or adaptation. Mitigation means reducing the impacts caused by climate change through the reduction of greenhouse gases emissions, ie by addressing the problem directly at its source. Adaptation means acting on a particular vulnerable system in response to current or projected climate change in order to minimize the impact on this system, ie dealing with the symptoms of the problem (**??**).

Mitigation has received far more attention than adaptation, both politically and scientifically. That is because mitigation, by focusing on addressing the cause of the

[1] $Pcal$: Peta Calories, $1 Pcal$is equals to10^{15} Calories

problem, reduces the impacts of climate change everywhere, including the locations where adaptation is hard to implement due to local constraints. In addition, greenhouse gas emissions are easier to be monitored quantitatively than the effectiveness of an adaptive measure, in terms of future impacts avoided (**??**).

Despite the obvious need for mitigation, there are also good arguments for the adoption of adaptive measures. Firstly, greenhouse gas emissions are already affecting climate conditions, meaning that mitigating measures will not soften the impacts that are already happening (**??**). Secondly, climate will continue to change in the near future, due to the accumulation of greenhouse gases and the inertia of the climate system (**??**). Thirdly, the effect of reducing greenhouse gas emissions will take decades to produce concrete results, while adaptive measures pay off in a much shorter period. Fourthly, adaptation can be implemented on a local/regional scale, making its effectiveness less dependent on external actions (**??**).

Adaptation and mitigation are not mutually exclusive alternatives, on the contrary, these are complementary to each other. This is because their have distinct characteristics, timescales and steakholders.

According to **??**), the process of planning climate change adaptation strategies is the act of using current and future climate information to review the appropriateness of current practices, policies and structures. Planning adaptation strategies involves asking questions such as: How do climatic and non-climatic conditions of the future differ from those of the past? Do these changes interfere in the current decision making process? What is the ideal balance between the risks of acting too soon or too late? The process of adaptation comes down to making recommendations about what should be done more, less or different, and with what resources it will be done.

According to **??**) and **??**) the process of adaptation to climate change has several key dimensions, which are as follows:

- **Climate Sensitive Domains:** Adaptation is relevant to all climate related domains. (Agriculture, forestry, water management, public health, disaster prevention, etc.)

- **Types of climate disasters:** Adaptation can be motivated by several types of climate disasters, the ones that are already occurring or the ones that will occur in the future.

- **Predictability of climate change:** Some aspects of climate change can be predicted with a reasonable degree of confidence (eg variation in average temperatures), while others have a high degree of uncertainty in their prediction (eg changes in routes and intensity of hurricanes).

- **Conditions not related to the weather:** The adaptation process should not only consider the variables related to climate, but also the environment, politics and culture of the place where it is being implemented.
- **Intentionality:** Adaptation can be autonomous (when individuals act individually without an upper control over them) or intentionally planned (when there is institutional control over the measures being taken).
- **Time:** Adaptation can be reactive (happens after impacts occurrence) or proactive (when the adaptation is done before major damages occurs).
- **Planning horizon:** The adaptation planning horizon can vary substantially, from a few months to several decades.
- **Form:** The adaptation process is interdisciplinary and involves technical, institutional, legal, educational and behavioral measures. Research and data collection can also be considered adaptive measures (in a general context) as they facilitate the implementation of effective actions to reduce climate risks.
- **Actors:** Adaptation involves a large number of people of different hierarchical levels, as well as various public and private institutions.

Based on the work of **??**), **??**) suggested some prerequisites for climate change adaptation to be effective. The following list presents these prerequisites and what should be done to achieve each one:

- **Be aware of the problem:** Measuring vulnerability to climate change.
- **Availability of adaptation measures:** Encouraging researches that leads to the development of new adaptation options.
- **Information about these measures:** Identifying and measuring the effectiveness of adaptive measures.
- **Availability of resources to implement these measures:** Assessing the benefits of adaptation, identifying ways to increase resource efficiency, and provision of additional resources.
- **Cultural acceptance of these measures:** Informing people about the risks and about the adaptation measures to increase the acceptability of unfamiliar measures.
- **Incentives for the implementation of these measures:** Identifying obstacles to the implementation of effective measures and suggesting options for overcoming these obstacles.

As mentioned earlier, the process of designing and implementing policies that aims to reduce vulnerability to climate change involves a large number of people from different ranks. For **??**), the participation of the following groups is essential to the success of this process:

- **Scientists:** Scientists produce essential knowledge, which shows us why current policies, practices and infrastructures are no longer appropriate for the future.
- **Professionals:** These are the people who really implement the recommended changes. They can provide information on how things are currently being done and why they are done in that way. This information is the starting point for planning change.
- **Decision makers:** Leaders of government agencies, business managers and other decision makers are critical parts to the adaptation process. They are the people who define what are the priorities and who decide which measures will be implemented and which not.
- **Analysts:** Political analysts and economists can help to choose which adaptation measures are priorities based on a cost-benefit analysis or any other criteria defined by decision makers.

Due to resource constraints, in some cases, adaptive measures can not be implemented immediately and a slower adaptation process is therefore required. Several authors have identified criteria for prioritizing adaptation measures (**????????**). There is an general agreement that anticipating adaptation is particularly favorable if:

- There is urgency for risk mitigation.
- There is a assurance that these risks will increase in the future (with high degree of reliability).
- Future impacts are potentially catastrophic or irreversible.
- Decisions have long-term effect.
- The adaptation takes a long time to be implemented and start to produce results.

In contrast, delaying the adaptation process may be viable if:

- Current and future risks are moderate.
- The adaptation process is very expensive.
- Options that produce quick responses are evaluable.

3.4 Adaptation Strategies for Agricultural Water Management

Agriculture is the most water consuming sector in the world. Conducting water management for this sector is becoming an increasingly complex work, as now this must be done within the context of the progressive reduction of water availability. On the past years, several studies have been conducted to identify the main impacts caused by climate change on agriculture, as well as what would be the most appropriate measures to be taken to adapt to this new scenario (**??**).

The implementation of adaptive measures should vary according to local conditions. For example, in areas where there is significant economic and social inequality and water scarcity has not become a matter of urgency yet, water management should focus primarily on ensuring equal access to water (**??**).

Interventions should be made not only on the supply side, but also on the demand side. On the supply side, changes can be made to increase reservoir storage capacity or to find alternative water sources. On the demand side, what can be done is to prioritize the allocation of water to sectors that use it most efficiently (**????**). Science has to adapt as well, more multidisciplinary approaches needs to be done in order to deal with multidisciplinary issues; science also have to strengthen the comunication with decision makers (**??**).

An optimistic future will depend on whether agriculture will be able to consume water on an sustainability way or not. This will depend on a set of actions that may not produce results in the short-term. Ensuring economically efficient water use and promoting water and soil conservation are the priority areas of action (**??**).

Even when policies are well defined, user's training and/or orientation is required. For example, improving the efficiency of irrigation methods is only an option for groups that already have a certain understanding of what alternative technologies are and how important are to implement these in practice (**????**).

Implementing adaptive measures can be challenging for both farmers and managers. In the short term, cultural and financial barriers may limit adaptation to the adoption of low cost and ease to implement measures. Long-term measures that requires changes in infrastructure, technology or governance are more difficult to implement (**??**).

??) evaluated various types of adaptation strategies for agricultural water management. As a result, the authors were able to summarize what are the main objectives that the adaptation process should achieve, the main adaptive measures that can be used to achieve these objectives, and the main mechanisms to address the impacts of climate change. This information can be viewed in the Figure **??**.

In irrigated agriculture, a change in an irrigation method can cause a significant reduction in water footprint and ,thus, in water consuption. Using dripping irrigation

instead of sprinkler irrigation can result in a water savings of over 30 % (**??**). According to **??**) drip technology could reduce the total water footprint by 5%, when compared to sprinkler. According to **??**) China's average water footprint per ton of wheat under sprinkler irrigation was 21% higher than that under micro-irrigation in 2014. Improving the irrigation efficiency has been identified as a major strategy to adapt to future climate and socioeconomic change globally and in major arid regions (**????????**). However, more efficient irrigation is only one aspect of adaptation to global change, others improvements are necessary to ensure food security and mitigates impacts in agriculture, for instance the use of mulching and cover crops (**????**).

Figure 1 – Adaptation measures that offsets the potential negative impact of climate change for agricultural water management. Source: (??)

Adaptation needs	Measure	Mechanism to overcome the impacts of climate change
I. Improve resiliency and adaptive capacity	(1) Implement regional adaptation plans	Enhances effectiveness of adaptation measures
	(2) Improved monitoring and early warning	Mitigates consequences of adverse events
	(3) Improve coordination planning	Enhances effectiveness of adaptation measures
	(4) Innovation and technology	Improves effectiveness of adaptation measures and reduces costs
II. Response to changes in water availability	(5) Innovation: water use efficiency	Increases water availability
	(6) Improve soil moisture retention capacity	Increases water use efficiency
	(7) Small-scale water reservoirs on farmland	Increases water management flexibility at the local level
	(8) Improve the reservoir capacity	Increases management flexibility and water availability at regional level
	(9) Water reutilisation	Increases water availability
	(10) Improve water charging and trade	Decreases inefficient use of water
	(11) Re-negotiation of allocation agreements	Improves water use efficiency
	(12) Set clear water use priorities	Improves water use efficiency
	(13) Integrate demands in conjunctive systems	Increases management flexibility and water availability
III. Response to floods and droughts	(14) Create/restore wetlands	Reduces flood peaks
	(15) Enhance flood plain management	Reduces flood vulnerability
	(16) Improve drainage systems	Reduces extent and duration of flooding
	(17) Farmers as 'custodians' of floodplains	Decreases risk of flood damages
	(18) Hard defences	Decreases risk of flood damages
	(19) Increase rainfall interception capacity	Reduces flood peaks at the local level
	(20) Introduce drought resistant crops	Improves agronomic water use efficiency
	(21) Insurance to floods or drought	Decreases economic losses to the farmer
IV. Response to increased irrigation requirements	(22) Change in crops and cropping patterns	Decreases economic risk to farmers
	(23) Improve practices to retain soil moisture	Decreases the need for additional water to crops
	(24) Develop climate change resilient crops	Mitigates impacts of climate change
V. Response to changes in agricultural land use	(25) Relocation of farm processing industry	Maintains industrial activity
	(26) Addition of organic material into soils	Recovers soil functions
	(27) Introduce new irrigation areas	Develops new agricultural land
VI. Response to deterioration of water and soil quality	(28) Improve nitrogen fertilisation efficiency	Reduces agricultural diffuse pollution
	(29) Soil carbon management and zero tillage	Reduces soil erosion and improves soil water retention capacity
	(30) Protect against soil erosion	Reduces land degradation
VII. Response to loss of biodiversity	(31) Increase water allocation for ecosystems	Improves ecosystem services, effective at the global level
	(32) Maintain ecological corridors	Improves biodiversity with positive global consequences
	(33) Improve crop diversification	Improves biodiversity

3.5 Injustice, Equity and Adaptation

According to **??**) environmental injustice can be understood in two ways: the first would be related to the implementation of policies - or their omission - causing disproportionate risks to those most in need of financial and political resources; and the second would represent unequal access to environmental resources, expressed in both production and consumption of these resources.

Physical water scarcity and poor access to water are often mistaken for the same thing, but they are not. Access to water and water services are aspects of water security, but they do not depend solely on physical water scarcity, although this is often cited as the only reason. In most cases, what we have are consequences of mismanagement, bad political or economic policies masked as water scarcity. In this context, people who are mostly geographically, economically, institutionally and socially marginalized do not have or have poorly access to water (**??**).

According to **??**) water scarcity is mainly caused by a combination of three principal factors: power, poverty and inequality and not only by lack of physical water availability. The same author also pointed out depletion and degradation of the resource caused by non sustainable exploitation, population growth and unequal distribution or access to water was driven forces of scarcity, besides recognizes the role of institutions and politicians in this process. **??**) studied water access equity in India and concluded that the current social and institutional arrangement was creating inequities in the access to water for sheer survival in several locations and for specific social groups. The same author also found several factors that contributes for the enlargement of the inequities, some of they are: the enlargement of water scarcity, the use of the water for economic activities (such agriculture), the exploitation of water by large industries, and the action of of economic actors within industrial sector.

??) suggest that access to water is justiciable for at least three reasons:

- If water access was seen, as income and wealth, as a prerequisite for business and livelihood opportunities
- Water plays a key role in domestic work. Without easy access to water, the tasks of maintaining a home and bringing up children are constrained.
- The time spend in water collection deprives a part of the population of opportunities to live other aspects of life. Water equity cannot be judged only by the material circumstances of access, such as quantity of potable water available. Equity must be understood more holistically. It is the capabilities enabled by water access that really matter.

The impacts of climate change are contributing to exacerbate the problems of scarcity and equitable access to water, but when we talk about scarcity, equitable access and climate change impacts, little synergy is seen between this three different issues, then a more holistic view is needed wherefore appropriate adaptation strategies are adopted and resilience is built (**??**). International conventions are increasingly recognizing the need to engage resource stakeholders in agendas in order to achieve their desired aims, as part of more holistic approaches to sustainable development (**??**).

The issue of equity and justice, in the context of climate change, is discussed more on an international scale than on smaller scales, that often receive insufficient attention. This is worrying, as it is at these smaller scales that the process of adaptation potentially widens inequalities by creating winners and losers (**??**).

Climate change adaptation process, in some cases, may present significant dilemmas about justice, as the impacts of climate change contribute to the worsening of the already existing cases of injustice. These problems become even more prominent in highly resource-dependent communities, scenarios that are quite common in under developed countries (**??????**). In general, poorer communities will be most severely affected by the impacts of climate change, but not necessarily because of the impacts themselves, but because these communities are less resilient (**????**).

??) studied the implications of different spatial scales for the adaptation process, and developed a set of normative evaluative criteria for judging the success of adaptations at this different scales. They argued that, among other factors, the equity is a important element for judging success in terms of the sustainability of development pathways into an uncertain future.

3.6 Methods for Sustainability Assessment

In the last few decades, there have been extensive efforts on measuring sustainability. One example is the development of assessment tools based on sustainability indicators, known as sustainability indices. These sustainability indices have a common purpose: to measure the sustainability (**??**). Well-developed indicators ought to condense and unscramble significant information by measuring, quantifying/qualifying, and transmitting data in a way that is simple to understand (**??**). However, in their definition process, it should not only consider the technological issue, it should also take into consideration the environmental, social, institutional, and economic aspects related to sustainability (**??**).

Some authors have developed general sustainability indices, such as the Environmental Sustainability Index (**??**), Corporate Sustainability Indicators (**??**), the Barometer of Sustainability (**??**), Environmental Pressure Indices (**??**), Taking Sustainability Seriously (**??**), Sustainability Indicator Systems (**??**). Some sustainability indices are field-specific,

such as indicators for environment (**??**), agriculture (**??**), fossil fuel (**??**). Indices for water resource sustainability, for example, are the Water Poverty Index WPI (**??**), Canadian Water Sustainability Index CWSI (**??**), Watershed Sustainability Index WSI (**??**) and West Java Water Sustainability Index WJWSI (**??**). The main goal of all these indices is to measure sustainability, which can be used after that to help decision makers and other stakeholders accomplishing sustainable development. Additionally, the indices can also be used to communicate the progress of sustainability to wider community (**??**).

One important aspect of sustainability assessment is to set targets and then measure the distance between the target and the current state or trend (**??**). In terms of interpretation, if the indicator was applied over a long period of time, it can be used to determine a trend. In this case, we use reference points to measure the proportion of the change. The simplest reference point is the baseline. Baselines are starting points for measuring change from a certain state or date (**??**). We can also utilize absolute values, although them, by their own, may not entirely matter, since we need a notion of what is admissible. So the called reference values has the purpose of giving a meaning to absolutes values, establishing what is admissible, and differentiating them from raw data (**??**).

The scientific community emphatically suggests the adoption of indicators for the assessment and monitoring of advances towards sustainable development. Besides it, international organizations consider that indicators are effective decision-making instruments. The pertinence of indicators for the decision-making process is one of the most vital features of the indicators in relation to other forms of information. In any case, the quality and reliability of the indicators depends on the application of satisfactory and fitting criteria to evaluate them (**????**).

The selection of a appropriate indicator is extremely important. **??**) suggested observing the aspects listed below during the selection of an indicator.

- **Sensitive to change in time:** An indicator should be usable along a time series of data, so it can be possible to see how the indicator have changed over time.

- **Sensitive to change across space or within groups:** An indicator must represent the changes occurred across space or within groups.

- **Predictive or anticipatory:** An indicator should be capable of predict or anticipate the signs of unsustainable conditions, and once the signal is received, the indicators can be used to identify the main causes for the unsustainable signal.

- **Reference or threshold values available:** Indicators will be more useful if reference or threshold values to assess them are available.

- **Unbiased:** Biases in the selection of sustainability indicators may occur due to various reasons, such as the existing knowledge of the index developer, political interests, and the background given in the existing literature.
- **Appropriate data transformation:** For most indicators, the identified indicator is not the raw data. Therefore, to obtain the value for the indicator, appropriate data transformations or calculations are needed. It is important to carefully develop or adopt the appropriate method for transforming the data into the meaningful indicator value.
- **Integrative:** The main causes that lead to the not sustainable conditions must be known so the process could be understood as a whole.

The increasing of sustainable development concepts and environmental concerns has been leading to a broad and strongly application of indicators by a large number of users in different contexts, including water resources (**??????**). The United Nations World Water Assessment Programme (**??**) comments that "a staggeringly extensive array of indicators have been developed, or are proposed, to monitor the state, use and management of water resources, for a wide range of purposes." These indicators can give information on current conditions of water resources, including recognizing all components contributing to the enhancement of water resources management. This data can be utilized to communicate the current status of existing water resources to the wider community and are powerful decision making tools and key components to monitor advances towards sustainable development within the water sector (**??**).

??) identified 170 indicators related to water use and management and evaluate how each one of them perform against a set of sustainability criteria. They found that only 24 indicators fulfill the majority of the sustainability criterias. Among the 24 sustainable indicators, is the Water Footprint (**??**). **??**) points that water footprint is an indicator that allows a comprehensive view of the sustainability of water use and can be assessed within the framework of IWRM. In the next section, the Water Footprint indicator will be explained in a more detailed way.

3.7 Water Footprint

The concept of water footprint was first introduced by **??**) who, inspired by the concept of the ecological footprint by **??**), developed an indicator to investigate water consumption and pollution along supply chains. Today water footprint has taken on a far greater role than that, becoming a powerful tool for assessing the sustainability of water use, exploring the possibility of water use reduction and encouraging the replacement of inefficient and polluting methods with more efficient and cleaner ones (**??**).

Basically, the water footprint expresses the human appropriation of water in terms of volume. Comparing this water footprint with the water availability of the study area, it is possible to evaluate the sustainability of this appropriation, so that is possible, thus, to improve the decision-making process in water resources (**??**).

??) presents the three pillars of smart water allocation:

- **Water footprint benchmarks per basin:** Establish maximum volumes of water that can be consumed or polluted by human activities per basin. Aims to ensure water sustainability within each basin.
- **Reference water footprints for products:** Aims to encourage producers to reduce the water footprint of their products to a reasonable reference level.
- **Fair sharing of water footprint between communities:** It aims to contribute to the debate on social equity. Water allocation must be ecologically sustainable and resource efficient, but only this does not guarantee that it is socially fair. There is a need to be an international consensus on what makes the water footprint of a community fair or acceptable given the maximum value of sustainable water footprint per global citizen.

Using the water footprint indicator provides valuable information to facilitate the water allocation process, both economically and environmentally, as it provides new data to address water scarcity and pollution issues (**??**).

Water footprint has already been proven useful in assessing risks related to water scarcity and pollution. It can be used together with economic instruments to gauge the implications of a water scarcity scenario on the economic development of a certain region. Thus, the water footprint should be used by decision makers to communicate with a wider audience, beyond the scientific community (**??**).

There are three types of water footprint: green, blue and gray. The green water footprint refers to the use by humans of water that evaporates from the soil surface (mainly due to the growth of crops and forests used for logging). The blue footprint refers to the consumptive use of superficial runoff water, in other words, it is the volume collected from some water source (surface or groundwater reservoir) that does not return to its original source. The gray footprint refers to the appropriation of the ability to assimilate pollutants from a given water source, ie, it measures the volume of water needed to dilute a particular polluting load dumped in a water body (**??**).

How the water footprint will be expressed will depend on the focus of the work. It is possible to calculate the water footprint of a specific process within a production chain, product, consumer, consumer group, producer, an entire economic sector, geographical

area (rural property, watershed, municipality, state, country, or even the entire planet) (**??????????**).

The water footprint can be estimated by various methods, each with different degrees of accuracy and specific limitations. **??**) present a series of equations for calculating the footprint of various services, products, groups of people, etc. **??**) developed a way of estimating agriculture's water footprint using only remote sensing data. **??**) used the CROPWAT model as an auxiliary tool to calculate the water footprint of various crops.

In the subsection below will be presented the calculation methodology proposed by **??**) for estimating agriculture's water footprint (regardless of the type of crop).

Green Water Footprint Calculation

Green water footprint is calculated as the ratio of the volume of "green water" used for crop production $CWU_g(m^3/m^2)$ to its yield $Y(ton/m^2)$ (Equation **??**).

$$WF_{green} = \frac{CWU_g}{Y} \tag{3.1}$$

"Total green water" is calculated as the sum of the "green water" used in each month $u_g(mm/month)$ over the entire growing season. Assuming that the water demand of the crop is fully met, the monthly green water use will be the smallest value between the effective rainfall (P_{eff}) and crop evapotranspiration (ET_c) (Equation **??**).

$$u_g = min(P_{eff}, ET_c) \tag{3.2}$$

There are several methods available for estimating evapotranspiration. **??**) calculated the water footprint using different evapotranspiration estimation methods to determine the difference in the WF values obtained by the different methods. His conclusion was that the method chosen for estimating evapotranspiration (and then using it to estimate water footprint) does not significantly alter decisions at the policy level related to water resource management, thus it is possible to use any of the estimation methods without prejudice to the final decision.

Blue Water Footprint Calculation

The blue water footprint (m^3/ton) is calculated by Equation **??**, in a similar way to the green water footprint.

$$WF_{blue} = \frac{CWU_b}{Y} \tag{3.3}$$

Blue water u_b is defined as the water used for irrigating the plantation. On a monthly scale, assuming that the irrigation water demand will be fully met, blue water will be equal to the highest value between zero and the difference between crop evapotranspiration and effective rainfall (Equation **??**).

$$u_b = max(0, ET_c - P_{eff}) \tag{3.4}$$

Gray Water Footprint Calculation

The gray water footprint (m^3/ton) of a crop (Equation **??**) depends on the amount of fertilizer applied on it per square meter (kg/m^2), where $alpha$ is the fraction of fertilizer carried by the runoff. $c_{max}(mgl^{-1})$ is the maximum acceptable concentration, $c_{nat}(mgl^{-1})$ is the natural concentration of the pollutant in the receiving body of water, and Y is the crop yield.

$$WF_{grey} = \frac{\alpha.AR.Y}{c_{max} - c_{nat}} \tag{3.5}$$

Total Water Footprint Calculation

The total water footprint is calculated by the sum of the three types of water footprint (green, blue and gray) (Equation **??**).

$$WF = WF_{green} + WF_{blue} + WF_{grey} \tag{3.6}$$

3.8 Uncertainties and the Decision Making Process

According to **??**) the rational decision making process is one that can achieve the pre-set objectives effectively and efficiently. **??**) divides the rational decision making process into 6 steps, they are:

1. Problem Definition
2. Criteria Identification
3. Weighting of criterias
4. Generation of alternatives
5. Classification of alternatives according to the criteria
6. Optimal solution identification

However, the decision maker can exchange the best solution for one deemed acceptable or reasonable based on his own rationality or interest (**??**).

It is essential that the social dimension is also included in the decision-making process. **??**) observed that, in developed countries, the quality of decision-making increased when social impact assessment began to be done, which can be understood as the process of identifying future consequences for individuals, organizations or macro-social systems of actions that can be taken in the present.

One of the major difficulties of the decision making process in water resources is the uncertainties associated with the behavior of the systems under study, especially those associated with the random behavior of hydrological events. **??**) classify the uncertainties inherent in mathematical modeling of hydrological systems into three types:

Type I uncertainties: These are those caused by ignorance and/or difficulties in natural process representation. So far, they are impossible to avoid, since every model is just a simplification of what happens in reality. The greater the sophistication of the model, the lower is this type of uncertainty.

Type II uncertainties: They occur due to the determination of model parameters from inadequate field samples. They can be decreased by increasing the amount of information collected.

Type III uncertainties: They are inherent in natural processes. Since it is impossible to reduce them, the only thing you can do is to know them and incorporate them into the planning.

??) points out several factors that generate uncertainties in the management of water resources, they are: randomness of hydrological events, adoption of inaccurate models, simplifying hypotheses, relativity of the principles adopted and connection with environmental and socioeconomic components which present great variability.

Another type of decision-making uncertainty that has not been mentioned above is future-related uncertainty (or randomness), it happens because decision-making process occur to meet a multiple number of objectives and that complex negotiations will be necessary for the decision-making process to take place (**??**).

According to **??**), there are two types of approaches to dealing with future randomness related to hydrological uncertainties:

1. **Explicitly stochastic approaches:** use probabilistic models to simulate future-

related randomness. Decision making is solved by optimization

2. **Implicitly Stochastic Approaches:** Its use is more common than the previous approach. It is assumed that future hydrological events are known before the decision-making process.

??) points out four steps that can be taken when facing a uncertainty scenario:

1. Ignoring uncertainties, which is not a prudent attitude, because it generates many associated risks
2. Avoid uncertainties through mitigating measures. This reduces the negative impacts caused by them, although it does not eliminate the problem source.
3. Reduce uncertainties by deepening research and collecting more data and information.

Knowing the uncertainties embedded in the models is very important, as uncertainties generate risks that hinder the rational decision making process. According to **??**), the 4 steps for risk management analysis are:

1. Risk identification
2. Risk Qualification
3. Risk Minimization
4. Mitigation or remediation of risk effects

There are three criteria for uncertainty decision making (**????**):

1. MaxMin Criterion: It is supposed that the worst case scenario will happen
2. MaxMax Criterion: It is supposed that the best case scenario will happen
3. Hurwicz Criterion: It's a middle ground between the previous ones, in it the least regrets are calculated

The most used criterion in the area of water resources has been MaxMin, where decisions are made taking into consideration that the worst scenario (extreme drought) will happen (**??**).

3.9 Multi-objective Optimization Models

Multi-objective optimization has a huge practical importance, since nearly all real-world optimization problems and most practical decision-making problems are ideally suited to be modeled utilizing multiple conflicting objectives. However, in the past, due to lack of suitable solution methodologies, these problems were solved by transforming the multiples objectives into a single objective. In a single-objective optimization problem, the task is to find one solution and, extending that idea to multi-objective optimization, it may be wrongly assumed that the task in a multi-objective optimization is also to find an optimal solution. This type of approach was not satisfactory, because multi-objective optimization problems often have not only one solution, but several (known as Pareto-optimal solutions, if we have conflicting objectives), so it is important to find as many optimal solutions as possible and not just one single solution (**??**).

Another difference between single-objective and multi-objective optimization is that in the latter there is an additional multi-dimensional space in addition to the search space common to all optimization problems. This additional space is called objective space; For each point in the search space, there is a corresponding point in the objective space (**??**). Figure **??** shows the representation of the decision variable space and the corresponding objective space.

Several multi-objective optimization algorithms make use of the dominance concept. In these algorithms, two solutions are compared based on whether one dominates the other or not. According to **??**) we can say that a solution x_1 dominates another solution x_2 if the following conditions are true

1. The solution x_1 is no worse than x_2 in all objectives.
2. The solution x_1 is strictly better than x_2 in at least one objective.

As mentioned earlier there is usually not only a single solution to multi-objective optimization problems, but a set of solutions. According to **??**) the concept most commonly used to define this optimal solution set is the Pareto Optimality (**??**) which is defined by:

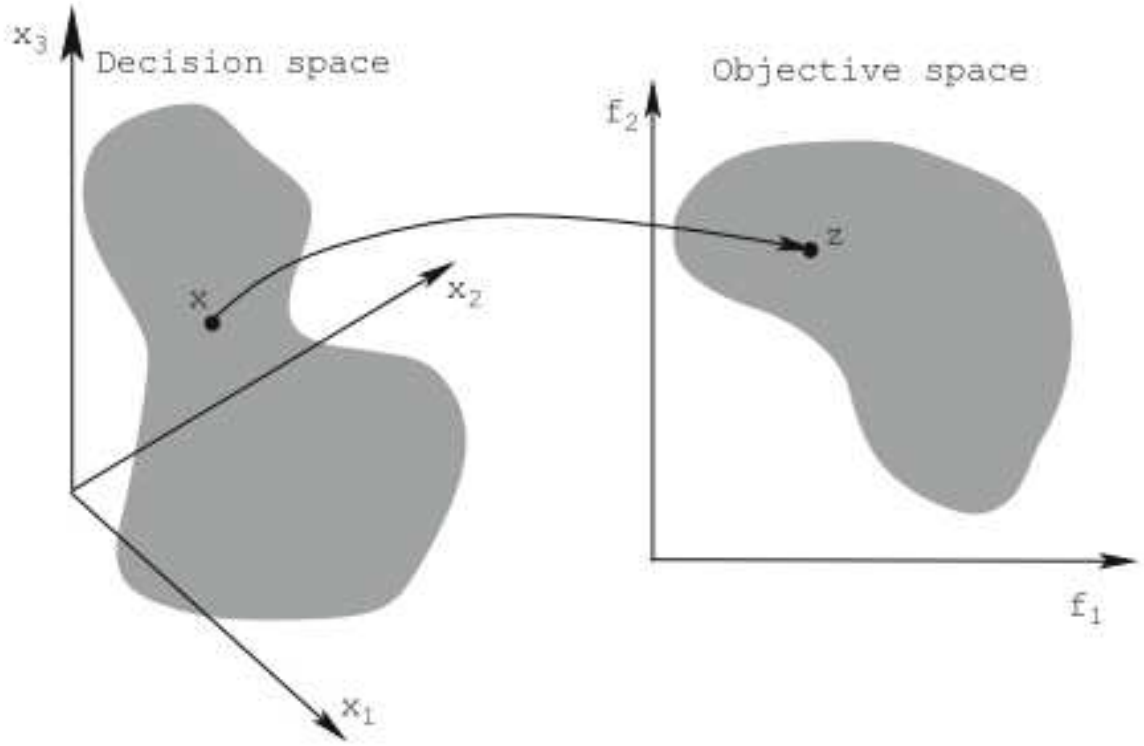
Pareto Optimal Definition: A point, $x^* \in X$, is Pareto optimal if there does not exist another point, $x \in X$ such that $F(x) \leq F(x^*)$, and $F_i(x) \leq F_i(x^*)$ for at least one function.

Where:

x: is a vector of decision variables

X: is the search space (often called the feasible decision space)

Figure 2 – Representation of the decision variable space and the corresponding objective space. Source: (**??**)



$F(x)$: is a vector of objective functions $F(x) = [F_1(x), F_2(x), ..., F_i(x)]$ which we want to minimize.

$F_i(x)$: is a objective function, also called criteria, payoff functions, cost functions, or value functions.

There are several methods used to solve multi-objetive optimization problems. Among them we can cite:

- **Weighted-Sum Approach**: The weighted-sum method, as the name suggests, join a set of objectives into a single objective by pre-multiplying each objective with a weight (**??**).
- **ε-Constraint Method**: Used for solving problems that have non-convex objective spaces, which weighted-sum approach faces difficulties (**??**).
- **Simulated Annealing**: This approach is used usually to solve large scale combinatorial optimization problems (**??**).
- **Quantum Annealing**: Similar to the Simulated Annealing, Quantum Annealing uses quantum algorithm and Quantum Adiabatic Computers to solve multi-objective combinatorial optimization (**??**).

- **Evolutionary Multi-objective Optimization (EMO) Method**: The algorithms that have propose to to deal with multi-objective optimization using evolutionary computation. There are several algorithms within this group, for instance: Strength Pareto Evolutionary algorithm (SPEA), Non-dominated Sorting Genetic Algorithm (NSGA), Vector-Evaluated Genetic Algorithm (VEGA), Pareto Archived Evolution Strategy (PAES), Particle Swarm Optimization, Artificial Immune Systems Algorithm, Estimation Distribution Algorithm, etc (**????**).

In this work, we choose to utilize SPEA2, a kind of genetic algorithm that belongs to the group of the evolutionary algorithms (EAs). During the last two decades, it was possible to see a dramatic increase in the development and application of various types of evolutionary algorithms, especially the genetic algorithms, undoubtedly the most popular of the several types of EAs. EAs have proven to be flexible and powerful tools for solving complex water resources problems and have been applied and different researches have been done in the water resource optimization (**??????**), including the optimization of the water use for agricultural irrigation (**??**). According to **??**), evolutionary computation will continue to evolve in the future as problems become more complex, uncertainties increases and social pressure for more innovative and efficient solutions increases.

4 Methodology

4.1 Strenght Pareto Evolutionary Algorithm 2 (SPEA2)

The Strength Pareto Evolutionary Algorithm (SPEA) is an algorithm for multiobjective optimization and an evolutionary algorithm of the field of evolutionary computing. It belongs to the field of evolutionary multi-object algorithms (EMO). SPEA is an extension of genetic algorithms used to solve multiobjective optimization problems. Other evolutionary algorithms similar to it are: Non-dominated Sorting Genetic Algorithm (NSGA), Vector-Evaluated Genetic Algorithm (VEGA), and Pareto Archived Evolution Strategy (PAES). There are two versions of SPEA, the original SPEA and its successor, SPEA2. It can be also mention two extensions, SPEA + and iSPEA (**??**).

The purpose of this algorithm is to locate and maintain a boundary of non-dominated solutions, also known as the Pareto Frontier. To do this it uses an evolutionary process (which includes procedures for genetic recombination and mutation) and a process that uses a combination of the concept of solution dominance with the neighborhood density concept (**??**).

Before detailing the operation of SPEA2, it is important to give a general explanation of the genetic algorithm, predecessor of SPEA. Genetic algorithms were first introduced by John Holland (**??**) and popularized by one of his students, David Goldberg (**??**).

These algorithms are inspired by the principle of natural selection and survival of the fittest, first introduced to the world in 1859 by English naturalist and physiologist Charles Darwin in his book "The Origin of Species." In his work, Darwin argues that, within a population, the fittest individuals are more likely to survive and, consequently, leave more offspring that will carry their genes and take them to future generations. Coupled with this process of natural selection are the phenomena of genetic recombination (also called "crossover") and mutation, which occur during the reproduction process and are vital to ensuring diversity among individuals and allowing fitters individuals to emerge in future generations.

According to **??**), there are basic procedures that are common to the implementation of any genetic algorithm, these are:

1. Choice of decision variables representation system

2. Generation of an initial population, containing various solutions to the problem.

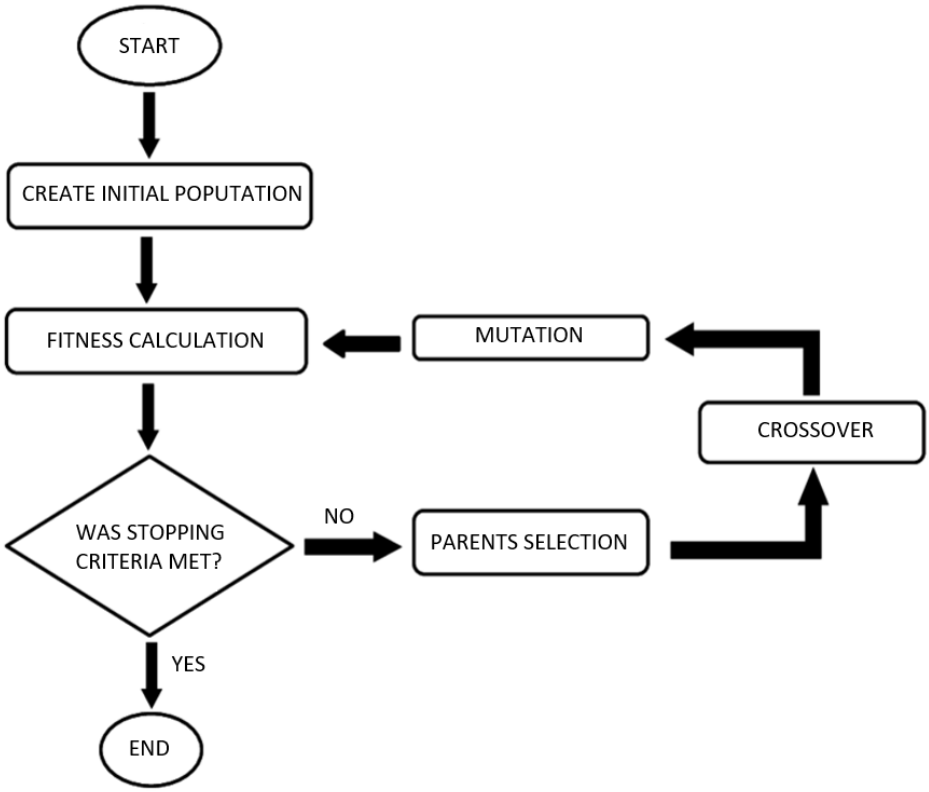
3. Definition of one or more objective functions

4. Specification of genetic operators for selection, recombination and mutation mechanisms

5. Determination of various vestments (initial population size, probability of recombination and mutation, termination condition, etc.)

The first version of the genetic algorithm, proposed by **??**), works in a relatively simple way to understand. First, possible solutions were represented in the form of "chromosomes", which are nothing less than strings of bits. The initial population consists of several randomly generated chromosomes from the search space (region where all solutions to the problem are contained). The next step is to evaluate the suitability of each solution using the objective function and then sort the solutions from the most fit to the least fit. The best chromosomes in the population are then transferred to an intermediate population, while the rest are discarded. A new generation of individuals is then produced by recombining the chromosomes of the intermediate population. A small percentage of the child chromosomes is modified by the mutation operator. This whole process is repeated, producing populations with increasingly fit individuals to the point where some termination criteria is met. This process is shown in Figure **??**.

Figure 3 – Genetic Algorithm.

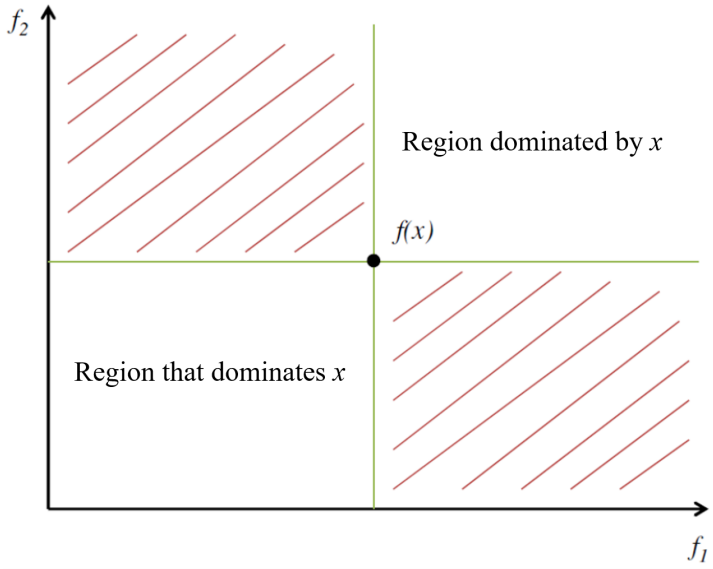


SPEA2 works similarly to Holland's original version, although it has some differences from it. Like Holland's algorithm, SPEA2 starts by generating an initial population composed of random individuals produced from the search space. After that, each individual's fitness is calculated (each individual has a fitness value for each objective function). These fitness values are subsequently used to analyze dominance relationships between individuals.

Consider a multiobjective optimization problem with r objectives, where we simultaneously want to minimize the r objective functions $f(x) = f_1(x), ..., f_r(x)$. One solution x is said to dominate another solution y if and only if $f_i(x) \leq f_i(y)$ to $i = 1, ..., r$ and $f_i(x) < f_i(y)$ for at least one objective function i.

Figure **??** presents, for a problem with two objectives, the region dominated by solution x, the region that dominates this solution, and the regions that neither dominate nor are dominated by it.

Figure 4 – Representation of the dominance concept in the objetctive's space.



A Strength value is calculated for each individual in the initial population, which is equal to the number of individuals dominated by the individual under analysis. Then, the Raw Fitness value is calculated, which is the sum of the Strengths of the individuals who dominate the individual under analysis. The more solutions dominated by an individual, the greater the value of their Strength, while the fewer individuals dominate the solution under analysis the lower their value of Raw Fitness. Therefore, if a solution is not dominated, the value of its Raw Fitness will be zero. When individuals are indifferent to each other (neither dominate nor are dominated by each other), no conclusion can be drawn from the concepts of dominance.

Since all non-dominated individuals will have the same value of Raw Fitness (zero),

some additional information is needed to differentiate them. In this case, the concept of neighborhood density is used to determine, among these individuals, which are the most fit. Neighborhood density is a decreasing function of the distance of the k nearest neighbor of the individual under analysis. In this study we considered $k = 1$. Equation **??** shows the formula for calculating neighborhood density.

$$D = \frac{1}{\sigma^k + 2} \tag{4.1}$$

Where:

D: Neighborhood Density

σ^k: Euclidean distance between individuals or, for $k = 1$, is Euclidean distance to nearest neighbor.

The neighborhood density value ranges from 0 to 0.5, where the highest value represents the case where the two individuals are equal (the Euclidean distance between them is zero). The lower the neighborhood density, the more isolated the solution is in relation to others, so it is more important to preserve it in order to maintain diversity among solutions (critical to helping the optimization method converge to the global optimum).

An individual's fitness will then be given by the sum of his Raw Fitness value and neighborhood density, as shown in Equation **??**. Then, the lower the value of fitness, the more fit the individual is, and the more likely they are to pass on their characteristics to the next generation.

$$F = RF + D \tag{4.2}$$

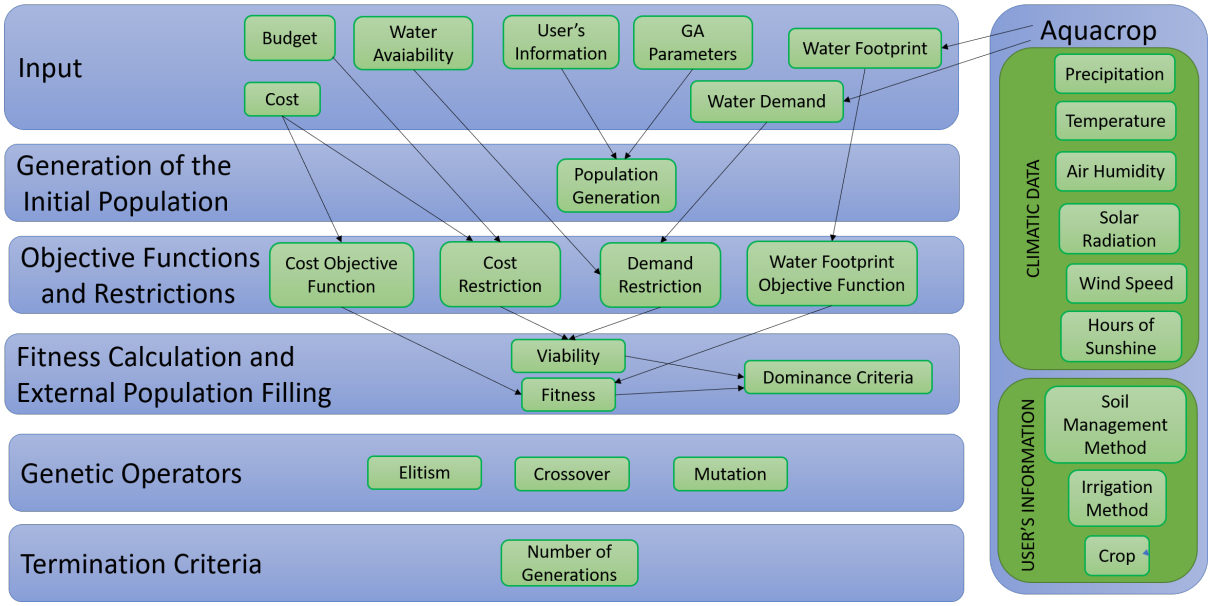
All non-dominated individuals in the population are transferred to the external population (population smaller than the initial population, which contains the best individuals and where the parents of the next generation will come from). If the external population is not fully populated, it is completed with dominated individuals, ranked in ascending order of Fitness value. If the number of non-dominated individuals exceeds the size of the external population, surplus solutions will be excluded in decreasing order of neighborhood density.

If the termination criterion is not met, individuals from the external population will be sent to genetic operators, where they will generate individuals for the new population, restarting the process, which will continue until a certain number of generations are reached or until termination criteria are met.

4.2 Optimization Algorithm

In order to obtain an algorithm that was capable of producing strategies for adapting to climate changes along the lines presented in this work, some adaptations were made to the original SPEA2 code. A code produced by **??**) (that is a adaptation of SPEA2 as well) was used as a basis for the development of the present source code. Figure **??** presents the general structure of the optimization algorithm, that will be detailed step by step into the following subsections. The code is presented integrally on Appendix **??**.

Figure 5 – General representation of the optimization algorithm.



4.2.1 Input

In order to the algorithm to work properly, a series of information should be provided either directly to the genetic algorithm (GA) or indirectly through Aquacrop. The data provided directly to the GA are the following:

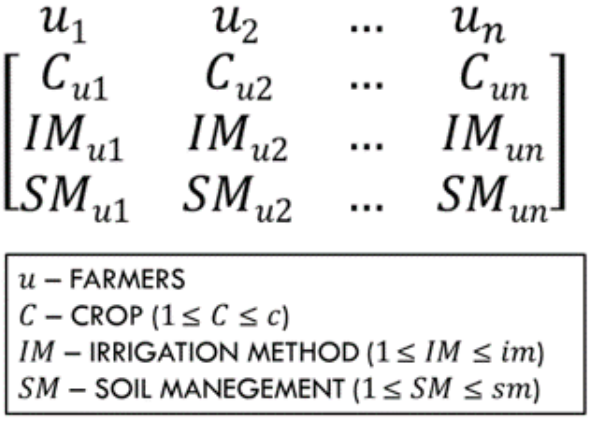
- **Budget:** The maximum value that should be expend on adaptation strategies.
- **Cost information:** The cost to make changes (in R\$/m^2) for each measure that could be taken.
- **Water availability:** The water availability (l/s) for all users considered into the adaptation process.
- **Users information:** Such as crop, irrigation method, and soil management method, provided according with the mathematical representation presented in the next topic.
- **GA parameters:** Number of individual in the initial and external population, probability of occurrence of crossover and mutations, and termination criteria.

- **Water demand:** It will be estimated by Aquacrop.
- **Water footprint :** It will be estimated by Aquacrop.

4.2.2 Mathematical Representation of the Problem

We choose to represent the problem mathematically through a two-dimensional matrix, where each column represents a user (u_n) and each row provides information about it. The first line contains information about the type of crop planted by that user (C_n), the second is the irrigation method used by him (MI_n) and the third is the soil management method practiced by him (MI_n). Figure **??** shows an example of a generic solution.

Figure 6 – Generic mathematical representation of a solution.



In order for the optimization algorithm to work properly, all information in the mathematical matrix must be numeric, so data on crop type, irrigation method and soil management had to be represented by numbers as explained below:

Crop Type: Crops suitable for cultivation in the study area were divided into c groups according to their water footprints. The value of the first row of the solution matrix ranges from 1 to c and indicates which crop group the user irrigates in their property. Where 1 represents the group that contains the crops with the largest water footprint and c is the group that has the lowest water footprint.

Irrigation Method: We considered the irrigation methods that are already used by the farmers and the most efficient ones. The total number of methods available for use (im) were identified by values ranging from 1 to (im), where, as for crops, they were organized according to their efficiency (here we consider the most efficient method as the one that wastes less water). The most inefficient method was identified by number 1, while the most efficient by the number im.

Soil management: The sm soil management strategies that could be implemented in the study area were identified and, as well as the previous characteristics, organized according to their effectiveness in saving water and consequently reducing the water

footprint. The value 1 was attributed to the no adoption of soil management methods, while the *sm* value was attributed to the most efficient soil management method.

4.2.3 Generation of the Initial Population

Before generating the initial population individuals, the study area current configuration was represented through the matrix presented in the previous section (same representation that will be adopted for the solutions). After that, initial population individuals were generated from the following rule: In each cell of the matrix, a random integer number will be stored. The value of that random integer number shall vary between the value stored in that same cell in the matrix that represents the current study area configuration and the maximum value that cell can get (c, im, or sm, for rows 1, 2, and 3 respectively).

Thus, the solutions generated will always be better (more efficient) or equal than the current configuration of the study area, therefore not allowing setbacks to be made. Limiting the maximum value of cells also prevents the suggestion of solutions that do not correspond to any methods (for instance, preventing a solution from suggesting that user x changes its irrigation method to method number 7, as there are only 6 methods available (ie method 7 does not exist)).

4.2.4 Aquacrop OS and the Water Footprint Calculation

Before initiating the optimization algorithm, the code uses Aquacrop OS software to calculate crop's water footprint. In the subsection below we will explain, in a general way, how Aquacrop works, how it differs from Aquacrop OS and how the genetic algorithm exchange information with this model.

4.2.5 Aquacrop

AquaCrop is a model for crop growth simulation, created by FAO to ensure food security and proper management of agriculture. It simulates the agricultural productivity of a given crop if a certain amount of water is supplied to it during its growing season. AquaCrop is particularly useful in cases where water is the limiting factor for crop yield.

There are a large number of crop growth simulation models available in the literature. Examples: DSSAT (**??**); CropSyst (**??**); Hybrid-Maize (**??**). However, a problem common to the vast majority of these models is the demand for a high amount of input data with high level of details, which is not available for the most part of the planet.

Aquacrop stands out from other models that serve for the same purpose as it because it requires a relatively smaller number of parameters to be set by the user, and

has been validated and applied to various crop types in multiple climate types and in different locations (**??**).

??) compared the performance of AquaCrop with CROPWAT (older version of AquaCrop) for estimating the water footprint of cotton in a region of northern Greece. The results showed superiority of AquaCrop in relation to the other model in this regard.

Currently, AquaCrop is one of the main tools used to calculate the water footprint of irrigated agriculture. It is possible to cite several works where this model was used for this purpose, among them we have: **??**), **??**) and **??**).

AquaCrop is available in three versions: A standalone Windows application, a GIS plugin and an open-source version for Matlab. In this work, we will use the Matlab version.

The following description of how AquaCrop works was based on its reference manual, available at **??**).

Similar to other crop growth models, AquaCrop is composed of a set of sub-models that simulates: the soil (and its water balance), the crops (its growth, development and yield), the atmosphere (its temperature, precipitation , evaporation, and concentration of carbon dioxide), and soil and crop management practices (irrigation and soil fertilization, for instance).

AquaCrop simulations are done on a daily time scale and can be represented by calendar days or growing degree days. AquaCrop simulates the soil water balance by accounting for the inlet and outlet water flows of a control volume, as shown by Equation **??**.

$$S_{[t]} = S_{[t+1]} + PR_{[t]} + IRR_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]} \tag{4.3}$$

Onde:
$S_{[t]}(mm)$ - Water stored in the soil at the end of the day t
$S_{[t+1]}(mm)$ - Water stored in the soil at the beginning of the day t
$PR_{[t]}(mm)$ - Daily rainfall t
$IRR_{[t]}(mm)$ - Irrigation water applied in a day t
$CR_{[t]}(mm)$ - Deep aquifer capillary rise in a day t
$ET_{[t]}(mm)$ - Daily actual evapotranspiration t
$RO_{[t]}(mm)$ - Daily surface runoff t
$DP_{[t]}(mm)$ - Percolation to deep aquifer in a day t

To calculate effective precipitation, surface runoff and soil water infiltration, AquaCrop uses the Soil Conservation Service (SCS) method. Actual evapotranspiration is separated into two parts: one non-productive (evaporation of water from the soil

surface) and one productive (transpiration from plants). Thus, it is possible to simulate the effect of management practices on these two plots separately. This program feature is fundamental for estimating the water footprint.

Evaporation from soil surface is calculated by multiplying potential evapotranspiration by factors that take into account soil water availability and the fraction of the soil surface that is covered by the leaves (canopy cover). The calculation of water evaporation over the uncovered soil surface is done in two steps. In the first step, which occurs whenever the soil is wet due to rain or irrigation, the evaporation rate is determined solely by the energy available to evaporate water. In the second, evaporation ceases to depend only on available energy, and now also depends on the hydraulic properties of the soil.

To estimate the biomass production (B) of a given crop, AquaCrop take into account two parameters: water productivity (WP) and crop transpiration (Tr) (Equation **??**). Water productivity is a parameter that expresses biomass production (kg) per m^2 of area, per mm of transpirated water, adjusted according to the evaporative demand of the atmosphere and the concentration of CO_2 in the air.

$$B = WP \times \sum Tr \tag{4.4}$$

It is possible to simulate various options of water supply, ranging from rainfed agriculture to fully irrigation. It is also possible to choose between different types of irrigation methods (surface, sprinkler or drip) and soil management practices (soil fertilization, plastic or organic mulch, barriers to reduce runoff, and plant control). The impact of water stress on plant growth is modeled with three types of response: change in leaf growth rate, stomatal closure and senescence acceleration.

Biomass production can be reduced by the action of some external agents, they are:

- **Temperature:** Extreme temperatures (too high or too low) affects crop growth
- **Soil Salinity:** High salinity soils have a negative influence on plant growth
- **Water stress:** Lack of water, especially at some stages of plant growth, can cause a significant decrease in productivity
- **Soil fertility:** Poorly fertile soils are limiting factors in crop growth

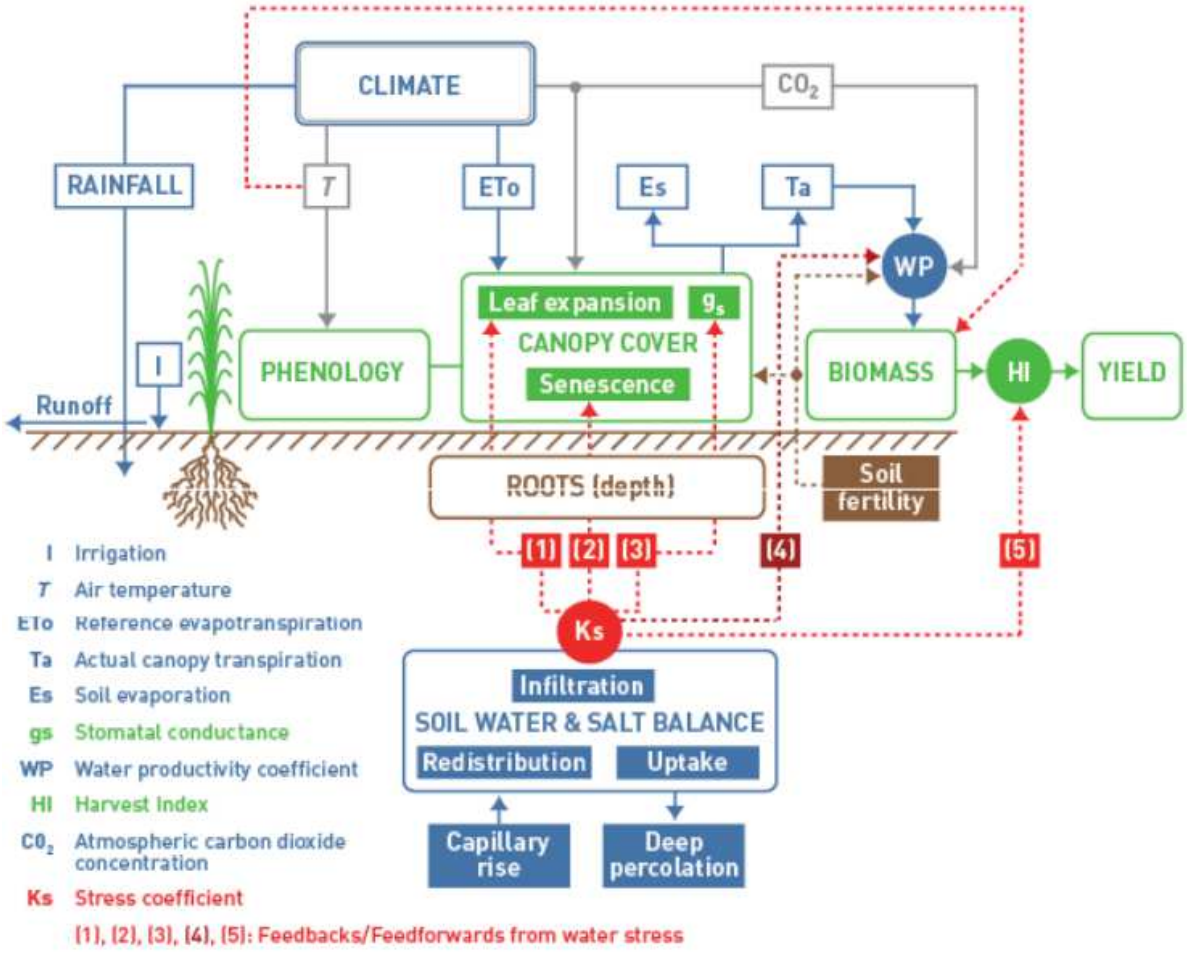
After estimating biomass, it is multiplied by the HI factor to obtain crop's yield Y. HI (harvest index) is the harvest factor and represents the percentage of biomass that actually becomes harvest. HI varies from culture to culture and is adjusted according to water and temperature stress, depending on how long the crop is exposed to stress

and how intense it is. For this, the harvest index reference value HI_0 is multiplied by an adjustment factor f_{HI}, as shown by Equation **??**.

$$HI = f_{HI} \times HI_0 \tag{4.5}$$

The overall structure of AquaCrop, including its main components, as well as the relationship between them, can be seen in Figure **??**.

Figure 7 – General operating structure of AquaCrop. Source:(**??**)



4.2.6 AquaCrop-OS

AquaCrop OpenSource (or AquaCrop OS) is an open-source version of AquaCrop, implemented in Matlab and also compatible with the free GNU Octave language. Unlike its original version, which was developed in Delphi and distributed only for Windows, AquaCrop OS can run on Windows, Macintosh and Lixus operating systems.

An additional feature of AquaCrop OS is the ability to perform multiple simulations simultaneously (Batch run), significantly reducing the total processing time for large or complex projects.

Among all the features of AquaCrop OS, perhaps the one that is most relevant to this work is its ease of integration with other models. AquaCrop OS follows the OpenMI (Open Modeling Interface) standard, which is basically an interface standard designed to allow data to be exchanged between different models at runtime. This ease of connection allows AquaCrop OS to be part of integrated models for water resources management.

4.2.7 GA - Aquacrop OS Interaction

Both input and output data from Aquacrop OS are done via text files (extension .txt). This feature has made it much easier to integrate AquaCrop OS with the genetic algorithm, as this file extension is very simple to open, read and edit in Matlab. Input files can be divided into two categories, essential and optional. The essentials files are the ones required to make the model work, while the optional ones may or may not be necessary, depending on the type of simulation you want to perform.

Essential input files include information such as: simulation's start and end date, climate data on daily basis (precipitation, temperature, air humidity, solar radiation, wind speed, hour of sunshine on a day, etc.), soil profile data, crop data, information on irrigation methods used, information on soil management strategies used, aquifer data (if present), and initial soil water content data. Optional input files may include data about: soil texture, soil hydraulics, crop rotation calendar and irrigation calendar.

Among all input files, GA received permission to edit the following parameters in the following files:

- **Crop parameters file:** All parameters can be edited.
- **Irrigation methods parameters file:** The parameters concerning the efficiency of the method and the percentage of soil surface that is wetted can be changed.
- **Soil management methods parameters file:** Two parameters can be changed. The first indicates whether or not there is mulching on the soil, while the second specifies the reduction in soil water evaporation due to the presence of mulching (the plastic mulching causes a greater reduction in evaporation than the organic).

After running Aquacrop, the results produced are written in the output files. Among the miscellaneous data provided by the program, only four variables are imported and used by the GA to calculate the water footprint and water demanded for irrigation, they are:

- Water evaporation from soil surface (Es) $[mm]$
- Crop transpiration (Tr) $[mm]$
- Crop Yield ($Yield$) $[ton/ha]$
- Water used for irrigation ($TotIrr$) $[mm/m^2]$: This data is used to calculate the farmer's water demand for irrigation

4.2.8 Water Footprint Calculation

Based on the data provided by Aquacrop, it is possible to calculate the water footprint (WF) in liters per kilogram (l/kg) using the Equation **??**. In this work only the blue and green portions of the water footprint were considered.

$$WF = 10 * \frac{Es + Tr}{Yield} \tag{4.6}$$

Before starting the interactive process, GA calculates the water footprint for all combinations of crop type, irrigation method and soil management. As this work considers six types of crops, six types of irrigation methods and three soil management possibilities (totaling 108 possible combinations, ie 108 WF calculations), it was realized that it was much faster (in processing time) to calculate the footprint of all possible scenarios than individually calculate the footprint of all users of all individuals of all generations (considering 1000 generations, 500 individuals per population and 27 users, there are 13.5 million WF calculations).

In this work, to estimate the water footprint of each farmer, a simulation of one year long as performed. The sowing data was always put in the begging of the dry period (were the demand for water for irrigation is bigger). So, the water footprint was estimated based on the amount of water needed to supply a specific crop along a year, divided by the annual yield of that same crop.

4.2.9 Optimization Objectives and Constrains

We define two objective functions for the adaptation process: one to minimize the system's WF, and another to minimize adaptation's financial cost. A set of Pareto solutions considering the two main objectives of the adaptation process, since these two main objectives are opposed (the more the efficiency increases, the more it costs) was also generated. The intention is to present this set of Pareto solutions to the users as a list of options from where they can choose one solution, in a participatory process, and implement it on the ground.

Objective # 1 Minimization of the water footprint

This objective function aims the maximization of the water use efficiency through the minimization of the sum of all users water footprint, as shown in Equation **??**.

$$f_1 = \sum_{i=1}^{u_n} WF_i \tag{4.7}$$

Where:

f_1: First objective function fitness value

u_n: : Number of users

WF_i Water footprint of user i (l/kg)

The formulation of this function has the purpose of inducing the optimization algorithm to prioritize smallholder users. This is possible because a reduction of the WF of a smallholder user has the same impact in the fitness value of the same reduction to a larger user. Reducing the WF of a large user costs more than reducing the WF of a small user, then it is more advantageous (for the optimization algorithm) to adapt the smaller user first.

Objective # 2 Minimization of the adaptation monetary cost

This objective function aims to minimize the monetary cost to implement the adaptation strategies. It is calculated based on what changes from one time step to the next and the cost to do so. Equation **??** shows the second objective function.

$$f_2 = \sum_{i=1}^{u_n} (c(MI_i) + c(MS_i)) * A_i \tag{4.8}$$

Where:

f_2: Second objective function fitness value

u_n: Number of users

$c(MI_i)$: Unitary cost $(R\$/m^2)$ to implement user's i new irrigation method

$c(MS_i)$: Unitary cost $(R\$/m^2)$ to implement user's i new soil management method

A_i: User's i irrigated area (m^2)

Variables $c(MI_i)$ and $c(MS_i)$ vary according to the different options of methods that the user could choose (each option has its specific cost). The value of these two variables is assumed to be equal to zero if there is no change in irrigation method or soil management method of the user i in the time step since we want to calculate the cost to change. The cost to change crop type was not taken into consideration in this work but in further research, it could be inserted through a $c(C_i)$v term into the equation.

Besides these two objectives, two constraints were imposed to ensure that the adaptation cost does not assume too high values and that the demand does not overcome water availability. Solutions that violates at least one constraint are considered unviable.

Restriction # 1: If the cost to implement a solution is bigger than a previously established value (budget), that solution is considered unviable. This constraint aims to prevent the suggestion of adaptation strategies that are out of the local user's financial capability.

Restriction # 2: If the total water demand (of all users) is bigger than the water availability for the time period, that solution is considered unfeasible. This constraint aims to prevent the algorithm to suggest solutions that are in controversy with the potential impacts of climate change.

In the study area, the adaptation strategies focus on more efficient irrigation methods, soil management methods and changes in irrigated area. Among the farmers considered, none currently uses improved soil management practices, so all the surveyed methods are suggestions for future adoption during the adaptation process. Among all practices, only the mulching practices were considered, since they are the only ones that are simultaneously simulated by Aquacrop OS and are compatible with local crops.

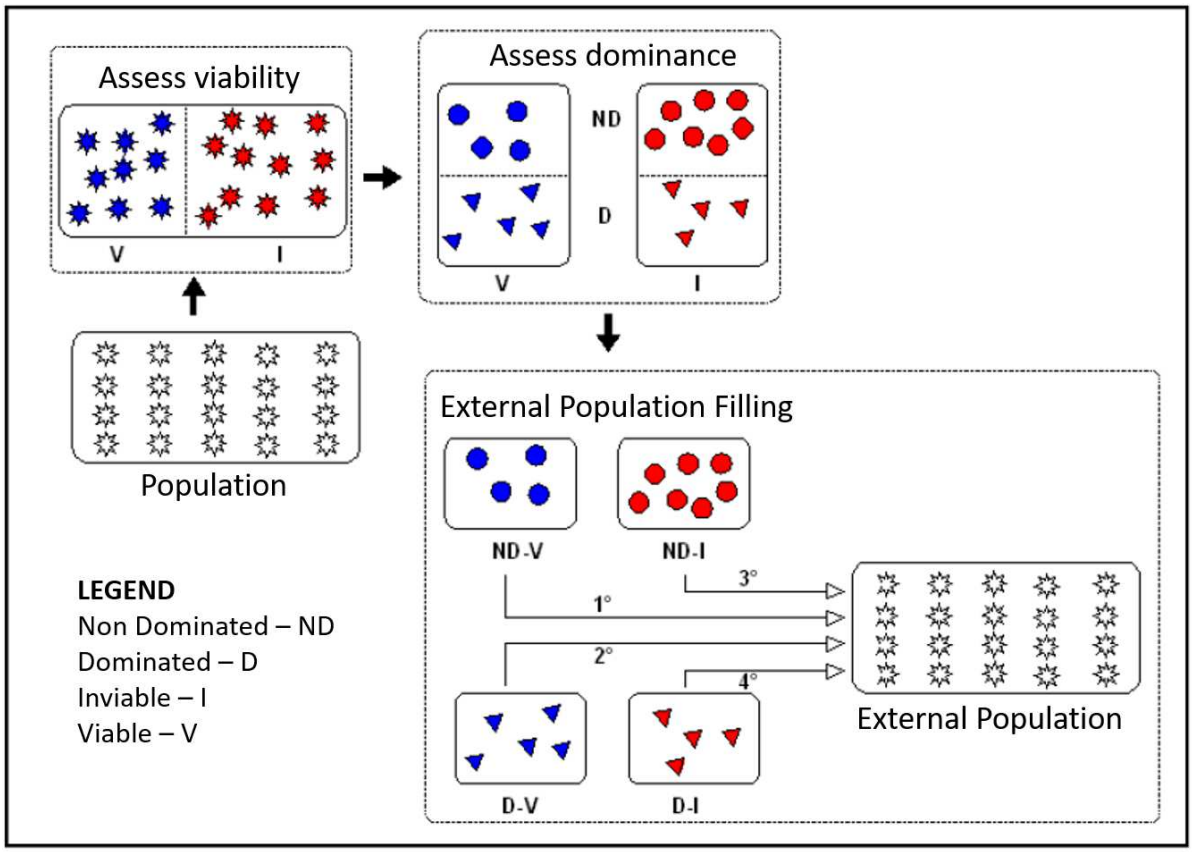
4.2.10 External Population Filling

After being divided into viable and unviable, the solutions are evaluated separately into each subgroup according to the concepts of dominance and neighborhood density, discussed earlier in this work. There is also the option of evaluating individuals firstly through the concept of dominance and then dividing them according to viability. However, in this paper we chose to use the first form because, in this case, it is more important that an individual is viable than not dominated.

After separating individuals by viability and dominance criteria, the external population is filled following the order of priority listed below and illustrated in Figure **??**. If it is not possible to allocate all individuals from the same subgroup into the external population, priority will be given to those with the lowest $Fitness$ value.

1. Viable and non-dominated individuals
2. Viable and dominated individuals
3. Inviable and non-dominated individuals
4. Inviable and dominated individuals

Figure 8 – External population filling according to the concepts of viability and dominance. Source: (**??**)



4.2.11 Selection of Individuals and Genetic Operators

The Tournament Method was used to select individuals for reproduction. This method begins randomly selecting two individuals from the external population, choosing the most suitable between this two and forwarding it to the reproduction mechanism. To determine which individual is more fit, we used the same criteria that was utilized to fill the external population as shown in Figure **??**. Thus, the best individuals and those who are in greater quantity in population are more likely to generate offspring.

The genetic operator used in this work was *Crossover* average (**??**). In this operator, the son is generated by the arithmetic mean of his two parents, as shown by Equation **??**. As in this work the solutions could only assume integer values, if the result is a decimal number, then it is rounded to the nearest integer.

$$Son_{i,j} = round\left(\frac{Father_{i,j} + Mother_{i,j}}{2}\right) \tag{4.9}$$

Where:

$Son_{i,j}$ is the element of line i and column j of son solution

$round()$ is the function that rounds a decimal number to its nearest integer

$Father_{i,j}$ is the element of line i and column j of father solution

$Mother_{i,j}$ is the element of line i and column j of mother solution

Both the genetic operator and the mutations were associated with a probability of occurrence. As in nature, reproduction by *Crossover* had a high probability of occurrence, while mutations had low probability. If the probability of occurrence was not met, the reproduction would not occur and the son would be considered as a identical copy of his father or mother (the one who had the highest fitness considering the same criteria previously mentioned).

Two types of mutation were used, one is a uniform mutation and the other is a directed mutation. The uniform mutation could be applied to all individuals if, of course, the probability of occurrence was met. Directed mutation was applied only to unviable individuals, in order to accelerate the convergence of the algorithm.

If the probability of occurrence of the uniform mutation would been met, the son solution was entirely replaced by a random solution generated in the same way as the individuals of the initial population, as explained in session **??**.

Directed mutation, unlike uniform mutation, was not applied to the sons, but to the parents. If the probability of occurrence of the mutation was reached and one of the parents was not viable, this individual was modified as shown by Equation **??**.

$$Father_{i,j} = round\Big(Father_{i,j} - (Father_{i,j} - IniConfig_{i,j}) * k\Big) \tag{4.10}$$

Where:

$Father_{i,j}$ is the element of line i and column j of father/mother solution

$round()$ is the function that rounds a decimal number to its nearest integer

$IniConfig_{i,j}$ is the element of line i and column j of study area current configuration matrix

k is a random number between 0 and 1.

This mutation works by lowering the cost to implement the adaptation strategy while decreases the reduction in water footprint. Thus, an solution that was previously considered unviable, because it had a higher cost than the previously established budget, may now be viable. However, a viable individual under the second constraint (which considers unviable all individuals who has demand greater than availability), may become unviable.

There is no directed mutation that can act simultaneously in favor of both constraints, since an improve in one represents an worsen in the other. In our case, it is more difficult to obtain solutions that comply with restriction 1 (cost) than with restriction 2 (availability), so it was decided to implement a mutation that would lower the cost, even if this would lead to an increase in demand.

4.2.12 Termination Criteria

The termination criteria defined is quite simple. The algorithm continues to make interactions (generations) indefinitely until the first viable solution is found, after that a predefined number of interactions (generations) are performed before the algorithm stops.

4.2.13 Seeding

A well-known heuristic technique in genetic algorithms used to accelerate the convergence process is *Seeding*. The *Seeding* process involves inserting one or more than one solutions that are potentially good candidates for solving the problem into the initial population (**??**). In this work, two simulations were made, one with *Seeding* and one without it, to determine if the use of this technique would produce any significant difference in the algorithm performance. The simulations were done in duplicate to ensure that the method converged.

Comparing simulations results with and without *Seeding*, it can be observed that the use of this technique made no difference in the number of generations, in other words it did not decrease the processing time. This may be due to the fact that directed mutation is already accelerating this process, making *Seeding* not very effective.

Looking at the Pareto frontier graphs without (Figure **??**) and with *Seeding* (Figure **??**), no significant difference could be seen between them. The use of *Seeding* may have helped the algorithm explore more search space locations, slightly improving the diversity of the solutions, but it did not cause a significant improvement of the final result.

Given these results, it was decided not to use *Seeding* in the next simulations, since it was seen that in this case this technique does not make significant difference in the algorithm performance and in the final results.

4.2.14 Elitism

Similar to *Seeding*, Elitism is another technique widely used to improve the performance of genetic algorithms. Elitism, in its essence, consists of allocating the best individuals of the current population directly into the next generation (without they having to go through the genetic operator mechanisms). This technique is used to preserve the best solutions found so far (**??**).

Figure 9 – Pareto frontier without the use of *Seeding*.

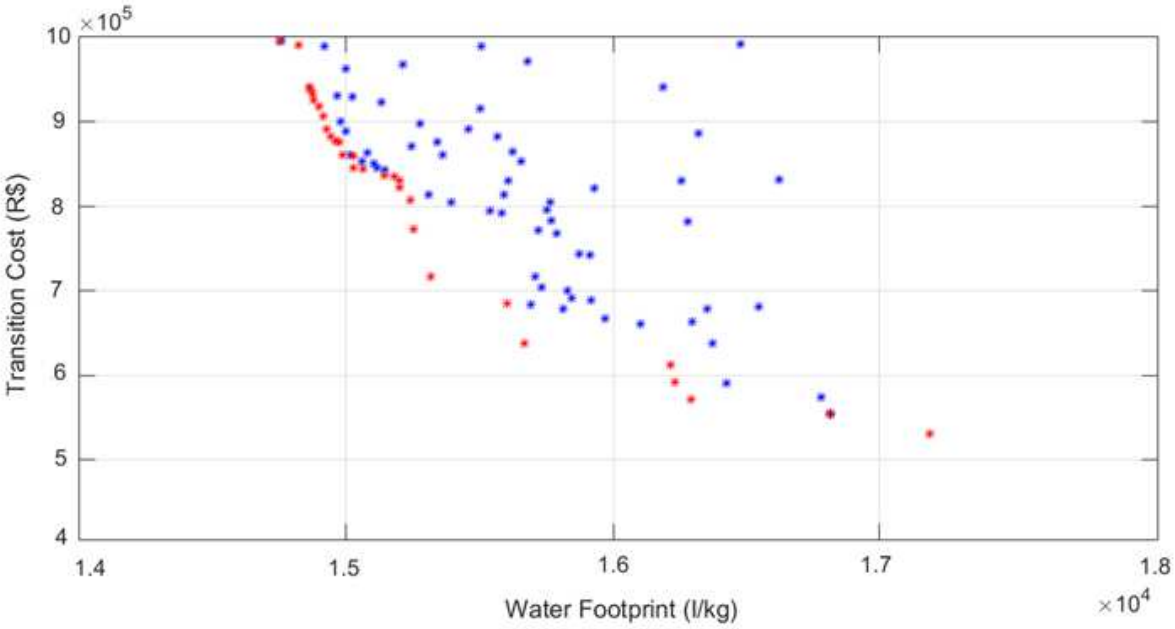
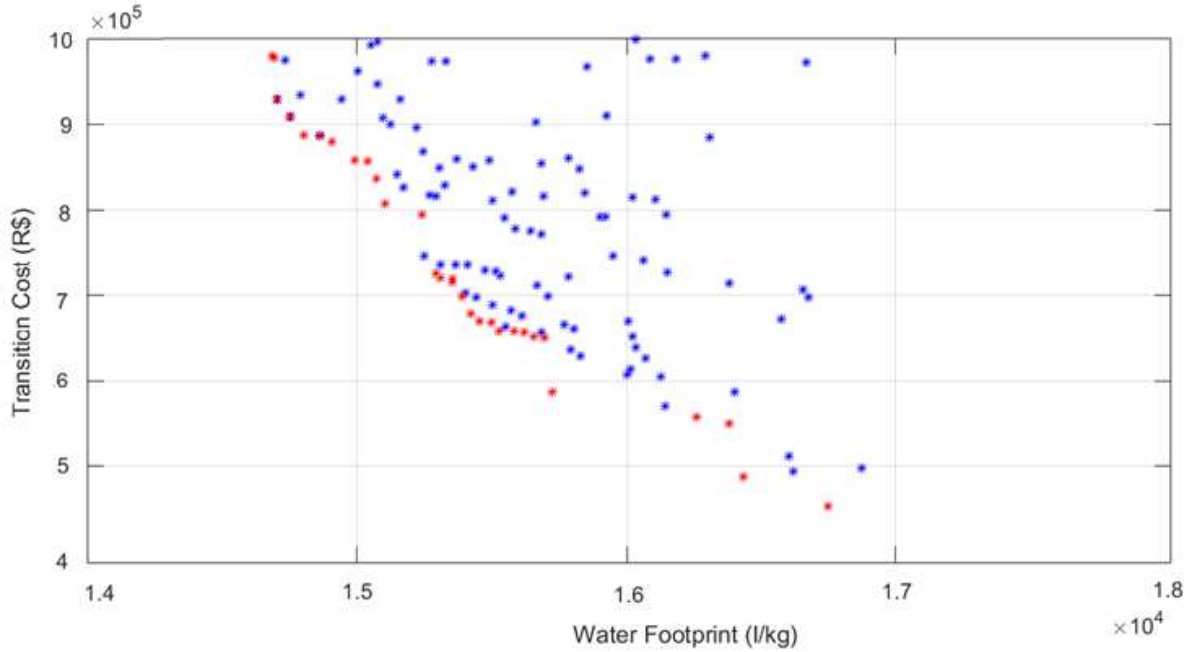


Figure 10 – Pareto frontier with the utilization of *Seeding*.



To test if the use of this technique would produce any significant difference in the algorithm performance, simulations were performed without and with the use of elitism. In those who used it, several numbers of individuals that pass directly to the next generation were tested (10, 50, 100, 150 and 200 individuals) in order to determine the optimal number of individuals.

Figure **??** shows that without the use of Elitism the Pareto frontier could not be

formed, since the algorithm converged to a single solution. So to prevent the happening of this problem, it is necessary to allocate the best solutions directly to the next generation.

Figure 11 – Pareto frontier without the use of Elitism.

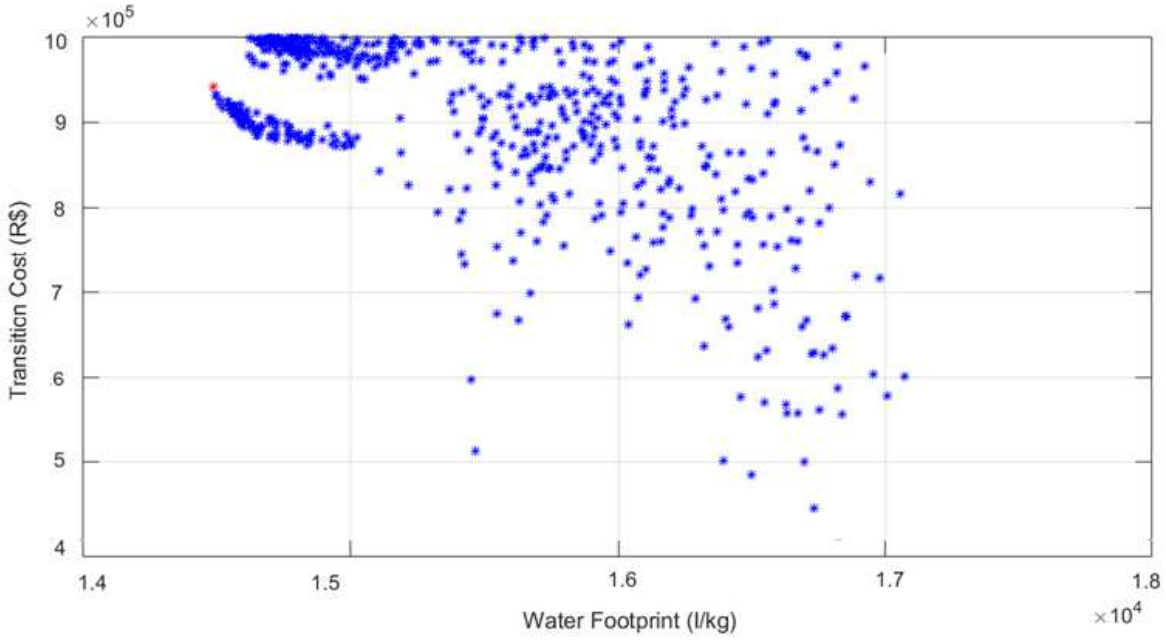


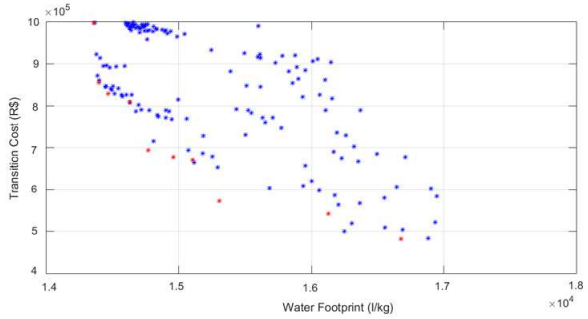
Figure **??** shows the Pareto frontiers for different numbers of individuals taken directly to the next generation by Elitism. Based on the analysis of these graphs, it is possible to conclude that the case **??**, where 50 individuals were used, was the one that presented the best result and, therefore, will be used from now on in the next simulations.

4.3 Optimization model

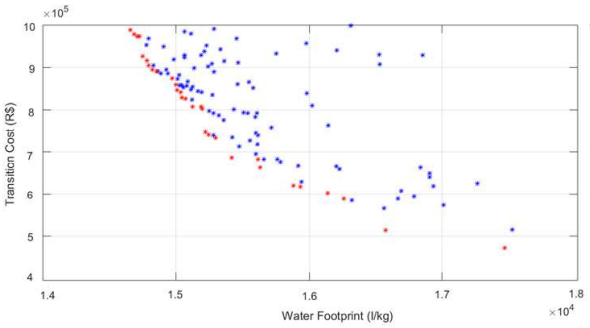
In the current research, an adaptation strategy in the agricultural sector is defined as all the potential changes or measures that a user can adopt in order to compensate the negative effects of climate change. The users can increase the water use efficiency/sustainability (changing to a more efficient irrigation method or adopting improved soil/crop management that requires less water) or reduce the crop area to consume less water, causing an undesirable effect of reduction in food production. Users will reduce crop area only if the strategy of the increase of water use efficiency/sustainability does not produce the expected results. The adaptation strategy is generated in several time steps. For the generation of each step, an optimization adaptation algorithm is executed once; in other words, the algorithm is designed to provide the answer for a single step and not for the complete adaptation strategy (set of all the steps) at once (Figure **??**). The proposed method helps to determine the way that the users should evolve the water usage from the current situation to the ideal situation (step by step), considering their living environment.

Figure 12 – Pareto frontiers for different numbers of individuals taken directly to the next generation by Elitism.

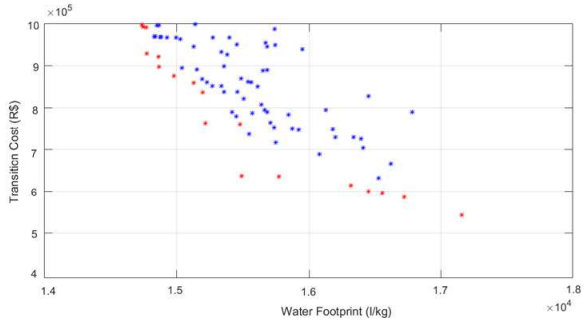
(a) 10 individuals



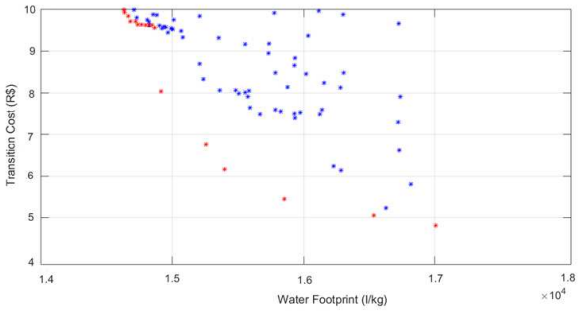
(b) 50 individuals



(c) 100 individuals



(d) 150 individuals



(e) 200 individuals

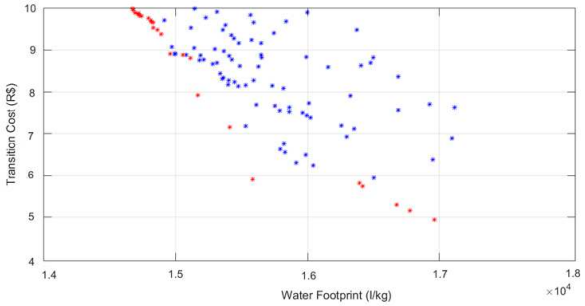
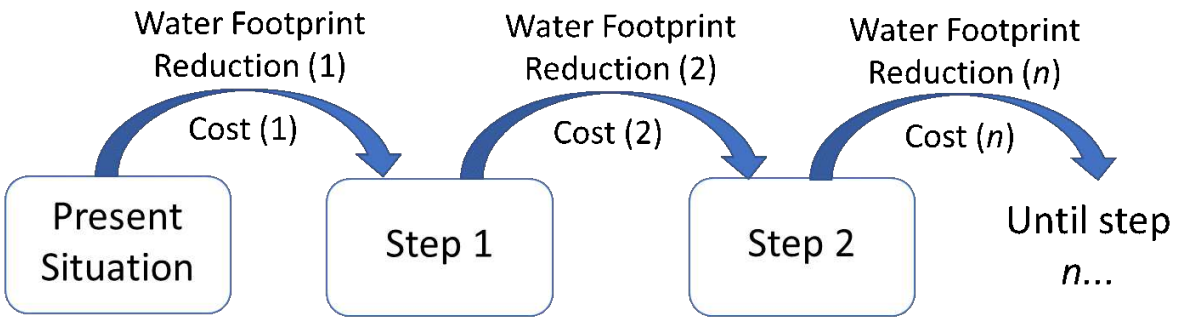


Figure 13 – Structure of the adaptation strategy produced with the proposed methodology.

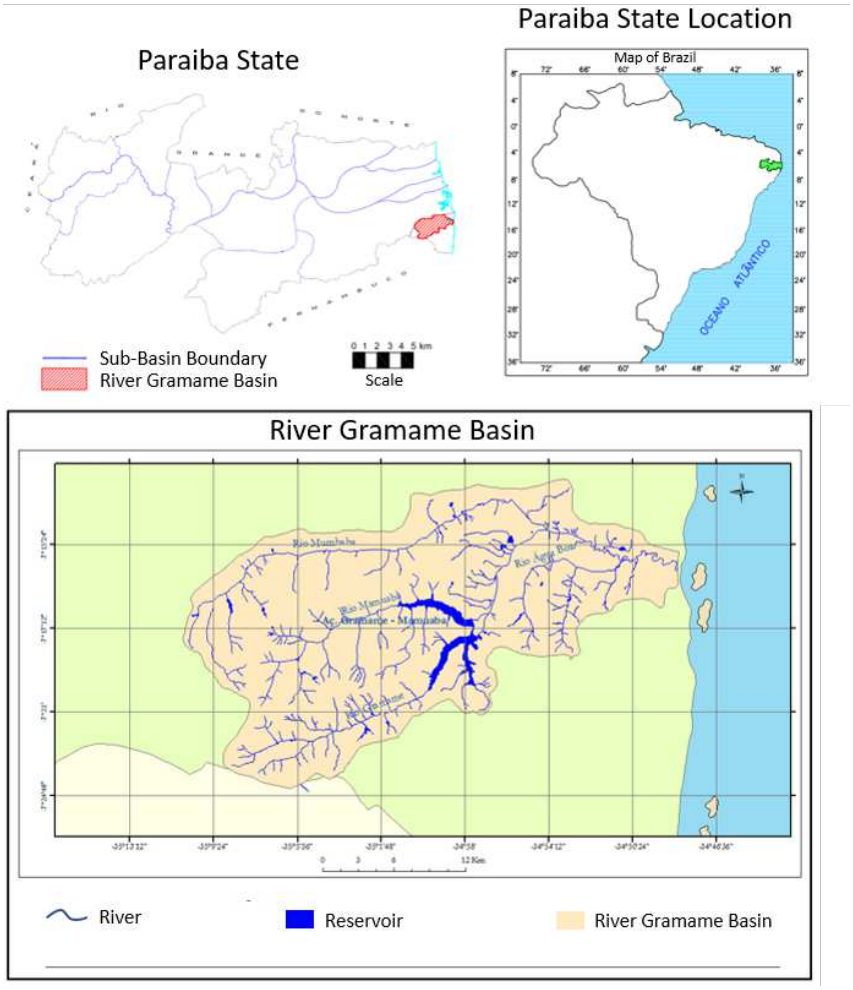


The size of the time interval considered in each step may be different (1, 2, 5, 10 years, etc.). Thus, the methodology users', e.g. the local water resources managers, can select the time period for achieving specific goals. Since each step is processed by a different optimization, these time ranges may also differ at each optimization step. It is also possible to consider additional changes, such as the climate, the users and the study area at each step, making the adaptation process much more flexible and dynamic. In the current research, the total time interval was defined from 2020 to 2070 and the time step was 10 years, hence the adaptation strategy was subdivided into 5 steps. Estimations about the last year of the decade were used to represent and product the results for the entire decade, since the strategies represents what should be done during the entire decade to reach its end adapted to the impacts of climate change that it is expected to occur within that same decade. After the completion of the first optimization set, one of the non-dominated solutions is selected as the starting point of the next optimization, which aims to determine the best strategies that are going to be used in the next step of the adaptation process, and so on. On the ground, this choice could be done by the farmers according to their interests. Since none solution is better than the other, one solution was picked randomly and was considered as if it was the farmer's choice, so the optimization process could be triggered.

5 Application

The Gramame river basin is located between latitudes $7°C11'$ e $7°C23'$ South and the longitudes $34°C86'$ e $35°C10'$ West on the southern coast of the state of Paraíba, Northeast of Brazil, as shown in Figure **??**. This basin is considered strategic due to its importance to the region. In it is inserted the main reservoir from the coastal region of the state, Gramame-Mamuaba. This reservoir is responsible for supplying water for the capital of the state of Paraíba, the city of João Pessoa, which there are 720,954 inhabitants according to **??**). In addition, the Gramame reservoir serves as a water source for irrigation (**??**).

Figure 14 – River Gramame basin. Sources:(**????**)



Within the Gramame basin there are three sub-basins: river Mumbaba sub-basin, river Mamuaba sub-basin and river Água Boa sub-basin. Gramame basin area as well as the area of its sub-basins can be seen in Table **??**.

Table 1 – River Gramame basin and its sub-basins areas. Source:(**??**)

Basin / Sub-basin	**Area**
Gramame Basin	589,1
Mumbaba Sub-basin	177,2
Mamuaba Sub-basin	128,0
Água Boa Sub-basin	65,4

Socio-economic characterization

The Gramame River basin is composed of the municipalities of Alhandra, Conde, Cruz do Espirito Santo, João Pessoa, Santa Rita, São Miguel de Taipu and Pedras de Fogo. The percentages of basin area participation by municipality are shown in Table **??** and the political map of the basin is shown in Figure **??**.

Table 2 – Participation of each municipality on the basin. Source:(**??**)

Municipality	**Municipality Area** (km^2)	**Municipality Area on basin** (km^2)	**Participation (%)**
Alhandra	224,42	99,72	16,93
Conde	164,10	76,47	12,98
Cruz do Espírito Santo	189,32	3,50	0,59
João Pessoa	209,94	59,07	10,03
Santa Rita	762,33	155,59	26,41
São Miguel de Taipu	63,60	2,20	0,37
Pedras de Fogo	348,02	192,56	32,69

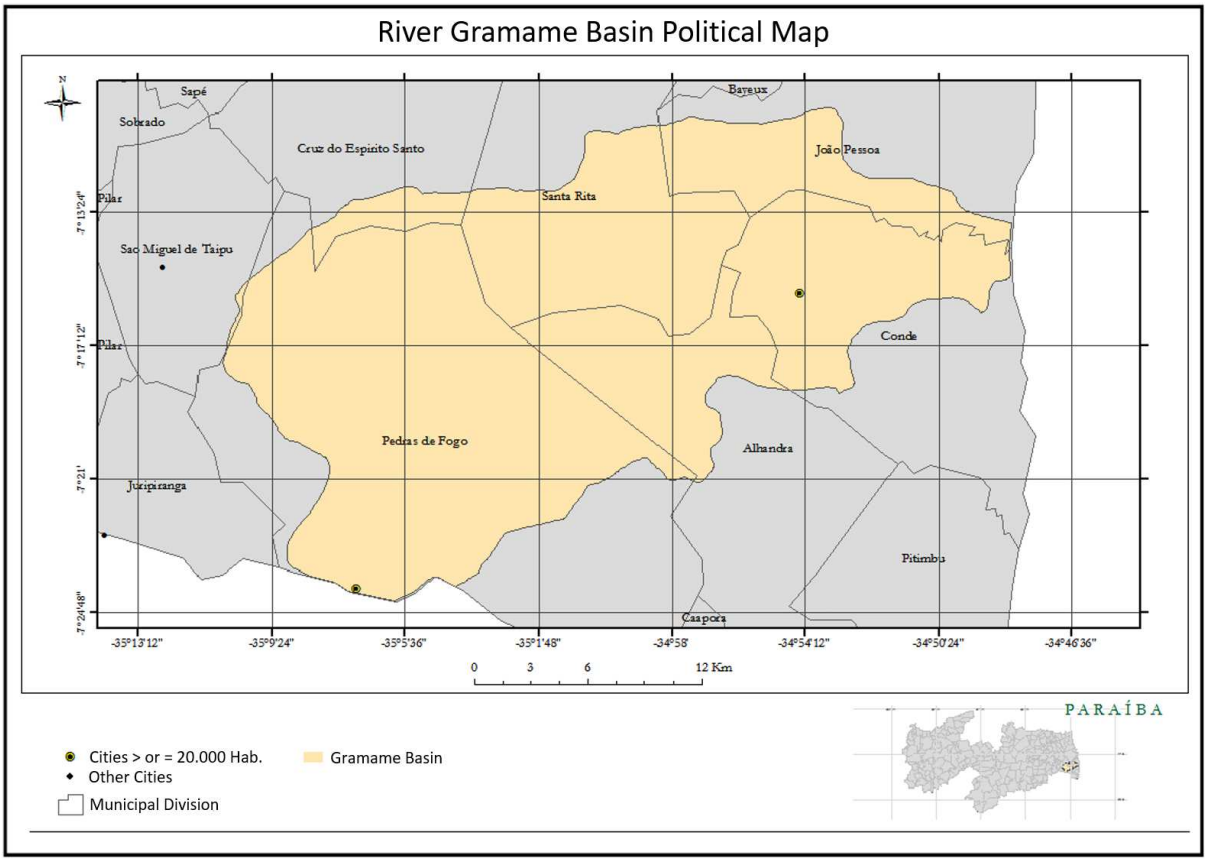
According to **??**), the main economic activities of the basin are:

- **Agricultural Activities:** It is the main economic activity of the basin, besides being the largest consumer of water. There are more than 100 irrigation projects, from the most varied sizes. Sugar cane and pineapple are the crops with the largest irrigated areas.
- **Industrial Production:** Most industries are in the industrial district of João Pessoa.
- **Mining:** There is exploration of sand, clay, limestone and mineral water.
- **Tourism and Leisure:** They are concentrated in the lower part of the basin, near the coast.

Land use and cover

This region is historically marked by an intense process of deforestation, both by the logging industry and for intensive sugarcane planting (**??**). With regard to land

Figure 15 – Political map of river Gramame basin. Source:(**??**)



cover, only 12.9% of the basin area still contains native land cover, the remained area was anthropomorphized. It is possible to check it in the Table **??** which shows land use and land occupation in 1998.

Table 3 – Basin land use. Source: (**??**)

Land use and cover	Area (ha)	Percentage
Atlantic Forest	3.820	6,5
Cerrado	1.137	1,9
Lowland Vegetation	2.074	3,5
Mangrove Vegetation	613	1,0
Anthropism	51.266	87,1
Sum	58.910	100,0

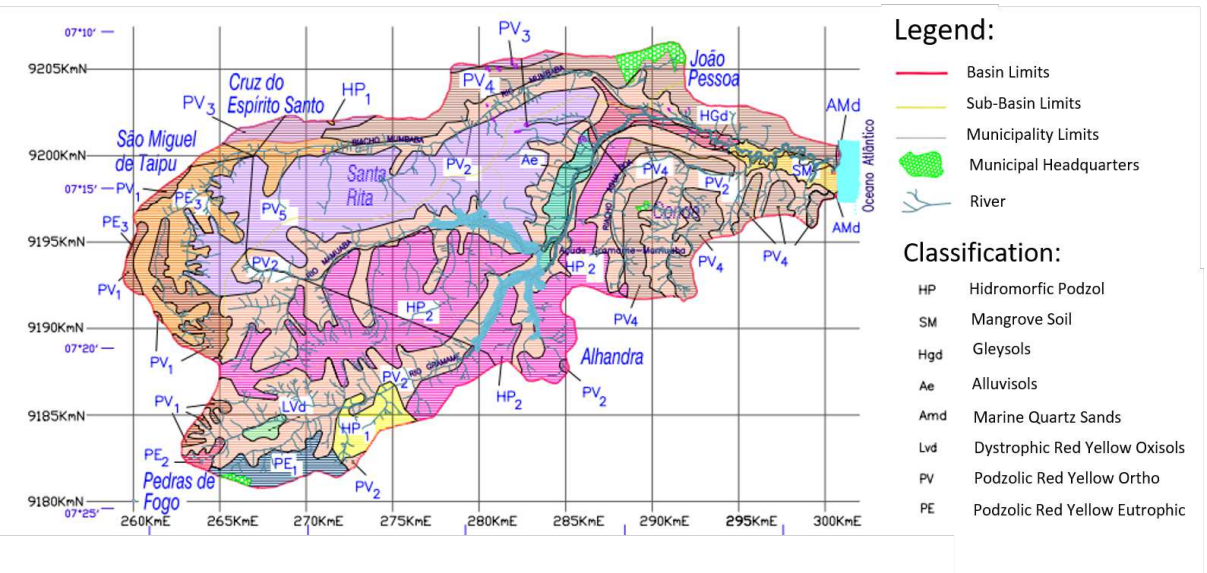
Soil

The main rivers of the basin have their springs located in its southwestern part, which is characterized by the presence of a crystalline complex where there is occurrence of faults and fractures in the rocks. From this point on, rivers begin to develop in sloping valleys extending to the eastern part of the basin. Because of this characteristic, the springs

are located in areas of low water availability. The perennialization of rivers only occurs from the moment they reach the high water potential sedimentary soil (**??**).

Looking at the soil map of the basin (Figure **??**), it is possible to realize that the predominant soil in the Mamuaba River sub-basin is the Hydromorphic Podzol. This type of soil is sandy and deep, with a high infiltration rate and low water retention. In addition, it is known to be a soil with retarded runoff (**??**).

Figure 16 – Pedological map of the Gramame river basin. Source: (**??**)



Climate characteristics

The Northeast region is characterized by a strong intra and interannual variability of the rainfall, with alternations between dry and rainy periods (**??**). In the study area, the dry season usually starts in September and ends in February and the rainy season usually begins in late April and ends in the end of July, with the other months having intermediate characteristics. Figure **??** shows months of occurrence of dry, wet and rainy periods, as well as precipitation and average daily evapotranspirations for the study area.

According to **??**), the average annual basin evapotranspiration is about 1312.5mm, while its average annual rainfall is around 1740mm. Using the FAO local climate estimator (New LocClim 1.10) (**??**), it was possible to obtain the monthly averages of precipitation and potential evapotranspiration in the basin, which can be seen in Figure **??**.

The geographical position of the state of Paraíba, close to the equator, the high incidence of solar radiation and the high number of hours of sunshine are determining factors for the occurrence of a warm climate, with an average annual temperature of 26.1 $^{\circ}C$, according to **??**).

Figure 17 – Dry, wet and rainy periods in the study area. Source: (**??**)

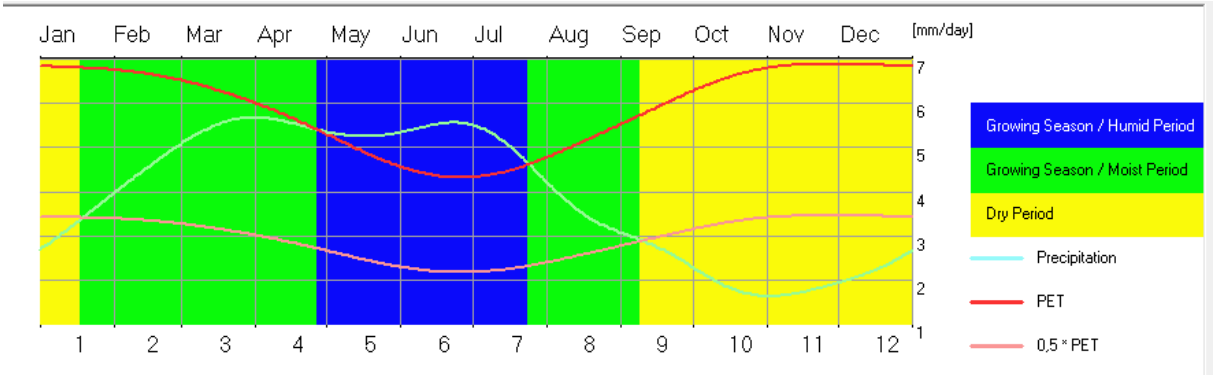
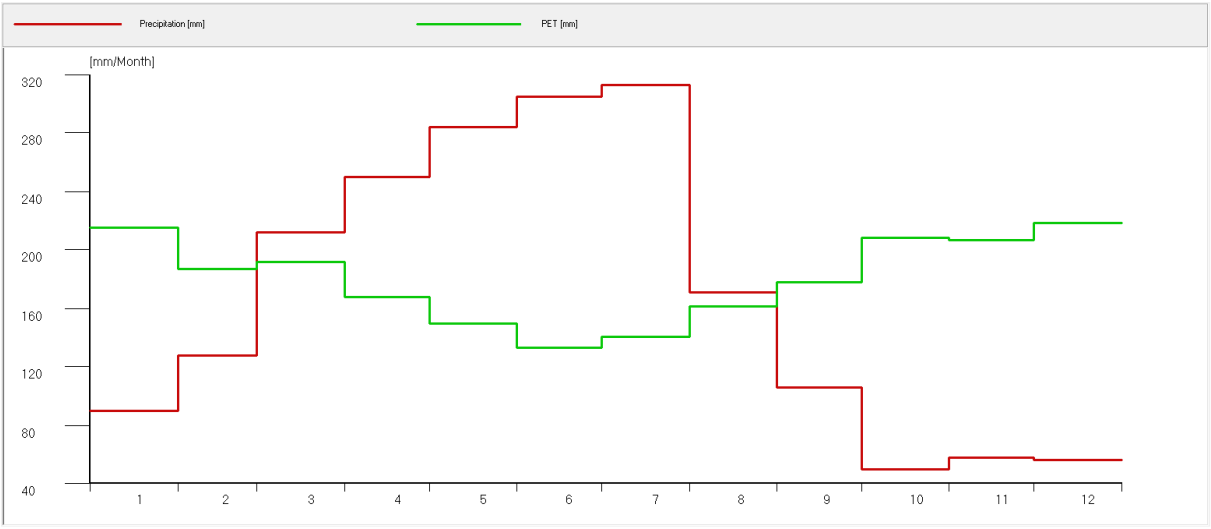


Figure 18 – : Monthly averages of precipitation and evapotranspiration for Gramame river basin. Source: (**??**)



Climate data can be obtained from João Pessoa weather station, which is in a short distance from the Gramame river basin. This climatological station is managed by the National Institute of Meteorology of Brazil (INMET), which makes all data freely available on its site.

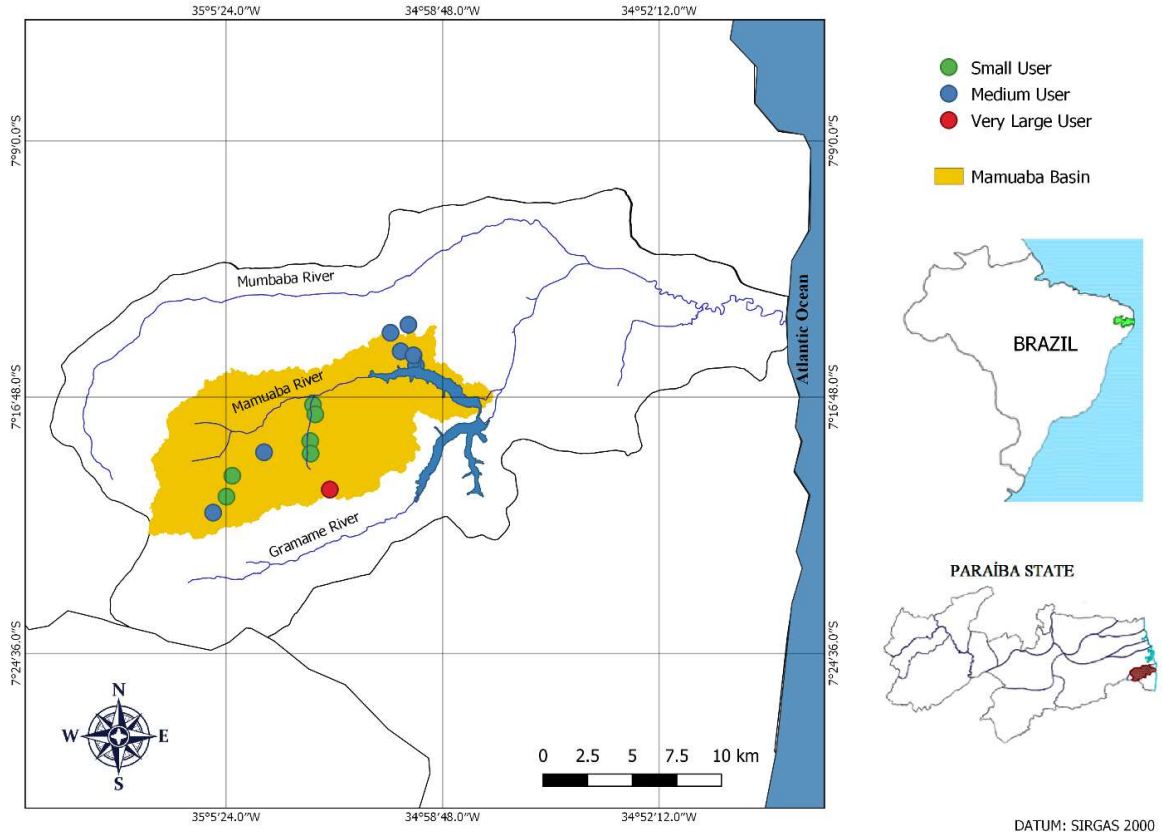
Daily data on sunshine, precipitation, radiation, minimum and maximum temperatures, humidity and wind speed (obtained both from FAO's local climate estimator and INMET), were treated and inserted in AquaCrop software to obtain a reference evapotranspiration estimation (essential data for the functioning of AquaCrop OS). Following this process, reference evapotranspiration, together with precipitation and maximum and minimum temperatures (all data on the daily scale), were used to feed the AquaCrop OS weather data input file. These data is presented on Annex **??** for each decade. Data for precipitation, temperature, and evapotranspiration changes from one decade to another to simulate the climate change effect (this topic will be better discussed forward in this

chapter).

Water users

On this research, only the farmers present in the River Mamuaba basin were considered. Figure **??** shows the location of this basin , within the Gramame basin. In this same figure, we can still see the location of farmers within the basin according to the size of the area irrigated by them.

Figure 19 – Farmers location.



A register of farmers made by **??**) (Table **??**) was used as a basis for the characterization of the farmers, although these data are out of date and no longer represent the reality of the basin, it serves as a scenario to test the operation of the proposed method.

Despite the farmers names are present in the original source, these were omitted and replaced by numbers in this work. Depending on the size of the area irrigated by each user (A), these were classified as: Very small ($A < 5ha$), small ($5 < A < 10ha$), medium ($10 < A < 50ha$, large ($50 < A < 100ha$) or very large ($A > 100ha$). The intervals presented above are the same intervals used by **??**) to classify the farmers based on the area irrigated by them.

In addition to this information, the Table **??** contains information about the crop, geographical coordinates, and the irrigation method used to irrigate each crop. None of the farmers utilizes any type of mulching or cover crop (at least we do not have any source informing about the utilization of this kind practice by the farmers in the study area), so all farmers are labeled with the "no mulching" status.

The water demands for each user were also reported by **??**), but since AquaCrop OS could calculate them, it was preferred to use the demands obtained by AquaCrop OS, because them would have to be recalculated anyway at all stages of optimization in order to take into account the increases in demands caused by the impacts of climate change.

Although the user's data is outdated (the data is from approximately 20 years ago), we believed that this is not a problem for our research. That is because, it is not the intention of this work to produce an adaptation strategy for the area in question, but rather, to present an innovative methodology for the creation of this type of strategy, which can be used in various types of cases and locations. Therefore, the application in the Mamuaba basin has only an expository aspect of how the methodology works in practice. In addition, even if current data on the study area were used, we believe that the final result will not differ much from that obtained, since, although the absolute values vary over time, the relationships between different values remain more or less constant (dripping irrigation will always be more expensive than conventional sprinkler), so that the trends (which, in the end, are what guide the adoption of adaptation strategies) remained the same. In other words, it doesn't matter if the simulation starts with data from 2000 or 2020, it will tend to similar results when it arrives in 2070.

Besides irrigation, water is also used for other purposes in the basin. In Table **??** is possible to see all cities that use water from the basin to urban population supply, as well as the respective demand value in l/s. Table **??** shows, for each sub-basin, the demand for rural population and industry supply in m^3/s. Those values of demand, from both tables, are estimations made by **??**) for the year of 2020.

Table 4 – Irrigators from the Mamuaba River Sub-basin. Source: (**??**)

Farmers	**Crop**	**Area (ha)**	**Classification**	**Coordinates UTM (km)**	**Irrigation Method**
1	Pineapple	30	MEDIUM	(279,9198)	Conventional Sprinkler
1	Pineapple	42	MEDIUM	(278,9198)	Center Pivot
2	Pineapple	4	SMALL	(274,9191)	Conventional Sprinkle
2	Yam	1,4	SMALL	(274,9191)	Conventional Sprinkle
3	Yam	1	SMALL	(274,9193)	Conventional Sprinkle
3	Pineapple	1	SMALL	(274,9193)	Conventional Sprinkle
3	Coconut	1	SMALL	(274,9193)	Conventional Sprinkle
3	Orange	1	SMALL	(274,9193)	Conventional Sprinkle
4	Pineapple	2,5	SMALL	(273,9192)	Conventional Sprinkle
4	Manioc Tree	2,5	SMALL	(273,9192)	Conventional Sprinkle
5	Beans	1	VERY SMALL	(274,9194)	Conventional Sprinkle
5	Corn	1	VERY SMALL	(274,9194)	Conventional Sprinkle
5	Yam	2	VERY SMALL	(274,9194)	Conventional Sprinkle
6	Beans	1	VERY SMALL	(269,9190)	Conventional Sprinkle
6	Yams	1	VERY SMALL	(269,9190)	Conventional Sprinkle
7	Pineapple	16	MEDIUM	(279,9197)	Center Pivot
7	Papaya	16	MEDIUM	(279,9197)	Center Pivot
8	Sugar Cane	600	VERY LARGE	(276,9186)	Giant Canon
9	Pineapple	15	MEDIUM	(279,9197)	Center Pivot
10	Pineapple	15	MEDIUM	(279,9196)	Conventional Sprinkle
10	Papaya	1	MEDIUM	(279,9196)	Conventional Sprinkle
11	Pineapple	1	SMALL	(269,9189)	Conventional Sprinkle
11	Yams	2	SMALL	(269,9189)	Conventional Sprinkle
11	Beans	2	SMALL	(269,9189)	Conventional Sprinkle
12	Pineapple	10	MEDIUM	(268,9188)	Conventional Sprinkle
13	Pineapple	10	MEDIUM	(271,9191)	Giant Canon
13	Sugar Cane	32	MEDIUM	(271,9191)	Giant Canon

Table 5 – Espected demand for urban population in 2020. Source: (**??**)

Municipalities	**Urban Population Demand** (l/s)
Bayeux	436,69
Cabedelo	292,16
João Pessoa	3.066,95
Conde	27,35
Pedras de Fogo	21,25
Várzea Nova	69,59

Table 6 – Espected demand for industries and rural population in 2020. Source: (**??**)

	Demand m^3/s	
Sub-basin	**Rural Population**	**Industries**
Água Boa	3.45	15
Gramame	7.90	244
Mamuaba	3.98	1
Mumbaba	5.74	629

Demand and Water Availability

The water availability of a basin represents the quantification of the water resources

within that basin without human intervention, i.e. in its natural state. It is represented by the arithmetic mean of the natural flows historical series. Its value indicates the theoretically maximum average flow rate that could be withdrawn from that basin. However, according to **??**), the maximum amount that can be made available for water use corresponds to a fraction of typically 60% of that maximum average flow rate. Table **??** shows the water availability of the Gramame basin and its sub-basins.

Table 7 – Water availability in River Gramame Basin. Source: (**??**)

Basin or Sub-basin	**Availability** m^3/s
Mamuaba Sub-basin	1,83
Mumbaba Sub-basin	2,38
Riacho da Salsa Sub-basin	0,51
Água Boa River Sub-basin	1,28
Gramame Basin	9,50

For Mamuaba sub-basin, where the farmers presented on Table **??** are, the availability is $1,83m^3/s$. If we multiply this value for the 60% fraction that is suggested by **??**), we only stay with approximately $1,0m^3/s$ for human use. In this work, we had considered the last value as the sub-basin water availability.

IPCC-derived projections for Brazil (**??**), considering scenario RCP 4.5 of Eta-HadGEM2ES model for the 2041-2070 period, were used to estimate future values of precipitation, air temperature, and water availability for each decade (step), considering the current conditions as the baseline (2020-2030). According to the projections, it is expected a:

- Reduction of 50 mm of surface flow until 2070;
- Increase of 6.7 °C (mean temperature) until 2100;
- Decrease of 22% on precipitation until 2100;

To estimate the reduction on water availability in the future decades, the reduction of the surface flow was considered to occur steadily on the 2020-2070 period. This can be considered a source of uncertainty and imprecision for the work, since, in practice, this dynamic occurs in a much more complex way. However, for the purposes of this research, the approximation that was made is considered satisfactory. To convert the reduction in surface flow into flow reduction (which is the parameter used to measure water avaliability), the water depth was multiplied by the area of the mamuaba basin and then divided by the simulation period.

Reductions in precipitation and increases in temperature were used to estimate the increase in demand, since both contribute to increasing the demand for water for irrigation.

To make this estimation, the Aquacrop software was used, since it is able to calculate the demand for irrigation. All other parameters were kept constant, while temperature and precipitation were changed to reflect the expected changes. Other parameters considered in the AquaCrop modeling process, like duration of sunshine, net solar radiation, air humidity, and wind speed were considered constant during the whole process because we can not find any prediction about the behavior of those variables along this period. This simplification is another possible source of uncertainties for the work, as some of the variables considered constant may vary over time, however, for the same reasons already mentioned above, we believe that these uncertainties did not affect the quality of the final results of the work.

Adaptation Cost

A survey on various irrigation methods was preformed in order to collect the following data: percentage of wetted soil, irrigation method efficiency, and cost estimate for implementing the method per unit of area. This survey included both the methods that are already used in the study area, as well as methods that are more efficient than those that may replace the current ones in the adaptation process. Table **??** shows a summary of those information (**????????**).

Table 8 – Information about the irrigation methods.

Irrigation Method	**% of wetted soil**	**Method Efficiency**	**Cost** $R\$/hc$
Conventional mobile sprinkler	100	70%	1500
Sprinkler with mini cannon	100	60%	2200
Sprinkler with giant cannon	100	50%	Not necessary
Center pivot	100	80%	3000
Micro sprinkler	40	90%	8000
Dripping	15	95%	8000

Similarly, information on soil management methods was collected in order to know the following data: reduction of water evaporation from the soil surface caused by the management practice, and estimated cost to implement the method per unit of area. Among the farmers considered, none used soil management practices, so all the surveyed methods are suggestions for future adoption during the adaptation process. Among all practices, only the mulching practices were considered, since they are the only ones that are simultaneously simulated by Aquacrop OS and are compatible with local crops. Table **??** shows a summary of those information (**??????**).

Similarly to user's data, cost information is also out of date and has uncertainties in its estimation process (old production dates, sources from other parts of the country, produced for different cases at different time periods, uncertainties already present in the original sources), however, for the same reasons already exposed in the topic about user's

Table 9 – Information about the soil management methods.

Soil Management Methods	**% reduction on soil evaporation**	**Cost** $R\$/m^2$
Without Mulching	0	0
Organic Mulching	50	0.05
Plastic Mulching	100	0.1

data, it was considered that, despite all these uncertainties, the credibility of the results obtained was not impaired.

5.1 GA Parameters

In this work, we used the following parameters in the evolutionary algorithm:

- Population: 500 solutions
- External population: 200 solutions
- Probability of occurrence of $Crossover$: 80%
- Probability of occurrence of uniform mutation: 30%
- Probability of occurrence of directed mutation: 10%
- Number of simulated generations after the appearance of the first viable individual: 1000 generations

These parameters were kept constant during all simulations and were defined based on the usual values found on literature and tests performed on the algorithm itself (trial and error).

6 Results and Discussion

The algorithm was used to generate an adaptation strategy to climatic change to a group of farmers in the river Mamuaba sub-basin, that are already mentioned in the Study Case topic. The time interval considered was from 2020 to 2070 and the time step considered was 10 years hence the adaptation strategy was subdivided into 5 steps.

The results will be presented and discussed within five different sub-topics:

1. **Climate change impacts:** In this topic are going to be presented the predict impacts of climate change (that the adaptation strategy will need to compensate for).

2. **Adaptation strategy:** Here will be presented the main results of this work and the general recommendations for the farmer extracted from these results.

3. **Equity and adaptation:** Here we will show an analysis of the adaptation strategy from the water justice point of view

4. **Crops x irrigation methods x soil management:** Here we will present a general recommendation for adaptation, for this particular study case, with regards to the many adaptations options that are available.

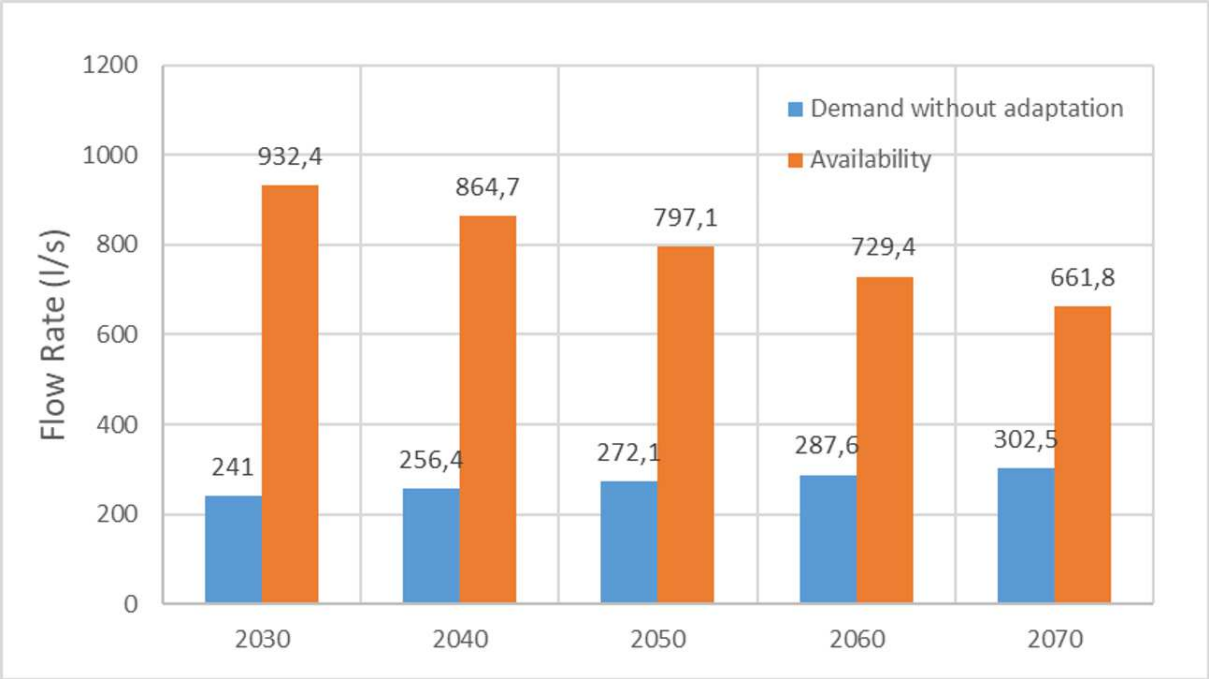
5. **Setting water footprint benchmarks:** Here we will use some results extracted from the main results to recommend water footprint benchmarks to the time interval considered (2020 – 2070).

6.1 Climate Change Impacts

Using the projections from **??**) it was possible to make estimatives of the reference evapotranspiration for each time step. With this estimative, we could use Aquacrop to estimate how the demand for water for irrigation would increase. Figure **??** shows how water availability will decrease according to **??**) and how the demand for water for irrigation in the study area will increase according to the estimative obtained through AquaCrop.

From the results shown above, the increase in mean temperature caused by climate change will lead to an increase in evapotranspiration, as well as an increase in the agricultural demand for water. The decrease in precipitation also causes an increase in demand since more irrigation water will be necessary to supply the deficit between the amount of rainfall and the water demand for crop growth.

Figure 20 – Climate change impacts on water demand/availability



On the water availability side, the reduction in surface flow will culminate with a reduction in the river's streamflow, consequently reducing the availability of water. So we could see that the adaptation strategy will have to compensate not only for the reduction in availability but for the increase in water demand as well.

At Brazil, we have similar studies pointing out to analogous results. According to **??**) climate change is concluded to have an enormous potential impact on the Semi-arid region of Brazil, with this phenomenon especially effecting river flow, water storage and irrigated production (even under plausible favorable changes in climate, these variables remain stressed). **??**) analyzed the impacts of climate changes on the flow and sediment production regimes in the Concórdia River drainage basin, in southern Brazil; the analysis shown a reduction in flow of 39.2% in the most favorable scenario and suggested that flood peaks could reach more extreme values in the future. **??**) discussed the influence of climate change and societal setting upon the value of forecasts of streamflows that replenish reservoirs in the semi-arid state of Ceará, Brazil, and they concluded that water demand for high-economic value activities are likely to increase in the future. According to **??**), is expected an increase in the dryness of the Northeast Brazil region, with rainfall reductions, temperature increases, water deficits increases and longer dry spells, leading to drought and arid conditions expected to prevail by the second half of the 21th century. **??**) examined the implications of changes in crop water demand and water availability for the reliability of irrigation; the study takes place in several countries, including Brazil, and the conclusions were that even in the relatively water-rich areas changes in water demand

will require appropriate improvements in crop cultivars, irrigation, drainage technology, and water management.

??) evaluated the effect of futures changes in precipitation and temperature distributions in the availability of water resources for agriculture in north-western Africa, region that, as the study area of this work, also have trends of decreasing precipitation and increasing temperatures; simulation results from this work also pointed out increasing demands and decreasing water availability that, in this particular case, will cause until 2050 the tripling of the basin water deficit.

6.2 Adaptation Strategy

Figure **??** shows the adaptation strategy generated by the genetic algorithm. That table alone says very little, but from it is possible to extract some valuable secondary data and conclusions, for instance: reduction on water footprint in each step, if small farmers were prioritized or not, and general recommendations for the farmers. All this secondary data will be presented and discussed in details on the next sections.

Figure 21 – Adaptation strategy.

	INITIAL																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	4	4	6	5	5	6	4	1	6	4	1	4	6	2	3	6	6	2	6	4	1	6	6	3			
Irrigation Method	4	4	3	3	3	3	3	3	3	3	3	3	3	3	4	4	1	4	3	3	3	3	3	3	3	1	1			
Soil manegement	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			

	2020 - 2030 (1)																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	4	4	6	5	5	6	4	1	6	4	1	4	6	2	3	6	6	2	6	4	2	6	6	3			
Irrigation Method	4	4	3	4	3	4	3	3	4	3	3	3	3	3	3	4	4	1	4	3	3	3	4	3	3	1	1			
Soil manegement	1	1	2	1	1	1	1	1	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	2	1	2	1			

	2030 - 2040 (2)																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	5	5	6	5	5	6	4	1	6	5	1	5	6	3	3	6	6	2	6	5	3	6	6	3			
Irrigation Method	4	4	3	5	3	4	3	3	5	3	4	4	4	3	3	4	4	1	4	3	4	3	4	3	3	1	1			
Soil manegement	1	1	2	1	1	1	2	1	2	1	1	1	1	1	2	1	1	1	1	1	1	1	2	2	2	2	1			

	2040 - 2050 (2)																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	5	5	6	5	5	6	4	1	6	5	1	5	6	3	3	6	6	2	6	5	3	6	6	3			
Irrigation Method	4	4	4	5	3	4	3	3	5	3	4	5	4	3	4	4	4	1	4	3	4	3	5	4	3	1	1			
Soil manegement	1	1	2	1	1	2	2	1	2	2	1	1	2	1	3	1	1	1	1	2	2	2	2	2	2	2	1			

	2050 - 2060																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	5	5	6	5	5	6	5	1	6	6	1	5	6	4	4	6	6	2	6	5	3	6	6	3			
Irrigation Method	4	4	4	5	3	5	4	4	5	4	4	5	4	3	5	4	4	1	4	3	4	4	5	4	3	1	1			
Soil manegement	1	1	2	1	1	2	2	1	2	2	1	1	3	2	3	1	1	1	1	3	3	2	2	3	2	2	1			

	2060 - 2070																													
	FARMERS																													
	M	M	P		P			P		MP			MP		M	MG	M		M		P			M	M			
Crop	6	6	6	5	5	6	5	5	6	5	1	6	6	1	5	6	4	4	6	6	2	6	5	3	6	6	3			
Irrigation Method	4	4	4	5	4	5	4	4	5	4	4	5	4	3	5	4	4	1	4	3	4	4	5	4	3	1	1			
Soil manegement	1	1	2	2	2	3	2	2	2	2	2	2	3	2	3	1	1	1	1	3	3	2	2	3	2	2	1			

LEGEND

CROP	1	CROP GROUP 1	**IRRIGATION METHOD**	1	ASPERSION WITH GIANT CANON	**SOIL MANEGEMENT**	1	WITHOUT MULCHING	**USERS**	MP	VERY SMALL
	2	CROP GROUP 2		2	ASPERSION WITH MINI CANON		2	ORGANIC MULCHING		P	SMALL
	3	CROP GROUP 3		3	CONVENTIONAL ASPERSION		3	PLASTIC MULCHING		M	MEDIUM
	4	CROP GROUP 4		4	CENTRAL PIVOT					G	LARGE
	5	CROP GROUP 5		5	MICRO ASPERSION					MG	VERY LARGE
	6	CROP GROUP 6		6	DRIPPING						

6.3 Pareto Frontiers

Figures **??** to **??** presents the Pareto Frontiers of all optimizations, one for each period/decade. From these graphs, we can see that there is one adaptation strategy for each amount of money invested which produces the best final result in terms of a reduction in total water footprint. Other works have already done similar cost-effectiveness approaches, as **??**) that made a cost-effectiveness analysis of four water-saving irrigation techniques that are widely implemented in China, and concluded that water-saving irrigation is cost-effective in coping with climate change and has benefits for climate change mitigation and adaptation and for sustainable economic development. **??**) also performed a cost-benefit analyses finding the most effective strategies to cope with climate changes impacts in River Thames basin in southern England. **??**) made marginal cost curves (MCCs) to rank packages of water saving techniques (deficit irrigation, mulching, and changing irrigation methods) according to their cost effectiveness to reduce the water footprint need to support the decision making.

Figure 22 – Pareto Frontier for 2020 – 2030 period

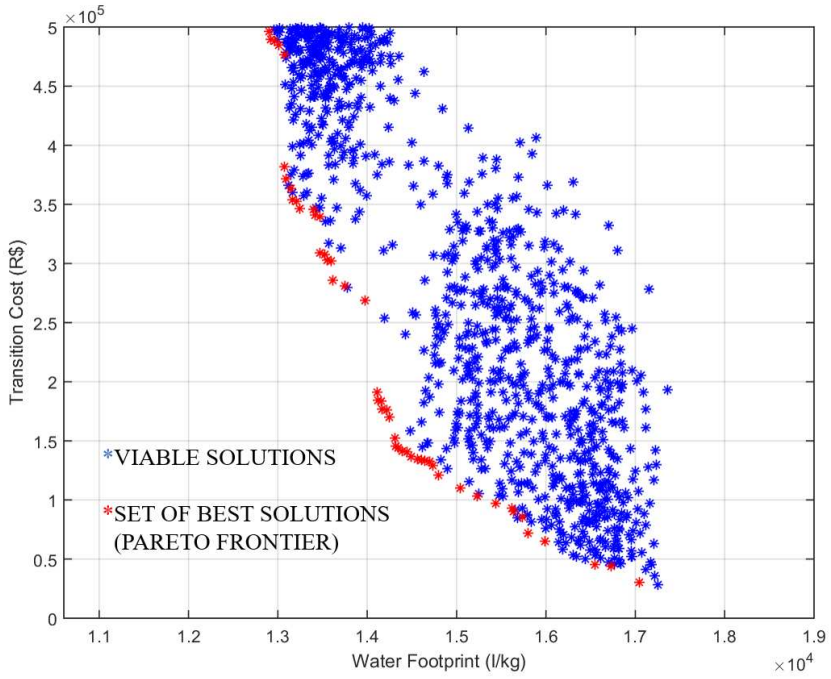


Figure 23 – Pareto Frontier for 2030 – 2040 period

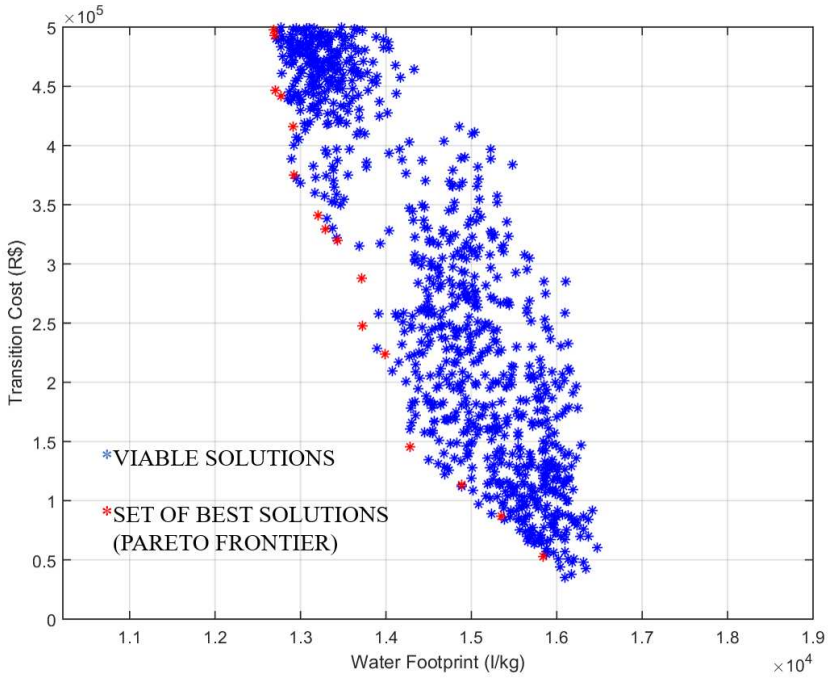


Figure 24 – Pareto Frontier for 2040 – 2050 period

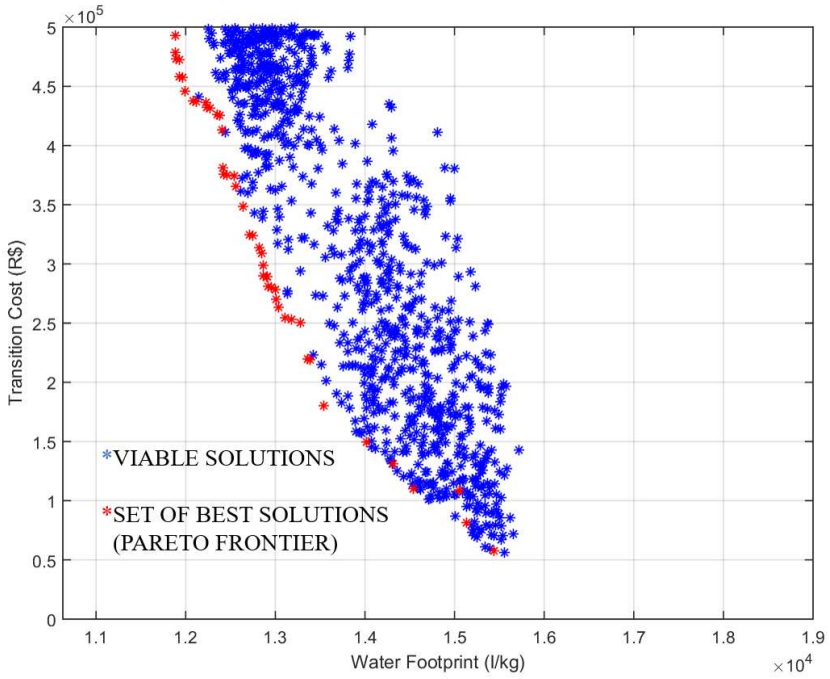


Figure 25 – Pareto Frontier for 2050 – 2060 period

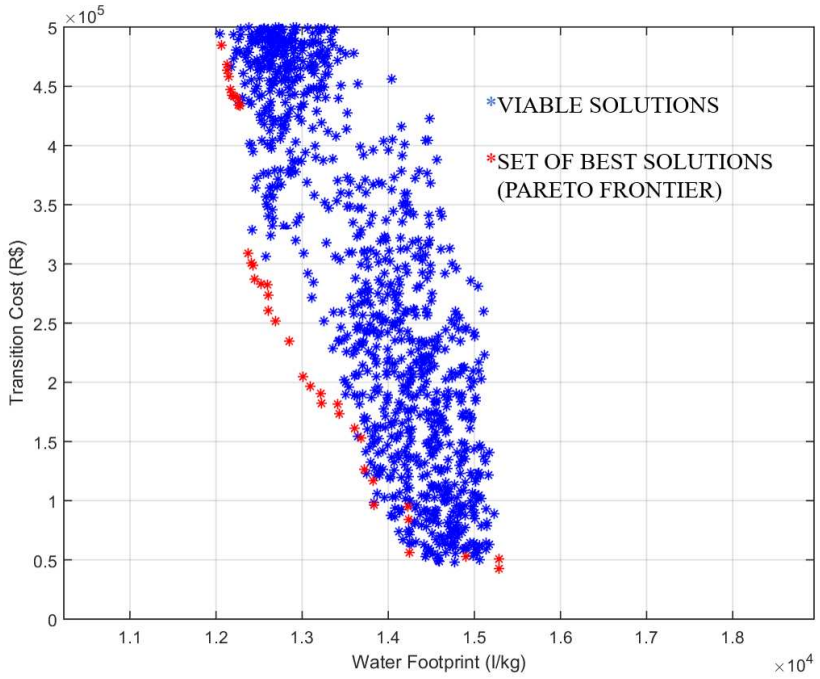


Figure 26 – Pareto Frontier for 2060 – 2070 period

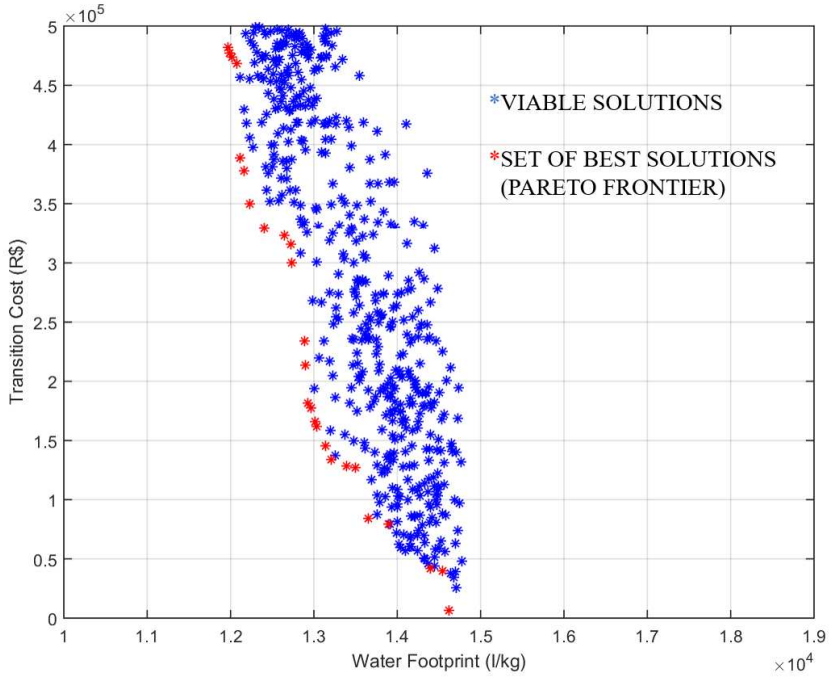
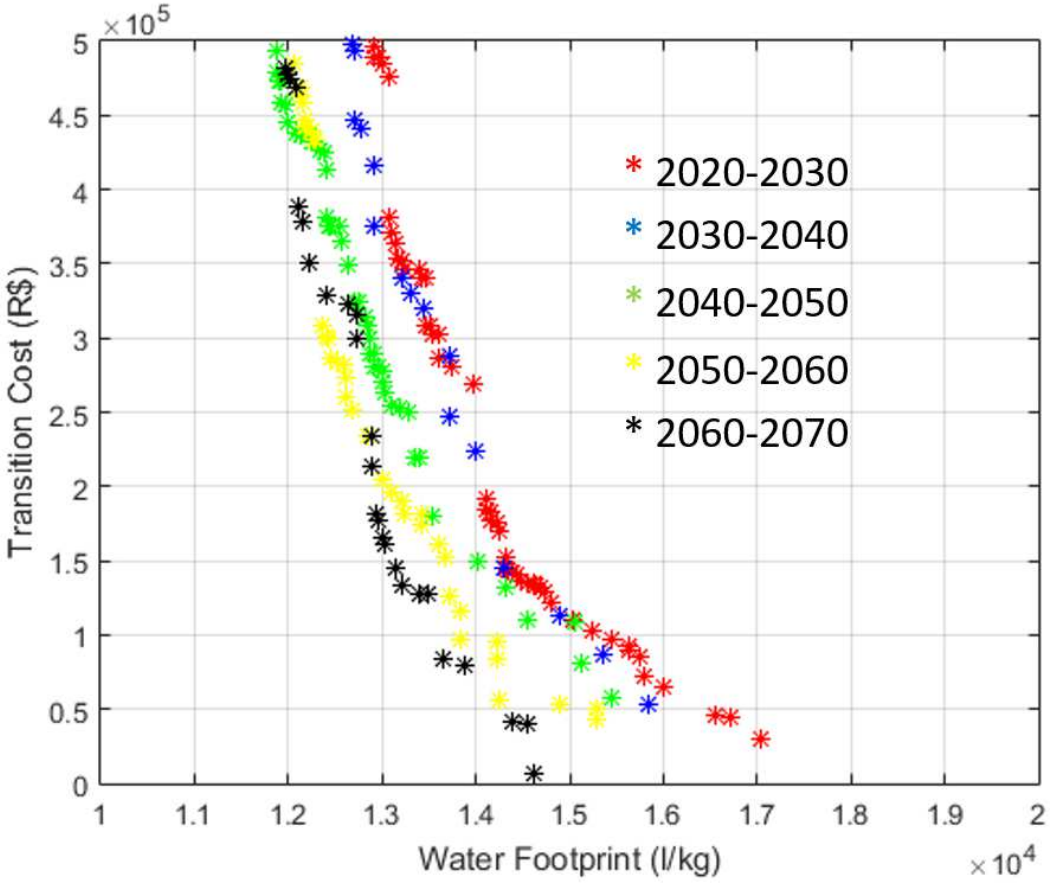


Figure **??** shows, in a single graph, the Pareto Frontiers of all periods, demonstrating that there is an evolution in sustainability/efficiency in water use across time because

of the measures taken on the previous decades, showing that the process of adaptation occurs in an evolutionary way.

Figure 27 – Pareto frontiers of all periods.



Similar sequential multiobjective optimization were already done in several other works, mainly with the objective of saving processing time on complex problems with substantial number of decision making variables (**??????????**). In these works, a complex optimization problem was subdivided into simpler ones, which, if solved in a sequential manner (with the result of the previous one serving as a starting point for the next optimization), it provided an approximate result for the more complex problem. Although the solution is being improved in each step, the goal remains in finding the final result. The method becomes attractive because it is faster.

In our case, the sequential optimization process was slightly different, firstly because the optimization problem was not simplified (as we were not interested in reducing the processing speed) and secondly because great importance was given to the intermediate stages (the evolution of the solution itself).This is a kind of solution that does not only care about the final result but, instead, gives to the transition process the same attention that is given to the final result. According to **??**), more attention has to be devoted

to understanding and managing the transition from current management regimes to more adaptive regimes that take into account environmental, technological, economic, institutional and cultural characteristics of river basins. It means that we have to move from a prediction and controlled water management to a more learning management, where more attention is given to local characteristics (**????**).

The Pareto Frontier can be a powerful tool to assist in the decision making process for water and environmental problems, having already been used for this purpose in several works (**??**) (**????**). Furthermore, all Pareto frontiers were analyzed in order to identify any potential pattern that could serve as a general recommendation to the farmers at each time period. Thus, for all the decades, except for the last one, it's obvious that the Pareto frontiers can be decomposed into two lines: one bottom line that is more horizontal, and an upper line that is more vertical (Figures **??** to **??**). That behavior shows that, until a certain cost (the intersection of the lines), the reduction in water footprint per unit of money invested is more gainful than beyond that point. The intersection point can be a good, simplified and general recommendation for the users. For instance, in the first three decades, the intersection point lies approximately at the cost of R$ 150000, while in the fourth decade it lies on R$300000 and in the last decade we can see only the vertical line.

Figure 28 – Pareto Frontier general recommendation for 2020 – 2030 period

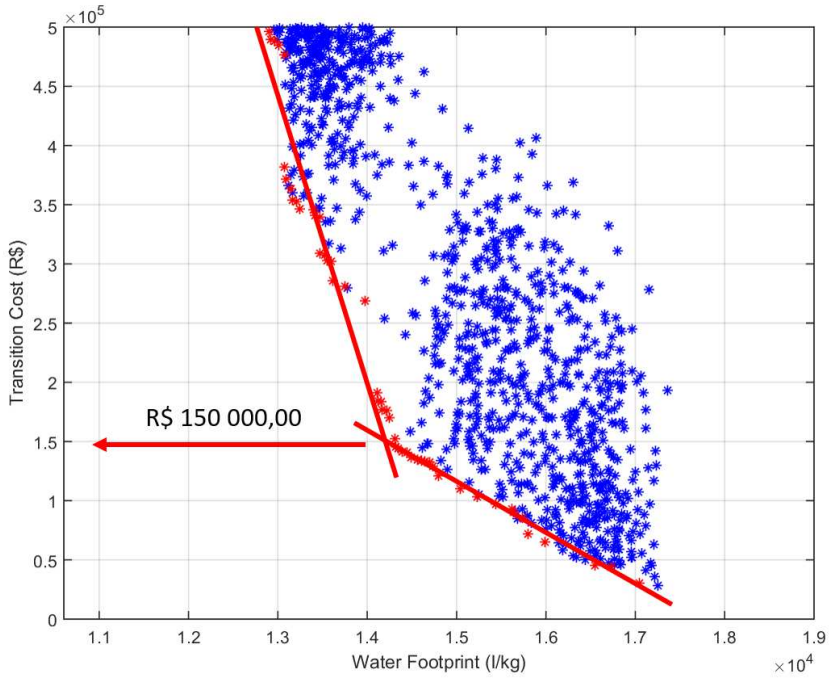


Figure 29 – Pareto Frontier general recommendation for 2030 – 2040 period

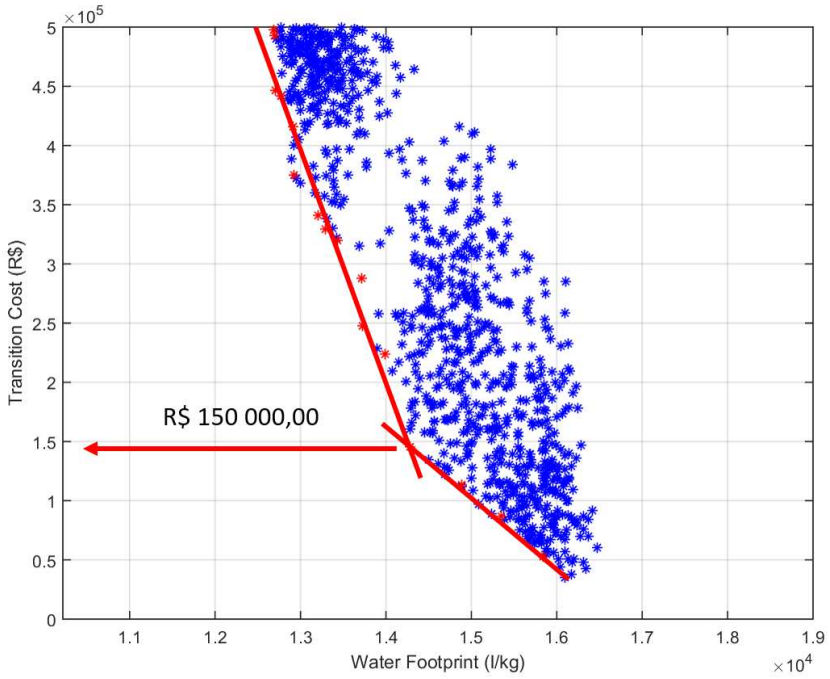


Figure 30 – Pareto Frontier general recommendation for 2040 – 2050 period

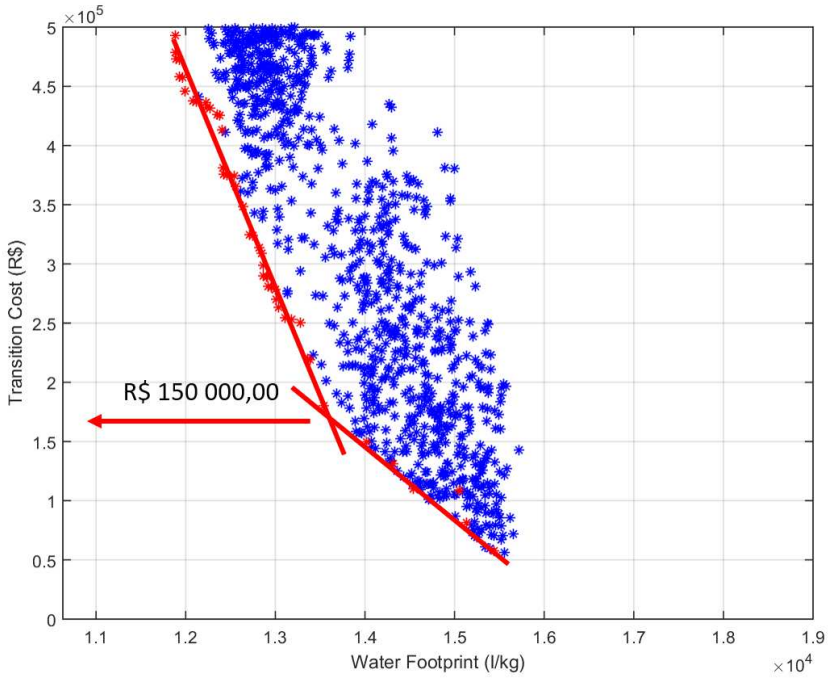


Figure 31 – Pareto Frontier general recommendation for 2050 – 2060 period

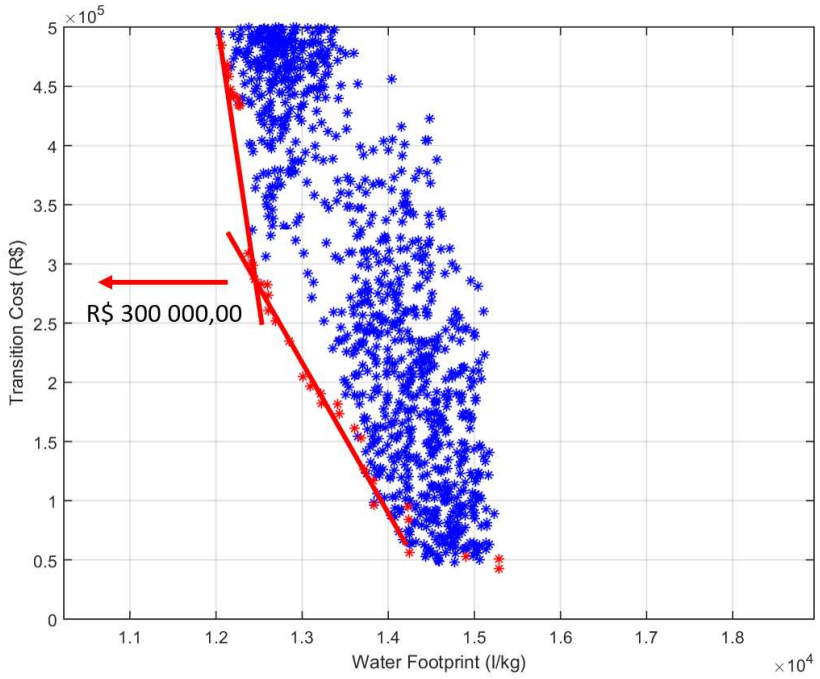
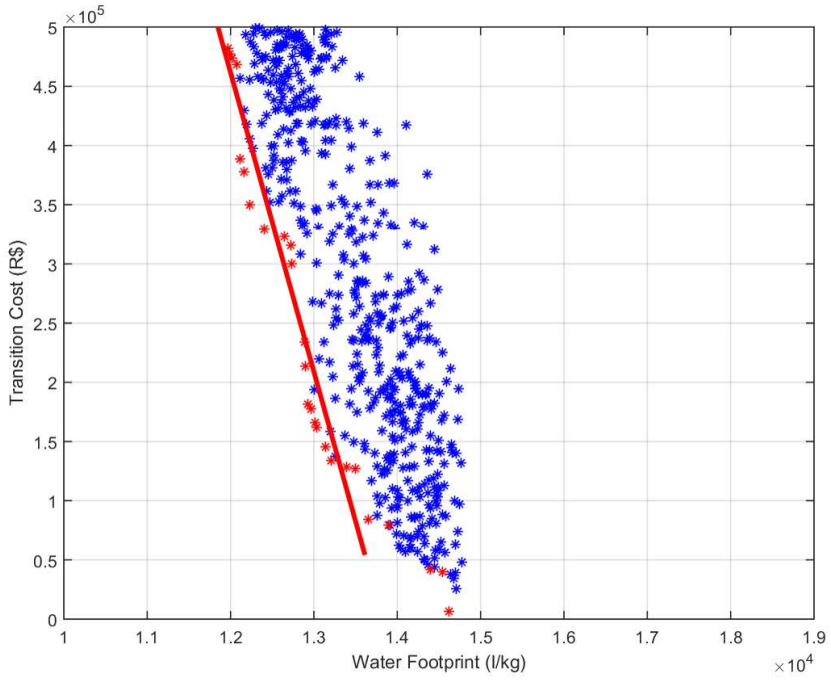


Figure 32 – Pareto Frontier general recommendation for 2060 – 2070 period

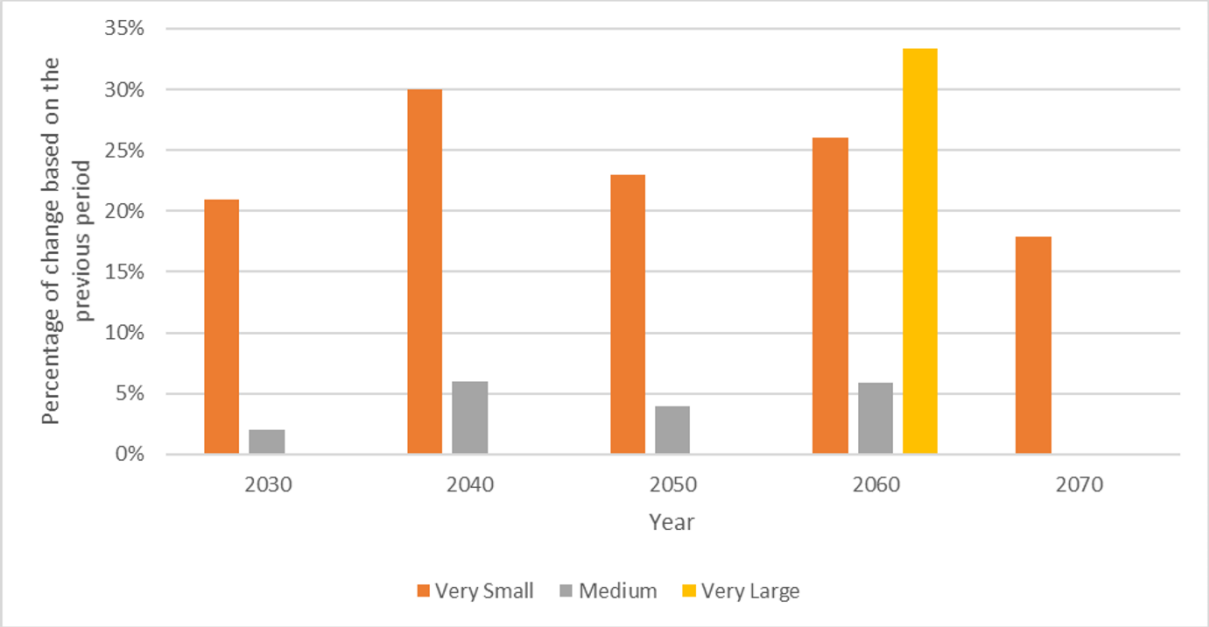


The intersection point could be a good, simplified and general recommendation for the farmers. For instance, in the first three decades, the intersection point lies approximately at the cost of R$ 150000, while in the fourth decade it lies on R$300000 and in the last decade we can see only the vertical line. That behavior on the Pareto frontier could be 'translated' to the farmer as: 'In the three first decades, we recommend investing R$150000 in adaptations measures. In the fourth decade, we recommend investing the double of this value. In the last decade, the best solution is probably adopting the cheaper strategy of the Pareto frontier.'

6.4 Equity and Adaptation

The classification of users based on the irrigated area was not inserted explicitly in the objective functions. Despite that, the final results showed that very small users were prioritized over medium and large ones, and received more adaptations measures, as shown in Figure **??**.

Figure 33 – Percentage of change based on farmer's irrigated area size



The way that the first objective function was written was the reason for this result. Since the first objective function is the sum of all user's WF, a specific reduction in the WF of a small user has the same impact (in the fitness value) with the similar one in a large user's WF. Reducing the WF of a large user costs more than reducing the WF of a small user, thus it is more advantageous to adapt the smaller first.

??) considers climate change as one of the factors that affects equity in natural-resource use, particularly in the developing world. So it is very important that the

adaptation strategy is done in that way (prioritizing the implementation of the adaptation measures on the smaller farmers) because household farmers are much more vulnerable to climate change impacts and have much less power to respond to these impacts (**??**).

In the present research, we were able to group together, in one single model, three important objectives (reducing water footprint, minimizing costs and seek for equity), with two of them explicitly and one implicitly included in the objective functions. This approach is of great importance, since little has been said about the joint resolution of issues adaptation and equity issues, being necessary more holistic approaches to build community resilience (**??**). According to **??**), finding equitable strategies are as important as to select efficient, robust, and flexible adaptation strategies.

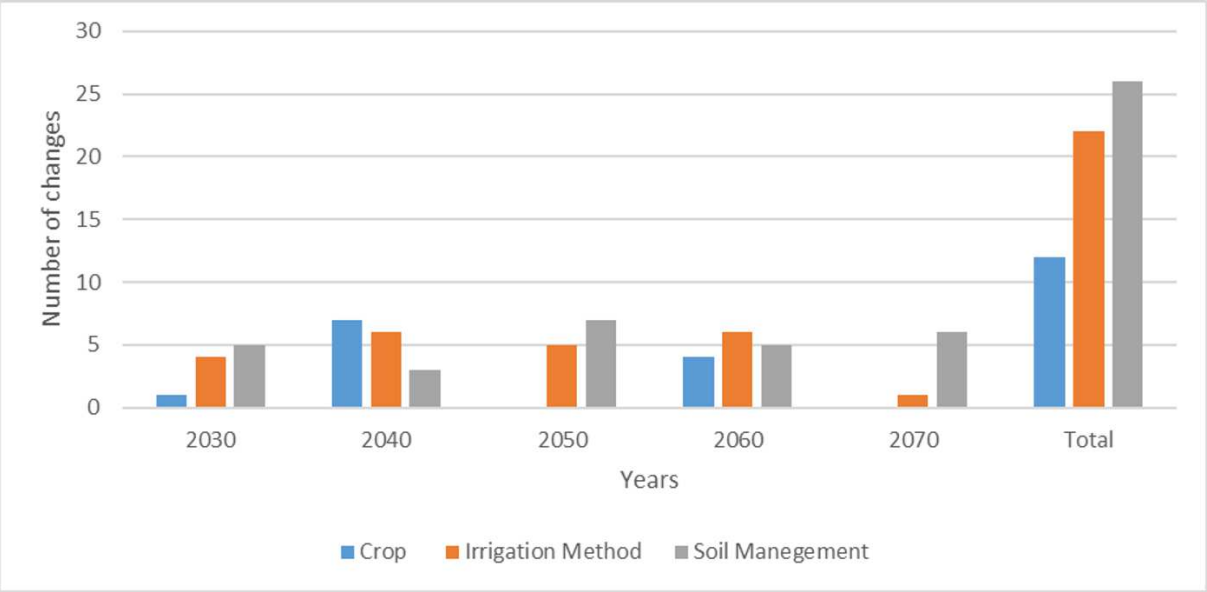
6.5 Crops x Irrigation Methods x Soil Management

Figure **??** shows the number of changes proposed by the adaptation strategy grouped into three categories: changes in crop type, changes in irrigation method, and changes in soil management methods. There is a clear preference for changes in irrigation methods and soil management methods rather than changes in crop types. These outputs could easily be transferred to the users, i.e. the farmers, in order to be replicated in the field. Practically this means that the farmers should prefer measures/changes that enhance the system's efficiency than solutions that propose the replacement of cultivations that consume more water with those that demand less water. Other works also have suggested the improvement of irrigation water use efficiency (including better irrigation techniques, mulching and cover crops) as a viable option for adaption to the impacts of climate change in agriculture (**????????**)

This behavior can be explained by the concept of WF, which takes into consideration both water consumption and crop yield. It is possible to have a decrease in WF at the same time that is an increase in water demand. As water demand is a constraint of the algorithm, it is possible that the algorithm had given preference to changes in irrigation methods and soil management methods rather than changes in crop types to avoid increases in water demand.

This kind of pattern is useful for a series of other reasons too. For instance, changes of crop types are most difficult to be applied on the ground because of market reasons, e.g. the demand of products does not vary, certain kind of crop do not have demand on local market, and due to social/cultural reasons, e.g. farmers already have expertise on the cultivation a certain kind of crop, and they not want to change to a crop unknown to them (**??**).

Figure 34 – Number of changes in crop, irrigation method and soil management.

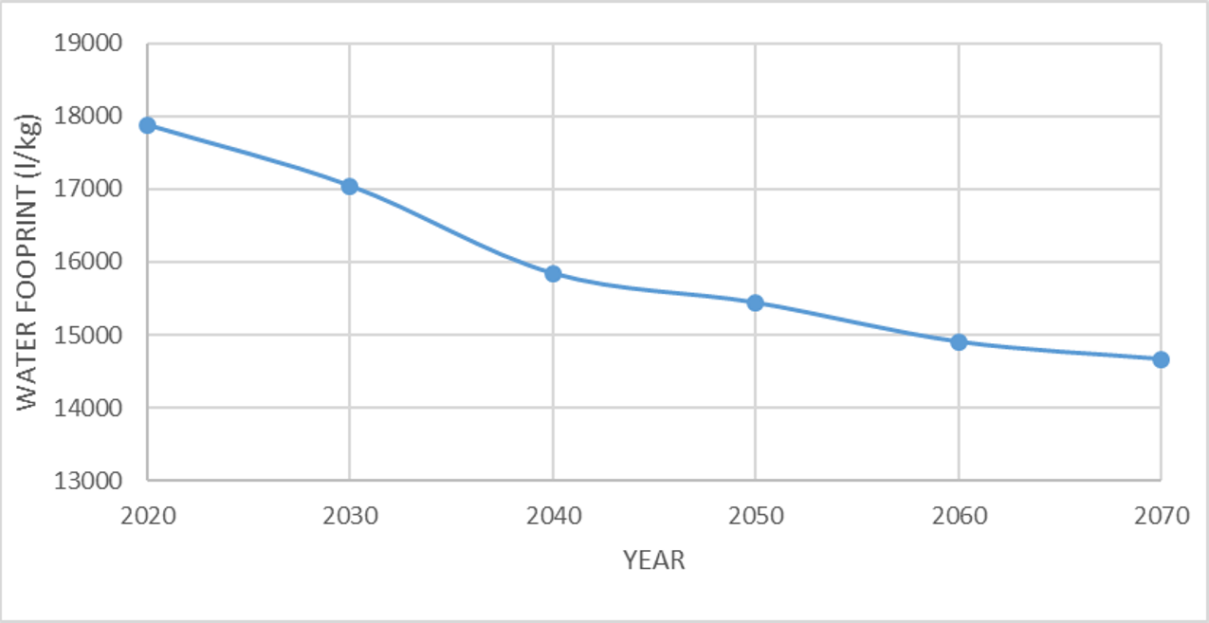


6.6 Setting Water Footprint Benchmarks

The evolution in time of the total WF of all users, as depicted in Figure **??**, demonstrates a decreasing trend. In the first years, there were bigger reductions that in the last years. This is due to the fact that the more WF is reduced the more it costs to reduce it even more (the more efficient the irrigation method is, the more expensive it is). An additional argument is that in adaptation measures, there is an initial increased cost to apply the measure, with the benefits to be more obvious in the long term, i.e. after the year 2050.

The water footprint values can serve as benchmarks to monitor the adaptation strategy implementation process on the ground. According to **??**), benchmarks for the WF of crop production can serve as a reference and be helpful in setting WF reduction targets. Other authors have already set water footprint benchmarks to serve as targets in the process of reduction in water consumption (**????**).

Figure 35 – Evolution of water footprint.



7 Conclusions

All the results obtained from this research take us to the following conclusions:

- The adaptation strategy should compensate not only for the reduction in availability but for the increase in water demand as well.
- Through the adaptation strategies, it was possible to identify general recommendations to be followed by the farmers, as:
    1. For the first decades, until a certain cost, the reduction in water footprint per unit of money invested is more effective than beyond that point in time. For the last decades, the best solution is probably adopting the cheaper strategy of the Pareto frontier.
    2. There is a clear recommendation for changes in irrigation and soil management methods rather than changes in crop types.
- There is an evolution in sustainability/efficiency in water use along time due to the measures taken in the first decades, showing that the process of adaptation occurs in an evolutionary way.
- The adaptation strategies have contributed positively to mitigate the power and opportunities differences that exists between householders and big farmers, as is possible to see that small farmers received more adaptations measures than large farmers.
- Based on local characteristics, we have set water footprint benchmarks to be used as sustainability goals in order to monitor and evaluate the adaptation strategy implementation process on the ground.
- We believe that the results and conclusions presented in this work will be especially important for stakeholders strategic decisions, in the form of supporting material to guide public policies and government investments.

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Appendix

APPENDIX A – Source Code

```
format long
%Number of generations
n_ger=10;
%number of individuals into initial population
n_popu=500;
%number of individuals into external population
n_popu_ext=200;
%probability of crossover occurring
p_cross=0.8;
%probability of mutation occurring
p_mut=0.3;
%probability of occurrence of targeted mutation
p_mut_dir=0.1;
%number of users
n_usuarios=27;
%Avaliability (l/s)
q_100=147.9;
q_100=q_100/1000; %m3/s
%Number of crops
n_crop=6;
%Number of irrigation methods
n_irrig=6;
%Number of soil management methods
n_mane=3;
%Cultivation time of each crop (days)
t_days=[90 120 364 90 90 120];
t_sec=t_days*24*60*60;
%number of objective functions
n_funcoes=2;
%budget
custo_limite=500000;

%Cost (R$/m2)
cost=[0 0 0 0 0 0
      0 0.22 0.15 0.3 0.8 0.8 %cost to change irrigation method
      0 0.05 0.1 Inf Inf Inf]; %cost to change mulching practice

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Initial Configuration

%Users configuration at the beginning of the period
IniConfig= [6 6 6 5 5 6 5 5 6 5 1 6 6 1 5 6 4 4 6 6 2 6 5 3 6 6 3
4 4 4 5 3 5 4 4 5 4 4 5 4 3 5 4 4 1 4 3 4 4 5 4 3 1 1
1 1 2 1 1 2 2 1 2 2 1 1 3 2 3 1 1 1 1 3 3 2 2 3 2 2 1];

%Maximum values that the solution can assume (used in reproduction,
    ↪ to avoid the birth of unviable children)
MaxConfig=[ 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
            6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
            3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3];

%Maximum area per user (m2)
A_max=[300000 420000 40000 14000 10000 10000 10000 10000 25000 25000 10000
    ↪ 10000 20000 10000 10000 160000 160000 6000000 150000 150000 10000 10000
    ↪ 20000 20000 100000 100000 320000];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 %generating initial population
 popu_inicial=zeros(3,n_usuarios,n_popu);
for k=1:n_popu
    for j=1:n_usuarios
        for i=1:3
            if i==1
            popu_inicial(i,j,k)=IniConfig(i,j)+round((n_crop-IniConfig(i,j))*
                ↪ rand(1));
            elseif i==2
            popu_inicial(i,j,k)=IniConfig(i,j)+round((n_irrig-IniConfig(i,j))*
                ↪ rand(1));
            else
            popu_inicial(i,j,k)=IniConfig(i,j)+round((n_mane-IniConfig(i,j))*
                ↪ rand(1));
            end
        end
    end
end

for k=1:n_popu
    popu_inicial(1,:,k)=IniConfig(1,:);
```

```
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Water footprint estimation

matriz_PH=zeros(n_crop,n_irrig,n_mane);
matriz_TotIrr=zeros(n_crop,n_irrig,n_mane);
for cropt=1:n_crop
for irrig=1:n_irrig
for mane=1:n_mane

if cropt==1
%Dry Bean
crop={'Maize'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 3);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 2);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 1);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/11');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 59);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 888);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 903);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 1298);%
```

```
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
fprintf(fid2,'HIstart : %f \n', 650);%
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
fprintf(fid2,'Flowering : %f \n', 233);%
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days
    ↪ %% \n');
fprintf(fid2,'YldForm : %f \n', 668);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress
    ↪  %% \n');
fprintf(fid2,'Tbase : %f \n', 9);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no
    ↪ longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 30); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 0);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', 45);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', 50);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 0);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', 5);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', 0);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1:
    ↪  Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full
    ↪ biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', 14);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass
    ↪ production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', 0);%
```

```
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig
    ↪ degree days %% \n');
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n'
    ↪ );
fprintf(fid2,'PctZmin : %f \n', 70);%
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 1.70);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.5);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.019);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.006);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 10); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 250000);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.0225);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.99);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.00881);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.118);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.10);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
```

```
fprintf(fid2,'fage : %f \n', 0.15);%
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n')
    ↪ ;
fprintf(fid2,'WP : %f \n', 15);%
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage (
    ↪ of WP) %% \n');
fprintf(fid2,'WPy : %f \n', 90);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %%
    ↪ \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n'
    ↪ );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.40);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress
    ↪ before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 5);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \
    ↪ n');
fprintf(fid2,'a_HI : %f \n', 10);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', 5);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference
    ↪ %% \n');
fprintf(fid2,'dHI0 : %f \n', 10);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n')
    ↪ ;
fprintf(fid2,'Determinant : %f \n', 1);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', 100);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs
    ↪  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.15);%
```

```
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress effects on canopy stomatal control %% \n');
fprintf(fid2,'p_up2 : %f \n', 0.15);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress effects on canopy senescence %% \n');
fprintf(fid2,'p_up3 : %f \n', 0.15);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', 0.15);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.65);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 2.5);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 2.5);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 2.5);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination %% \n');
fprintf(fid2,'fshape_w4 : %f \n', 1);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
```

```
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
fprintf(fid2,'beta : %f \n', 12);
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
fprintf(fid2,'GermThr : %f \n', 0.2);

fclose(fid2);
end

elseif cropt==2
%Tomato
crop={'Tomato'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 3);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 2);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 1);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/12');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 43);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 891);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 1533);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 1933);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
```

```
fprintf(fid2,'HIstart : %f \n', 525);%
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
fprintf(fid2,'Flowering : %f \n', 750);%
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days
    ↪ %% \n');
fprintf(fid2,'YldForm : %f \n', 1050);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress
    ↪  %% \n');
fprintf(fid2,'Tbase : %f \n', 7);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no
    ↪ longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 28); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 1);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', 40);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', 45);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', 10);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', 5);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1:
    ↪  Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 0);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full
    ↪ biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', -999);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass
    ↪ production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', -999);%
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig
    ↪ degree days %% \n');
```

```
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n'
    ↪ );
fprintf(fid2,'PctZmin : %f \n', 70);%
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.5);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.024);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.006);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 20); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 33333);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.0067);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.75);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.004);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.007504);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.1);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
fprintf(fid2,'fage : %f \n', 0.15);%
```

```
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n') ;
fprintf(fid2,'WP : %f \n', 18);%
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage ( of WP) %% \n');
fprintf(fid2,'WPy : %f \n', 100);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %% \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n' );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.63);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 0);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \ n');
fprintf(fid2,'a_HI : %f \n', -9);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', 3);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference %% \n');
fprintf(fid2,'dHI0 : %f \n', 15);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n') ;
fprintf(fid2,'Determinant : %f \n', 1);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', 100);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.15);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress effects on canopy stomatal control %% \n');
```

```
fprintf(fid2,'p_up2 : %f \n', 0.5);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_up3 : %f \n', 0.7);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', 0.92);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.55);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal
    ↪ control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination
    ↪ %% \n');
fprintf(fid2,'fshape_w4 : %f \n', 1);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0
    ↪  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to
    ↪ deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop
    ↪ growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
```

```
fprintf(fid2,'beta : %f \n', 12);
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
fprintf(fid2,'GermThr : %f \n', 0.2);

fclose(fid2);
end

elseif cropt==3
%Sugar Cane
crop={'Maize'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 1);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 1);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 0);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/08');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 7);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 60);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 330);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 365);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
fprintf(fid2,'HIstart : %f \n', 0);%
```

```
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
fprintf(fid2,'Flowering : %f \n', -999);%
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days
    ↪ %% \n');
fprintf(fid2,'YldForm : %f \n', 73);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress
    ↪  %% \n');
fprintf(fid2,'Tbase : %f \n', 9);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no
    ↪ longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 40); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 0);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', -999);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', -999);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 0);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', -999);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', -999);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1:
    ↪  Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full
    ↪ biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', 12);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass
    ↪ production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', 0);%
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig
    ↪ degree days %% \n');
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
```

```
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n'
    ↪ );
fprintf(fid2,'PctZmin : %f \n', 70);%
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 1.80);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.3);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.013);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.003);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 6.5); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 140000);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.0091);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.95);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.076);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.125);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.10);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
fprintf(fid2,'fage : %f \n', 0.15);%
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n')
    ↪ ;
```

```
fprintf(fid2,'WP : %f \n', 30);%
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage (
    ↪ of WP) %% \n');
fprintf(fid2,'WPy : %f \n', 100);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %%
    ↪ \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n'
    ↪ );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.35);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress
    ↪ before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 0);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \
    ↪ n');
fprintf(fid2,'a_HI : %f \n', -999);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', -999);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference
    ↪ %% \n');
fprintf(fid2,'dHI0 : %f \n', -999);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n')
    ↪ ;
fprintf(fid2,'Determinant : %f \n', 0);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', 0);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs
    ↪  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.25);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_up2 : %f \n', 0.5);%
```

```
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_up3 : %f \n', 0.6);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.55);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal
    ↪ control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination
    ↪ %% \n');
fprintf(fid2,'fshape_w4 : %f \n', 1);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0
    ↪  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to
    ↪ deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop
    ↪ growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
fprintf(fid2,'beta : %f \n', 12);
```

```
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
fprintf(fid2,'GermThr : %f \n', 0.2);

fclose(fid2);
end

elseif cropt==4
%Potato
crop={'Potato'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 2);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 2);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 1);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/11');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 200);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 1079);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 984);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 1276);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
fprintf(fid2,'HIstart : %f \n', 550);%
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
```

```
fprintf(fid2,'Flowering : %f \n', 0);%
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days
    ↪ %% \n');
fprintf(fid2,'YldForm : %f \n', 700);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress
    ↪  %% \n');
fprintf(fid2,'Tbase : %f \n', 2);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no
    ↪ longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 40); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 0);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', -999);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', -999);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 0);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', -999);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', -999);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1:
    ↪  Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full
    ↪ biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', 7);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass
    ↪ production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', 0);%
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig
    ↪ degree days %% \n');
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n'
    ↪ );
```

```
fprintf(fid2,'PctZmin : %f \n', 70);%
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 1.5);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.5);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.016);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.004);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 15); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 40000);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.006);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.92);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.002);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.01615);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.1);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
fprintf(fid2,'fage : %f \n', 0.15);%
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n')
    ↪ ;
fprintf(fid2,'WP : %f \n', 18);%
```

```
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage (
    ↪ of WP) %% \n');
fprintf(fid2,'WPy : %f \n', 100);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %%
    ↪ \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n'
    ↪ );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.75);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress
    ↪ before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 2);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \
    ↪ n');
fprintf(fid2,'a_HI : %f \n', -999);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', 10);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference
    ↪ %% \n');
fprintf(fid2,'dHI0 : %f \n', 5);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n')
    ↪ ;
fprintf(fid2,'Determinant : %f \n', 0);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', -999);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs
    ↪  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.2);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_up2 : %f \n', 0.55);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
```

```
fprintf(fid2,'p_up3 : %f \n', 0.7);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', -999);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.7);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', -999);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal
    ↪ control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination
    ↪ %% \n');
fprintf(fid2,'fshape_w4 : %f \n', -999);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0
    ↪  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to
    ↪ deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop
    ↪ growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
fprintf(fid2,'beta : %f \n', 12);
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
```

```
fprintf(fid2,'GermThr : %f \n', 0.2);

fclose(fid2);
end

elseif cropt==5
%Sorghum
crop={'Sorghum'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 3);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 2);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 1);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/12');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 136);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 1583);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 1579);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 1760);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
fprintf(fid2,'HIstart : %f \n', 1041);%
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
fprintf(fid2,'Flowering : %f \n', 306);%
```

```
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days %% \n');
fprintf(fid2,'YldForm : %f \n', 719);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress %% \n');
fprintf(fid2,'Tbase : %f \n', 8);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 30); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 1);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', 40);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', 45);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', 10);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', 5);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', 12);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', 0);%
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig degree days %% \n');
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n' );
fprintf(fid2,'PctZmin : %f \n', 70);%
```

```
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 1.8);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.3);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.016);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.004);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 3); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 200000);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.006);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.9);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.009862);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.012);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.07);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
fprintf(fid2,'fage : %f \n', 0.3);%
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n')
    ↪ ;
fprintf(fid2,'WP : %f \n', 33.7);%
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage (
    ↪ of WP) %% \n');
```

```
fprintf(fid2,'WPy : %f \n', 100);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %%
    ↪ \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n'
    ↪ );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.45);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress
    ↪ before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 4);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \
    ↪ n');
fprintf(fid2,'a_HI : %f \n', 1);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', 3);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference
    ↪ %% \n');
fprintf(fid2,'dHI0 : %f \n', 25);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n')
    ↪ ;
fprintf(fid2,'Determinant : %f \n', 1);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', 100);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs
    ↪  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.15);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_up2 : %f \n', 0.7);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_up3 : %f \n', 0.7);%
```

```
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', 0.8);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.7);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal
    ↪ control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 6);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 3);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination
    ↪ %% \n');
fprintf(fid2,'fshape_w4 : %f \n', 1);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0
    ↪  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to
    ↪ deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop
    ↪ growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
fprintf(fid2,'beta : %f \n', 12);
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
fprintf(fid2,'GermThr : %f \n', 0.2);
```

```
fclose(fid2);
end

else
%Maize
crop={'Maize'};
for i=1:1
fid2 = fopen('Crop.txt','wt');

fprintf(fid2,'%%%% ---------- Crop parameters for AquaCropOS ---------- %%\n');
fprintf(fid2,'%%%% Crop Type (1: Leafy vegetable, 2: Root/tuber, 3: Fruit/grain
    ↪ ) %%\n');
fprintf(fid2,'CropType : %f\n', 3);%
fprintf(fid2,'%%%% Calendar Type (1: Calendar days, 2: Growing degree days)\n')
    ↪ ;
fprintf(fid2,'CalendarType : %f \n', 2);%
fprintf(fid2,'%%%% Convert calendar to GDD mode if inputs are given in calendar
    ↪  days (0: No; 1: Yes) %%\n');
fprintf(fid2,'SwitchGDD : %f \n', 1);%
fprintf(fid2,'%%%% Planting Date (dd/mm) %%\n');
fprintf(fid2,'PlantingDate : %s \n','01/09');%
fprintf(fid2,'%%%% Latest Harvest Date (dd/mm) %%\n');
fprintf(fid2,'HarvestDate : %s \n','30/12');%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to emergenc \n');
fprintf(fid2,'Emergence : %f \n', 80);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to \n');
fprintf(fid2,'MaxRooting : %f \n', 1400);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to senescence %%\n'
    ↪ );
fprintf(fid2,'Senescence : %f \n', 1400);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to maturity %% \n')
    ↪ ;
fprintf(fid2,'Maturity : %f \n', 1700);%
fprintf(fid2,'%%%% Growing degree/Calendar days from sowing to start of yield
    ↪ formation %% \n');
fprintf(fid2,'HIstart : %f \n', 880);%
fprintf(fid2,'%%%% Duration of flowering in growing degree/calendar days (-999
    ↪ for non-fruit/grain crops) %% \n');
fprintf(fid2,'Flowering : %f \n', 180);%
fprintf(fid2,'%%%% Duration of yield formation in growing degree/calendar days
    ↪ %% \n');
```

```
fprintf(fid2,'YldForm : %f \n', 750);%
fprintf(fid2,'%%%% Growing degree day calculation method %% \n');
fprintf(fid2,'GDDmethod : %f \n', 2);%
fprintf(fid2,'%%%% Base temperature (degC) below which growth does not progress
    ↪  %% \n');
fprintf(fid2,'Tbase : %f \n', 8);%
fprintf(fid2,'%%%% Upper temperature (degC) above which crop development no
    ↪ longer increases %% \n');
fprintf(fid2,'Tupp : %f \n', 30); %
fprintf(fid2,'%%%% Pollination affected by heat stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolHeatStress : %f \n', 1);%
fprintf(fid2,'%%%% Maximum air temperature (degC) above which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmax_up : %f \n', 40);%
fprintf(fid2,'%%%% Maximum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmax_lo : %f \n', 45);%
fprintf(fid2,'%%%% Pollination affected by cold stress (0: No; 1: Yes) %% \n');
fprintf(fid2,'PolColdStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum air temperature (degC) below which pollination
    ↪ begins to fail %% \n');
fprintf(fid2,'Tmin_up : %f \n', 10);%
fprintf(fid2,'%%%% Minimum air temperature (degC) at which pollination
    ↪ completely fails %% \n');
fprintf(fid2,'Tmin_lo : %f \n', 5);%
fprintf(fid2,'%%%% Biomass production affected by temperature stress (0: No; 1:
    ↪  Yes) %% \n');
fprintf(fid2,'BioTempStress : %f \n', 1);%
fprintf(fid2,'%%%% Minimum growing degree days (degC/day) required for full
    ↪ biomass production %% \n');
fprintf(fid2,'GDD_up : %f \n', 12);%
fprintf(fid2,'%%%% Growing degree days (degC/day) at which no biomass
    ↪ production occurs %% \n');
fprintf(fid2,'GDD_lo : %f \n', 0);%
fprintf(fid2,'%%%% Shape factor describing the reduction in biomass productig
    ↪ degree days %% \n');
fprintf(fid2,'fshape_b : %f \n', 13.8135);%
fprintf(fid2,'%%%% Initial percentage of minimum effective rooting depth %% \n'
    ↪ );
fprintf(fid2,'PctZmin : %f \n', 70);%
fprintf(fid2,'%%%% Minimum effective rooting depth (m) %% \n');
fprintf(fid2,'Zmin : %f \n', 0.30);%
```

```
fprintf(fid2,'%%%% Maximum rooting depth (m) %% \n');
fprintf(fid2,'Zmax : %f \n', 2);%
fprintf(fid2,'%%%% Shape factor describing root expansion %% \n');
fprintf(fid2,'fshape_r : %f \n', 1.3);%
fprintf(fid2,'%%%% Shape factor describing the effects of water stress on root
    ↪ expansion %% \n');
fprintf(fid2,'fshape_ex : %f \n', -6);%
fprintf(fid2,'%%%% Maximum root water extraction at top of the root zone (m3/m3
    ↪ /day) %% \n');
fprintf(fid2,'SxTopQ : %f \n', 0.0104);%
fprintf(fid2,'%%%% Maximum root water extraction at the bottom of the root zone
    ↪  (m3/m3/day) %% \n');
fprintf(fid2,'SxBotQ : %f \n', 0.0026);%
fprintf(fid2,'%%%% Exponent parameter for adjustment of Kcx once senescence is
    ↪ triggered %% \n');
fprintf(fid2,'a_Tr : %f \n', 1);%
fprintf(fid2,'%%%% Soil surface area (cm2) covered by an individual seedling %%
    ↪  \n');
fprintf(fid2,'SeedSize : %f \n', 6.5); %
fprintf(fid2,'%%%% Number of plants per hectare %% \n');
fprintf(fid2,'PlantPop : %f \n', 75000);%
fprintf(fid2,'%%%% Minimum canopy size below which yield formation cannot occur
    ↪  %% \n');
fprintf(fid2,'CCmin : %f \n', 0.049);%
fprintf(fid2,'%%%% Maximum canopy cover (fraction of soil cover) %% \n');
fprintf(fid2,'CCx : %f \n', 0.96);%
fprintf(fid2,'%%%% Canopy decline coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CDC : %f \n', 0.01);%
fprintf(fid2,'%%%% Canopy growth coefficient (fraction per day/GDD) %% \n');
fprintf(fid2,'CGC : %f \n', 0.0125);%
fprintf(fid2,'%%%% Crop coefficient when canopy growth is complete but prior to
    ↪  senescence %% \n');
fprintf(fid2,'Kcb : %f \n', 1.05);%
fprintf(fid2,'%%%% Decline of crop coefficient due to ageing (day) %% \n');
fprintf(fid2,'fage : %f \n', 0.3);%
fprintf(fid2,'%%%% Water productivity normalized for ET0 and C02 (g/m2) %% \n')
    ↪ ;
fprintf(fid2,'WP : %f \n', 33.7);%
fprintf(fid2,'%%%% Adjustment of water productivity in yield formation stage (
    ↪ of WP) %% \n');
fprintf(fid2,'WPy : %f \n', 100);%
fprintf(fid2,'%%%% Crop co2 sink strength coefficient %% \n');
```

```
fprintf(fid2,'fsink : %f \n', 0.5);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by Steduto et al. 2007 %%
    ↪ \n');
fprintf(fid2,'bsted : %f \n', 0.000138);%
fprintf(fid2,'%%%% WP co2 adjustment parameter given by FACE experiments %% \n'
    ↪ );
fprintf(fid2,'bface : %f \n', 0.001165);%
fprintf(fid2,'%%%% Reference harvest index %% \n');
fprintf(fid2,'HI0 : %f \n', 0.48);%
fprintf(fid2,'%%%% Initial harvest index %% \n');
fprintf(fid2,'HIini : %f \n', 0.01);%
fprintf(fid2,'%%%% Possible increase of harvest index due to water stress
    ↪ before flowering %% \n');
fprintf(fid2,'dHI_pre : %f \n', 0);%
fprintf(fid2,'%%%% Coefficient describing positive ed vegetative formation %% \
    ↪ n');
fprintf(fid2,'a_HI : %f \n', 7);%
fprintf(fid2,'%%%% Coefficient describing negative impact on harves %% \n');
fprintf(fid2,'b_HI : %f \n', 3);%
fprintf(fid2,'%%%% Maximum allowable increase of harvest index above reference
    ↪ %% \n');
fprintf(fid2,'dHI0 : %f \n', 15);%
fprintf(fid2,'%%%% Crop Determinancy (0: Indeterminant, 1: Determinant) %% \n')
    ↪ ;
fprintf(fid2,'Determinant : %f \n', 1);%
fprintf(fid2,'%%%% Excess of potential fruits %% \n');
fprintf(fid2,'exc : %f \n', 50);%
fprintf(fid2,'%%%% Percentage of total flowering at which peak flowering occurs
    ↪  %% \n');
fprintf(fid2,'MaxFlowPct : %f \n', 33.33);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on affect canopy expansion %% \n');
fprintf(fid2,'p_up1 : %f \n', 0.14);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_up2 : %f \n', 0.69);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_up3 : %f \n', 0.69);%
fprintf(fid2,'%%%% Upper soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_up4 : %f \n', 0.8);%
```

```
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy expansion %% \n');
fprintf(fid2,'p_lo1 : %f \n', 0.72);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy stomatal control %% \n');
fprintf(fid2,'p_lo2 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy senescence %% \n');
fprintf(fid2,'p_lo3 : %f \n', 1);%
fprintf(fid2,'%%%% Lower soil water depletion threshold for water stress
    ↪ effects on canopy pollination %% \n');
fprintf(fid2,'p_lo4 : %f \n', 1);%
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ expansion %% \n');
fprintf(fid2,'fshape_w1 : %f \n', 2.9);
fprintf(fid2,'%%%% Shape factor describing water stress effects on stomatal
    ↪ control %% \n');
fprintf(fid2,'fshape_w2 : %f \n', 6);
fprintf(fid2,'%%%% Shape factor describing water stress effects on canopy
    ↪ senescence %% \n');
fprintf(fid2,'fshape_w3 : %f \n', 2.7);
fprintf(fid2,'%%%% Shape factor describing water stress effects on pollination
    ↪ %% \n');
fprintf(fid2,'fshape_w4 : %f \n', 1);
fprintf(fid2,'%%%% Adjustment to water stress thresholds depending on daily ET0
    ↪  (0: No, 1: Yes) %% \n');
fprintf(fid2,'ETadj : %f \n', 1);
fprintf(fid2,'%%%% Vol below saturation at which stress begins to occur due to
    ↪ deficient aeration %% \n');
fprintf(fid2,'Aer : %f \n', 5);
fprintf(fid2,'%%%% Number of days lag before aeration stress affects crop
    ↪ growth %% \n');
fprintf(fid2,'LagAer : %f \n', 3);
fprintf(fid2,'%%%% Reduction to p_lo3 when early canopy senescence is triggered
    ↪  %% \n');
fprintf(fid2,'beta : %f \n', 12);
fprintf(fid2,'%%%% Proportion of total water storage needed for crop to
    ↪ germinate %% \n');
fprintf(fid2,'GermThr : %f \n', 0.2);

fclose(fid2);
end
```

```
1015
end

%Crop mix file
for i=1
1020 fid2 = fopen('CropMix.txt','wt');
fprintf(fid2,'%%%% ---------- Crop mix options for AquaCropOS ---------- %% \n'
    ↪ );
fprintf(fid2,'%%%% Number of crop options %% \n');
fprintf(fid2,'%f \n',1);
fprintf(fid2,'%%%% Specified planting calendar %% \n');
1025 fprintf(fid2,'N \n');
fprintf(fid2,'%%%% Crop rotation filename %% \n');
fprintf(fid2,'CropRotation.txt \n');
fprintf(fid2,'%%%% Information about each crop type %% \n');
fprintf(fid2,'%%%% CropType, CropFilename, IrrigationFilename %% \n');
1030 fprintf(fid2,'%s, Crop.txt, IrrigationManagement.txt \n',crop{:});

fclose(fid2);
end

1035 %Crop Rotation file
for i=1:1
fid2 = fopen('CropRotation.txt','wt');
fprintf(fid2,'%%%% --------- Crop rotation time-series for AquaCropOS ---------
    ↪  %% \n');
fprintf(fid2,'%%%% PlantDate HarvestDate Crop %% \n');
1040 fprintf(fid2,'01/05/2019 30/09/2019 %s \n',crop{:});
fclose(fid2);
end

%FieldManagement.txt
1045 if mane==1
    Mulches=0;
    fMulch=0.5;
elseif mane==2
    Mulches=1;
1050     fMulch=0.5;
else
    Mulches=1;
    fMulch=1;
end
```

```
for i=1:1
fid2 = fopen('FieldManagement.txt','wt');

fprintf(fid2,'%%%% -- Soil parameter inputs for AquaCropOS %%%%\n');
fprintf(fid2,'%%%% Soil surface covered by mulches (0: No; 1: Yes) %%%%\n');
fprintf(fid2,'Mulches : %f \n', Mulches);
fprintf(fid2,'%%%% Area of soil surface covered by mulches during growing \n');
fprintf(fid2,'MulchPctGS : %f \n', 50);
fprintf(fid2,'%%%% Area of soil surface covered by mulches outside growing \n')
    ↪ ;
fprintf(fid2,'MulchPctOS : %f \n', 50);
fprintf(fid2,'%%%% Soil evaporation adjustment factor due to effect of mulches
    ↪ %%\n');
fprintf(fid2,'fMulch : %f \n', fMulch);
fprintf(fid2,'%%%% Surface bunds present (0: No; 1: Yes) %%\n');
fprintf(fid2,'Bunds : %f \n', 0);
fprintf(fid2,'%%%% Bund height (m) %%\n');
fprintf(fid2,'zBund : %f \n', 0);
fprintf(fid2,'%%%% Initial water height in surface bunds (mm) %%\n');
fprintf(fid2,'BundWater : %f \n', 0);

fclose(fid2);

end

%Running AquaCrop Model
AquaCropOS_RUN

%reading Aquacrop output data
temp=importdata('Sample_WaterFluxes.txt');
WaterFluxes=temp.data;
clear temp;

Es=sum(WaterFluxes(:,15)); %(mm) Evaporation from soil surface

Tr=sum(WaterFluxes(:,17)); %(mm) Crop transpiration

if irrig==1
    Es=Es/0.5;
elseif irrig==2
    Es=Es/0.6;
elseif irrig==3
```

```
    Es=Es/0.7;
elseif irrig==4
    Es=Es/0.8;
elseif irrig==5
    Es=Es/0.9;
else
    Es=Es/0.95;
end


temp=importdata('Sample_FinalOutput.txt');
FinalOutput=temp.data;
clear temp;

Yield=sum(FinalOutput(:,2)); %(ton/ha) Crop Yield

if cropt==3
    if irrig==1
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.5;% (mm) Total
            ↪ Irrigation
    elseif irrig==2
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.6;
    elseif irrig==3
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.7;
    elseif irrig==4
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.8;
    elseif irrig==5
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.9;
    else
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/0.95;
    end

else
    if irrig==1
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.5); % (mm)
            ↪ Total Irrigation
    elseif irrig==2
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.6);
    elseif irrig==3
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.7);
    elseif irrig==4
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.8);
```

```
    elseif irrig==5
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.9);
    else
        matriz_TotIrr(cropt,irrig,mane)=sum(FinalOutput(:,3))/(2*0.95);
    end
end

matriz_PH(cropt,irrig,mane)=10*(Es+Tr)/Yield; %(l/kg)

end
end
end

cont_interacao=0;
cont_parada=0;
parar=0;
while parar==0

for ger=1:n_ger

PH=zeros(1,n_usuarios,n_popu);
Q_total=zeros(n_popu);
TotIrr=zeros(1,n_usuarios,n_popu);
for creature=1:n_popu
for user=1:n_usuarios
    TotIrr(1,user,creature)=matriz_TotIrr(popu_inicial(1,user,creature),
        ↪ popu_inicial(2,user,creature),popu_inicial(3,user,creature));
    PH(1,user,creature)=matriz_PH(popu_inicial(1,user,creature),popu_inicial(2,
        ↪ user,creature),popu_inicial(3,user,creature));
end
for u=1:n_usuarios
    %flow to irrigate total area
    Q_total(creature)=Q_total(creature)+TotIrr(1,u,creature)*A_max(u)/(1000*
        ↪ t_sec(popu_inicial(1,user,creature)));
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Feasibility of solutions
inviaveis=zeros(n_popu);

%Calculates the cost of each individual
```

```
custo=zeros(1,1,n_popu);
for k=1:n_popu
    for j=1:n_usuarios
        for i=2:3
            if popu_inicial(i,j,k)>IniConfig(i,j)
                custo(1,1,k)=custo(1,1,k)+cost(i,popu_inicial(i,j,k))*A_max(j);
            end
        end
    end
    if custo(1,1,k)>custo_limite
        inviaveis(k)=1;
    end
end

%Unviability by demand greater than availability
for u=1:n_popu
    if Q_total(u)>q_100
        inviaveis(u)=1;
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Objective functions

%calculation of objective functions
aptidao=zeros(1,n_funcoes,n_popu);%creating matrix to store the value of
    ↪ fitness

%calculation of the first objective function
for k=1:n_popu
     aptidao(1,1,k)= sum(PH(1,:,k));
end

%calculation of the second objective function
aptidao(1,2,:)= custo(1,1,:);

%standardization of fitness values
maior_aptidao=max(aptidao,[],3);
menor_aptidao=min(aptidao,[],3);

aptidao_norm=zeros(1,n_funcoes,n_popu);
for k=1:n_popu
```

```
    aptidao_norm(:,:,k)=100*(aptidao(:,:,k)-menor_aptidao)./(maior_aptidao-
        ↪ menor_aptidao);
end

%Strength of individuals
strength=zeros(n_popu);
for i=1:n_popu
    if inviaveis(i)==0
        for j=1:n_popu
            if inviaveis(j)==0
                if and(and(aptidao_norm(:,1,i)<=aptidao_norm(:,1,j),aptidao_norm
                    ↪ (:,2,i)<=aptidao_norm(:,2,j)),or(aptidao_norm(:,1,i)<
                    ↪ aptidao_norm(:,1,j),aptidao_norm(:,2,i)<aptidao_norm(:,2,j
                    ↪ )))
                    strength(i)=strength(i)+1;
                end
            end
        end
    else
        for j=1:n_popu
            if inviaveis(j)==1
                if and(and(aptidao_norm(:,1,i)<=aptidao_norm(:,1,j),aptidao_norm
                    ↪ (:,2,i)<=aptidao_norm(:,2,j)),or(aptidao_norm(:,1,i)<
                    ↪ aptidao_norm(:,1,j),aptidao_norm(:,2,i)<aptidao_norm(:,2,j
                    ↪ )))
                    strength(i)=strength(i)+1;
                end
            end
        end
    end
end

%Raw Fitness of individuals
raw_fitness=zeros(n_popu);
for i=1:n_popu
    if inviaveis(i)==0
        for j=1:n_popu
            if inviaveis(j)==0
                if and(and(aptidao_norm(:,1,i)<=aptidao_norm(:,1,j),aptidao_norm
                    ↪ (:,2,i)<=aptidao_norm(:,2,j)),or(aptidao_norm(:,1,i)<
                    ↪ aptidao_norm(:,1,j),aptidao_norm(:,2,i)<aptidao_norm(:,2,j
                    ↪ )))
```

```
                raw_fitness(j)=raw_fitness(j)+strength(i);
            end
        end
    end
else
    for j=1:n_popu
        if inviaveis(j)==1
            if and(and(aptidao_norm(:,1,i)<=aptidao_norm(:,1,j),aptidao_norm
                ↪ (:,2,i)<=aptidao_norm(:,2,j)),or(aptidao_norm(:,1,i)<
                ↪ aptidao_norm(:,1,j),aptidao_norm(:,2,i)<aptidao_norm(:,2,j
                ↪ )))
                raw_fitness(j)=raw_fitness(j)+strength(i);
            end
        end
    end
end
end

%Calculation of neighborhood density of individuals
distancia_euclidiana=NaN(n_popu,n_popu);
for i=1:n_popu
    restante=i+1;
    for j=restante:n_popu
        distancia_euclidiana(i,j)=sqrt((aptidao_norm(1,1,j)-aptidao_norm(1,1,i))
            ↪ ^2+(aptidao_norm(1,2,j)-aptidao_norm(1,2,i))^2);
        distancia_euclidiana(j,i)=distancia_euclidiana(i,j);
    end
end
densidade_vizinhanca=1./(2+distancia_euclidiana);

%Fitness calculation
fitness=zeros(n_popu);
for i=1:n_popu
    temp=densidade_vizinhanca(i,:);
    fitness(i)=max(temp)+raw_fitness(i);
end

%filling the external population
aptidao_ext=zeros(1,n_funcoes,n_popu_ext);
viabilidade_ext=zeros(n_popu_ext);
q_ext=zeros(n_popu_ext);
custo_ext=zeros(n_popu_ext);
```

```
popu_ext=zeros(3,n_usuarios,n_popu_ext); %creating the matrix to store the
    ↪ individuals of the external population
for i=1:n_popu_ext
    %making, initially, the first individual of the population to be
        ↪ the best individual. After that, it will be compared with
        ↪ each other individual of the population. If a individual is
        ↪ found to be better than the best so far, this will be the
        ↪ new best.
    n_melhor=1;
    viabilidade_melhor=inviaveis(1);
    raw_fitness_melhor=raw_fitness(1);
    aptidao_melhor=fitness(1);
    for j=2:n_popu
        if viabilidade_melhor==0 %if the best individual is viable
            if inviaveis(j)==0 %if the individual in comparison is viable
                if raw_fitness_melhor==0 %if the best individual is viable
                    ↪ and not dominated
                    if raw_fitness(j)==0 %if the individual in comparison is
                        ↪ viable and not dominated
                        if fitness(j)<aptidao_melhor
                            n_melhor=j;
                            viabilidade_melhor=inviaveis(j);
                            raw_fitness_melhor=raw_fitness(j);
                            aptidao_melhor=fitness(j);
                        end
                    end
                else %if the best individual is viable and dominated
                    if raw_fitness(j)==0 %if the individual in comparison is
                        ↪ viable and not dominated
                        n_melhor=j;
                        viabilidade_melhor=inviaveis(j);
                        raw_fitness_melhor=raw_fitness(j);
                        aptidao_melhor=fitness(j);
                    else %if the individual in comparison is viable and
                        ↪ dominated
                        if fitness(j)<aptidao_melhor
                            n_melhor=j;
                            viabilidade_melhor=inviaveis(j);
                            raw_fitness_melhor=raw_fitness(j);
                            aptidao_melhor=fitness(j);
                        end
                    end
```

```
            end
        end
    else %if the best individual is not viable
        if inviaveis(j)==0 %if the individual in comparison is viable
            n_melhor=j;
            viabilidade_melhor=inviaveis(j);
            raw_fitness_melhor=raw_fitness(j);
            aptidao_melhor=fitness(j);
        else %if the individual in comparison is not viable
            if raw_fitness_melhor==0 %if the best individual is
                ↪ unviable and not dominated
                if raw_fitness(j)==0 %if the individual in comparison is
                    ↪  unviable and not dominated
                    if fitness(j)<aptidao_melhor
                        n_melhor=j;
                        viabilidade_melhor=inviaveis(j);
                        raw_fitness_melhor=raw_fitness(j);
                        aptidao_melhor=fitness(j);
                    end
                end
            else %if the best individual is unviable and dominated
               if raw_fitness(j)==0 %if the individual in comparison is
                   ↪  unviable and not dominated
                   n_melhor=j;
                   viabilidade_melhor=inviaveis(j);
                   raw_fitness_melhor=raw_fitness(j);
                   aptidao_melhor=fitness(j);
               else %if the individual in comparison is unviable and
                   ↪ dominated
                    if fitness(j)<aptidao_melhor
                        n_melhor=j;
                        viabilidade_melhor=inviaveis(j);
                        raw_fitness_melhor=raw_fitness(j);
                        aptidao_melhor=fitness(j);
                    end
               end
            end
        end
    end
end
```

```
    popu_ext(:,:,i)=popu_inicial(:,:,n_melhor); %storing the best
        ↪ individual in the external population
    custo_ext(i)=custo(1,1,n_melhor);
    viabilidade_ext(i)=inviaveis(n_melhor);
    q_ext(i)=Q_total(n_melhor);
    aptidao_ext(:,:,i)=aptidao(:,:,n_melhor);

    %removing the best individual (who was transferred to the external
        ↪ population) from the selection process, so that in the next
        ↪ cycle the second best will be selected as the best.
    inviaveis(n_melhor)=1;
    raw_fitness(n_melhor)=Inf;
    fitness(n_melhor)=Inf;
end

%Transferring the 50 best individuals of this generation directly to
    ↪ the next generation (Elitism), so as not to lose the best
    ↪ solutions found so far.

for ini=1:50
    popu_inicial(:,:,ini)=popu_ext(:,:,ini);
end

for ini=1:10
    if viabilidade_ext(ini)==0
        x=aptidao_ext(1,1,ini);
        y=aptidao_ext(1,2,ini);
        plot(x,y,'b*')
        xlim([10000,19000]);
        ylim([0,custo_limite]);
        xlabel('Water Footprint (l/kg)')
        ylabel('Transition Cost (R$)')
        grid on
        hold on
    end
end

filho=IniConfig;

for i=51:n_popu

%Selection of individuals for reproduction
```

```
%draws two random individuals
colocacao1=round(rand(1)*n_popu_ext);%saves the individual's
    ↪ classification (1 is the fittest)
if colocacao1==0
    colocacao1=1;
end
colocacao2=round(rand(1)*n_popu_ext);
if colocacao2==0
    colocacao2=1;
end
%selects the best of both and sends it to reproduction
if colocacao1<colocacao2
    pai=popu_ext(:,:,colocacao1);
    colocacao_pai=colocacao1;
else
    pai=popu_ext(:,:,colocacao2);
    colocacao_pai=colocacao2;
end

%repeats the draw for mother's selection
colocacao3=round(rand(1)*n_popu_ext);
if colocacao3==0
    colocacao3=1;
end
colocacao4=round(rand(1)*n_popu_ext);
if colocacao4==0
    colocacao4=1;
end
if colocacao3>colocacao4
    mae=popu_ext(:,:,colocacao3);
    colocacao_mae=colocacao3;
else
    mae=popu_ext(:,:,colocacao4);
    colocacao_mae=colocacao4;
end

%Performs targeted mutation
if custo_ext(colocacao_pai)>custo_limite
    for col=1:n_usuarios
        for lin=1:3
```

```
            pai(lin,col)=pai(lin,col)-round((pai(lin,col)-IniConfig(lin,col))*
                ↪ rand(1));
        end
    end
end
if custo_ext(colocacao_mae)>custo_limite
    for col=1:n_usuarios
        for lin=1:3
            mae(lin,col)=mae(lin,col)-round((mae(lin,col)-IniConfig(lin,col))*
                ↪ rand(1));
        end
    end
end

% crossover
sorteado=rand(1);
if sorteado<=p_cross
    for col=1:n_usuarios
        for lin=1:3
            filho(lin,col)=round((pai(lin,col)+mae(lin,col))/2);
        end
    end
else
    if colocacao_pai>colocacao_mae
        filho=pai;
    else
        filho=mae;
    end
end

%performs uniform mutation
sorteado=rand(1);
if sorteado<=p_mut
    for col=1:n_usuarios
        for lin=1:3
            if lin==1
                filho(lin,col)=IniConfig(lin,col)+round((n_crop-IniConfig(lin,
                    ↪ col))*rand(1));
            elseif lin==2
                filho(lin,col)=IniConfig(lin,col)+round((n_irrig-IniConfig(lin,
                    ↪ col))*rand(1));
            else
```

```
                filho(lin,col)=IniConfig(lin,col)+round((n_mane-IniConfig(lin,
                    ↪ col))*rand(1));
            end
        end
    end
end

popu_inicial(:,:,i)=filho;

end

cont_interacao=cont_interacao+1;
fprintf('I'm in genaration %i \n',cont_interacao)
if viabilidade_ext(1)==0
    fprintf('The best individual is viable \n')
    cont_parada=cont_parada+1;
end

end

if cont_parada>1000
    parar=1;
    x=zeros(30);
    y=zeros(30);
    for ponto=1:30
        x(ponto)=aptidao_ext(1,1,ponto);
        y(ponto)=aptidao_ext(1,2,ponto);
    end
    plot(x,y,'r*')
    xlim([10000,19000]);
    ylim([0,custo_limite]);
    xlabel('Water Footprint (l/kg)')
    ylabel('Transition Cost (R$)')
    grid on
    hold on
    saveas(gcf,'pareto.png')
end
end
```

Annex

ANNEX A – Climatic Data

! ¤- ! [							
I IXLL oт {IX3	t ↑т дGiXLЙЫIX	wLpGLЙЫIX	¤т Iix↑L↑ЧLЦ	- IGpLpт	¹ т ½XGpLpт oIX' т I↑IX	9↑LiXX↑LIIiXLЙЫIX от wтыг↑x IIGLЦ	
DIXLL ЧGLЦ	I I	a WI ч GLЦ	a GII ч	a L↑ч	ミ	I ↓	I I
2ч	чч2	2ч	чч2	чч2	чч2	2ч	2ч
2,	чч2	чч2	чч2	чч2	чч2	2ч	2ч
2н	чч2	чч2	чч2	чч2	чч2	2ч	2ч
2,	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2ч	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2н	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2,	2ч	чч2	чч2	чч2	2ч	2ч
2н	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2,	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2н	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2,	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2н	ч2	2ч	чч2	чч2	чч2	2ч	2ч
2ч

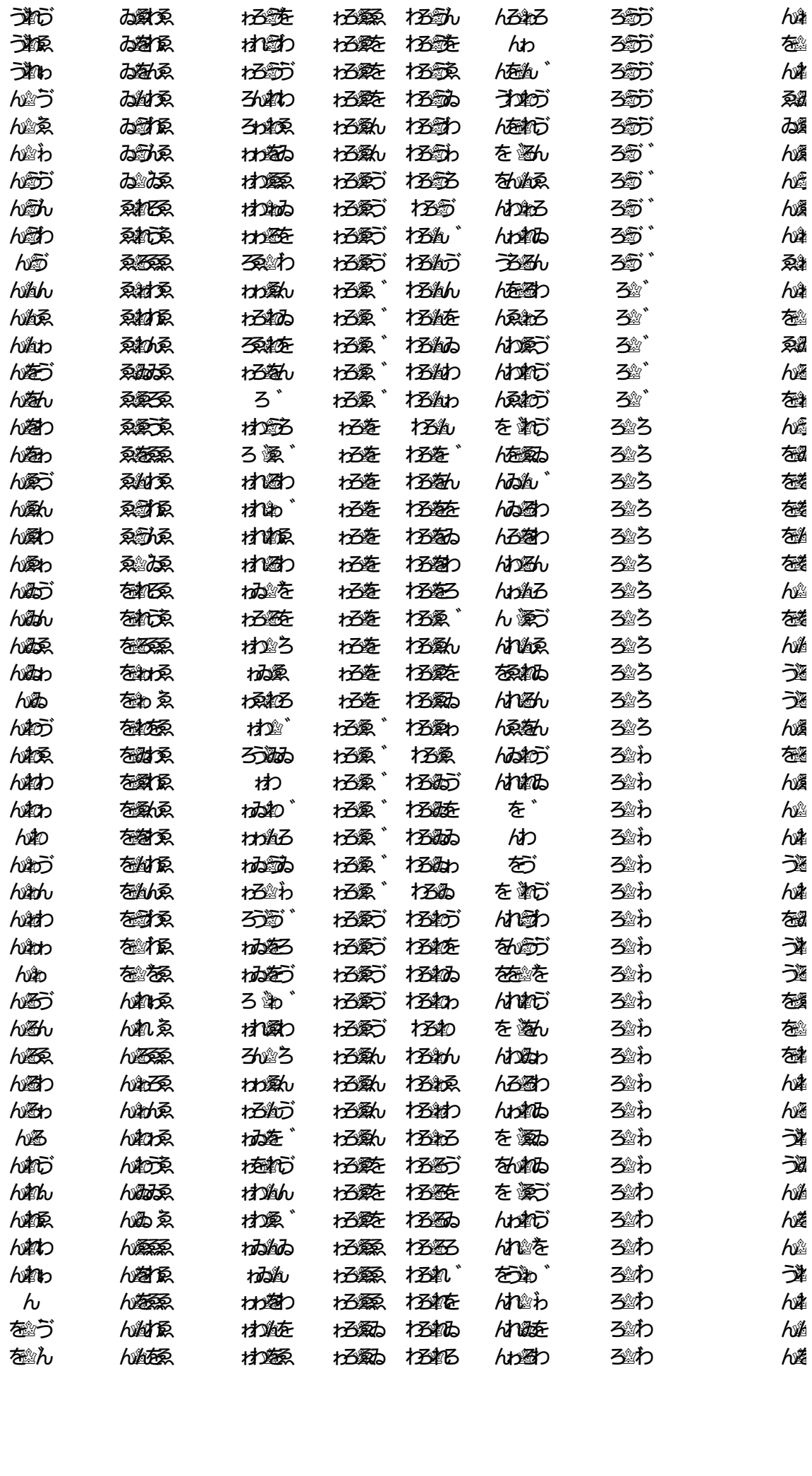
をゑ	んゐ	わゐゑゐ	われん゛	われわゑ	をゑゔ	ろわ	ん
をわ	ん゛゛	わゑをを	われん゛	われわゎ	をんわ	ろわ	ゔ
をわ	ゔわゐ	わゐゑん	われゔ	われゎ	んゎわわ	ろわ	ん
を゛	ゔれ゛	わわろ	われゔ	われろん	んろんろ	ろゐ	ん
をゔ	ゔわ	わゐゔ	われん	われゑ	をゔわ	ろゐ	ん
をん	ゔろゔ	わゑゑ	われを	われろゎ	をゔ	ろゐ	ゔ
をゑ	ゔわゎ	わゑゑ	われを	われれ゛	を ゐ	ろゐ	ん
をわ	ゔをを	わわゔ	われゑ	われわん	んれわ	ろゐ	ん
をわ	ゔわ	わゐゎ	われゐ	われわゐ	ををゎ	ろゐ	ん
をゔ	ゔわゐ	わゐゔ	われわ	われわろ	をんろ	ろゑ	ん
をん	ゔわゔ	わゑわゔ	われわ	ゎゔ	をんわわ	ろゑ	ゔ
をゑ	ゔゎ	われろ	われゎ	ゎを	んろわわ	ろゑ	を
をわ	ゔを	わゑわゐ	われろ	ゎわ	ををわわ	ろゑ	ゔ
をゎ	ゔゐ゛	わわを	われ	ゎ゛	を ゔ	ろを	ん
をん	ゔわ	わゑわ	われ゛	ゎん	ををわ	ろを	ゔ
をゔ	ゔん	わを	われん	ゎゐ	をゔわゔ	ろを	ん
をん	ゔを	わゐゑ゛	われを	ゎろ	をゑゐ	ろん	ん
をゑ	ゔわ	わろゑ	われゑ	ゎん゛	を わ	ろん	ん
をわ	ゔん	わゐを゛	われゐ	ゎを	を ろ	ろん	ん
をゎ	ゔん	わゑわ	われゎ	ゎわ	をゑわ	ろゔ	ゔ
をを	ゔわ	わを゛	われろ	ゎん	をゔわ	ろゔ	ん
をん	ゔを	わゑわ	われ゛	ゎん	をんゔ	ろゔ	ゔ
をゑ	ゔん゛	わゑゑ゛	われん	ゎゐ	をゑん	ろ゛゛	ゔ
をわ	ゔわ	われを	われを	ゎろ	をゔわゔ	ろ゛゛	を
をゎ	ゔを	わん	われゐ	ゎゔ	んれわゐ	ゎ	ん
をゑ	ゔゔ゛	わわゔ	われゎ	ゎゑ	んれゑ	ゎ	ん
をゔ	ゔわ	わわわ	われゑ	ゎゎ	んれゔ	わわろ	ん
をん	ゔゐ	わゐわ	われゔ	ゎゔ	んろゎ	わわろ	ん
をゑ	ゔん	わろわん	われを	ゎゑ	んゑわゔ	わわゎ	を
をわ	゛	ろゑゎ゛	われゐ	ゎゎ	んをわゑ	わわゎ	ゑ
をゎ	わ	ろをろゔ	われろ	ゎわ゛	んゔわゔ	わわわ	ゑ
をゐ	を	ろんわゐ	われ゛	ゎを	んゔを	わわわ	ゑ
をゔ	れ゛	ろんゑ	われん	ゎわ	んゎゑ	わわゐ	ゑ
をん	わ	わを゛	われゐ	ゎゎ゛	を ゐ	わわゐ	ん
をん	ゑ	わゑん	われゎ	ゎを	んれゔ	わわゑ	ん
をゑ	ゔ	わわん	われゎ゛	ゎわ	んろゔ	わわを	ん
をわ	ろ	わわ	われを	ゎゎ	んゑを	わわを	を
をゎ	ゐ	わを゛	われわ	ゎん	んゎゑ	わわん	ん
をゎ	ん	わろ	われゎ	ゎわ	んろん	わわゔ	ん
をわ	わ	わゐん	われん	ゎろ	んゎを	わわゔ	ん
をゔ	ゐ	わゑ	われゐ	ゎん	んゑろ	われ゛	ん
をゔ	ん	わゐゔ	われろ	ゎゐ	を ゔ	わろ	ん
をん	ゐ	わゑを	われゔ	ゎ゛	んれろ	わろ	ん
をゑ	わ	わわ゛	われゑ	わゔん	んわわ	わろ	ん
をゑ	ん	わわわ	われゎ	わゔゐ	んをを	わわ	を
をわ	ゑ	わわを	ろ ゔ	わゔ゛	を わ	わわ	ん
をわ	ゐ	ろをゔ	ろ ゑ	わゔん	んろゑ	わゐ	ゑ
をわ	ん	わゎ゛	ろ わ	わゔゐ	んれゔ	わゐ	ん
をゎ	ろ	わゑん	ろ ゔ	わゔろ	ををわ	わゑ	ん
をゎ	ゐ	わんわ	ろ ゑ	わゔん	をゎわ	わを	ゔ

をわ　　ぜづ　　わわんわ　　ろ゛ろ　　わづんぬ　　なえぇづ　　わろん　　んぜ
をわ　　ぜんわ　　ろ゛ろづ　　ろ゛んづ　　わづんろ　　すれぜわ　　わろづ　　えぇ
をわ　　ぜんを　　ろをろん　　ろ゛んぬ　　わづをづ　　んわれわ　　わろ゛　　えぇ
をわ　　ぜん゛　　わえぇろ　　ろ゛んろ　　わづをえ、　　なぬぇづ　　わろ゛　　うぜ
をわ　　ぜ゛わ　　わわんわ　　ろ゛をん　　わづをろ　　をづえ、　　わわぁ　　んぜ
をわ　　ぜ゛ん　　わわ゛を　　ろ゛をわ　　わづえづ　　をづぬわ　　わわろ　　んぜ
をわ　　ぜ゛ろ　　わわを゛　　ろ゛を　　わづえぇ、　　んれぜわ　　わわわ　　んぜ
をわ　　ぜ゛ぇ　　わわん　　ろ゛えを　　わづえわ　　んれわづ　　わわわ　　んぜ
をわ　　ぜ゛゛　　ろぬんろ　　ろ゛えわ　　わづぬ゛　　んれわえ、　　わわぬ　　えぜ
をわ　　ぜれわ　　わぬ゛ん　　ろ゛ぬ゛　　わづぬを　　ををぁ゛　　わわえ、　　んぜ
をわ　　ぜれん　　わえぜわ　　ろ゛ぬえ、　　わづぬわ　　をぁ゛を　　わわを　　うぜ
をわ　　ぜれろ　　わわえ、゛　　ろ゛ぬろ　　わづぬ　　をづわえ、　　わわん　　んぜ
をわ　　ぜれぜぬ　　わえぜを　　ろ゛わづ　　わづわん　　んれ゛わ　　わわづ　　んぜ
をわ　　ぜれろづ　　わをわわ　　ろ゛わぬ　　わづわぬ　　なえ゛を　　わわ゛　　うぜ
をわ　　ぜれわ　　わんぜわ　　ろ゛わ　　わづわろ　　なぬんえ、　　わわ゛　　うぜ
をわわ　　ぜれぇ、　　わをろ゛　　ろ゛わん　　わづわづ　　んわれわ　　わわろ　　んぜ
をわわ　　ぜれぁ゛　　わわれん　　ろ゛わわ　　わづわを　　んえぜわ　　わわろ　　をわ
をわわ　　ぜれわ　　わ　　ろ゛ろ゛　　わづわわ　　んわ　　わわわ　　んぜ
をわわ　　ぜれぇ、　　わぬぬづ　　ろ゛ぜを　　わづわ　　をんわろ　　わわわ　　んぜ
をわわ　　ぜれづ　　わわわ　　ろ゛ぜわ　　わづぜん　　んれわえ、　　わわぬ　　をぁ
をわわ　　ぜれろ　　ろをわぬ　　ろ゛われ゛　　わづぜえ、　　んわわろ　　わわえ、　　えぇ
をわわ　　ぜれぬ　　ろ゛ろ　　ろ゛わえ、　　わづぜわ　　をぁづ　　わわを　　をわ
をわえ、　　ぜれを　　わろわづ　　ろ゛わわ　　わづろ　　んわ゛を　　わわん　　をぜ
をわえ、　　ぜれづ　　ろ゛をろ　　ろづ゛づ　　わづわん　　を゛　　わわづ　　をわ
をわん　　ぜれえ、　　わぜぬ　　ろづ゛え　　わづわえ、　　をんわぬ　　わわ゛　　んぜ
をわん　　ぜれわ　　わえわぬ　　ろづ゛わ　　わづわわ　　をえぇづ　　わぬ　　んぜ
をわづ　　ぜれわ　　わわんえ、　　ろづづ゛　　わづわろ　　んわぜわ　　わぬろ　　んぜ
をわづ　　ぜれえ、　　をわろ　　ろづ゛え、　　わん゛う　　づぬえづ　　わぬわ　　わぬ
をわ　　ぜれえ、　　わづぇわ　　ろづ゛わ　　わん゛を　　ん゛ぜん　　わぬわ　　をぇ
をわ　　ぜれぇを　　わづをろ　　ろづん゛　　わん゛ぬ　　んぬぇぬ　　わぬわ　　んぜ
をわわ　　ぜれぇを　　わぬわろ　　ろづんを　　わん゛わ　　んわぁ゛　　わぬぬ　　んぜ
をわわ　　ぜれぇを　　わえぇをを　　ろづんわ　　わん゛　　んわづん　　わぬえ、　　んぜ
をわわ　　ぜれえ、　　わぬれわ　　ろづん　　わんづ　　んわぜを　　わぬを　　んぜ
をわえ、　　ぜれぬ　　わえぇえ、　　ろづをん　　わんぜん　　を゛うづ　　わぬん　　んぇ
をわん　　ぜれわ　　わえわろ　　ろづをぬ　　わんえ、　　んわれわ　　わぬづ　　んぜ
をわん　　ぜれろ　　わぬ　　ろづをろ　　わんぜわ　　んわ゛を　　わぬづ　　んぜ
をわづ　　ぜれづ　　わづえ、　　ろづえ゛　　わんぜわ　　をんわづ　　わぬ゛　　んぜ
をぬ　　ぜれぜを　　われわ　　ろづえを　　わんづ　　んれぁ゛　　わえ、　　をぇ
をぬわ　　ぜれぬわ　　わをぁぬ　　ろづえわ　　わんん゛　　をえぇを　　わえろ　　うぜ
をぬわ　　ぜれわ゛　　わえんん　　ろづえろ　　わんんづ　　をぁをん　　わえろ　　んぁ
をぬわ　　ぜれぇ、　　わを゛う　　ろづぬづ　　わんんん　　をえをん　　わえわ　　うぜ
をぬえ、　　ぜれわ　　を　　ろづぬを　　わんんえ、　　すれぜわ　　わえわ　　わぇ
をぬん　　ぜれぇ、　　わえれ、　　ろづぬぬ　　わんんぬ　　んわえぬ　　わえぬ　　んぜ
をぬづ　　ぜれぇ　　わぬわづ　　ろづぬろ　　わんんわ　　づわぜを　　わえぬ　　ぬぇ
をえ、　　ぜれぬ　　わぬぁづ　　ろづわ゛　　わんんわ　　んわづわ　　わええ、　　んぜ
をえわ　　ぜれん　　わ゛わ　　ろづわん　　わんんわ　　んれぁ゛　　わええ、　　んぜ
をえわ　　ぜれろ　　わ゛わ　　ろづわえ、　　わんんろ　　んわ゛を　　わえを　　うぜ
をええ、　　を　　わぬん゛　　ろづわわ　　わん　　を゛えぬ　　わえん　　んぜ
をえん　　ぜを　　わ゛ぬぬ　　ろづわろ　　わんん　　んろ゛わ　　わえん　　うぜ
をえづ　　ぜん　　ぜぬぬ　　ろづわ゛　　わんを゛　　うぜろん　　わえづ　　わぜ

をを　　を゛　　わろれを　　ろづわづ　　わんを゛　　づえわ　　わをづ　　ゑゑ
ををわ　　を　　ぬ゛　　ろづれを　　わんを゛　　づんわ　　わを、゛　　わん
ををわ　　を、　　んれろ　　ろづれを、　　わんをづ　　づえんろ　　わを、゛　　わを
ををを、　　ぬ　　わづれを、　　ろづわ　　わんをづ　　んろんを、　　わを、゛　　づん
ををん　　ゎ　　わわれろ　　ろづわ　　わんをづ　　んわをん　　わを　　をを
ををづ　　ゎ　　わろをを　　ろづゎ　　わんをづ　　んれんろ　　わを　　をゑ
をんわ　　れ゛　　われ　　ろづろ゛　　わんを゛　　を゛わ　　わをろ　　づん
をんわ　　づづ　　ゑ、　　ろづろづ　　わんを゛　　んぬをわ　　わをろ　　わゑ
をんを、　　づを　　ろろをを　　ろづをん　　わんを゛　　んづれづ　　わをろ　　ぬを
をんん　　づんを、　　ろれわ゛　　ろづをを　　わんを゛　　づゎ゛　　わをろ　　わを
をづ　　づをわ　　わをわを、　　ろづをを　　わんん　　ん゛を、　　わをろ　　んを
をゑわ　　う、　　ろを、　　ろづろを、　　わんろ　　ん゛をん　　わをわ　　ぬん
をゑわ　　づわづ　　ろづづ゛　　ろづをぬ　　わんろ　　うろんろ　　わをわ　　ゑを
をゑを、　　づわを、　　ろををぬ　　ろづをぬ　　わんわ　　づえわ　　わをわ　　ぬを
をうづ　　づをわ　　わぬぬ　　ろづをぬ　　わんわ　　んづをわ　　わをわ　　んを
を゛　　づ　　わろれわ　　ろづをわ　　わんぬ　　んをわ　　わをわ　　をん
を゛わ　　んをん　　ろん゛ん　　ろづをわ　　わんを、　　んをれぬ　　わをわ　　ゑを
を゛を、　　んんぬ　　ゎ゛　　ろづをわ　　わんを　　んわれぬ　　わをわ　　づを
を゛ん　　んをろ　　ろ゛をぬ　　ろづをわ　　わんん　　んわをん　　わをわ　　をを
を゛づ　　んぬづ　　われを、　　ろづをわ　　わんづ　　んぬをづ　　わをわ　　をん
んれわ　　んわぬ　　ろわ゛わ　　ろづをぬ　　わんづ　　んをゎ゛　　わをわ　　ぬを
んれわ　　んわろ　　われ　　ろづをぬ　　わんろ　　んをれぬ　　わをわ　　づを
んれん　　んわづ　　ろれん゛　　ろづろを、　　わんをわ　　んんわ　　わをろ　　わ
んれづ　　を、　　ろををを　　ろづろを、　　わんをぬ　　んろゎ　　わをろ　　ゑん
んろ　　をゑわ　　ろづをを　　ろづをを　　わんをを　　んれわを、　　わをろ　　をを
んをわ　　をを゛　　ろわづ　　ろづをん　　わんをづ　　んををを　　わをろ　　ぬを
んろを、　　ををを　　ろろれづ　　ろづろづ　　わん゛　　うろをぬ　　わをろ　　わを
んろづ　　ををぬ　　うをぬ　　ろづろ゛　　わんゎ　　うを　　わを　　ゎ
んゎ　　をれろ　　ろろゎ　　ろづゎ　　わんぬ　　づわを、　　わを　　わん
んゎわ　　をろ゛　　わををづ　　ろづわろ　　わんを　　んれんを、　　わを、゛　　んん
んわを、　　をれん　　わんをわ　　ろづわ　　わん゛　　をづをわ　　わを、゛　　うん
んわづ　　をを、　　われろ　　ろづわぬ　　わづ　　んわをわ　　わをづ　　をん
んゎ　　ををわ　　わを゛を　　ろづわを　　わづれゎ　　んわゎ゛　　わをづ　　ん゛
んわわ　　をんわ　　われぬ　　ろづわづ　　わづわを、　　んろづ　　わをん　　をん
んわを、　　をを　　わづゎわ　　ろづゎ　　わづれん　　んれをわ　　わをん　　を゛
んわづ　　をぬ゛　　んんわ　　ろづわろ　　わづろ　　んづわづ　　わをを　　わん
んぬ　　をわづ　　ろわぬ゛　　ろづわわ　　わづをわ　　すわづ　　わをを　　ぬん
んぬわ　　をんん　　ろづわん　　ろづわを、　　わづをを、　　うろん　　わをを、　　をを
んぬを、　　をろん　　ろ゛わぬ　　ろづわづ　　わづろづ　　ん゛　　わをぬ　　をを
んぬづ　　をわん　　ろづわぬ　　ろづぬ　　わづわろ　　んろわろ　　わをわ　　をを
んをん　　ぬ゛ん　　わろ゛　　ろづぬわ　　わづわぬ　　んを　　わをわ　　をん
んをわ　　ぬをん　　ろれろを、　　ろづぬを、　　わづんん　　づえわづ　　わをわ　　わん
んをん　　ぬろん　　ろわろづ　　ろづぬん　　わづわ　　うをんを、　　わをろ　　わん
んをを、　　ぬわん　　ろ゛わぬ　　ろづわづ　　わづろづ　　ん゛　　わをぬ　　をを
んをづ　　ぬれん　　ろづわぬ　　ろづぬ　　わづわろ　　んろわろ　　わをわ　　をん
んん、　　ぬ゛ん　　わろ゛　　ろづぬわ　　わづわぬ　　んを　　わをわ　　をを
んんわ　　ぬをん　　ろれろを、　　ろづぬを、　　わづんん　　づえわづ　　わをわ　　わん
んんん、　　ぬろん　　ろわろづ　　ろづぬん　　わづわ　　うをんを、　　わをろ　　わん
んんづ　　ぬわん　　ろ゛わぬ　　ろづわづ　　わづろづ　　ん゛　　わをぬ　　をん
んんわ　　ぬをん　　ろづわぬ　　ろづぬ　　わづわろ　　んろわろ　　わをわ　　ぬん
んんん　　ぬろを　　ろ゛わ　　ろづをを　　わづをわ　　すわをん　　わをぬ　　ゑを

んんづ みれづ ろわんぬ ろうを゛ わづえん うぬづわ わえぬ みれ
んんわ みれろ う゛゛ ろづんろ わづを づんえ、 わえわ わ
んんえ、 わ わ ろれんん ろづんぬ わづをぬ づん を わえろ われ
んんづ わづを ろれをわ ろづんん わづをづ づづをわ わぬ われ
ん わ わんづ ろろをわ ろづづ わづんわ づんわづ わわ゛ わを
ん えん わんろ をわぬ ろづづわ わづんえ、 れえわ わわづ われ
ん うん わをぬ ろうんぬ ろづを わづん゛ うんえ、 わわん みれ
づわ わえん わぬ ろづづ゛ わづをわ ん んえん わわを を
うわ わえ、 わんぬ ろづ わづをん づわをを わわぬ るん
うん わえぬ わろろ ろづえ、 わづろ づんを わわわ をん
うろ わわん わろん ろづう わづえ、 んえんを わわわ をを
うをわ わわろ ろづわ ろわろ わづ゛゛ んわづ わわろ るを
うをん わわぬ ろづをを ろわぬ わわわ んををん わわ゛ るん
うわ わろづ わわろ゛ ろわを わんん んぬわづ わわづ をん
うわわ わをわ わんわ ろわ゛ わろろ んわえわ わわん んれ
うわん わわ、 わんづ ろをわ わろろ んわろ わわを を
うわ わ゛゛ んぬ ろをえ、 わ ろ゛ うんん゛ わわぬ わを
うわわ わ わ ろれえぬ ろをづ わわわ ろわぬ わわわ わを
うわん わをん ろんをを ろわ わんん んんん゛ わわわ るを
うえぬ わをわ わわわわ ろわわ わわろ んづえ、 わわろ をん
うをわ わんを わわんん ろわを わわを うれ わろ゛ をを
うをん わん わんえ、 ろわづ わぬ んを わろづ をん
うえ、 わえぬ わわろ ろわろ わえぬ んづわ わえを をん
うえわ わえ、゛ わんわ ろわわ わえづ んんわづ わろえ、 をを
うえん わえわ ろれわ ろわを わえわ うわえぬ わろぬ みれ
うえを わぬづ ん ろわづ ろえろ わえを んを゛づ わろろ をん
うをわ わえわ ろをん ろえろ わえぬ ろわを んをづ わろろ をん
うをん わわづ ろうわ ろえぬ わえん うろえ、 わわづ るん
うん わわわ ろえぬ ろええ、 わえん ろわろ んづえわ わわん るん
うんわ わわづ ろづえわ ろえづ わんろ んづえわ わわん るん
うんえ、 わわわ ろんづ ろえ、 わんえ、 ん わ わわを るん
うんづ わろづ ろんえぬ ろえわ わ ん゛ んづわづ わわぬ るん
うづ わえぬ ろんろ ろえぬ わわ んえわ わわわ るん
うづわ わわ゛ ろづろづ ろえん わを うわづ わわわ るん
うづん わわろ をわ゛ ろ゛、 わ゛ ずえん ろ゛゛ んん
うづづ わわろ わわんん ろえろ わん゛ぬ んをえ、 ろ゛うん
うわ ろ゛ん ろええろ ろえわ わん んわわづ ろ゛う るん
うわ ろ゛わ わろをづ ろええ、 わわわろ をづわ ろ゛を んん
うん ろづ゛ ろわえわ ろえん わわわぬ んわえわ ろ゛え、 みん
うづ ろ゛え、 われ ろを゛ わわわづ んわえづ ろ゛ぬ ん
゛ ろ゛わ うえぬ ろんろ わわえろ んんえん ろ゛わ わわ
われわ ろん゛ をえづ ろんわ わわえぬ うぬえわ ろ゛ろ わわ
われ、 ろんを ん゛づ ろんぬ わわえづ うづえわ ろ゛゛ わわ
われん ろんわ ろんえん ろんを わわわろ んえわづ ろづ゛ るん
われづ ろんろ ろづえ、 ろんづ わわんぬ んんえわ ろづづ るん
ろ ろをづ ろえ、 ろづ わわんん んえんえ、 ろづを るん
ろわ ろをを ろわを ろづろ わわわ んえを ろづえ、 みん
ろわ ろをぬ ろんわ ろづわ わわわ うええわ ろづぬ みん
ろえ、 ろをわ ろ えわ ろづん わわえ、 すわづ ろづわ るん
ろえ、 ろを ろ えわ ろづん わわえづ んづえわ ろづわ を

ぬん　ろあ、゛　ろづぬろ　ろ ぬづ　われぬろ　んづぬん　ろぬろ　あぬ
ぬづ　ろあづ　ろんれづ　ろ ぬ゛　われぬわ　んぬれあ、　ろぬづ　あぬ
ぬわ　ろあん　ろ ぬあぬ　ろ ぬわ　われぬを　んわあづ　ろんゝ　をね
ぬわ　ろあを　わぬあん　ろ ぬわ　われぬづ　んあ゛わ　ろんづ　んぬ
ぬわ　ろあを、　ろわを゛　ろ ぬえ、　われあろ　づぬあん　ろんを　みぬ
ぬわ　ろあぬ　ろわぬろ　ろ ぬん　われあわ　づわぬづ　ろんを　みぬ
ぬわ　ろあぬ　ろ ぬあを、　ろ ぬづ　われあを、　んづぬを　ろんぬ　をね
ぬわを、　ろあぬ　ろをぬみ　れれ　われあづ　んをあぬ　ろんぬ　あぬ
ぬん　ろあぬ　ろわんわ　われれわ　われを　ずぬあん　ろんわ　みね
ぬん　ろあぬ　ろを゛づ　われれわ　われあわ　んわぬを　ろんわ　あぬ
ぬづ　ろあぬ　ろづぬん　われれを、　われあぬ　ずれぬづ　ろんろ　あぬ
ぬづ　ろあぬ　ろあ゛わ　われれを　われあを　ずわを、　ろんゝ　あね
ぬわ　ろあぬ　ろわぬを　われれづ　われあづ　うろんゝ　ろを゛　みね
ぬわ　ろあを、　わをれわ　われれ゛　われを゛　んをれづ　ろをづ　ん
ぬわ　ろあを　ろんろわ　われろわ　われんろ　ずれあん　ろをづ　あぬ
ぬわ　ろあを　ろをぬろ　われろわ　われんわ　づわぬを　ろあん　あぬ
ぬわ　ろあん　あれづ　われろぬ　われんを、　ずれわ　ろあを　わね
ぬわ　ろあづ　ろんぬろ　われろを、　われんを　んぬ　ろあを　あぬ
ぬを、　ろあ、゛　ろづれぬ　われろん　われんづ　んろわろ　ろあを、　をね
ぬを、　ろあを　わをれわ　われろづ　われん゛　を ぬ、　ろあぬ　ん
ぬん　ろあろ　ろづぬを　われろ゛　われごろ　んをあわ　ろあぬ　あぬ
ぬん　ろあわ　わろろ゛　われんろ　われごわ　んわぬを　ろあわ　をん
ぬづ　ろあわ　ろわわ　われわ　われごわ　んんわ゛　ろあわ　みね
ぬづ　ろあぬ　ろんんを、　われわぬ　われごを、　んぬ　ろあわ　あぬ
ぬ　ろあを、　わろあろ　われを、　われごを　んぬあわ　ろあわ　をね
ぬ　ろあん　ろんあづ　われを　われごん　ずれあわ　ろあろ　みん
ぬわ　ろあづ　ぬわ　われん　われごづ　ずれを　ろあろ　わね
ぬわ　ろあを゛　ろわわろ　われわ゛　われ゛　うろぬわ　ろあを　みね
ぬわ　ろん　あづ゛　われわ　われぬろ　ろんゝ　ろあを　わね
ぬを、　ろんろ　んぬづ　われわろ　われぬわ　うづあん　ろあを　わを
ぬを、　ろんわ　ろわあを、　われわわ　われぬわ　うろんろ　ろあ、゛　みね
ぬん　ろんぬ　をぬわ　われわわ　われぬぬ　れごづ　ろあ、゛　わね
ぬづ　ろんを、　わあわ　われわぬ　われぬえ　わんを、　ろあ、゛　ろね
ぬづ　ろんを　んんづ　われわを、　われぬを　ろねづ　ろあ、゛　わを
あ、　ろんん　ろろをづ　われわを　われぬん　うえあん　ろあづ　わを
あわ　ろんづ　ろわねづ　われわん　われぬう　ずれわ　ろあづ　みね
あわ　ろん゛　ろづわ　われわづ　われぬ゛゛　んをあわ　ろあづ　をね
あわ　ろあ゛　わぬぬろ　われわ゛　われぬ゛゛　んろあづ　ろあづ　んん
あわ　ろあろ　う゛　われぬ　わろ　んぬれぬ　ろあづ　わね
あを、　ろあわ　ろえぬを　われぬろ　わろれろ　んんんを、　ろあづ　あね
あん　ろあわ　ろぬあ、　われぬろ　わろれわ　うろねづ　ろあづ　みん
あん　ろあぬ　ろえれわ　われぬわ　わろれわ　うぬあん　ろあづ　みを
あづ　ろあを、　ろわれん　われぬわ　わろれわ　うわ゛わ　ろあづ　みね
あづ　ろあを　ろぬあろ　われぬわ　わろれぬ　んえぬを　ろあづ　みぬ
あを　ろあん　ろ ぬえ、　われぬぬ　わろれを、　んをわろ　ろあづ　をね
あを　ろあづ　ろ ぬわ　われぬを、　わろれを、　んぬあづ　ろあづ　をね
あわ　ろあ゛　ろえあろ　われぬを、　わろれを　んんあわ　ろあづ　あね
あわ　ろ゛　わわろ　われぬを　わろれん　ん あづ　ろあづ　をを
あわ　ろあろ　ぬ　われぬを　わろれん　うんあづ　ろあづ　ろん
あわ　ろあわ　わわれろ　われぬん　わろれづ　うをわろ　ろあ、゛　をね



わ　ろん、　ろうれ、　わろろ　わろっ　んっを　ろ、　る
わ　ろっる、　ろんっ　わろわ　わろっ　んぬっ　ろ、　る
わ　ろっる、　ろんを　わろわ　わろっぬ　んを、ぬ　ろ、　る
わ　ろっる、　ろんる、　わろわ　わろっぬ　ん わ　ろ、　る
わ　ろっる、　うれを　わろわ　わろっる、　うんれぬ　ろを　わ
わ　ろっる、　わんわ　わろわ　わろっる、　んをんろ　ろを　う
わ　ろっる、　れをん　わろんぬ　わろっを　うぬっ　ろを　れ
わ　ろっ、　われ　わろんぬ　わろっを　を れぬ　ろをろ　
わ　ろっる、　ろんっぬ　わろんぬ　わろっん　うれぬわ　ろをろ　る
わ　ろっる、　ろをれわ　わろんる、　わろっん　うぬ、っ　ろをろ　み
わ　ろっる、　ろっ　わろんる、　わろっっ　ん っん　ろをわ　を
わ　ろっる、　ろぬ、　わろんる、　わろっっ　ん っろ　ろをわ　み
を　ろっる、　ろんを　わろんを　わろっ　ん っわ　ろをわ　み
を　われる、　わっを　わろんを　わろっ　んんれぬ　ろをわ　ん
っ　われる、　ろっわ　わろんを　わろっ　うれろ　ろをぬ　み
ん　われる、　ろれろ　わろんん　わろ　うわっっ　ろをぬ　わ
る、　われる、　ろをれ　わろんん　わろ　うれっわ　ろをぬ　る
る、　わろる、　ろっん　わろんん　わろっろ　うをれっ　ろをる、　わ
る わ　わろる、　ろっん　わろんん　わろっろ　うをれっ　ろをる、　わ

ｷｵｷｵ□ｷｵｳｷ

ＩＩＸＬＱ ｏｔ {ＩＸ３	ｔ↑ｔдＱｉＸ↑ＬＩＹＩＸ	ｗＬｐＱＬＩＹＩＸ	¤ｔ Ｉｉｘ↑Ｌ↑ＣＬ	- ＩＧｂＬＱｔ	ｔ½ＸＱＧｂＬＱｔ ｏＩＸ ｔ Ｉ↑ＩＸ	９↑ＬｉＸＸ↑ＬＩＱｉＸ↑ＬＩＹＩＸ ｏｔ ｗｒｙｔ↑ｘＩＱＱＬ
ＤＩＸ↑ＬＱ↓ｂＱＬ	ＩＩ	ａ ＷＩｗＱＱＬ	ａ ＱＩＵＩ	ａ Ｌ⇋Ｉ	ミ	Ｉ⇵	ＩＩ
ぁわ	わぃねぇ	ろをんぇ	わっぃわ	わっをぁ、	んぃぇづ	ろっをを	ゑ
ぁ、	わぃん	ぃぇぇぇ	わっぃわ	わっをを	んろわ〝	ろっをを	を
ぁん	わろ	ぃぇろ	わっぃわ	わっをを	ん ゎろ	ろっをん	を
ぁゑ、	わぁわ	ろ ゎわ	わっぃわ	わっをを	ん ゎゑ、	ろっをづ	を
ぁわ	わっをを	ゎゑ、	わっぃわ	わっをん	れぃづ	ろっをづ	わ
ぁぬわ	わゎ	ろ ゎゑ、	わっぃねぇ	わっをん	んぬろん	ろっをづ	を
ぃづ	わぃわ	ろうぁろ	わっぃねぇ	わっをん	んぬぇづ	ろっを〝	を
ぃん	わぃん	ろをれづ	わっぃを、	わっをん	うわぁわ	ろっを〝	ゑ
ぃわ	わぃろ	ろ ゎろ	わっぃを、	わっをづ	んん	ろゎん	を
ぃわ	わぃを、	ろぬぁろ	わっぃを、	わっをづ	うわ゛わ	ろゎろ	ぬ
ぃわづ	わゎ〝	ろゑぃをを	わっぃをを	わっをづ	んわぇぬ	ろゎろ	ゑ
ぃわを、	わぁわ	ろうゎ〝	わっぃをを	わっをづ	んわゎ〝	ろゎわ	を
ぃわ	わぁん	ぃれぃづ	わっぃん	わっを〝	んんぁをを	ろゎわ	を
ぃゎ	わぇわ	ぃれぃをを	わっぃれづ	わっを〝	んをゎを、	ろゎわ	を
ぃろん	わぇをを	ろ ゎゑ、	わっぃれづ	わっを〝	んを゛を	ろゎわ	を
ぃぁわ	わっをろ	ぃれぃん	わっぃれ〝	わっを〝	んわゎわ	ろゎぬ	を
ぃろ	わっをを、	ろ ゎゑ、	わっぃれ〝	わっを〝	ん ゎぇん	ろゎぬ	を
ぃれん	わゎん	んぇづ	わっろ	わっを〝	うづぁをを	ろゎを、	わ
ぃれわ	わゎを、	ぃれ゛ろ	わっぁろ	わっを〝	うろゎ〝	ろゎをを	を
〝	わっづ	ぃれぃぬ	わっぁろ	わっを〝	んんぇん	ろゎをを	を
づ゛ん	わ゛を、	ろんぃわ	わっぁわ	わっを〝	うわぁわ	ろゎをを	を
づ゛わ	わ゛〝	わろぃづ	わっぁわ	わっん	んをぁわ	ろゎん	を
づ゛〝	わ゛を、	ぃれぇを、	わっぁわ	わっん	んわん〝	ろゎづ	を
づぁん	わぃろ	ぃれぬづ	わっぁぬ	わっん	んわろん	ろゎづ	を
づぁわ	わぃをを	ろうぁわ	わっぁを、	わっを〝	んぬぇづ	ろゎ〝	を
づぁづ	わっぁろ	ぃれぇろ	わっぁを、	わっを〝	んろぃを、	ろゎ〝	を
づぁん	わっぁん	ろうぁをを	わっぁをを	わっを〝	んわぁん	ろゎ〝	を
づぁわ	わぃわ	ろうぁをを	わっぁん	わっを〝	をう゛わ	ろづ	を
づん	わぃわづ	わろぃわ	わっぁん	わっを〝	んれぃろ	ろっろ	ん
づぁん	わぃぬ	ろ ゎわ	わっぁづ	わっを〝	んぬわわ	ろっろ	を
づぁわ	わぃ〝	ろうぁぅづ	わっろ〝	わっを〝	んれぇづ	ろっろ	を
づぇづ	わぁを、	ろ ゎゎ	わっぃゎ	わっをづ	んろぃろ	ろっわ	を
づぁを、	わぁろ	ぃれぃづ	わっぃゎ	わっをづ	んゑ゛わ	ろっわ	を
づぁわ	わぁん	ろうぁぬ	わっぃろ	わっをづ	うろ゛わ	ろっわ	を
づぬづ	わぁわ	ぃれぃろ	わっぃわ	わっをづ	んをんろ	ろっわ	を
づぬを、	わを〝	ぃれ゛ろ	わっぃわ	わっをん	んろ゛を	ろっぬ	ん
づぬわ	わぃを、	わろっを、	わっぃわ	わっをん	んぬれぬ	ろっぬ	ん
づぃづ	わっわ	わろをづ	わっぃぬ	わっをを	んわぬわ	ろっぬ	ん
づぃを、	わっづ	ろ ゎぬ	わっぃぬ	わっをを	んうぁわ	ろっを、	を
づぃわ	わ゛ぬ	ぃわっぬ	わっぃを、	わっをを、	ををぁん	ろっを、	う
づぉづ	ぬれろ	わろぃろ	わっぃを	わっをを、	んんれづ	ろっを	を
づぉを、	ぬれん	ろんれぬ	わっぃを	わっをぬ	うわぁわ	ろっを	を
づぉわ	ぬぁぬ	わろぬ〝	わっぃん	わっをぬ	んわろん	ろっを	ん
づろづ	ぬゎ	わっぃづ	わっぃん	わっをわ	んれれぬ	ろっを	ん
づろを、	ぬぃん	わっをぬ	わっぃづ	わっをわ	んろ゛わ	ろっん	ん
づろわ	ぬぃわ	ぃれぇづ	わっぃ〝	わっをわ	んぬろん	ろっん	を

んんづ わろ ろわんぬ われん われをん うぬわ わぬぬ みを
んろわ わんぬ う〝〝 われろ〝 われをづ うんをん わぬわ わん
んろを、 わをを ろれんん われゎ われろわ うん〆を わぬろ わん
んろづ わを、〝 ろれをわ われを、 われをを うづをわ わぬ わぬ
ん〆わ わをろ ろろをわ われゎづ われゎ うんわづ わわ〝 わん
ん〆を、 わぬぬ をわぬ われろ われわ れぬゎ わわづ わん
ん〆づ わんん ろわぬぬ われぬ われん うんを、 わんん みを
うれわ わわ わぬぬ われん われろ ん〆ん わんを んを
うれわ わわわ われぬぬ われぬ われを、 うぬをを わんぬ をを
うれん わをん わろろろ われぬわ われゎ〝 ずん〆を わんわ をを
うろ わろ わろぬん われをを われぬわ んを〆を わんわ をを
うをわ わんね ろうれわ われぬ〝 われぬん ん〆づ わんろ るん
うをん わ〆ん ろうをを われをわ われをろ んををん わゎ〝 るを
うゎ わ〆ろ わわろ〝 われをね われを、 んぬわづ わわづ んん
うれわ わを、 われんわ われをん われを、〝 んわぬわ わんん んを
うれん わんづ われづ われを わんをわ んわゎろ わんを をを
うゎ わんわ ねね われをわ われをん うぬん〝 わんぬ わん
うれわ わをを ろれをね われをを われんろ ろれね わわわ わん
うれん わを ろんをを われをづ われんを、 んんん〝 わわわ るん
うぬ わを、 わわれわ われんろ われん〝 んづを、 わんろ を
うぬわ わぬ〝 わわれん われんぬ われづぬ うれ わろ〝 を
うぬん わぬわ われを、 われんを われづづ んを〆わ わろづ を
うを、 わんん わわんろ われん〝 われ〆わ んづ〆わ わをを を
うをわ わわわ われわわ われづろ われ〆を んんわづ わろを、 を
うをん わんを われをわ われづぬ わろ うわをぬ わろぬ みん
うを わんろ ん われをを わろれね うづれね わをわ わん
うをわ わをを ろ〆ん われづ〝 わろれづ んを〆づ わろろ を
うをん わろろ ろうれわ われろ わろをわ うれをぬ ゎろ るん
うん わんを ろ〆をぬ われわ わろろを、 うろを、 わんづ を
うんわ わんろ ろうをわ われを わろろ〝 んづをわ わんん るん
うんを、 ろ〆を ろんろづ われう わろわん んづれづ わんを るを
うんづ ろ〆ろ ろんぬぬ わ わろわん んづれづ わんね るん
うをづ ろづん ろんづろ わろれわ わろれろ んをわわ わんわ るん
うをわ ろづわ ろうろづ わろれを、 わろれぬ うろわづ わんわ るん
うをん ろんづ ろをれ〝 わろれん わろわづ うわをん ゎ るを
うをづ ろんぬ われんん わろれ〝 わろぬわ んを、 ろ〆〝〝 んん
う〆わ ろん ろをぬろ わろろろ わろぬを、 んわわづ ろ〆う るを
う〆わ ろをを わろをづ わろをわ わろぬ〝 をづ〆わ ろ〆を んん
う〆ん ろをわ ろわをわ わろろを、 わろをわ んれづわ ろ〆を るん
う〆づ ろをづ ろをを わろろん わろをを んれをづ ろ〆ぬ 〆
〝 ろをを、 うをぬ わろろ〝 わろを、〝 んんをん ろ〆わ わん
れわ ろをわ ををづ わろゎ わろをわ うぬぬわ ろ〆ろ わを
れを、 ろぬ〝 づ わろわわ わろをを うづをわ ろ〆〝 わん
れん ろをを ろんれん わろれぬ わろを〝 をを〆わづ ろづ〝 るを
れづ ろをぬ ろうをを、 わろれを わろんわ んんをわ ろづう を
ろ ろをろ ろをを、 わろわづ わろんを、 んを んを、 ろづを るん
ろわ ろわ〝 ろをを を わろわ〝 わろんづ んを〆を ろづを、 ぬん
ろわ ろれん ろんぬわ わろれろ わろづろ うろをわ ろづぬ みを
ろを、 ろれを、 ろんをを わろわわ わろを わろわづ うれをづ ろ〆わ るを
ろを、 ろれわ ろ をわ わろわを わろをわ んづをわ ろづわ を

ぁん　ろねわ　ろうごろ　わろねを　わろご゛　んうごん　ろごろ　をぇ
ぁご　ろねろ　ろんねご　わろねご　わろぁろ　んぬねる、　ろご　るぇ
ぁわ　ろねわ　ろ゛るぬ　わろぬ　わろぁぬ　んわるご　ろん゛　をぇ
ぁわ　ろぁ゛　わぬるん　わろぬろ　わろぁを　んるぁわ　ろんご　んぇ
ぁわ　ろぁご　ろぁを゛　わろぬわ　わろぁ゛゛　ごぬるん　ろんを　みぇ
ぁわ　ろぁん　ろぁろ　わろぬる、　わねねろ　ごわごご　ろんを　みぇ
ぁわ　ろぁん　ろ゛るる、　わろぬを　わねねわ　んうぬを　ろんぬ　をね
ぁわる、　ろぁん　ろをぁぬ　わろぬご　わねねを　んをるぬ　ろんぬ　るぇ
ぁん　ろぁん　ろわんわ　わろる、　わわねご　ごれるん　ろんわ　みね
ぁん　ろぁん　ろをぁう　わろるろ　わわろ　んわぬを　ろんわ　るぇ
ぁご　ろぁん　ろうごん　わろるわ　わわるわ　ごれごご　ろんろ　をね
ぁご　ろぁん　ろるぁわ　わろるぬ　わわるぬ　ごわねる、　ろん　るぇ
ぁわ　ろぁん　ろわるを　わろるを　わわるを　うろん゛　ろをご　みね
ぁわ　ろねご　わをねわ　わろるん　わわるん　んをねご　ろをご　うぇ
ぁわ　ろぁ゛　ろんるろ　わろる、　わわる゛　ごれるん　ろをご　るぇ
ぁわ　ろぁ゛　ろをるろ　わろを　わわねろ　ごわぬを　ろるん　るぇ
ぁわ　ろねわ　るねご　わろるわ　わわねわ　ごわねわ　ろるを　わね
ぁわ　ろねろ　ろんるろ　わろるわ　わわねぬ　んぬ　ろるを　をね
ぁる、　ろねわ　ろうねぬ　わろるる、　わわねを　んろねろ　ろるる、　をね
ぁる、　ろねわ　わるねわ　わろるを　わわねん　を る、　ろるぬ　うぇ
ぁん　ろねぬ　ろうねを　わろるん　わわぁ゛　んをるわ　ろるぬ　をね
ぁん　ろねる、　わろる゛　わろを゛　わわねわ　んわ゛を　ろるわ　をぇ
ぁご　ろねを　ろわねわ　わろんね　わわねろ　んんぁ゛　ろるわ　みね
ぁご　ろねん　ろあんる、　わろんわ　わわねわ　んぬ　ろるわ　るぇ
ぁぬ　ろねご　わろるろ　わろんわ　わわねぬ　んぬるわ　ろるわ　んね
ぁぬ　ろぬ　ろあるご　わろんぬ　わわねる、　ごれるわ　ろるろ　みぬ
ぁねわ　ろぬろ　ぁわ　わろんる、　わわねを　ごれ゛を　ろるろ　わね
ぁねわ　ろぬわ　ろわねろ　わろんん　わわねご　うろぬわ　ろるを　みね
ぁねわ　ろぬわ　るるご゛　わろんご　わわね゛　ろんん゛　ろるを　わぇ
ぁぬる、　ろぬぬ　んぬご　わろんん゛　わわぬ　うごるん　ろるを　わぇ
ぁぬる、　ろぬる、　ろわるる、　わろご　わわぬろ　うろんろ　ろる、゛　みね
ぁん　ろぬん　をぬわ　わろるろ　わわぬわ　れごご　ろる、゛　わね
ぁご　ろぬご　わるわ　わろるわ　わわぬわ　わんる、　ろる、゛　ろね
ぁご　ろぬ゛　んんご　わろるわ　わわぬぬ　ろわご　ろる、゛　わぇ
ぁる、　ろる、　ろろるご　わろるぬ　わわぬる、　うるるん　ろるご　わ
ぁるわ　ろるろ　ろわねご　わろるる、　わわぬを　ごわねわ　ろるご　みね
ぁるわ　ろるわ　ろうごわ　わろるを　わわぬん　んをるわ　ろるご　をね
ぁるわ　ろるわ　わぬぬろ　わろるん　わわぬん　んろるご　ろるご　んね
ぁるわ　ろるぬ　う゛　わろるご　わわぬご　んぬんぬ　ろるご　わる
ぁるる、　ろるる、　ろるぁを　わろご゛　わわぬ゛　んんんる、　ろるご　るね
ぁるん　ろるを　ろぬる、　わろご゛　わわる、　うろわご　ろるご　みる
ぁるん　ろるん　ろるねわ　わろ゛　わわるろ　うぬるん　ろるご　みね
ぁるご　ろるご　ろわねん　わろぁろ　わわるろ　うわ゛わ　ろるご　みる
ぁるご　ろる、゛　ろぬるろ　わろぁろ　わわるわ　んるんを　ろるご　るね
ぁを　ろるを　ろ ねる、　わろ゛わ　わわるわ　んをねろ　ろるご　をね
ぁを　ろるろ　ろ ねわ　わろ゛わ　わわるわ　んぬるご　ろるご　をね
ぁるわ　ろるわ　ろるるろ　わろ゛わ　わわるぬ　んんるわ　ろるご　るね
ぁるわ　ろるわ　わわる　わろ゛ぬ　わわるる、　ん るご　ろるご　んね
ぁるわ　ろるぬ　ぬ　わろ゛ぬ　わわるる、　うんるご　ろるご　ろん
ぁるわ　ろるる、　わわねろ　わろ゛る、　わわるを　うをねろ　ろる、゛　をる

わ　ろをを　ろうれる、　わろえ、　わわをを　んう゛を　ろる、゛　る゛
わ　ろをう　ろんう　わろを　わわるん　んぬわ　ろる、゛　をれ
わ　ろを゛　ろんを　わろを　わわるう　んをるね　ろる、゛　る゛
わ　ろん　ろんるる、　わろん　わわるう　ん゛ねわ　ろる、゛　る
わ　ろんわ　うれを　わろん　わわる、゛　うんれね　ろを　わ゛
わ　ろんわ　わんわ　わろん　わわる、゛　んをんろ　ろを　う
わ　ろんえ、　れんん　わろう　わわを　うぬわう　ろを　れ
わ　ろんを　われ　わろう　わわを　を゛ねる　ろをろ　
わ　ろんう　ろんうぬ　わろう　わわをろ　うれぬわ　ろをろ　る
わ　ろう　ろぬれわ　わろ゛゛　わわをろ　うえるう　ろをろ　ぬ
わ　ろうわ　ろう゛　わろ゛゛　わわをわ　ん゛るん　ろをわ　を
わ　ろうぬ　ろぬる、　わろ゛゛　わわをわ　ん゛んろ　ろをわ　ぬ
を　ろうを　ろろんを　わわ　わわをわ　ん゛わ　ろをわ　ぬ
を　ろうう　わわうを　わわ　わわをわ　んんれね　ろをわ　ん
るう　ろ゛　ろろわ　わわ　わわをわ　うんろ　ろをね　ぬ
るん　ろわ　ろれるろ　わわれる　わわをね　うわうう　ろをね　わ
る、　ろえ、　ろをれ゛　わわれる　わわをね　うれわ　ろをね　る
る、　ろう　ろろうん　わわれる　わわる、　うをれう　ろる、　わ
るわ　わわれる　ろろうん　わわれる　わわる、　うをれう　ろる、　わ