PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

ADAPTATION TO CLIMATE CHANGE IN BASINS WITHIN THE CONTEXT OF THE WATER-ENERGY-FOOD NEXUS

VICENTE GABRIEL JANDER PALMA

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
SEBASTIÁN VICUÑA DÍAZ

Santiago de Chile, September 2021

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Grateful to my parents and family, my friends from both the city I was born in and the one in which I studied, my guide professor for all his time and advice, and to the sacred Yerba Mate, that kept me awake and active to write this thesis.

ACKNOWLEDGEMENTS

From the journey of this whole thesis process, I would like to thank particularly to Sebastián Vicuña, who oriented the experience and constantly guided the work, so it could have the best outcome. To Oscar Melo for all his advice in the agricultural and irrigation aspects, and Álvaro Lorca alongside Marcel Favreau for ther advise and contribution in the energetic and hydropower aspects. To Iñigo Ricalde and Marcos Canales for their complementary support in computational-related guidance. To Eduardo Bustos, for providing the WEAP model from CCGUC as a starting point of this research. And lastly to James Tomlinson, for helping to develop further PYWR features needed for this work.

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ABSTRACT

Climate change effects implicate uncertainty over different areas, one of them being water resources, and the different productive activities associated. Moreover, many regulations, agreements and infrastructure works were developed without considering climate change impacts over temperatures, precipitation levels and flow availability; so it is necessary to rethink these tools for a more efficient water use under a given regulatory system and diverse productive interests. The decision of which adaptation strategy must be implemented to maintain a productive system's performance in a Water-Energy-Food (WEF) nexus basin must be addressed, considering the balance between productive water use and environmental maintenance of the ecosystem. Recently, the Maule basin in Chile has been affected by water shortage events, generating negative repercussions over crop production and water rights permissibility, raising concerns about the future events. This study presents a modelation of the Maule basin and the impacts of certain climate change scenarios over it, alongside a comparative analysis of adaptative strategies implementation; both from a Supply (Reservoir Operation) and Demand (Irrigation Efficiency and Water Rights) Side Water Management. The respective basin modelling, including the physical, hydrological, productive and regulatory features, is done with the PYWR computational tool; alongside the WEAP software for water runoff representations. Additionally, a Multi Objective Evolutionary Algorithm (MOEA) is used, known as NSGA-III, to generate optimal portfolios of different articulated strategies; and therefore different alternatives that adapt to the proposed objectives. Results show that there is a trade-off between environmental and productive goals, however, under an integral approach, the productive agents can incur in a win-win scenario if the multi-objective analysis consider both hydropower and crop production in a WEF nexus type basin.

Keywords: Water Resources, Climate Change, Reservoir Operation, Multiobjective Optimization, Water-Energy-Food Nexus.

RESUMEN

Los efectos del cambio climático implican incertidumbre sobre diferentes áreas, una de ellas los recursos hídricos y sus actividades productivas asociadas. Además, muchas regulaciones, acuerdos y obras de infraestructura se desarrollaron sin considerar los impactos sobre las temperaturas, los niveles de precipitación y la disponibilidad de caudales; por lo que es necesario replantear estas herramientas para un uso eficiente del agua bajo un sistema regulatorio dado y diversos intereses productivos. La decisión de qué estrategia de adaptación debe ser implementada para mantener el desempeño de un sistema productivo en una cuenca del nexo Agua-Energía-Alimento debe ser abordada considerando el equilibrio entre el uso productivo del agua y la mantención ambiental del ecosistema. Recientemente, la cuenca del Maule en Chile se ha visto afectada por eventos de escasez hídrica, generando repercusiones negativas sobre la producción de cultivos y la permisividad de los derechos de agua, lo que genera preocupación por los eventos futuros. Este estudio presenta una modelación de la cuenca del Maule y los impactos de catorce escenarios de cambio climático sobre la misma, junto con un análisis comparativo de la implementación de estrategias adaptativas; tanto desde el punto de vista de la Oferta (Operación de Embalses) como de la Demanda (Eficiencia de Riego y Derechos de Agua). La modelación de la cuenca, incluyendo las características físicas, productivas y de regulación, se realiza con la herramienta computacional PYWR. Adicionalmente, se utiliza un Algoritmo Evolutivo Multiobjetivo (MOEA) para generar portafolios óptimos de estrategias. Los resultados muestran que existe un *trade-off* entre los objetivos ambientales y productivos, sin embargo, bajo un enfoque integral, los agentes productivos pueden incurrir en un escenario *win-win* si el análisis multiobjetivo considera tanto la producción hidroeléctrica como la de cultivos en un contexto Agua-Energía-Alimento.

Palabras Claves: Recursos Hídricos, Cambio Climático, Operación de Embalses, Optimización Multiobjetivo, Nexo Alimentación-Agua-Energía.

1. INTRODUCTION

Climate change is a phenomenon of global impact, producing among its many other consequences an uncertainty related to the availability of water resources (Kundzewicz et al., 2018), generating negative potential outcomes in terms of accessibility and management. More specifically, increasing emissions of greenhouse gases are posing as a threat to water dependant systems by increasing average temperatures and causing changes in the amount and intensity of precipitations (Rana, Moradkhani, & Qin, 2017). The number of hot days is projected to increase in most land regions, so is the risk from droughts and precipitation deficits; which translates into adverse consequences for agricultural livelihoods, reduction of cereal crops production, damage to ecosystems, among others; with a high confidence level of estimation (IPCC, 2018).

With the increasing urgency to replace the traditional and fragmented approach of water management by a more holistic system view (Giupponi & Gain, 2017), an IWRM has proven to be a promising instrument for exploring Climate Change Adaptation (CCA). Moreover, the Agenda 2030 of the United Nations (UN, 2015) has provided a new framework in which IRWM and CCA are considered as components of the planetary efforts towards sustainable development goals (SDG) 6 (ensure availability and sustainable management of water and sanitation for all) and 13 (take urgent action to combat climate change and its impacts). Interaction and resolution between water agents is fundamental for allowing their different requirements to be met, considering the increasing demand in time due to population growth and climate change repercussions (Haddeland et al., 2014); furthermore, planification and management can effectively maintain or increase different water demand coverage levels and reduce the negative impacts in future economies caused by disruptive impacts in water availability (Holmatov, Lautze, Manthrithilake, & Makin, 2017).

Within the water resources productive activities affected by climate change, two of the most important are irrigation and hydropower production (Vicuña, Leonardson, Hanemann, Dale, & Dracup, 2008; Vicuña, McPhee, & Garreaud, 2012a), which are fundamental to sustain the actual levels of population and their energetic demands. In the context of water resources and the climate change impacts that affects them, a new paradigm has emerged to link this main economic activities related to water and bring balance in potentially conflicting sectoral conflicts: the Water-Energy-Food (WEF) nexus (Smajgl, Ward, & Pluschke, 2016), which is defined by the Food and Agriculture Organization (FAO) as a conceptual approach to generate a better understanding of the interactions between the natural environment and human activities (FAO, 2014). In this context, it is fundamental to acknowledge that large-scale water infrastructure projects can have synergetic impacts, producing hydro-power and providing water storage for irrigation and urban uses, but the priorities given to each activity and the potential impacts downstream demonstrate that the different agents must follow an IWRM-focused plan to reach a more sustainable future (Cai, Wallington, Shafiee-Jood, & Marston, 2018).

In order to mitigate the negative impacts over WEF type systems, it is necessary to generate climate change adaptation strategies, which in many cases focus on an efficient and sustainable management of the water resources, rather than on infrastructural projects (Ludwig, van Slobbe, & Cofino, 2014; Rasul & Sharma, 2016) like reservoirs, channels, intakes, coatings and others. This take on climate change adoption can be categorized as Water Demand Side Management (DSM) (Brooks, 2006), which include a series of frequently used measures, such as restriction in consumption (Naqvi, Kumar, De, & Sejian, 2015), adjustments in water allocation and/or water rights (Bonelli, Vicuña, Meza, Gironás, & Barton, 2014; Bigelow & Zhang, 2018) and increasing the efficiency of the productive activities such as water quality treatment and irrigation (Connor, Schwabe, King, & Knapp, 2012; Alkaya, Bogurcu, Ulutas, & Demirer, 2015; Hong & Yabe, 2017). The other category corresponds to Water Supply Side Management (SSD), and includes non-structural measures (although it tends to be related to infrastructural projects) like modifications in reservoir operation (Brekke et al., 2009; Ahmadianfar & Zamani, 2020) and effluent reuse (Lavrnić, Zapater-Pereyra, & Mancini, 2017).

One specific location that would require adaptation to climate change is the Maule Basin (Vicuña Díaz & Meza, 2012b), occupying the whole administrative region area of the same name in Chile, South America; with a considerable reduction in the main river's mean flows (Arriagada, Dieppois, Sidibe, & Link, 2019) due to lowering in precipitation levels, an increase in temperatures (Chadwick, Gironás, Vicuña, Meza, & McPhee, 2018) (projection to 2050, using a Global Circulation Model (GCM) under different Greenhouse Gas (GHG) emission scenarios) and glacier retreats. According to the Climate Risk Atlas (ARCLIM) of the Environmental Ministry, precipitation levels in the Maule region will decrease by 16% by 2065 (Vicuña et al., 2020), the rate of future decrease in hydroelectric generation in the region classifies between high and very high (around 27% less energy availability) (Lorca, Saumda, & Tapia, 2020), and the highest risk indicators in agriculture/irrigation country-wide, going from moderate to very high, are found in the very same region (Pica-Téllez et al., 2020).

As to why the importance of this particular basin; it's productive activities dependent on water, mainly irrigation and hydroelectricity generation, are fundamental to the country's GDP, which includes over 240,000 ac that correspond to more than 20% of irrigated areas in Chile (INE, 2007) and the hydroelectricity produced in the region represents 12.8% of the total energetic production in the country (CEN, 2021). It has a total area of 20,295 km^2, with a mixed but predominant snowy regime that produces the maximum stream flows in the thaw seasons (October-December) (Pizarro, Vergara, Rodríguez, Sanhueza, & Castro, 2010). The water users in the Maule basin includes farmers, hydropower production, forestry companies, industrial activities and water treatment; in which the crop season demands matches the months with the higher stream flows due to snowy regime predominance. There are multiple agreements and legal resolutions in the area that binds the water allocation to the different productive activities (Vicuña Díaz & Meza, 2012b), prioritizing irrigation over any other uses; however, the actual allocation doesn't consider the future uncertainties of precipitation reduction and temperature increase, a situation that would incur in a deficit on agricultural and hydroelectric production, therefore requiring adaptation strategies. This in an opportunity to update the water resource management in the Maule region, and consider an IWRM focus that connects the different productive agents in the water allocation policies, leaving behind the traditional fragmented approach and open the possibility to explore the WEF nexus in an area that produces a considerable amount of the crops and electricity for the entire country.

The purpose of this study is to analyze different alternatives of climate change adaptation strategies, with a multi-objetive focus, implemented to the upper section of the Maule Basin; which contains a productive scheme that can be examined as a Water-Energy-Food nexus type system. These strategies will be non-structural, and both Water Demand Side Management (DSM) and Water Supply Side Management (SSM) type with an special focus on non-infrastructural management, as this type of approach presents as a priority in the water-centered public policy agenda in Chile (Donoso & Molinos-Senante, 2017). The adaptation proposals make a portfolio of solutions, that present different alternatives depending on the objective, and it's level of preference over others. The proposed structure is that in the first place, context and state of the art about adaptation strategies focused on DSM and SSM are presented along the main mechanisms used in the different cases, then, the case of study and the water resources model employed to represent the basin section. Thirdly, the problem formulation, with the explanation of the relevant parameters of the model that will evaluate the adaptation strategies with a multi-objective focus. Subsequently, the results of the study as a portfolio of solutions determined by multi-objective optimization, and finally, the conclusions and discussions about the whole research, including limitations, suggestions to the water allocation methods/policies in the area and possible upcoming research that may be originated from this one.

2. BIBLIOGRAPHICAL REVIEW

2.1. Climate Change Impact Quantification

Climate change is expected to impact and alter the hydrological cycle worldwide, and subsequently affect water availability and demand (Haddeland et al., 2014); manifesting a fluctuation in runoffs depending on the region of analysis. Even without the effects of direct human intervention taken into account, referred to as the naturalized hydrological cycle, many General Circulation Models (GCMs) still project variation into future global runoff levels. However, future climate change impact assessments are highly uncertain, and depend largely on which climate model is used (Hagemann, Chen, & Clark, 2013); which are affected by systematic errors and tend to result in a directly forced hydrological simulation. However, future water resource availability can be represented through an integral lens; in which multiple impact models are used for climate change impact studies (Haddeland et al., 2011). In first instances the combination of GCMs, global hydrology models (GHMs) and emission scenarios would only be used to represent water availability projections in a naturalized hydrological cycle, although more recent research has included the anthropogenic impacts on hydrology for a more representative output (Haddeland et al., 2014).

2.2. Water-Energy-Food Nexus

In the context of large-scale investments, policymakers and water resources; existing water nexus frameworks remain largely water-centric and therefore partial by privileging one sector over all the others, a phenomenon that demonstrates the lack of cross-sectorial approaches into investment strategies (Smajgl et al., 2016). Historically, the nexus conceptualisations have been largely depoliticized, ignoring the different political trajectories that regulate a water food and energy planning system (Foran, 2015). However globally the concept of the Water-Energy-Food Nexus may be discussed, it is still a subject of multiple interpretations, frameworks and methodologies defining the inter-linkages between the three elements.

There are two fundamental sub-nexus that must be included in the conceptual frame for conducting effective operational policies in economies of water, farming and energy; which are the water-food trade and the energy-climate change (Allan, Keulertz, & Woertz, 2015), increasing awareness in the hierarchy of engagement as an essential priority for any considerations made with a system that interconnects water consumption, energy production and crop irrigation for food generation. A co-provision framework can significantly advance in terms of integrative analysis for water resources, and is useful in undertaking a substantive examination of issues of trade-offs and synergies (Kurian, 2017); hence it is imperative to articulate the energy and food production, concatenated with ecological welfare and political/regulatory thresholds, in any proposed adaptation strategy that involves water resources.

Given the multi-objective nature of the competing productive activities and ecosystem in a WEF nexus type basin, a synergistic benefit scheme can be used to generate a win-win scenario with reduced water shortages, increased hydropower benefits and larger food production quantities; considering water resource management adaptation strategies and multi-objective optimization to generate a Pareto Frontier of optimal solutions, translated as a portfolio of possible strategies and their degree of implementation (Dhaubanjar, Davidsen, & Bauer-Gottwein, 2017; Uen, Chang, Zhou, & Tsai, 2018).

2.3. Water Resources Management as an Adaptation Strategy

Due to the impact of climate change over water uses, adaptation measures should be a priority to institutions involving this resource; as the ideal environment for successful, cost-effective adaptation is characterized by water management policies and institutions that are resilient and robust to uncertainty (Olmstead, 2014). Consequently, the importance of institutions to the magnitude, nature and even the direction of adaptation to climate change implications for water resources cannot be overstated. The challenge rises when in order to deal with these complex problems, water management issues should generally consider multiple decision criteria and large numbers of possible alternatives, usually characterized by high uncertainty, complex interactions and conflicting interests of multiple stakeholders, but also of a multiplicity of compartments such as ecosystems and different economic sectors (Giupponi & Gain, 2017). Multi-criteria analysis methods are very well suited to water policy problems, given the intertwined uses and values that this resource has; allowing the balance for multiple objectives and assessing priorities among values that are often hard to monetize (Miller & Belton, 2014). Among these methods, Multi-objective Optimization Problems (MOOPs) rank as one of the more representative (Malekmohammadi, Zahraie, & Kerachian, 2011; Hatamkhani & Moridi, 2019), in which simultaneous optimization of several incommutable and often competitive/conflicting objectives is conducted. This method, in the majority of cases, doesn't present a single optimal solution to satisfy all goals but rather a set of technologically efficient non-inferior or Pareto optimal solutions (Davijani, Banihabib, Anvar, & Hashemi, 2016).

In order to generate a framework for assessing the effects of adaptation measures, it is necessary to determine the water availability and interactions conditions (Liu et al., 2018), which leads to modelling a representation of the hydrologic cycle and the hydro geological processes, among their interaction with the productive activities such as irrigation, hydroelectricity, water treatment, industrial use and others. One of the many computational tools to generate this representation is the Water Evaluation and Planning System (WEAP) (Sieber, 2006), a software developed by the Stockholm Environmental Institute which specifically takes an integrated approach to water resources planning; and has more than 300 scientific publications to date that use it in their procedure (SEI, 2021). Applications vary but are not limited to generating models to represent the Water-Enery-Food nexus and the future climate and socioeconomic changes under a wide range of combined scenarios (Momblanch et al., 2019), testing the water demand management scenarios in a water-stressed basin (Lévite, Sally, & Cour, 2003), balancing future water demand and availability (Höllermann, Giertz, & Diekkrüger, 2010) or simply modelling the surface water resources allocation (Adgolign, Rao, & Abbulu, 2016).

However, mathematical river basin management models typically adopt predefined reservoir operation rules or single-period optimization schemes to allocate the available water resources optimally among competing users (WEAP enters this category); hence, they are not able to identify the optimal operation of the system's components using multi-level optimization (Mousavi, Anzab, Asl-Rousta, & Kim, 2017). Nonetheless, applications of simulation-optimization technology has been growing rapidly in the past decade, specially for multi-level optimization models which have to run multiple times. For the case of Water Resource Management, a new generalized water resource network modelling Python library called PYWR is available (Tomlinson, Arnott, & Harou, 2020), capable of simulating customizable water allocation and operation rules throughout complex multi-purpose managed water systems at each user-defined step with a multi-scenario method and multi-objective optimization formulation inputs; therefore allowing the inclusion of climate change impacts upon a water-resource based system and inclusion of MOOPs to represent the adaptation strategies results.

2.3.1. Water Supply Management

Water Resources Management can be ascribed into SSM, or supply side management, which seeks to secure the long-term resilience of the water supply (Department for Enviroment, 2020); by countering the decline in water supply due to expected reductions from climate change and, simultaneously, restoring sustainability of ground and surface water sources. These actions are increasingly challenging, due to urban expansion and population growth (Amara & Kansal, 2021). The regular and most antique way of managing water supply is to generate abstractions, from groundwater or superficial sources, in order to comply with demand limits. Besides abstraction; infrastructure investment like desalination, reservoirs, bulk water transfers and effluent reuse are typical SSM measures adopted by countries (Tlili, Alkanhal, Othman, Dara, & Shafee, 2020). In order to correctly manage this supply alternatives, the capacity of generating models to represent this measures is imperative for an authentication analysis. However, groundwater modelling had been historically challenging, and has led to all-time low levels in aquifers; generating the need to include groundwater systems in life-cycle assessments (Gejl et al., 2018). Surface-level water is, on the other hand, an easier to model counterpart (P. Deb, Kiem, & Willgoose, 2019) as the physical and visible manifestation of it allows to directly measure the values on different riverbed points, stream flow gauges and reservoir levels among others. This capacity provided necessary frameworks in order to generate surface water allocation policies, reservoir operation rules and ecological flow establishment; measures that tend to be significantly cheaper and often as efficient as infrastructural ones (Wu et al., 2017).

In terms of water allocation, there are several methods used to define the flow availability for allocation, and by which mechanism it will be assigned to the different interested agents. These methods employ the economic principles of scarce resource allocation (economic efficiency, equity and criteria for allocation), and often consider efficacy, administrative feasibility and sustainability (Dinar, Rosegrant, & Meinzen-Dick, 1997). The first mechanism consists in Marginal Cost Pricing (MCP), which targets a price for water to equal the marginal cost of supplying the last unit of that water (maximizing social welfare) (del Carmen Munguía-López, Sampat, Rubio-Castro, Ponce-Ortega, & Zavala, 2019), the second one is Public/Administrative Water Allocation, in which the state decides what water resources can be used by the system (Wang, Fang, & Hipel, 2003), the third one is water markets (Chong & Sunding, 2006), in which there is an exchange of water-use rights, and the last one corresponds to user-based allocation (Dinar et al., 1997), where collection action institutions with authority to make decisions allocate the water rights. Whatever mechanism is chosen, traditional methods aren't usually updated with the required frequency; therefore fail to consider the climate uncertainty factors and potential supply shortage (Loch, Adamson, & Auricht, 2020). Most recent water allocation models proposed in literature consider an adaptive distribution, that adjusts automatically within the availability and the level of demand in order to generate efficient water supply (Groves et al., 2015; Graveline, 2016; Liu et al., 2018).

Another method of SSM consists in the determination of the Reservoir Operation Regime, which usually consists on generating a Standard Operation Rule (SOP) in order to discharge as a function of the current storage and input flow, with a known demand (Bolouri-Yazdeli, Haddad, Fallah-Mehdipour, & Mariño, 2014); this rules tend to be linear decision rules (LDRs). However, there are more complex rules to operate reservoirs, such as stochastic dynamic programming (SDP) and nonlinear decision rules (NLDR) with various orders of inflow and reservoir storage volume. One widely used mechanism to decrease shortage peaks in reservoir operation correspond to Hedging Rules (HRs), in which operation rules are modified to discharge fewer amounts of water in supply-shortage periods (Draper & Lund, 2004; Brekke et al., 2009; Neelakantan & Sasireka, 2013; Ahmadianfar & Zamani, 2020). Besides the operation rules, the amount of storage available in a reservoir can be conceptually divided in several zones, most commonly the division is among the following five sub-zones (Jain, 1993):

- Dead Storage Zone: Absorbs some sediment entering the reservoir, or provide minimum head for hydropower plants. Water to be utilized only under extreme dry situations. Lowest zone.
- Buffer Zone: Level zone under extreme drought situations, release from reservoirs caters to essential needs (restrained releases).
- Conservation Zone: Water is stored to satisfy the demands for conservation purposes (hydropower, irrigation, water supply, etc.).
- Flood Control Zone: Exclusively earmarked for absorbing floods during high flow periods.
- Spill Zone: Flood rise during extreme floods and spilling, releases at maximum.

Operation rules, hedging and zone division may be combined to operate the reservoir at an optimal level, in terms of balancing demand satisfaction with maintaining acceptable levels for possible recreational uses (Bayesteh & Azari, 2021).

2.3.2. Water Demand Management

On the contrary to SSM, DSM or demand side management has to face the fact that worldwide water demand is rising inexorably (unlike water supply sources), and projections of continuing growth over coming decades are sustained by increasing population, a globalized world and technological industry expansion (Butler & Memon, 2005). Meeting this increasing demand from existing resources is an uphill struggle, particularly in water stressed regions, in the developed and developing countries alike. It is a fact that water consumption changes from country to country, depending on several factors including climate, availability of resources, technological advancement, water price structure, incentives and legislative provisions (Grafton, Ward, To, & Kompas, 2011; Spang, Moomaw, Gallagher, Kirshen, & Marks, 2014). Effective demand-side measures will be vitally important in the coming decades, along with increasing the actually low public awareness of the need to reduce water consumption and more government supplementation to induce water efficiency to different users (Department for Enviroment, 2020).

Typical water demand side management include but aren't limited to: adjusting household water consumption (Stavenhagen, Buurman, & Tortajada, 2018), tackling urban leakage of water companies (Girard & Stewart, 2007), generating a non-household market of alternative water suppliers (known as water markets) (Bjornlund, 2003; Chong & Sunding, 2006), working with other government departments (Subteam, 2009), behavioral change in the public (Hill & Symmonds, 2011), rainwater harvesting (Aladenola & Adeboye, 2010) and improving efficiency of water consuming productive activities (Rockström, 2003; Evans & Sadler, 2008); particularly with a strong focus on agricultural ecosystems, given that they represent the main water demand activity worldwide with approximately an 80% of total consumption (Velasco-Muñoz, Aznar-Sánchez, Belmonte-Ureña, & Román-Sánchez, 2018).

Recently, there has been an intensification and modernization of irrigation systems, while requiring investment of scarce capital resources could thus substantially be reducing non-beneficial water consumption and help in coping with increasing water scarcity (Bekchanov, Ringler, Bhaduri, & Jeuland, 2016). In many locations, improvement of the efficiency of irrigation canals and implementation of field efficiency investments and practices, such as drip irrigation, and alternate dry or short furrow irrigation would substantially improve economic outcomes (Thompson, PANG, & LI, 2009). Changes in irrigation technology can be modeled through different approaches; considering specific technologies with a distinct water requirement and crop yield, generating a production function that implicitly considers irrigation technology through changes in water distribution uniformity, or water saving-cost effectiveness with a cost per unit of saved water through irrigation efficiency improvements and implicitly considers irrigation technology with assumptions about the share of water intake delivered to the farm gate (conveyance efficiency) or the share of applied water that is beneficially used for crops (water application efficiency).

As much as a relevant topic that increasing Irrigation Efficiency (IE) is, it can be counterproductive if basin-scale water accounting isn't considered along with behavioral responses of irrigators to subsidies to increase in IE (Grafton et al., 2018). This increases must be accompanied by robust water accounting and measurements, a cap on extractions, an assessment of uncertainties, the valuation of trade-offs and a better understanding of incentives and behavior of irrigators, or on the contrary, evidence shows that increases in IE for field crops are rarely associated with increased water availability at a larger scale (Perry, Steduto, & Karajeh, 2017). This phenomenon can be explained partly with the recognizable Jevon's Paradox; which establishes that farmers may adjust their behavior in response to the change in irrigation efficiency, for example by switching to higher-revenue crops that are more water intensive or by irrigating previously unirrigated land, resulting in an increase rather than a decrease in water consumption (Sears et al., 2018). So, with each IE proposed modification, an integral strategy should arise to ensure measure's effectiveness.

In retrospect, it is fundamental that SSM and DSM aren't seen as mutually exclusive strategies, on the total opposite, they should complement each other in order to achieve the IWRM focus that is becoming a main strategy of adaptation to climate change impacts.

3. CASE STUDY

This chapter describes the case study of the Maule Basin, including the hydrological properties, different water allocation policies, productive activities reservoir operation rules and the climate change models used to represent the impacts over the water resources of the system.

3.1. Maule Basin: A Water-Energy-Food Nexus Case Study

Maule basin in Chile has multiple productive activities that depend on water resources, hence there are many water users with shared interests; with a vast majority of them being on agricultural production and hydropower generation. There are two main counterparts involved in the local water allocation process: the Public Works National Ministry (MOP), and the private energy company ENEL. The MOP intercedes for the irrigation agents, as it builds and supervises the reservoirs with an agricultural purpose through the Direction of Hydraulic Works, DOH (DOH, 2021), along conducting the water allocation process, in this case by water rights assignment, through the General Waters Direction (DGA) (DGA, 2021), and ENEL by managing the reservoirs that are linked to hydropower generation through the companies Colbun and ENEL (Colbun, 2021). In this particular location, reservoirs share the common interest as they contain both agriculture and hydropower destined water.

The upper section of the basin is perhaps the most relevant in terms of water resources activity, as it contains the entirety of the hydroelectric power plants in the administrative region and approximately 75% of the irrigation hectares (CCGUC, 2016). In fact, instead of the traditional water rights assignment and markets that are present in the lower section, the upper section has multiple resolutions, agreements and decrees in terms of water allocation in order to manage and comply with the different agents involved. The study area has five main rivers: Maule (240km), Cipreses/Invernada (46 km), Melado (49 km), Las Garzas (20 km) and Claro (42 km) (DGA, 2005), in addition to more than 600 irrigation channels from multiple irrigators, both individual and organized (DGA, 2004). In terms of storage, there are five main units in the area: Maule Lagoon (1,420 Hm^3), Invernada Lagoon (179 Hm^3), Melado Reservoir (135 Hm^3), Colbun Reservoir (1,544 Hm^3) and Machicura Reservoir (52 Hm^3) (DGA, 2005). Figure 3.1 illustrates Maule basin section of interest, with the water bodies and irrigation channels included.

All the rivers of interest converge at some point into Maule, and most irrigation areas are located after the convergence; while Melado and Invernada contain artificial reservoirs in order to manage discharge flows. Hydroelectric generation is the other prominent activity, as the area of interest contain nine hydropower generation plants; two of them being reservoir types and the other seven run-of-the-river (Generadoras, 2021).

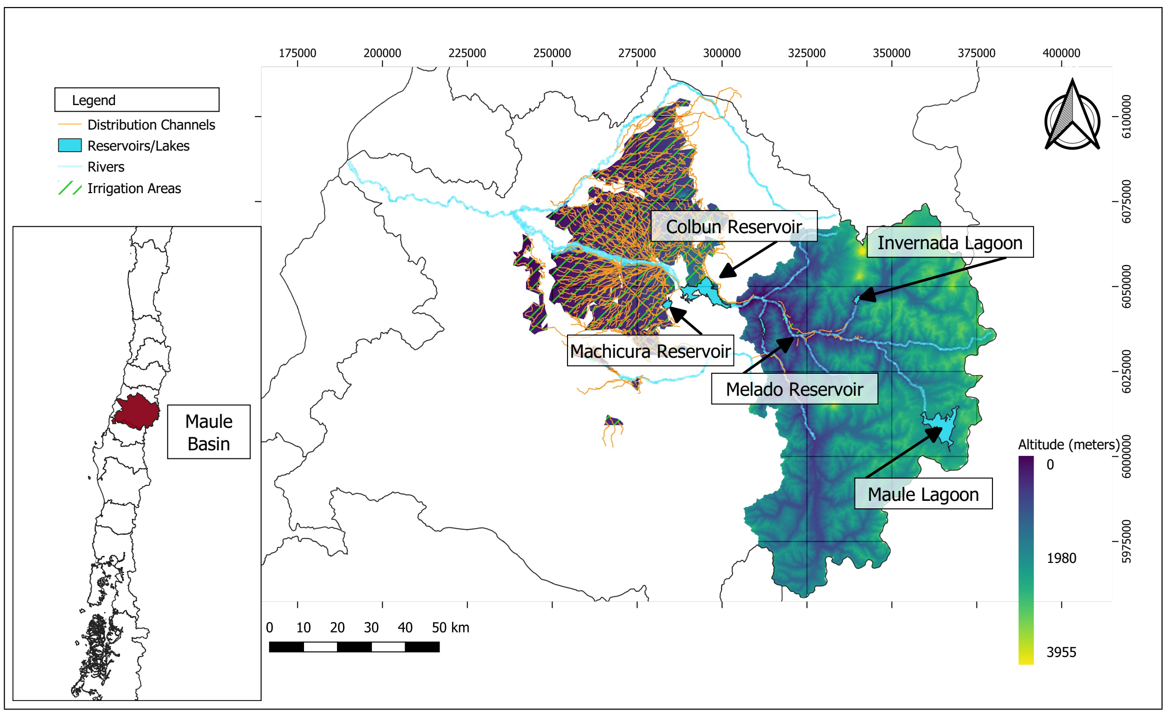

Figure 3.1. Maule basin with the area of study highlighted, and the main reservoirs indicated. In orange, the different irrigation channels, and in green linear fill the irrigated areas.

Due to the shared interest in water resources from different agents, a legal agreement was established in 1947 between the DOH (back then called the Irrigation Department) and ENEL (now owner of ENDESA, whom is part of the agreement) to define the Maule Lagoon management, zone definition and discharging priorities (ENDESA, 1947). The agreement starts stating the construction and subsequent capacity expansion of the artificial lagoon, responsibility of MOP, with the existence of three different zones: a conservation zone set to supply water and energetic deficits with normal use, a buffer zone with restricted uses and a dead storage zone only available under special circumstances. Figure 3.2 illustrates the different zones, with their respective assigned volumes.

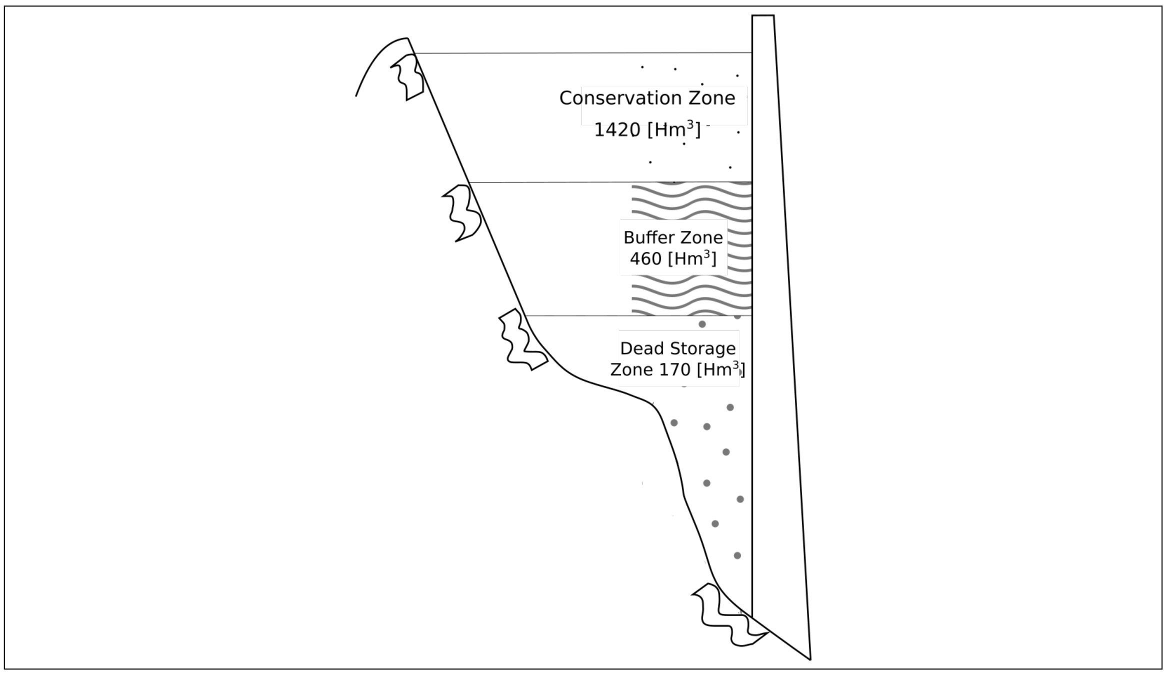

Figure 3.2. Maule Lagoon operation zones according to ENEL-MOP Agreement from 1947, with a Conservation Zone (unrestricted discharges), a Buffer Zone (restricted releases) and a Dead Storage Zone (prohibits releases) (ENDESA, 1947).

The agreement also establishes a priority to irrigation, given a percentage each month of the maximum stationary flow as the first demand (D_t) that the reservoir has to provision (representing the watering season) in case of shortage. When the storage is in the buffer zone, it may only release (R_t) a maximum of 80% of current storage (S_t) plus 80% of that month's inflow (Q_t). Storage may not exceed the reservoir capacity, and above that level all surplus is released. This operation based on different levels can be expressed with Equation 3.1.

$$R_t(S_t, Q_t) = \begin{cases} 0 & \text{if } S_t + Q_t \leq 170 \text{ [Hm}^3\text{]} \\ min[D_t, 0.8(S_t + Q_t - 170)] & \text{if } S_t + Q_t \leq 630 \text{ [Hm}^3\text{]} \\ min[D_t, (S_t + Q_t - 262)] & \text{if } S_t + Q_t \leq (1420 + D_t) \text{ [Hm}^3\text{]} \\ S_t + Q_t - 1420 & \text{if } (1420 + D_t) \text{ [Hm}^3\text{]} \leq S_t + Q_t \end{cases} \tag{3.1}$$

Considering the following notation:

- R_t: Water release in timestep t [Hm^3]
- Q_t: Water inflow to the reservoir in timestep t [Hm^3]
- S_t: Storage level in timestep t [Hm^3]
- D_t: Irrigation demand in timestep t [Hm^3]

Given the different demands according to the month, there are two possible Standard Operation Rules (SOP) graphs to illustrate the agreement in this case, the first is when the demand is lower than 80% of the Buffer Zone plus 80% of the inflow, in which case the graph only has one slope that corresponds to the restriction of releases of the buffer zone, and the second corresponds to the case in which the demand is greater than the previously mentioned sum, where there are two different slopes separating the two top zones, considering that the system might release from both the conservation and the buffer zone. The agreement also establishes the maximum release, which is 800 Hm^3, so the demand cannot exceed this value. Figure 3.3 shows both cases of possible demands, with their respective SOP rules of the Maule Lagoon, considering the intervals where the Storage plus inflow is lesser than the demand, in which case there is shortage; where the demand is supplied accordingly and where there is flooding and the excess water is released.

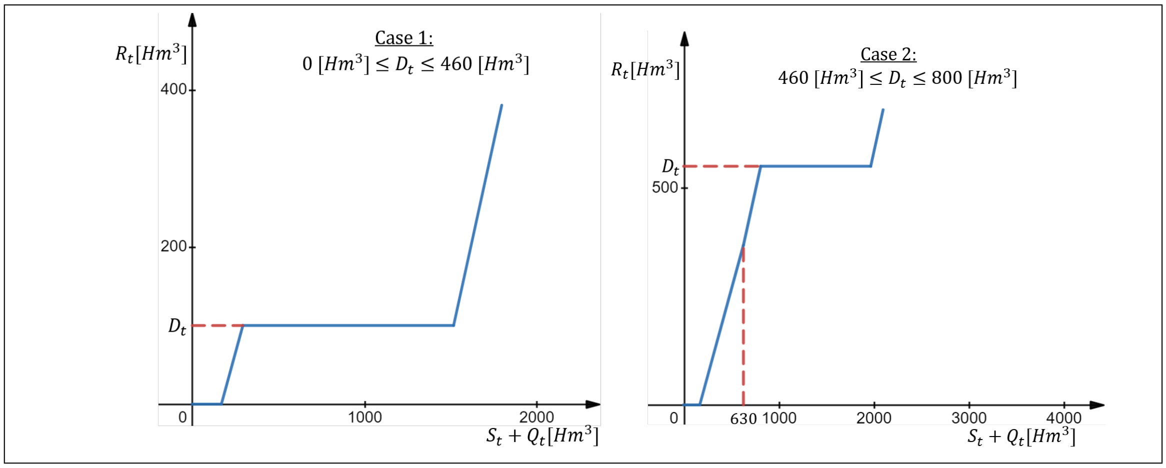

Figure 3.3. Standard Operation Rules (SOP) for both demand cases in Maule Lagoon: the first one consisting on a level of demand that doesn't represent a possibility for multiple zone-discharge, and the second one with a higher level that translates in more than one zone discharge. Note that in the second case, the slope decreases past a point, indicating a more restrictive release limit (ENDESA, 1947).

The agreement also states that ENDESA can use the releases assigned to irrigation with hydropower generation purposes, as long as it ensures the watering season's necessary flow deliverance.

After the construction of both Colbun and Machicura reservoirs, both containing hydropower generation plants, a legal resolution was emitted by the DGA for ENEL in 1983, in order to manage properly the attribution of water rights for both irrigators and hydroelectric plants (DGA, 1983). In this case, water rights for Colbun are assigned with an annual mean flow of 190 m^3/s, with non-consumptive nature, and an instantaneous maximum of 280 m^3/s. This allocation prioritizes irrigation rights, which are consumptive in nature and must be respected. The values of the consumptive rights assigned to irrigators are shown in Table 3.1, with a monthly allocation that considers the watering season. In case of shortage, when the river's availability is lower than the assigned water rights, the new value of the water rights that has to be respected correspond to the whole river's availability.

Table 3.1. Consumptive water rights in Resolution 105, from 1983. Values are monthly average (DGA, 1983).

Month	**Flow** (m^3/s)
January	200
February	180
March	120
April	80
May	40
June	40
July	40
August	40
September	60
October	140
November	180
December	200

The river availability is measured in a stream flow gauge station called *Maule en Armerillo*, which considers a flow restitution by adding the flow delivered in an irrigation channel previous to it, and flow from a discharge channel of river Melado after it; methodology that was recently updated according to the ordinance 681/13 of the DGA (DGA, 2013). Colbun has the obligation to restitute the consumptive flows indicated in Resolution 105, after the hydropower production of both Colbun and Machicura Plants. Figure 3.4 illustrates every hydropower plant in the area of interest, and specifies the streamflow gauge location; hence where the restitution is calculated for the assigned consumptive water rights.

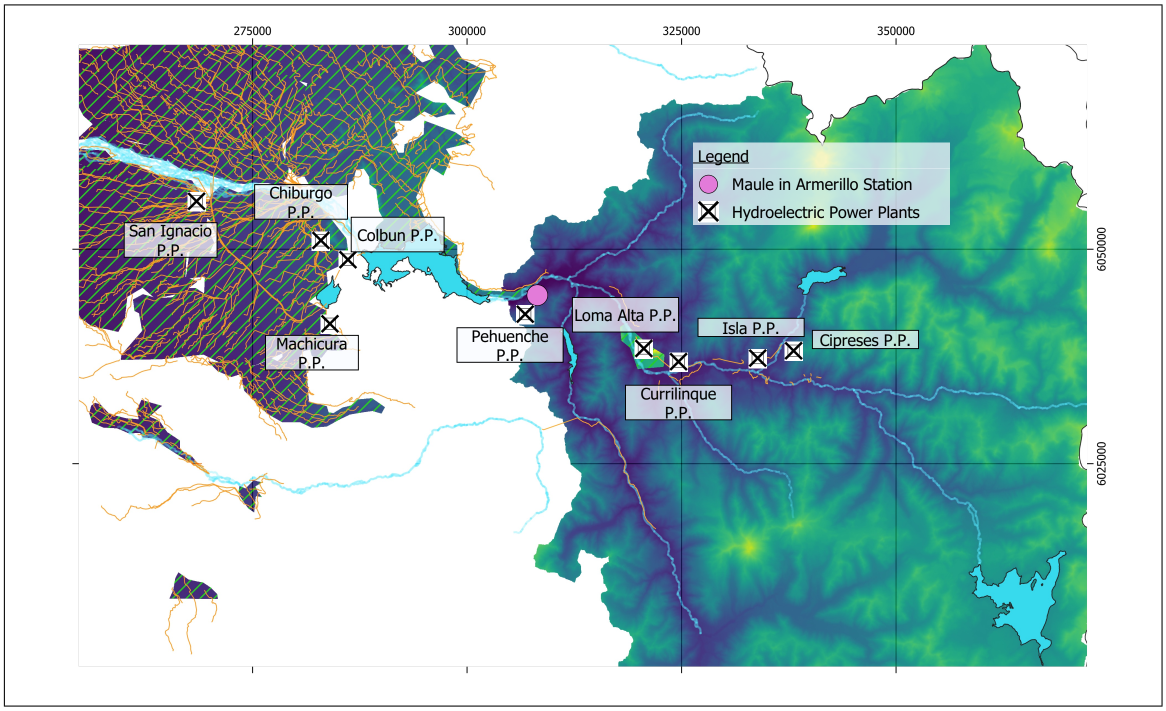

Figure 3.4. Hydroelectric Power Plants and Streamflow Gauge locations included in the study area. A total of nine hydropower plants, and a relevant streamflow gauge location (Maule in Armerillo Station) that restitutes flow for the calculation of resolution 105's consumptive rights.

Considering both the MOP-ENEL legal agreement from 1947 and the MOP Resolution 105/83, the consumptive water rights assigned to irrigation can be described with Equation 3.2.

$$Q_t^{IRR} = \begin{cases} Q_t^{NR} + Q_t^{ML} & \text{if } Q_t^{NR} \leq Q_{AG47} \text{ [m}^3/s] \\ Q_t^{NR} & \text{if } Q_{AG47} \leq Q_t^{NR} \leq Q_{R105} \text{ [m}^3/s] \\ Q_{R105} & \text{if } Q_{R105} \leq Q_t^{NR} \text{ [m}^3/s] \end{cases} \tag{3.2}$$

Considering the following notation:

- Q_t^{IRR}: Consumptive Water Rights for irrigation in timestep t [m^3/s]

- Q_t^{NR}: Water flow from natural regime (no additional reservoir discharge) in timestep t [m^3/s]
- Q_t^{ML}: Maule Lagoon water releases in timestep t [m^3/s]
- Q_{AG47}: Seasonal flows established in ENEL-MOP Legal Agreement from 1947 [m^3/s]
- Q_{R105}: Monthly flows established in MOP's Resolution 105/83 [m^3/s]

The basin contains irrigation of a large area for crop production, a considerable amount of hydropower plants and an outflow that eventually converges to a water treatment plant for urban consumption, consequently it qualifies as a WEF nexus basin; with Colbun (owned by ENEL) being the main player in energy production, the thousands of farmers and water user associations in food production, and the DGA in terms of regulations (given the resolutions, agreement in effect and consumptive water rights). Additional relevant stakeholders include the Energy Minister (MinEnergía) and National Electric Coordinator (CEN), given the high percentage of national electric production in the area, different institutions belonging to the Ministry of Agriculture (MinAgri) such as the Agrarian Office of Studies and Policies (ODEPA) and National Irrigation Comission (CNR) due the relevant amount of crops in the study area, and the Ministry of the Environment (MMA) as the entity that establishes and supervises the environmental flows.

3.2. Climate change impacts quantification over Maule Basin upper section

In order to represent the impacts of climate change over Maule Basin, seven different Global Circulation Models are used across two different emission scenarios. Under these scenarios, average temperatures in the area are expected to increase up to 1.9°C, and precipitation levels can decrease below 65% (considering a monthly average value). These models across scenarios are extracted from the platform created by CR2 and CCGUC (CR2 & CCGUC, 2021), which specifically scaled the models across scenarios for the study area. Table 3.2 shows the different models used, and the institution of origin.

Scenarios are based on the different Representative Concentration Pathways (RCPs), which form a set of greenhouse gas concentration and emissions pathways designed to support research on impacts and potential policy responses to climate change. For this particular case, a first scenario considered corresponds to the ”Business as Usual”, a baseline scenario that does not include any specific climate mitigation target known as RCP8.5 (Riahi et al., 2011). The second scenario is a pathway that describes trends in long-term, global emissions of greenhouse gasses peaking around 2060 and then declining through the rest of the century, known as RCP6 (Masui et al., 2011).

Table 3.2. Different climate change models used for the projection of hydrological impacts, each from a different institution, included in the future projections from the WEAP model provided by the UC Global Change Center (CCGUC, 2019).

Center	Model
Canadian Center for Climate Modeling and Analysis (CCCMA)	GCM 3
Geophysical Fluid Dynamics Laboratory (GFDL)	CM 2
Goddard Institute for Space Studies (GISS)	AOM
Max Planck Institute for Meteorology (MPI)	ECHAM 5
Meteorological Research Institute (MRI)	CGCM 2.3.2.
National Institute for Enviromental Studies (NIES)	MIROC 3
United Kingdom Met Office (UKMO)	HADCM 3

The crossing between scenarios and models generate 14 different pathways, translated in 14 different series for both monthly average precipitation and temperature between 2020 and 2060, then the WEAP model use it as input and with Equation 4.1 estimates the runoff for each catchment, which will sum up to the flow in Armerillo Station. The average monthly flow for each scenario-model articulation is shown in Figure 3.5, with all combinations resulting in a lower value than the historical one (between 1980 and 2020).

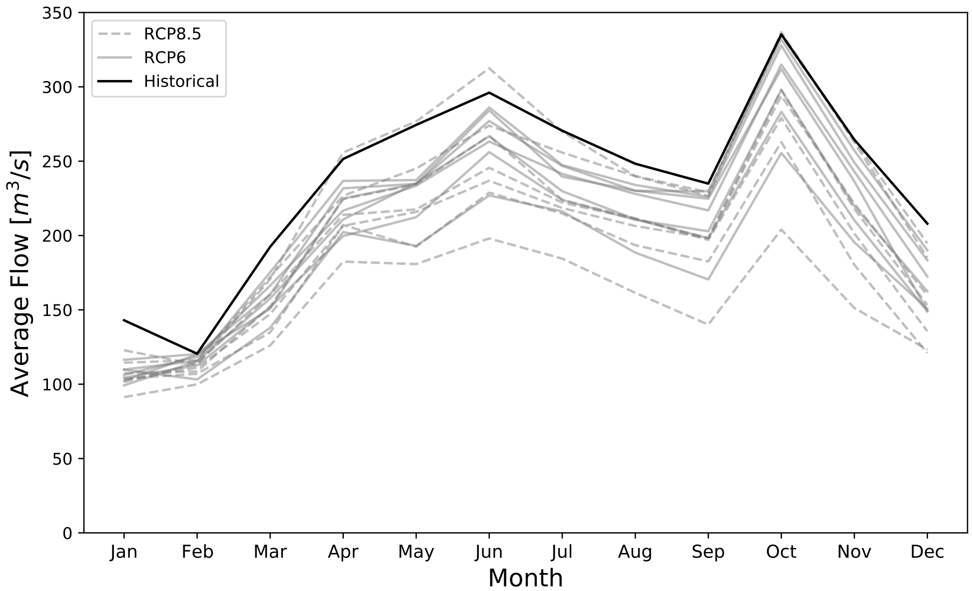

Figure 3.5. Projected impact over Armerillo station's monthly average flow, using the seven different climate change models over both RCP8.5 and RCP6 scenarios. In black, the historical flows between 1980 and 2020, in dashed gray the RCP8.5 emission scenarios and in straight gray the RCP6 emission scenarios. 13 out of 14 scenarios contain a lower annual average flow than the historical.

The 14 scenarios generate different inputs for the water resources model done with PYWR, as catchments $I^s_{c,t}$ (from Equation 4.2) depend on the runoff value calculated by WEAP. These inputs are what define each scenario, with different catchment inflows and a different level of average flow in the Armerillo Station, which corresponds to the reconstituted flow of every catchment in the system.

4. METHODOLOGY

This chapter describes the methodology used in the respective study, including the computational modellation of the area of interest and the strategies for climate change adaptation, both with an SSD and DSM focus that consider the nexus between irrigation, hydropower production and local policies that allocate water resources.

4.1. Water Resources Simulation of the Maule Basin

Maule basin upper section can be described as a hydrological system that interacts with demand sites such as hydropower plants, irrigation hectares, and includes assigned water rights and five reservoirs with distinct operation rules and hydraulic restrictions. Given the Water-Energy-Food nexus system in the zone, WEAP is a feasible computational software to model the physical and productive interaction as a whole due to its integrated water resources planning approach (Sieber, 2006).

A WEAP model from the upper section of the basin developed by the Climate Risk Atlas Project (Vicuña et al., 2020) is used, including the five reservoirs, nine hydropower plants, thirty-four flow requirement spots, eight demand sites and eighty-three catchments. Figure 4.1 shows the schematic view of the WEAP model provided.

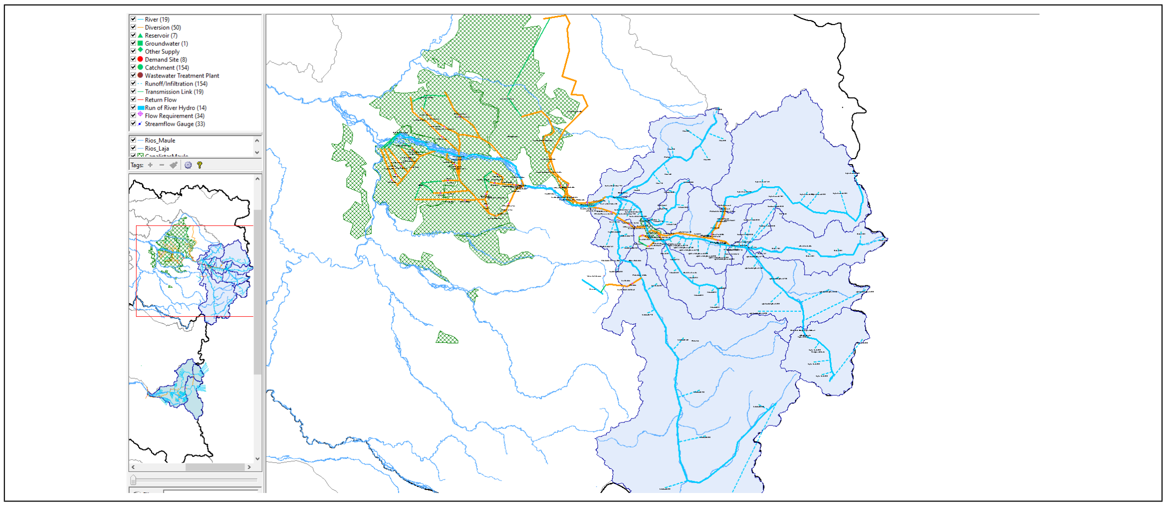

Figure 4.1. Upper Maule Basin WEAP Model. A computational model consisting on various types of nodes, hydrological parameters and allocation policies, provided by the UC Global Change Center (Vicuña et al., 2020)

This model can be used to represent the hydrologic interactions of the system, given that it uses precipitation and temperature as inputs to compute the estimated stream flows in all the different rivers by using the Soil-Moisture Method (Clapp & Hornberger, 1978) expressed in Equation 4.1.

$$RT(t) = \sum_{j=1}^{N} A_j (P_e(t) z_{1,j}^{RRF_j} + f_j k_{s,j} z_{1,j}^2) \tag{4.1}$$

Considering the following notation:

- $RT(t)$: Surface and interflow runoff in timestep t
- A_j: Area of cover fraction j
- $P_e(t)$: Effective precipitation in timestep t
- $k_{s,j}$: Root Zone Saturated Conductivity for land cover fraction j
- f_j: Partitioning coefficient related to soil, land cover type and topography for land cover fraction j

- RRF_j: Runoff Resistance Factor of land cover j
- $z_{1,j}$: Relative Storage given as a fraction of the total effective storage of the root zone for the land cover fraction j

The WEAP tool can also be used to represent the water rights and allocation mechanisms in the area, like Resolution 105 and the MOP-ENEL Agreement, by using Key Assumptions and creating functions in reservoirs and in flow requirement nodes that regulate the flow to each destination. Despite how useful for representing the current and future scenarios WEAP is, it isn't capable of conducting multi-level optimization (Mousavi et al., 2017), or as proposed in this study, multi-objective evolutionary algorithms (MOEA) to produce portfolios of non-inferior solutions. Nonetheless, WEAP is still useful for conducting non-linear calculation like runoff, based on future precipitation and temperature projections.

In order to conduct a MOEA analysis in the Maule basin, the PYWR library presents itself as a useful tool (Tomlinson et al., 2020), being able to replicate the system's flow distribution, storage and allocation; alongside conducting multi-objective optimization for future scenarios. PYWR nodes can have restrictions (i.e. maximum or minimum flows), and parameters may be a function of external data (i.e. a given series or dataframe) or model states (i.e. the storage in a reservoir). This Python library connect nodes through links, and uses costs assigned in each node to conduct a linear optimization and minimize cost or maximize benefit. Also, as it is written in python, it enables external execution like the cloud or in High Performance Computing (HPC).

There are certain necessary nodes to include in the model in order to be representative, given their relevance to the water allocation structure of the area. The five reservoirs are imperative to consider, and so are the seven demand nodes, which represent the thousands of irrigation agents that own irrigation channels. The catchments can be simplified into fifteen main nodes, supplying each river with stream flow across the basin. In Figure 4.2, a representation of the relevant nodes for the PYWR modelling can be seen as part of the map.

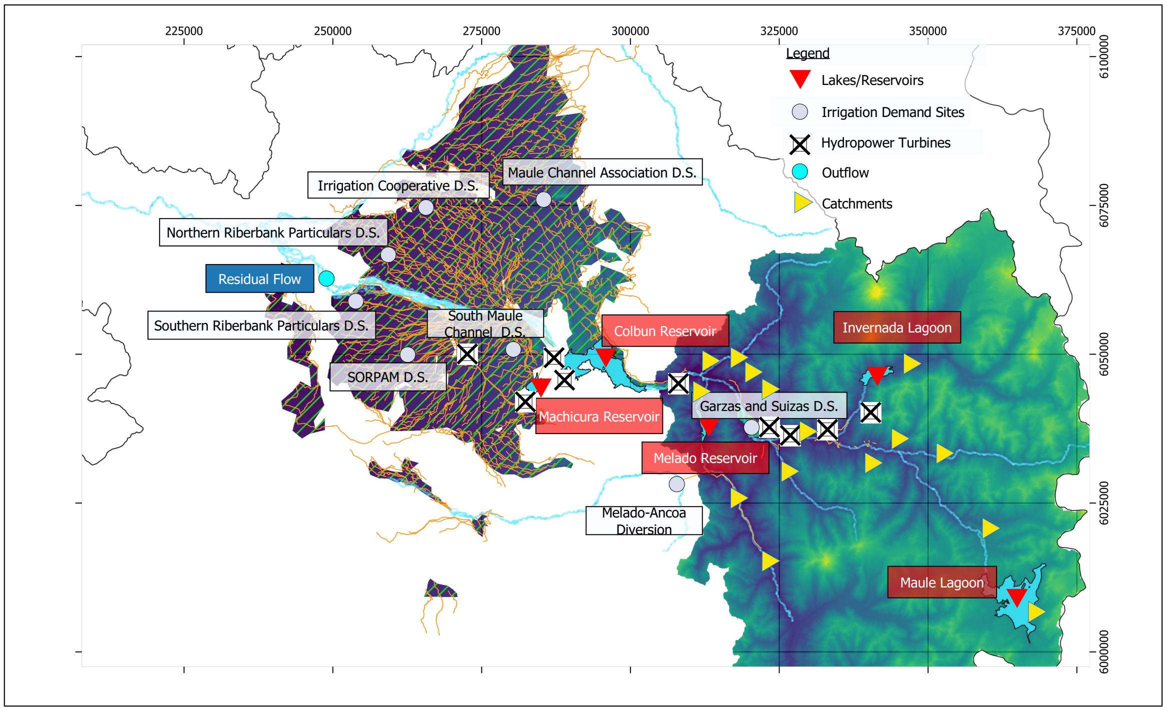

Figure 4.2. Sites of interest for the water resources model, such as demand sites, hydropower plants, reservoirs, catchments and outflows. The sites of interest are restricted to the study area.

The hydric balance of the system can be expressed through Equation 4.2 for the upper section of the basin.

$$\sum_{r=1}^{5} S^s_{r,t-1} + \sum_{c=1}^{15} I^s_{c,t} = \sum_{ds=1}^{8} D^s_{ds,t} + O^s_t + \sum_{r=1}^{5} S^s_{r,t} + \sum_{r=1}^{5} RE^s_{r,t} \tag{4.2}$$

Considering the following notation:

- $S^s_{r,t}$: Storage of reservoir r, in scenario s at timestep t
- $I^s_{c,t}$: Input flow of catchment c in scenario s at timestep t
- $D^s_{ds,t}$: Demand delivered at demand site ds in scenario s at timestep t
- O^s_t: Output residual flow in scenario s at timestep t
- $RE^s_{r,t}$: Evaporation of reservoir r in scenario s at timestep t

In addition to the node locations that give sequentiality to the network, the attributes of each one must be defined depending on the node type. Storage nodes can be defined with storage capacity, maximum and minimum storage and cost. The different zones can be represented as a maximum flow node that the reservoir may release, remembering that the Buffer Zone constraints releases in the fraction that the buffer coefficient indicates. The Inactive Zone in this case can be represented as a minimum storage, as it is meant to be a zone that cannot have releases in regular scenarios. Table 4.1 shows the properties of the different reservoirs in the Maule basin upper section.

Table 4.1. Properties of the different reservoirs in the study area, included in the WEAP model provided by CCGUC. Monthly Values means that each month there is a different storage value for the Top of Buffer Zone (CCGUC, 2019).

Reservoir	Storage Capacity [Hm^3]	Top of Buffer Zone [Hm^3]	Top of Inactive Zone [Hm^3]	Buffer Coefficient
Maule Lagoon	1,420	630	170	0.8
Invernada Lagoon	179	Monthly Values	0	0.5
Melado Reservoir	135	Monthly Values	102	1
Colbun Reservoir	1,544	Monthly Values	428	0.85
Machicura Reservoir	52	42	42	0

Besides the common properties, evaporation is a relevant output to the model, so it is necessary to generate demand nodes that directly extract the evaporation flow from storage nodes. To this extent, two zones have been defined that specify the amount of estimated millimeters that evaporate per month, shown in Table 4.2.

Table 4.2. Monthly evaporation values for reservoirs in the study area, divided by their altitude. Values extracted from the WEAP model provided by the UC Global Change Center (CCGUC, 2019).

<table>
<tr><th rowspan="2">Month</th><th colspan="2">Upper Zone Evaporation [mm]</th><th colspan="3">Lower Zone Evaporation [mm]</th></tr>
<tr><th>Maule Lagoon</th><th>Invernada Lagoon</th><th>Melado Reservoir</th><th>Colbun Reservoir</th><th>Machicura Reservoir</th></tr>
<tr><td>January</td><td colspan="2">200.7</td><td colspan="3">200.5</td></tr>
<tr><td>February</td><td colspan="2">178.6</td><td colspan="3">162.6</td></tr>
<tr><td>March</td><td colspan="2">158.5</td><td colspan="3">140.6</td></tr>
<tr><td>April</td><td colspan="2">102.8</td><td colspan="3">87.1</td></tr>
<tr><td>May</td><td colspan="2">59.3</td><td colspan="3">49.6</td></tr>
<tr><td>June</td><td colspan="2">31</td><td colspan="3">32</td></tr>
<tr><td>July</td><td colspan="2">37.7</td><td colspan="3">42.8</td></tr>
<tr><td>August</td><td colspan="2">54.6</td><td colspan="3">62.7</td></tr>
<tr><td>September</td><td colspan="2">79.6</td><td colspan="3">78.1</td></tr>
<tr><td>October</td><td colspan="2">104.5</td><td colspan="3">101</td></tr>
<tr><td>November</td><td colspan="2">147</td><td colspan="3">137.7</td></tr>
<tr><td>December</td><td colspan="2">194</td><td colspan="3">180.4</td></tr>
</table>

Besides reservoirs, hydropower plants are nodes that have to be represented in the system as well. There are nine hydropower plants, which produce energy (E_m) as indicated in Equation 4.3, both in WEAP modelling (calculated directly) and configured in the water resources network as a recorder.

$$E_m = Q_m \cdot F_m \tag{4.3}$$

Considering the following notation:

- E_m: Energy Produced in a month [W]
- Q_m: Volume through turbine [m^3/s]
- F_m: Hydro Generation Factor [kg/ms^2]

The Hydro Generation Factor (F_m) is defined in Equation 4.4.

$$F_m = \rho_w \cdot H_{net} \cdot \eta_{gen} \cdot \eta_{turb} \cdot g \tag{4.4}$$

Considering the following notation:

- ρ_w : Water density (1000 [kg/m^3])
- η_{turb} : Turbine efficiency
- g : Gravity acceleration [m/s^2]
- η_{gen} : Plant factor
- H_{net} : Fixed head (Run of the river) or Drop elevation (Reservoirs) [m]

The properties of each plant must be specified, which are extracted from the WEAP model and shown in Table 4.3.

Table 4.3. Properties of the different hydropower plants in the study area, extracted from the WEAP model provided by the UC Global Change Center (CCGUC, 2019).

Power Plant	Type	Max Turbine Flow [m^3/s]	Turbine Efficiency [%]	Plant Factor [%]	Fixed Head [m]
Cipreses	Run-of-the-river	36.4	75	100	Invernada Lag. Elevation-965
Isla	Run-of-the-river	84	87	100	93
Currilinque	Run-of-the-river	85.4	92	100	114.29
Loma Alta	Run-of-the-river	99	82	100	50.4
Pehuenche	Run-of-the-river	300	90	100	Melado Res. Elevation - 460
Chiburgo	Run-of-the-river	14	95	100	118
Colbun	Reservoir	280	83	95	Colbun Res. Elevation - 232
Machicura	Reservoir	280	95	95	Machicura Res. Elevation - 13
San Ignacio	Run-of-the-river	194	98	95	20

Demand sites are also an important aspect of the model that has to be parameterized, in which the eight sites have different areas and percentage of consumptive water rights. However, given the similar types of crops within the basin, the annual demand per hectare is treated as equal in every site. The total demand per site is calculated annually, and then is weighted by the normalization of the monthly consumptive water rights assigned for irrigation and the annual mean of this very same rights. Equation 4.5 describes the procedure.

$$Qd_t^{ds} = \frac{Q_t^{IRR}}{Q_{mean}} \cdot \frac{A^{ds} \cdot Dem}{12} \tag{4.5}$$

Considering the following notation:

- $Qd_{t,ds}$: Monthly water demand of demand site ds in timestep t [m^3/s]
- Q_t^{IRR} : Consumptive water rights assigned to irrigation per month [m^3/s], obtained in Equation 3.2
- Q_{mean} : Annual mean of consumptive water rights assigned to irrigation per month [m^3/s]
- A_{ds} : Irrigation area of demand site ds [ha]
- Dem : Yearly demand of water per hectare [m^3/ha · year]

Besides demand sites, the water allocated to each irrigation channel differs from the water efficiently used in crop consumption; given the different levels of technical efficiency that each farmer possesses. This type of efficiency is defined as the ratio between the allocated water to a crop and the amount that is effectively applied to it(Losada Villasante, 1994). So, the consideration for water rights respective to each demand site irrigation channel has to comply with Equation 4.6.

$$Qal_t^{ds} = Q_t^{IRR} \cdot \%_{WR}^{ds} \tag{4.6}$$

Considering the following notation:

- Qal_t^{ds} : Water rights fraction flow assigned to Demand Site ds in timestep t [m^3/s]

- Q_t^{IRR} : Consumptive water rights assigned to irrigation per month [m^3/s], obtained in Equation 3.2 [m^3/s]
- $\%_{WR}^{ds}$: Percentage of consumptive water rights assigned to demand site ds

Subsequently, after establishing all the relevant parameters and nodes, the WEAP model provided by CCGUC is used as a reference to generate the equivalent via PYWR, however the catchments in the water resources model can only correspond to streamflows as this library isn't able to conduct non-linear procedures. In consequence, the WEAP model is used to produce the stream flows that serve as input to the water resources model made with PYWR using Equation 4.1. In Figure 4.3, the resulting network model is shown, with red nodes being reservoirs, blue nodes catchments, yellow nodes demand sites and gray nodes links, hydropower plants, flow requirements and hydraulic restrictions like reservoir maximum releases and channel maximum flows.

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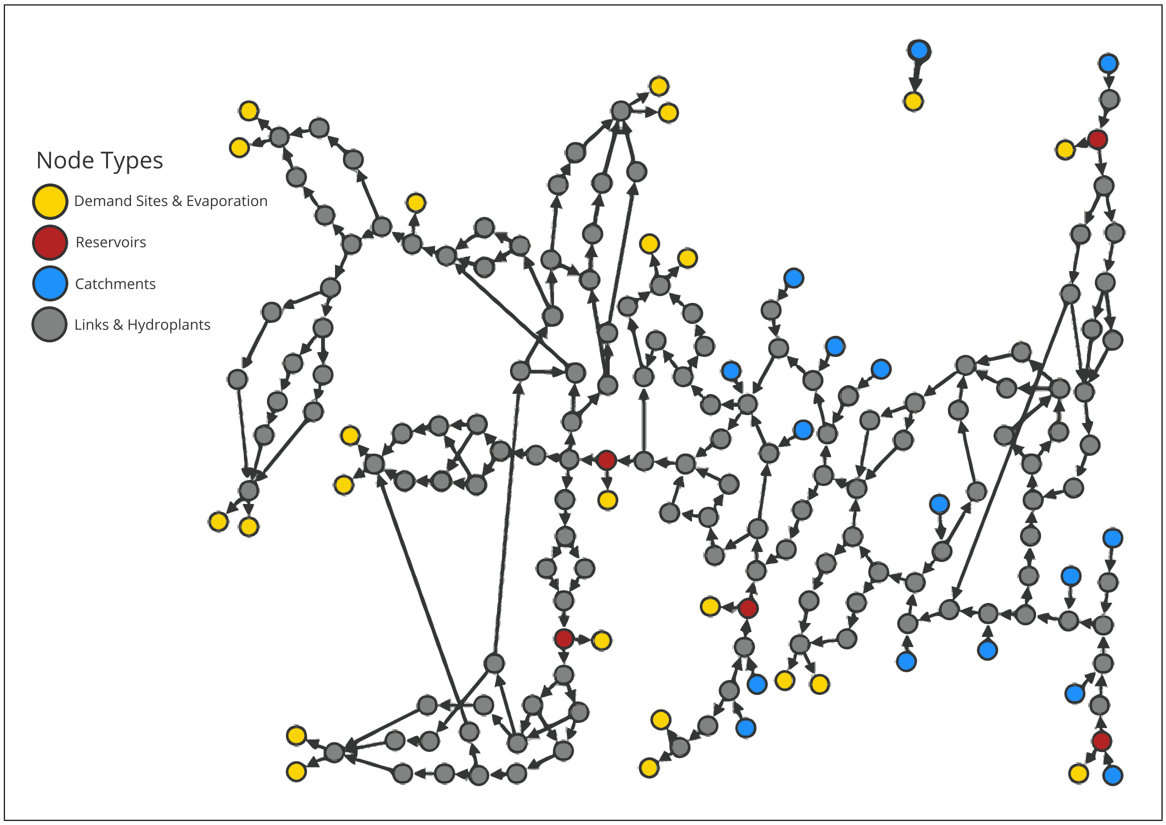


Figure 4.3. Water resources model made with PYWR to represent the study area of the Maule basin. The model consists in 195 nodes, with their respective types illustrated in the legend. The one demand site connected to the catchments separated from the main network were used to represent the consumptive water rights in resolution 105.

Using the water resources model done with PYWR represents a computational enhancement in terms of efficiency compared to WEAP, as it reduces the processing time for a model that contains multiple scenarios through a simultaneous calculation (Tomlinson et al., 2020). WEAP, on the other hand, calculates each scenario individually, hence the processing time is directly proportional to their number.

The model done with PYWR is programmed to measure criteria for water resource system performance evaluation like reliability, resiliency and vulnerability (Hashimoto, Stedinger, & Loucks, 1982) among others through the output recorders. The Maule basin upper section model records the Demand Deficit ($Def_t^{ds,s}$) as the difference between the monthly water rights amount assigned per demand site ($Qal_t^{ds,s}$) and the real flow allocated to the same demand site ($Q_t^{ds,s}$) for each timestep and scenario, as Equation 4.7 shows.

$$Def_{t,ds}^{s} = max[0, Qal_t^{ds,s} - Q_t^{ds,s}] \tag{4.7}$$

The total system deficit per timestep (Def_t^s) then can be summarized in Equation 4.8.

$$Def_t^s = \sum_{ds}^{8} Def_t^{ds,s} \tag{4.8}$$

The Failure event ($F_{t,ds}^s$) is also a recorder, which counts every time the system has an unsatisfactory output (a month with deficit (Def_t^s) for any demand site), seen in Equation 4.9.

$$F_t^s = \begin{cases} 1 & \text{if } Def_t^s > 0 \\ 0 & \text{if } Def_t^s = 0 \end{cases} \tag{4.9}$$

The transition from a satisfactory state to an unsatisfactory state, used to point the failure's time of duration (Hashimoto et al., 1982) is defined in Equation 4.10 as W_t^s.

$$W_t^s = \begin{cases} 1 & \text{if } F_t^s = 0 \wedge F_{t+1}^s = 1 \\ 0 & \text{if otherwise} \end{cases} \tag{4.10}$$

In consequence, the reliability (Rel^s), resilience (Res^s) and vulnerability (Vul^s) for each scenario is computed as Equations 4.11, 4.12 and 4.13 show, respectively.

$$Rel^s = 1 - \frac{\sum_t^n F_t^s}{n} \tag{4.11}$$

$$Res^s = \frac{\sum_t^n W_t^s}{\sum_t^n F_t^s} \tag{4.12}$$

$$Vul^s = \sum_{ds}^{8} max[Def_{t,ds}^s] = max[Def_t^s] \quad \text{for } t = \{1, ..., n\} \tag{4.13}$$

The other type of recorders used in the water resources model are Hydropower Generators, that use the exact same procedure shown in Equation 4.3 to compute the output. In addition, reservoirs contain restrictions given by their hydraulic capacities and policies of the area.

- Reservoir Filling: Reservoirs only prioritize their filling ($S_t^s \leq S_{t+1}^s$) when the flow in natural regime (Q_t^{NR}) is higher than the amount of consumptive water rights assigned for irrigation (Q_t^{IRR}).

$$S_t^s \leq S_{t+1}^s, \quad \text{if } Q_t^{NR} > Q_t^{IRR} \tag{4.14}$$

- Reservoir Release: The maximum release value (MR_t^s) corresponds to the minimum value between the reservoir's Water Release Operation Rules (R_t^s) and their Maximum Hydraulic Flow (MHF_t^s) (each reservoir has a different function that depends on the previous timestep storage level).

$$MR_t^s = min[R_t^s(S_t^s, Q_t^s), MHF_t^s(S_{t-1}^s)] \tag{4.15}$$

- Reservoir Capacity: Reservoirs can only store water between the levels of their maximum capacity (K) and their inactive zone (I).

$$I \leq S_t^s \leq K \tag{4.16}$$

- Reservoir Evaporation: Each month, reservoirs evaporate a certain amount of volume dependant on the month, the area (shown in Table 4.2) and the storage level, hence the resulting volume is calculated as the product between the evaporation in the zone ($Ev_{t,r}[m]$) in and the surface water area of the reservoir ($A_{t,r}[m^2]$), obtained through the different Elevation-Volume curves of the WEAP model.

$$RE_t^s = Ev_{t,r}^s \cdot A_{t,r}^s(S_t^s) \tag{4.17}$$

Verification can be done by comparing the reservoir levels of the WEAP model and the one done via PYWR. Figure 4.4 shows this comparison between the calibration years of 1980 and 2007. As observed, each reservoir adapts with statistical accuracy, detailed in Table 4.4, showing a considerable amount of correlation that validates the use of the model done with PYWR as an alternative that represents the Maule basin physical processes, hydrologic interactions and policies for allocation.

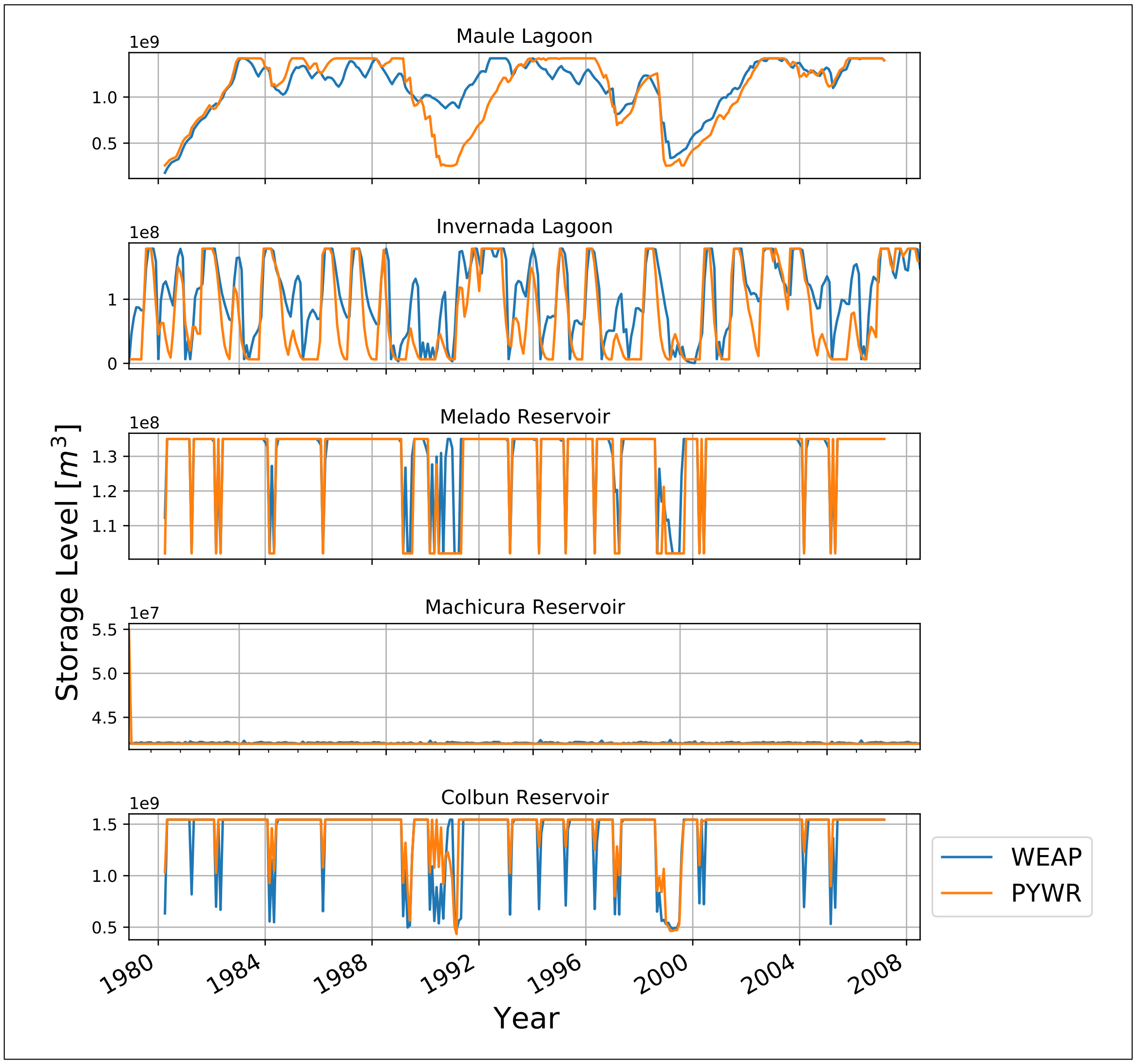


Figure 4.4. Historical comparison between reservoir levels obtained with the modeled values in the water resources model and the WEAP software

Table 4.4. Water Resources model statistical adjustment to the WEAP software model.

Reservoir	Mean Adjustment [%]	Coefficient of Determination (R^2)
Maule Lagoon	95.9	0.72
Invernada Lagoon	95.1	0.67
Melado Reservoir	99.1	0.75
Colbun Reservoir	92.2	0.7
Machicura Reservoir	99.9	1

4.2. Multi-objective evaluation of implementation strategies considering climate change impacts

Water resource management studies, both in SSM and DSM, often use different resolution techniques to ensure water security and supply; with a wide range of increasingly sophisticated alternatives that allow to consider an IWRM focus. Some of these alternatives include complex Bayesian models (Castelletti & Soncini-Sessa, 2007), long term robust planning and timing with non-stationary probabilities (Waheed, Grigg, & Ramirez, 2021), using a wide range of softwares programs for modelling (Chen, Shams, Carmona-Moreno, & Leone, 2010) and more recently, using artificial intelligence (Xiang, Li, Khan, & Khalaf, 2021). The generation of a portfolio of optimal solutions considering a multi-objective focus has been presented as a feasible alternative when it comes to representing a basin with Water-Energy-Food nexus, given the different productive activities and environmental goals that may not be directly quantified by the same measuring parameters (Trindade, Reed, & Characklis, 2019; Yazdandoost & Yazdani, 2019).

Given the nature of this study, in which a basin containing WEF nexus is involved, the proposed approach consists on generating a set of solutions with a multi-objective focus; in which the optimization implies decision-making problems with multiple objectives that can be represented in numerical terms (Sawaragi, NAKAYAMA, & TANINO, 1985), resolving in the form of a frontier of denominated Pareto or Non-Inferior solutions. This perspective allows to include and contrast the priorities of the different stakeholders and producing agents in the area, intertwining environmental requirements, hydroelectric production and consumptive water rights assurance. Each objective is indeed represented as a numerical value, however, as they are not directly commensurable, there is never a unique solution to the problem, and it will always imply certain trade-offs that should be discussed between the agents of interest (Huskova, Matrosov, Harou, Kasprzyk, & Lambert, 2016).

Combining climate change adaptation strategies with multi-objective optimization can provide a portfolio of balanced indicators that ensure an environmental flow, reduce production deficits and maximize system performance (Hashimoto et al., 1982). However, in realistic terms, it is necessary to project the financial impact of the strategies, in order to generate feasible incentives for the involved stakeholders to apply the proposed adaptations. The portfolios end up representing the different objectives prioritized depending on the combination of strategies, and to which degree they are implemented. In this case, both adoption strategies proposed consist on the modification of the main existing regulation agreements for water allocation and reservoir operation, so in order to represent a coherent proposal to climate change mitigation they must follow certain rules. In the first place, the base model should be able to accurately represent the impact of the proposed strategies, not only on a hydrologic and climatic level, but also in a productive and financial one. Secondly, dealing with the uncertainty of climate change requires the capability of generating future scenario's simulation, using coherent models that represent adequately the hydrological, economical and allocative repercussions over the whole system; and articulating these scenarios with the probabilistic estimation of occurrence, as each scenario often depends on the estimated level of emissions. In the third place, each stakeholder and agent of interest must be considered when choosing the ”best” portfolio, as each objective aligns with a different priority, giving an integrated approach of water resources management that balances each necessity. It's important to emphasize that the portfolio of solutions operates under an uncertain future, so it will never guarantee an ideal system performance into the future.

The system (basin) in this case is represented by the water resources model, and it is combined with a Multi Objective Evolutionary Algorithm (MOEA); which replicate genetic mutations of the optimization variables, creating new and better solutions (according to the objectives) based on the pre-existing ones (Van Veldhuizen & Lamont, 1998), with a number of N iterations until the dominating solution presents the optimal value of at least one objective. MOEAs can obtain the final solution from the decision maker's preferences either before (*a priori*), during (*progressive*) or after (*a posteriori*) the optimization process, and support the amount of non-linear equations given in a model of water resources management nature (Y Al-Jawad & M Kalin, 2019). In this specific case, the algorithm used corresponds to the Non-dominated Sorting Genetic Algorithm III (NSGA-III) (K. Deb & Jain, 2013), based on progressive optimization and useful when the number of objectives are over three (Kesireddy, Shan, & Xu, 2019), because the process of selecting Pareto fronts implies the association to reference line instead of crowding distance.

4.3. Adaptation Strategies Considered

The proposed adaptation strategies for this case consist on updating the two main regulatory mechanisms on the area: both the 1947 Agreement between ENEL and MOP, and the DGA Resolution N°105 from 1983.

Since the Agreement establishes the Standard Operation Rules for Maule Lagoon, a possible renewal of the regulation implies a modification in the operation rules of the reservoir, in this particular scenario by including a hedging method to secure water storage for prolonged deficit periods (Draper & Lund, 2004; Neelakantan & Sasireka, 2015; Cai et al., 2018), with a trade-off that implies reducing reservoir discharge in small deficit periods.

On the other hand, the Resolution establishes a static, constant amount of consumptive water rights assigned each month without an update that may consider the technification of irrigation methods. This tends to be an incentive for irrigators to maintain the irrigation techniques, and hence the application efficiency maintains a relatively stable level through time (Ørum, Boesen, Jovanovic, & Pedersen, 2010), moreover in Chile where water right holders are taxed when their consumption/use is below their assigned share, as part of the Law N°20.017 of 2005 (Rivera D, 2015). So the implementation strategy consists on generating a dynamic water right allocation (Y. Yu et al., 2017; Gómez-Limón, Gutiérrez-Martín, & Montilla-López, 2020), where the level of technification and irrigation efficiency, as well as the crop distribution, is considered in order to prevent over-assignment and unnecessary water dispersion by evaporation or percolation.

Both adoption strategies can be combined to create a universe of possible portfolios that respond to a multi-objective focus, combining both Supply Side Management (reservoir operation buffering) and Demand Side Management (adapting allocation to efficiency), and establishing an Integrated Water Resource Management approach to regulation and legislation. As a strategy that affects directly water users and depends on their actions, it is necessary to contrast the costs of implementation against the benefits of the outcomes, to generate a mutually beneficial scenario in which water efficiency is correctly incentivized.

4.3.1. Reservoir Operation Modification: Introducing Hedging Rules

Hedging rules are introduced as a recurring water management technique to adapt reservoir discharge levels facing expected periods of extended water shortage. In this case, a hedging rule that modifies the operation of Maule Lagoon is proposed, as the actual regulation comes from an Agreement that was signed more than 70 years ago and didn't consider Climate Change Adaptation into the reservoir management.

The historical operation of Maule Lagoon consists of three reservoir zones, which determine the upper and lower limits for the discharge curve functions. A one-point linear hedging would imply the creation of a new zone (Draper & Lund, 2004) below the buffer zone, in which water releases would be with a higher level of restriction (translated in a lower buffer coefficient). Figure 4.5 shows the new Hedging zone, above the Dead Storage and below the Buffer. This new zone sets a new limit in an accumulated volume of β, which is one parameter that is considered as a variable which will be later used as input to the multi-objective evolutionary algorithm.

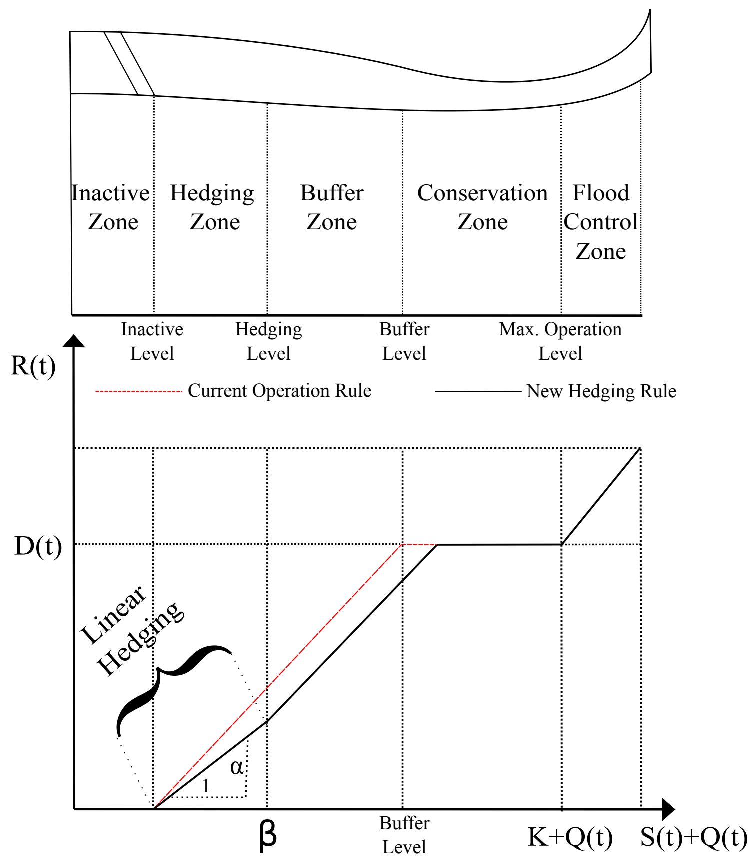


Figure 4.5. Maule Lagoon operation zones with one point hedging, including the new hedging zone which contains a variable amount of volume covered.

Introducing a one-point linear hedging rule implies the modification of the Release Function, which is dependant on the current storage and the inflow of each timestep. Equation 4.18 illustrates the new piecewise function that represents the proposed hedging rule, in which there is a second interval with a buffer coefficient of α, defined as a lower value than the historical one (value of 80%) and also a parameter to be considered as an input variable to the multi-objective evolutionary algorithm. Another new value corresponds to β, defined as the hedging zone that will restrain releases in the proportion of the stated hedging coefficient, and will also serve as an input to the model. The rest of the piecewise function is determined by linear calculation, considering the buffer coefficient as the slope of the interval, and both scenarios of a level of demand lower and higher than the Conservation Zone capacity.

$$\mathrm{R}_t(S_t, Q_t) = \begin{cases} 0 & \text{if } S_t + Q_t \leq 170 \text{ [Hm}^3\text{]} \\ min[D_t, \alpha(S_t + Q_t - 170)] & \text{if } S_t + Q_t \leq \beta \text{ [Hm}^3\text{]} \\ min[D_t, 0.8(S_t + Q_t(1.25\alpha(\beta - 170)))] & \text{if } S_t + Q_t \leq 630 \text{ [Hm}^3\text{]} \\ min[D_t, (S_t + Q_t - (126 + 0.8(\beta - 1.25\alpha(\beta - 170))))] & \text{if } S_t + Q_t \leq (1420 + D_t) \text{ [Hm}^3\text{]} \\ S_t + Q_t - 1420 & \text{if } (1420 + D_t) \text{ [Hm}^3\text{]} \leq S_t + Q_t \end{cases} \tag{4.18}$$

Considering the following notation:

- R_t: Water release in timestep t [Hm^3]
- Q_t: Water inflow to the reservoir in timestep t [Hm^3]
- S_t: Storage level in timestep t [Hm^3]
- D_t: Irrigation demand in timestep t [Hm^3]
- α: Buffer coefficient of Hedging Zone $D = \{0.6 \leq \alpha \leq 0.8\}$
- β: Hedging Zone volume [Hm^3] $D = \{170 \text{ Hm}^3 \leq \beta \leq 630 \text{ Hm}^3\}$

There are two different cases of a graphic representation of the hedging rule, considering that the demand is a variable that depends on the month and the other reservoir's levels. The two alternatives are set on the amount of demand because if it's higher than the storage capacity in the buffer zone, it means that the reservoir has to release water from both the conservation and the buffer zone, each with different buffer coefficients (conservation zone doesn't have a release restriction). Figure 4.6 shows the graphical representation of the one-point linear hedging for both scenarios, applied to Maule Lagoon. Between 170 Mm^3 and β Mm^3 levels of storage and inflow, the releases are restricted in an order of α, which is also the slope of the function.

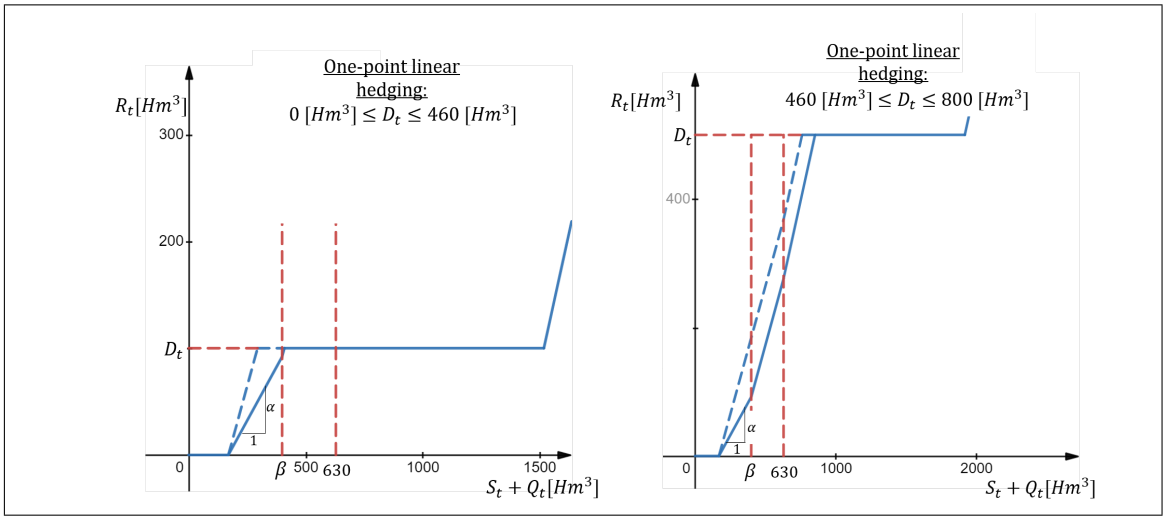


Figure 4.6. One point linear hedging rule for both demand cases in Maule Lagoon. The dashed blue line indicated the previous operation rule, while the continuous line the new hedging-based operation. There are two variables, which are α (new slope for the discharge curve) and β (new domain for the discharge function).

The historical monthly Demand Level for Maule Lagoon average between the years 1989 and 2007 is 29.23 Mm^3, with a standard deviation of 42.43 Mm^3. This means that the first case shown in Figure 4.6 would represent the monthly operation rule for Maule Lagoon more than 99.9% of the time if linear Hedging have been implemented.

4.3.2. Adaptative Water Allocation: Irrigation Technification

As agricultural information is updated to 2020, procedure done in Appendix A, an adaptation strategy can be proposed with a Demand Side Management, in which crops that present a lower Net Hydric Demand (NHN) and higher technification are prioritized over others. Historical data validates the estimation that crops that downtrend in the area are Cereals and Legumes/Tubers, and crops that uptrend are fruits and vineyards; which matches the proposed strategy of giving priority in the crop distribution to lower NHN values and higher technification. Subsequently, the adaptation strategy consists in generating an adaptative water allocation (Qad_t^{ds}) that adjusts the quotas to the level of technification in each demand site as Equation 4.19 represents, instead of being a fixed monthly value like Resolution 105 establishes; in which the additional efficiencies (uniformity, conductivity and storage) are represented as a static parameter (C^{ds}) (estimated in Appendix A), and the new Net Hydric Demands (NHN_t^{ds}) and application efficiencies ($\epsilon_{ap,t}^{ds}$) are considered.

$$Qad_t^{ds} = \frac{NHN_t^{ds}}{C^{ds} \cdot \epsilon_{ap,t}^{ds}} \tag{4.19}$$

Changing the crop distribution has direct repercussions over the NHN and application efficiency of each demand site, so it is fundamental to link the alternation in irrigated areas with both values. Equation 4.20 calculates the new NHN for each demand site, considering both the base NHN of crops that aren't included in the adoption strategy, and the new adjusted value from adjusting their distribution.

$$NHN_t^{ds} = NHNB_t^{ds} + \sum_{i=1}^{4} \frac{A_t^{i,ds}}{A_t^{ds}} NHN^i \tag{4.20}$$

Considering the following terms:

- $NHNB_t^{ds}$: Summed based Net Hydric Need of additional crops of demand site ds $[m^3/ha/year]$
- NHN_i : Net Hydric Need of crop i $[m^3/ha/year]$
- $A_t^{i,ds}$: Area of crop i for demand site ds $[ha]$ at timestep t, with $i = \{$cereal, legumes, fruits, vineyards$\}$

So, two input variables are proposed as a part of the strategy; while assuming that the irrigated area for each demand site doesn't change, which are the amount of hectares of cereals ($K_t^{c,ds}$) and legumes/tubers ($K_t^{l,ds}$) that are going to be replaced by fruits and vineyards in each demand site, values that are subtracted of the base scenario areas for both crop types ($A_0^{c,ds}$ and $A_0^{l,ds}$):

$$A_t^{c,ds} = A_0^{c,ds} - K_t^{c,ds}, \quad D = \{0 \leq K_t^{c,ds} \leq A_0^{c,ds}\}$$

$$A_t^{l,ds} = A_0^{l,ds} - K_t^{l,ds}, \quad D = \{0 \leq K_t^{l,ds} \leq A_0^{c,ds}\}$$

Figure A.5 establishes that for each hectare of cereal or legume/tuber reduced, 36% of this increase goes to fruits and 64% to vineyards, so the following equality can be proposed:

$$A_t^{f,ds} = A_0^{f,ds} + 0.36(K_t^{c,ds} + K_t^{l,ds})$$

$$A_t^{v,ds} = A_0^{v,ds} + 0.64(K_t^{c,ds} + K_t^{l,ds})$$

However, this crop distribution rotation isn't an instantaneous event, and is considered as a gradual 5-year process of installation and increasing production level until reaching stability; based on the Public Study by the Office of Study and Agrarian Policies (ODEPA) conducted in 2010 (ODEPA, 2010). The crop rotation process can start any year, which is stated as SY_j (Starting Year), different for both cereal and legumes. Equation 4.21 shows the gradual implementation of the new crop areas for fruits and vineyards, for the first 5 years of production (first year has a production level of zero), with different starting years for both cereal c and legume l replacement, considering the proportion assigned to fruits and vineyards (G^i) (0.36 and 0.64, respectively). It is important to state that from the first year since SY_j, cereal and legume area is reduced by the total amount of respective K_t^i, as the hectares of soil are now in transition.

$$A_t^{i,ds}(t) = \begin{cases} A_0^{i,ds} & \text{if } t \leq SY_j \\ A_0^{i,ds} + 0.02G^i K_t^{j,ds} & \text{if } t = SY_j + 1 \\ A_0^{i,ds} + 0.37G^i K_t^{j,ds} & \text{if } t = SY_j + 2 \\ A_0^{i,ds} + 0.64G^i K_t^{j,ds} & \text{if } t = SY_j + 3 \\ A_0^{i,ds} + 0.85G^i K_t^{j,ds} & \text{if } t = SY_j + 4 \\ A_0^{i,ds} + G^i K_t^{j,ds} & \text{if } SY_j + 5 \leq t \end{cases} \quad i = \{f, v\}, \quad j = \{c, l\} \tag{4.21}$$

An important assumption made by the proposed adaptation strategy consists on a constant irrigated area for all demand sites between 2020 and 2060, in order to avoid the uncertainties that imply the different possible agriculture expansion models, and land feasibility in the study area. A second assumption is that every demand site starts the crop replacement for either legumes or cereals in the same year, as a way of representing the average trend in all the farmers in the study area; which can be part of a technification plan to boost irrigation efficiency from any possible stakeholder, such as one of the many institutions in the Agriculture Ministry.

Considering a base application efficiency for the year 2020 as $\epsilon_{ap,0}^{ds}$, the new application efficiency for each demand site ($\epsilon_{ap,t}^{ds}$) can be calculated with Equation 4.22.

$$\epsilon_{ap,t}^{ds} = \epsilon_{ap,0}^{ds} + \tau_{ap}^{ds} \cdot (K^{c,ds} + K^{l,ds}) \tag{4.22}$$

In which the crop distribution variation impact over application efficiency is estimated with the rate of variation in application efficiency over decrease in cereal and legume/tubers per demand site (τ_{ap}^{ds}), as Equation 4.23 shows.

$$\tau_{ap}^{ds} = \frac{\Delta \epsilon_{ap}^{ds}}{\Delta A^{c,ds} + \Delta A^{l,ds}} \quad [ha^{-1}] \tag{4.23}$$

Table 4.5 illustrates the application efficiency rates for each demand site.

Table 4.5. Application efficiency rate per replaced hectare, for each demand site. Based on the historical irrigation technification levels per demand site (ODEPA, 2020).

Demand Site	τ_{ap}^{ds} [10^{-3} $\%/ha$]
Garzas and Suizas	84.3
SORPAM	3.64
South Maule Channel	1.64
Maule Channel Association	2.25
Irrigation Cooperative	3.52
Northern Riverbank Particulars	132.4
Southern Riverbank Particulars	131.2
Melado Ancoa Diversion	3.32

Given that crop replacement is a structural strategy (implies the physical intervention and installation of irrigation technology), a cost-benefit analysis is considered in order to incentivize the farmers for the execution of it. Two types of benefit are considered for agricultural production: the base benefit of all the crop types that aren't modified, and the marginal benefit from replacing the legume and cereal hectares. The reason of this division is to consider the economical impacts of climate change over the whole demand site, and not just over the replaced hectares; as adaptation strategies also can increase the benefit for the whole site (because of the reduction in deficit levels). Another type of benefit to be considered is the hydropower production one, since it also works as an incentive for hydro plant owners to implement the adaptation strategies.

The Total Benefit (TB), for instance, corresponds to the sum of the Agricultural Benefits (AB) and the Hydropower Benefits (HPB).

$$TB = ANB + HPB \text{ [MM USD]} \tag{4.24}$$

The Total Total Agricultural Benefits (TAB) of the agricultural production is considered in Equation 4.25, including both the base benefits (BB_t^{ds}) and the crop replacement (TRB) ones.

$$TAB = \sum_{t=1}^{T} \sum_{ds=1}^{8} BB_t^{ds} + TRB \text{ [MM USD]} \tag{4.25}$$

For the benefit of crops that aren't modified, named Base Benefits (BB_t^{ds}), and in order to include losses from deficits and water shortage, the benefit per demand site multiplies the Base Income (BI_t^{ds}) with the deficit factor of that year, calculated as the average deficit fraction of the whole year, and subtracts the Base Cost (BC_t^{ds}). This linear repercussion is based on the multiproduct firm concept (Heady, 1951), which establishes a multi-input and multiproduct production function that considers every input and output of the farming process; then multiplies them by their respective prices and subtracts the cost to the income to obtain the net benefit. In this case, water shortages aren't expected to affect the price of inputs (given that water rights are free of tenancy), but rather the output quantity in the system. According to the crop yield response to water, there is effectively a range in which the crop production can be assumed as a linear function of the water input (Steduto, Hsiao, Fereres, & Raes, 2012), even if a mild level of deficit is considered. Given the elevated amount of farmers in the area and scarce available information about their distribution, it is assumed that water deficits affect each crop in the same proportion, without prioritizing the irrigation of the ones with higher marginal benefit over others. The Base Benefit per demand site is shown in Equation 4.26.

$$BB_t^{ds} = \frac{Q_t^{ds}}{Qad_t^{ds}} BI_t^{ds} - BC_t^{ds} \text{[MM USD]} \tag{4.26}$$

The crop income (CI_c) and crop costs (CC_c) are extracted from the financial information of (ODEPA, 2010) and ODEPA's data sheets, and then multiplied by the fraction of each crop type respective to the demand site (f_c^{ds}) (shown in Figure A.4). This marginal value is then multiplied by the total demand site area, as shown in Equations 4.27 and 4.28

$$BC^{ds} = A^{ds} \cdot \sum_{c=1}^{9} (f_c^{ds} \cdot CC_c) \quad \text{[MM USD]} \tag{4.27}$$

$$BI^{ds} = A^{ds} \cdot \sum_{c=1}^{9} (f_c^{ds} \cdot CI_c) \quad \text{[MM USD]} \tag{4.28}$$

Table 4.6 shows the marginal income and costs per hectare for each demand site, based on their crop fraction besides cereal, legume, fruit and vineyard type.

Table 4.6. Annual base costs and income in the study area, as a weighted average of every crop in the demand site not included in the replacement strategy.

Demand Site	Yearly Income [10^3 USD/ha]	Yearly Costs [10^3 USD/ha]
Garzas and Suizas	1.47	0.51
SORPAM	2.25	1.31
South Maule Channel	0.95	0.38
Maule Channel Association	1.68	0.78
Irrigation Cooperative	2.68	1.76
Northern Riberbank Particulars	5.57	3.31
Southern Riberbank Particulars	1.72	1.01
Melado Ancoa Diversion	2.01	1.04

For the benefit of crops involved in the replacement strategy, the whole financial process of crop conversion to fruit and vineyards is based on (ODEPA, 2010), with an average of 5 years for reaching production stability and with each year containing a different value of costs and incomes per hectare.

Consequently, the Total Replacement Benefit (TRB) for replacing the irrigation hectares can be estimated as the sum of all the marginal benefits (AdB_t) multiplied by the respective demand site replaced area ($K^{j,ds}$), for both cereal and legume hectares replaced, which can have a negative value in shortage periods given the income reduction.

$$TRB = \sum_{j=1}^{2} \sum_{ds=1}^{8} \sum_{t=1}^{T} (K_t^{j,ds} \cdot AdB_t^{i,ds}) \text{ [MM USD]} \tag{4.29}$$

The Additional Benefit ($AdB_t^{i,ds}$) of replaced crops is calculated as the subtraction of the Additional Income (AdI_c^i) and Additional Cost (AdC_t^i), considering each year of the replacement process and the start year for legume and cereal replacement (different variables). Additionally, and to include the opportunity cost of the strategy, the crop benefit of the replaced type i is added to the costs, and of course including the deficit factor of the respective year. Equation 4.30 illustrates this method, with r being the social discount rate for irrigation projects established by the Social Development Ministry, which in this case it corresponds to a 6% (MINDESO, 2016).

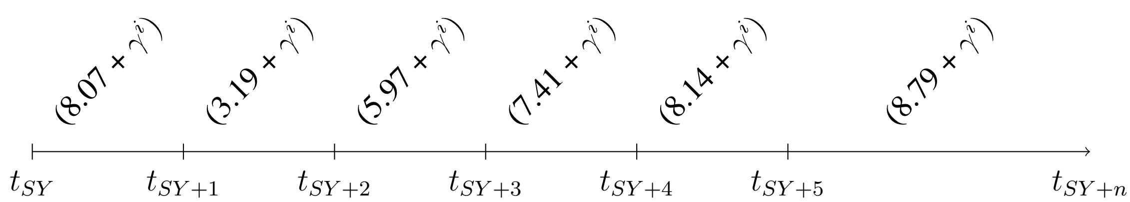
$$AdB_t^{i,ds} = \frac{\frac{Q_t^{ds}}{Qad_t^{ds}} AdI_t^i - (AdC_t^i + \gamma_t^i)}{(1+r)^t} \text{ [MM USD}/ha\text{]} \tag{4.30}$$

The opportunity cost ($\gamma_t^{i,ds}$) of replacing a crop type i for each demand site ds, at any timestep t can be calculated with Equation 4.31. Such value is included to represent the gross margin of the project (crop adoption) considering that it replaces a given crop structure, consequently being feasible for a social project assessment (in case of possible subsidies) and simultaneously acting as an incentive for farmers.

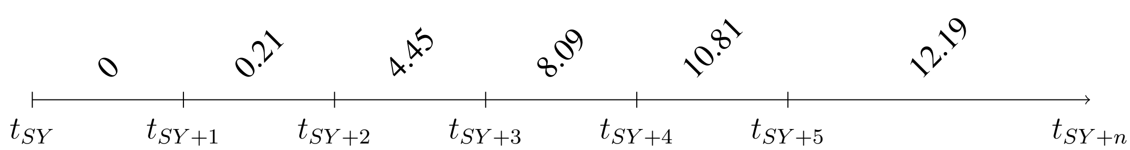
$$\gamma_t^{i,ds} = \frac{Q_t^{ds}}{Qad_t^{ds}} CI^i - CC^i \text{ [MM USD}/ha] \quad (4.31)$$

With the financial information of (ODEPA, 2010) and ODEPA's data sheets about cereals, legumes, fruits and vineyards marginal costs and income in the Maule region, it is possible to determine the financial timeline for crop substitution, in [10^3 USD/ha].

Costs Timeline [10^3 USD/ha]



Income Timeline [10^3 USD/ha]



Besides the benefits of changing the crop distribution to a more profitable kind, there is another benefit that comes from the hydropower production of all the nine hydropower plants in the area. To measure this recorder, an information set from the Energy Ministry is used. The database of the Long-Term Energy Planning (PELP) from the Energy Ministry contains the Marginal Costs for energy production projected until 2052, and additionally escalates the values for the Maule Region. The Planning database considers five different energy scenarios, going from A to E, which are detailed in Table 4.7.

Table 4.7. Energy Scenarios in PELP (2019), consisting of five main paths projected and based on different parameters that the Energy Ministry establishes (MinEnergía, 2019).

Factor	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Shutdown Intensity of Coal-Fired Plants	High	Low	High	Medium	High
Energy Demand	Low	High	Medium	Low	High
Technological Improvement on Battery Storage	High	Low	Medium	Medium	High
Enviromental Externality Costs	Current	Higher	Current	Higher	Current
Renewable Technology Costs	Low	Low	Medium	High	Low
Fossil Fuel Costs	Medium	High	Low	Low	High

The Marginal Energy Production Costs ($HPMgC_t$) are shown in Figure 4.7, in which the B Scenario from all five is considered for the effects of this study, given the correlation between RCP8.5, RCP6 and the assumption of a low intensity shutdown of coal-fired plants.

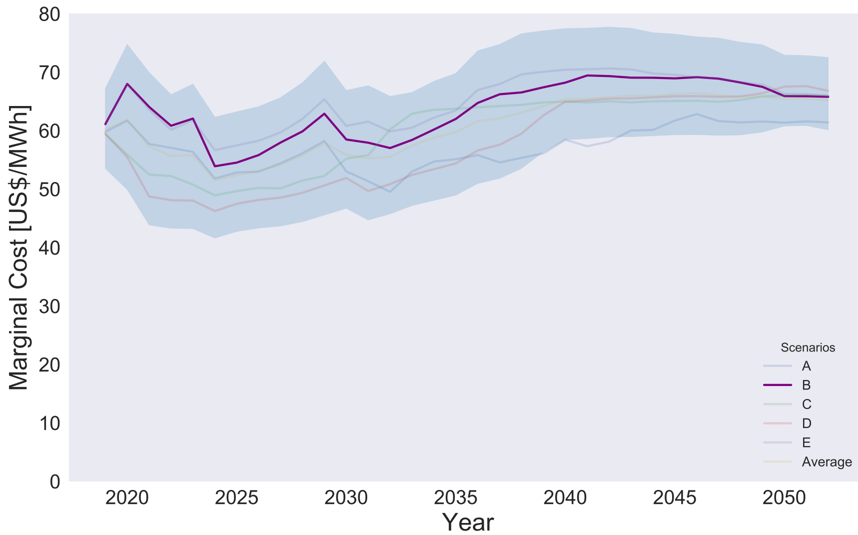


Figure 4.7. Projected marginal costs of energy production in Maule Region, for every energy scenario between 2020 and 2060. Scenario B is highlighted, as it has the highest correlation between the emission scenarios RCP8.5 and RCP6 (low shutdown intesity of coal-fired plants) (MinEnergía, 2019).

In order to calculate the total Hydropower Benefits (HPB), the Hydropower Production (HP_t) is multiplied by the Hydropower Marginal Cost ($HPMgC_t$), and then summed in all the timestep interval.

$$HPB = \sum_{t=1}^{T} (HPMgC_t \cdot HP_t^s) \quad \text{[MM USD]} \tag{4.32}$$

4.4. Multi Objective Evolutionary Algorithm

Given the proposed strategies and articulating them into a unique model, the input variables correspond to the Hedging Coefficient (α), the Hedging Storage Zone (β), the Cereal Replacement Area (K^{cer}) for each demand site, the Legume Replacement Area (K^{leg}) for each demand site, and the Start Year for both legume and cereal type crops

(SY). Table 4.8 summarizes the input configuration for the model. The combination of each variable among their respective bounds form the possible portfolios of adaptation strategies.

Table 4.8. Variable configuration for Multi-Objective Evolutionary Algorithm, each one as a different input that iterates between bounds.

Variable	Unit	Amount of variables	Lower Bounds	Upper Bounds	Details
Hedging Coefficient	[%]	1	0	80	Hedging coefficient to restrain water releases
Hedging Storage	[Hm^3]	1	170	630	Reservoir zone in which hedging is operative
Cereal Replacement	[ha]	8	0	A_0^{cer}	Amount of cereal hectares per demand site to be replaced
Legume Replacement	[ha]	8	0	A_0^{leg}	Amount of legume hectares per demand site to be replaced
Start Year	[year]	2	2025	2060	Start year of crop replacement

For the total 20 variables, the MOEA selects an initial population of P size that constitutes a combination of different portfolios, selecting randomly generated values between the given bounds. Next, it conducts a simulation for each portfolio and classifies the results in within a dominated or dominant category (depending on the objective's different directives).

There are four relevant types of objectives that respond to an Integrated Water Resource Management in this case. First, the environmental impacts of the strategies proposed, which can be simplified as the mean model downstream flow, as there are water users downstream and environmental ecosystems that benefit from an increased level; hence the output flow is an objective to maximize. Secondly, the agrarian system performance, which need to reduce deficits and failure events in the future, hence the three main criteria established by Hashimoto (Hashimoto et al., 1982) are used to evaluate the system (Reliability, Resilience and Vulnerability) as objectives; however with the significant assumption of maintaining the irrigated area in every demand site constant. Third, hydropower production over traditional non-renewable methods tends to be associated with reduced environmental pollution (Bildirici & Gökmenoğlu, 2017), so maximizing it is an objective of interest for generating a renewable and clean energy matrix for Chile, and also for the hydropower plant owners. Fourth and last, the financial feasibility of the adoption strategies may act as an incentive for the stakeholders to implement them, so it is adequate for the study to conduct a cost-benefit analysis for each considered scenario with and without strategies. Table 4.9 summarizes the objectives assigned to the MOEA model in order to generate a Pareto frontier.

A relevant issue in the stated objectives is the over-simplification of environmental considerations, as the outflow could be complemented with the water remanent from agricultural uses, ecological flow type thresholds, soil degradation, and specific flow objectives to secure water consumption downstream, among others. As this information is largely unavailable and/or complex to model, the outflow is established as the sole environmental indicator.

Table 4.9. Objectives configuration for MOEA model, each with a different directive according to the desired Pareto Frontier.

Objective		Unit	Directive	Details
Outflow	OF()	$[m^3/s]$	MAX()	Average output flow of the system
Agricultural Reliability	REL()	[%]	MAX()	Relative time in which the system didn't fail (every demand site without deficit)
Agricultural Resilience	RES()	[%]	MAX()	Time proportion in which the system recovers from a failure
Agricultural Vulnerability	VUL()	$[Hm^3]$	MIN()	Maximum deficit from summed demand sites in a timestep
Hydropower Production	HP()	[GWh]	MAX()	Yearly averaged hydroelectric production for all plants summed
Agricultural Benefits	INB()	[MM USD]	MAX()	Total benefits generated by agricultural base production and replacement
Hydropower Benefits	HPB()	[MM USD]	MAX()	Total benefits generated by hydropower production

After the Pareto frontier update, the dominant group is evolved emulating heretical modifications, and creates a new population of P size, same as the initial one, changing the variables within the given bounds. The process repeats N times until completion, and in complex models like the one in this study it is necessary to conduct thousands of iterations in order to converge to a stable Pareto Frontier. Figure 4.8 shows the process and interaction between the NSGA III algorithm and the water resources model done with PYWR.

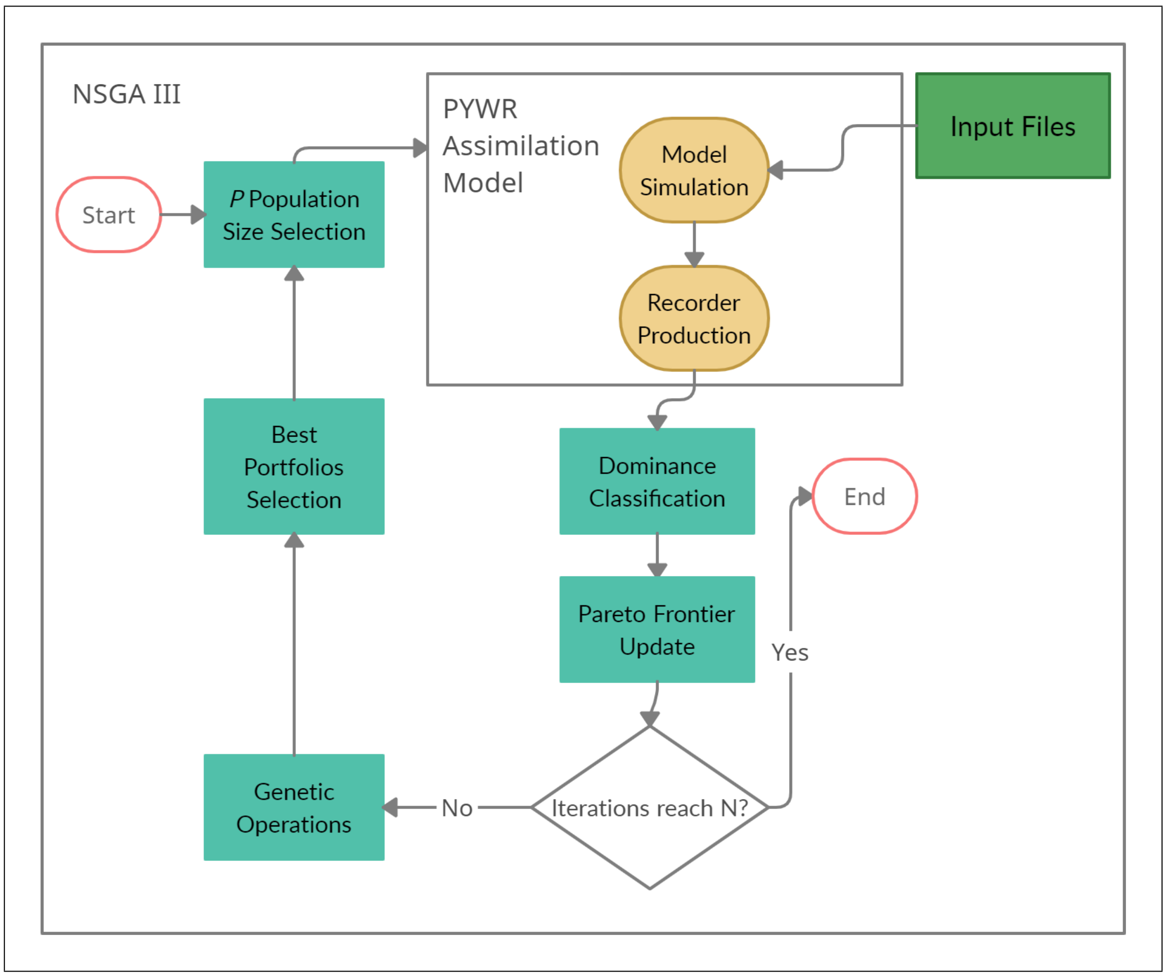


Figure 4.8. NSGA III algorithm articulation with PYWR Water Resources Model, considering the whole process of genetic operations and pareto frontier generation. Input files correspond to catchment stream flows, area-volume curves for the reservoirs and maximum hydraulic flow functions for different reservoir levels.

5. RESULTS AND DISCUSSION

The first relevant results are the climate change impacts over the area of interest without considering adaptation strategies, in order to quantify their feasibility. To establish a preliminary implementation, the water resources model is considered first with three representative scenarios and a specific portfolio for each one; to analyze the implementation of portfolios in the most pessimist of cases and compare it to the optimal one without adoption strategies. After that, the MOEA searches for the Pareto Frontier in every scenario separately, and also calculates the average aggregated value for all scenarios combined, giving a synthesis of the decided measures in general for the projected future.

5.1. Climate Change Impacts

First, it's important to establish the direct impacts of climate change when there aren't any adoption strategies considered, so the implementation of them is justified. System performance is evaluated for each scenario in Figure 5.1, which shows the result of the model for every scenario evaluating the three main performance indicators (Reliability, Resilience and Vulnerability) (Hashimoto et al., 1982) , alongside the system outflow as an indicator of environmental interest. Results indicate that in 13 out of 14 scenarios, the system will fail in certain intervals, as reliability fluctuates between 0.75 and 1, and with resilience having a bigger deviation in between 0.3 and 0.8; meaning that failures will tend to last a sustained amount of months.

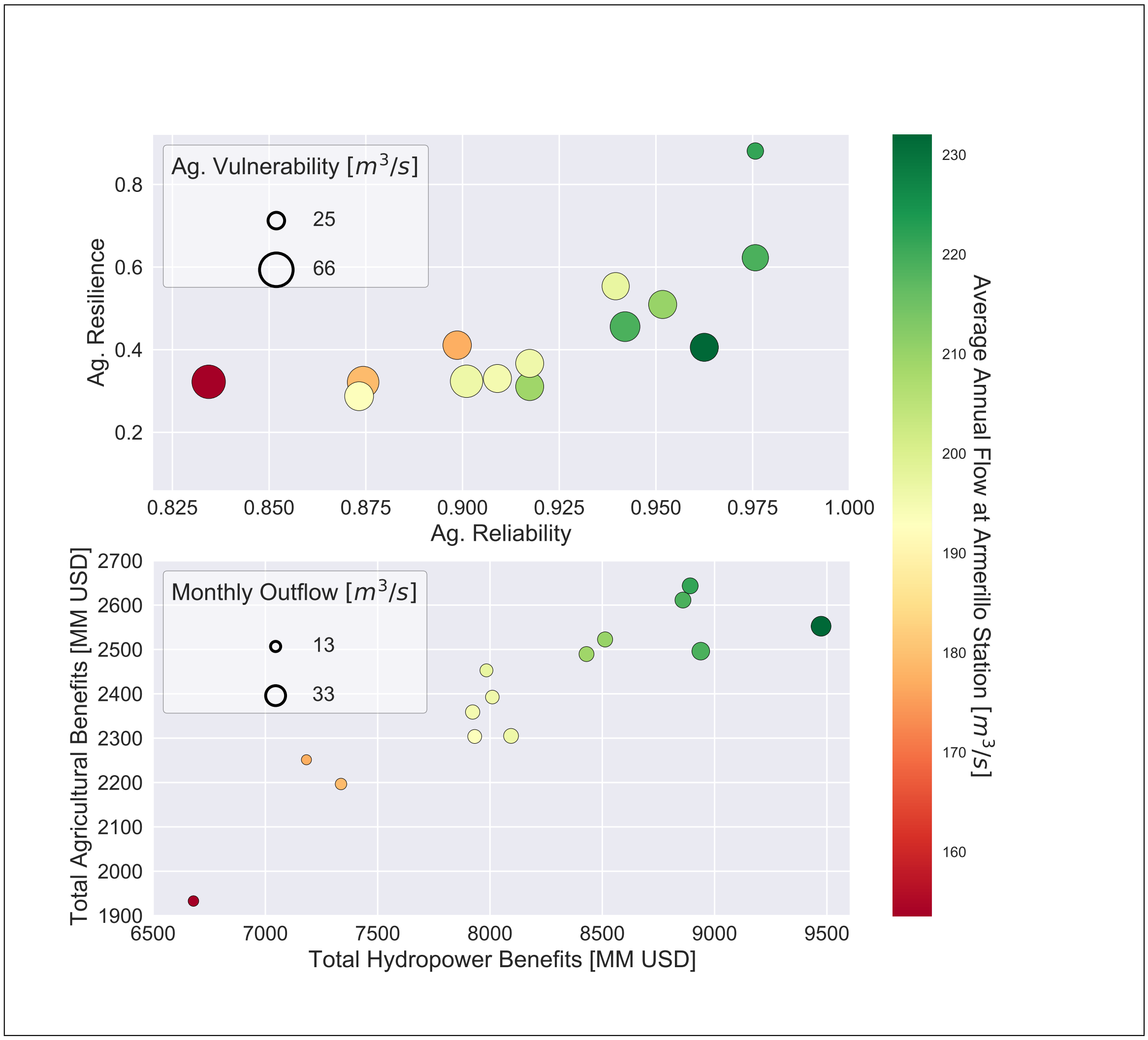


Figure 5.1. Averaged performance indicators for each of the 14 generated climate change scenarios, between the years 2020 and 2060. The colours show the different scenarios, categorized by the Armerillo Station annual flow.

Consequently, climate change adaptation strategies are imperative to consider, as the WEF nexus system in Maule Basin presents a projected failure into the future if the allocation and reservoir operating policies are kept without modifications.

5.2. Performance of Adaptation Strategies

The water resources model done with PYWR can be used to quantify the impact of adaptation strategies over performance before conducting a multi-objective analysis, with predetermined adoption levels. In order to generate the temporal visualization of adaptation effects, three scenarios are selected based on the projected flows in Armerillo Station; the one with the highest mean flow, the one with the closer value to the average, and the one with the lowest. Figure 5.2 shows the scenarios selected based on their flow levels, and the comparison to the historical data.

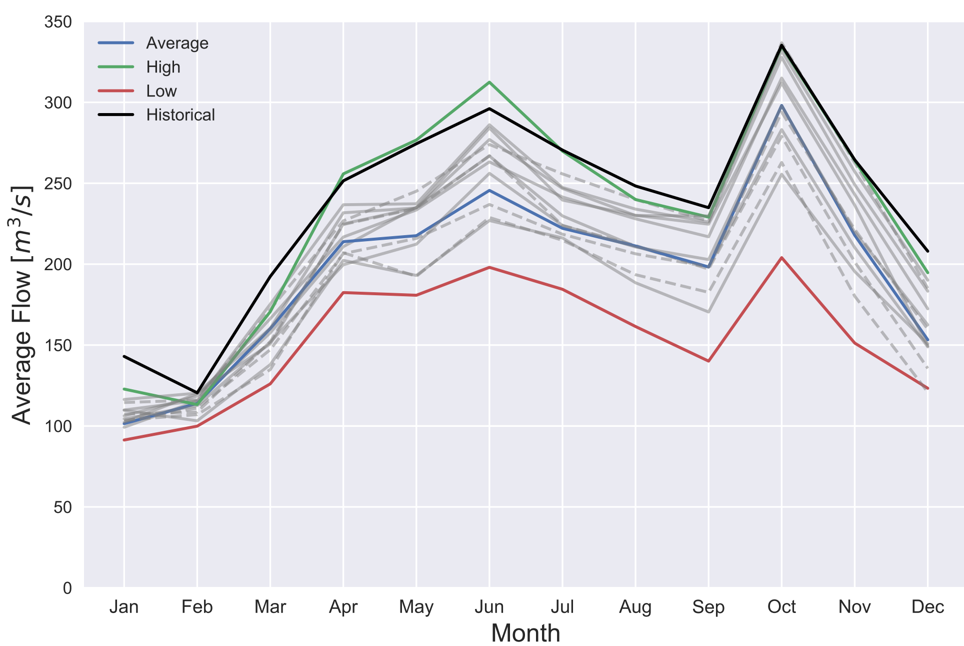


Figure 5.2. Three representative scenarios chosen from the projected impact over Armerillo station's monthly average flow, among the 14 climate change scenarios generated from the seven different climate change models over both RCP8.5 and RCP6 scenarios. In green, the highest flow scenario selected, in blue, the nearest scenario to the average flow, in red, the lowest flow scenario selected.

Each scenario is articulated with a different portfolio, depending on the adaptation level that can be implemented to mitigate the climate change impacts. In the case of the high flow scenario, the only adaptation strategy implemented consists on generating a dynamic water allocation that depends on the irrigation efficiency per demand site, but without replacing any crop area or changing the reservoir operation rules. For the average flow scenario, half of the reservoir's buffer zone is converted to a hedging zone, with a coefficient of release reduced in a 20% ($\alpha = 0.64$), and considering half of crop replacement in a 20-year period, with 5 years of transition. Third, for the low flow scenario a total crop replacement is considered, in which every cereal and legume is replaced with fruits and vineyards, starting in a 5-year period with the corresponding 5-year transition, alongside a complete conversion from buffer zone to hedging zone with a buffer coefficient reducing a half of it's value ($\alpha = 0.4$). Figure 5.3 exposes the different objectives for the three scenarios, with the time-lapse until 2060.

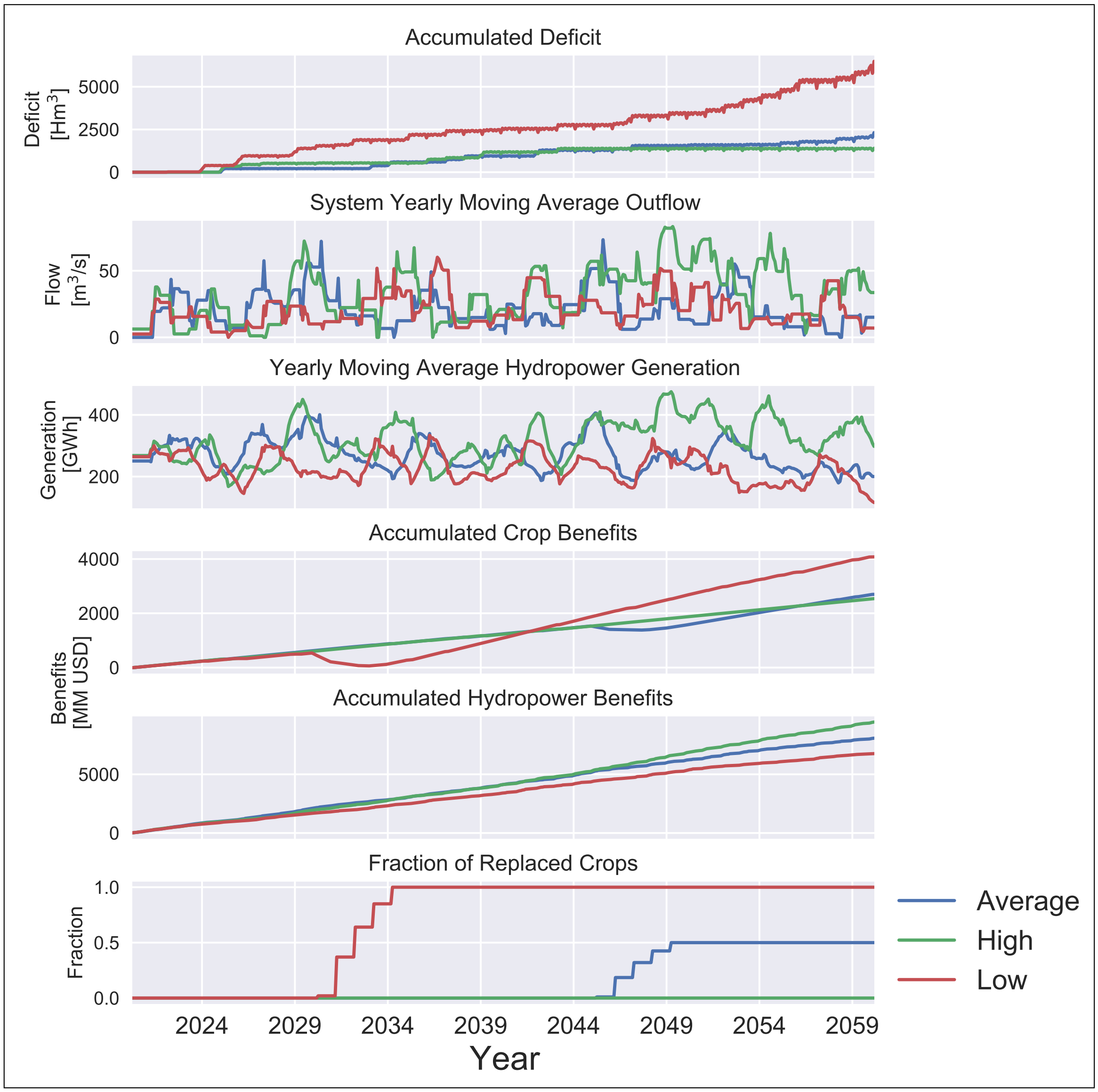


Figure 5.3. Performance results, for the three respective representative climate change scenarios: the highest registered flow at Armerillo Station in green (with no adaptation strategies), the closer-to-average flow in blue (with half of possible adaptation strategies implemented), and the lowest in red (with the totality of adaptation strategies implemented).

In the low flow scenario, the marginal benefits of crop replacement is higher, given that the replacement was done in an absolute proportion. Given that the base scenario without adoption strategies doesn't change the crop distribution (at least by assumption of this study), the high flow scenario doesn't contain marginal benefits linked to crop production; and shows that even with a lesser level of deficit and higher hydropower production, there is still a potential benefit that is lost by denying the technical improvement of the irrigated area, which is proportionally higher in the better scenarios given the lesser amount of deficits (benefits are multiplied by the deficit factor). Each scenario, going from worst to better, has a level of water deficit given the generalized precipitation reduction. This accumulated deficit fluctuates between 2,100 to 8,800 Hm^3, and if each scenario is considered without any adaptations, goes even in a higher range between 4,300 and 13,520 Hm^3 (not shown in Figure 5.3); so it is fundamental to consider adaptation strategies in order to increase the system's performance.

Hydropower production is an intercalated phenomenon, notably increasing in the first five years of crop replacement for both the average and low flow scenario, given that the demand in this first five years reach the minimum values and therefore allows a higher amount of flow to divert to all the non-irrigation channels.

5.3. Multi Objective Assessment of Adaptation Strategies

Once the water resources model is calibrated with the respective 14 generated scenarios, and verifying the convergence of values over several iteration quantities, a hundred thousand iterations of the algorithm are set for each scenario separately; in order to obtain the Pareto Frontier associated to each one. Each scenario produces 463 different optimal portfolios, each one with a different combination of measured objectives and selected variables. In order to quantify the adaptation strategies impact over the different performance indicators, Figure 5.4 shows the performance improvement of each scenario for all the algorithm's objectives, considering the averaged portfolio values for the case after adaptation strategies.

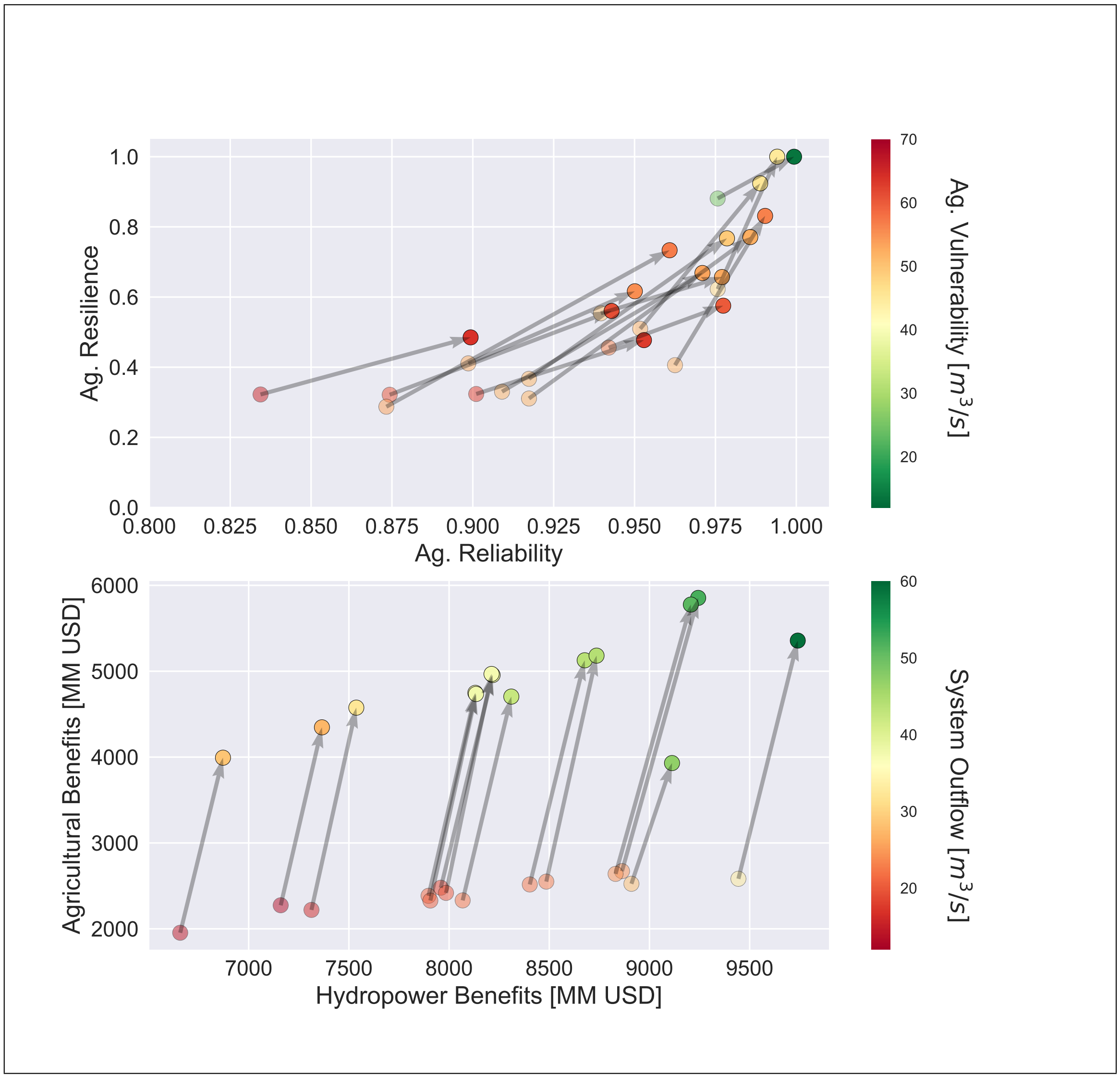


Figure 5.4. Evolution of performance indicators after implementing adaptation strategies for each one of the 14 generated climate change scenarios. Values per scenario are obtained from all the portfolios average.

On a general level, each scenario improves on almost every objective after the adaptation strategies; rectifying water resources management as an effective approach to climate change impacts mitigation. Out of 84 combinations of strategy-objective, 79 indicate an increase in performance after considering both the Resolution 105 and the ENEL-MOP Agreement modifications; and most notably, the 5 performance reductions occur only to the Vulnerability objective; establishing a trade-off in reducing Failure Event durations at expense of increasing the maximum deficit levels. This has direct causality from the Hedging Strategy, given that it has the side effect of increasing short-term deficits in exchange for reducing long-term ones.

Which variables are selected and with what frequency along scenarios is a key component to understanding their effects over the system, so Figure 5.5 shows the frequency of every variable selected in three representative portfolios: the highest, lowest and average flow scenarios from Figure 5.2.

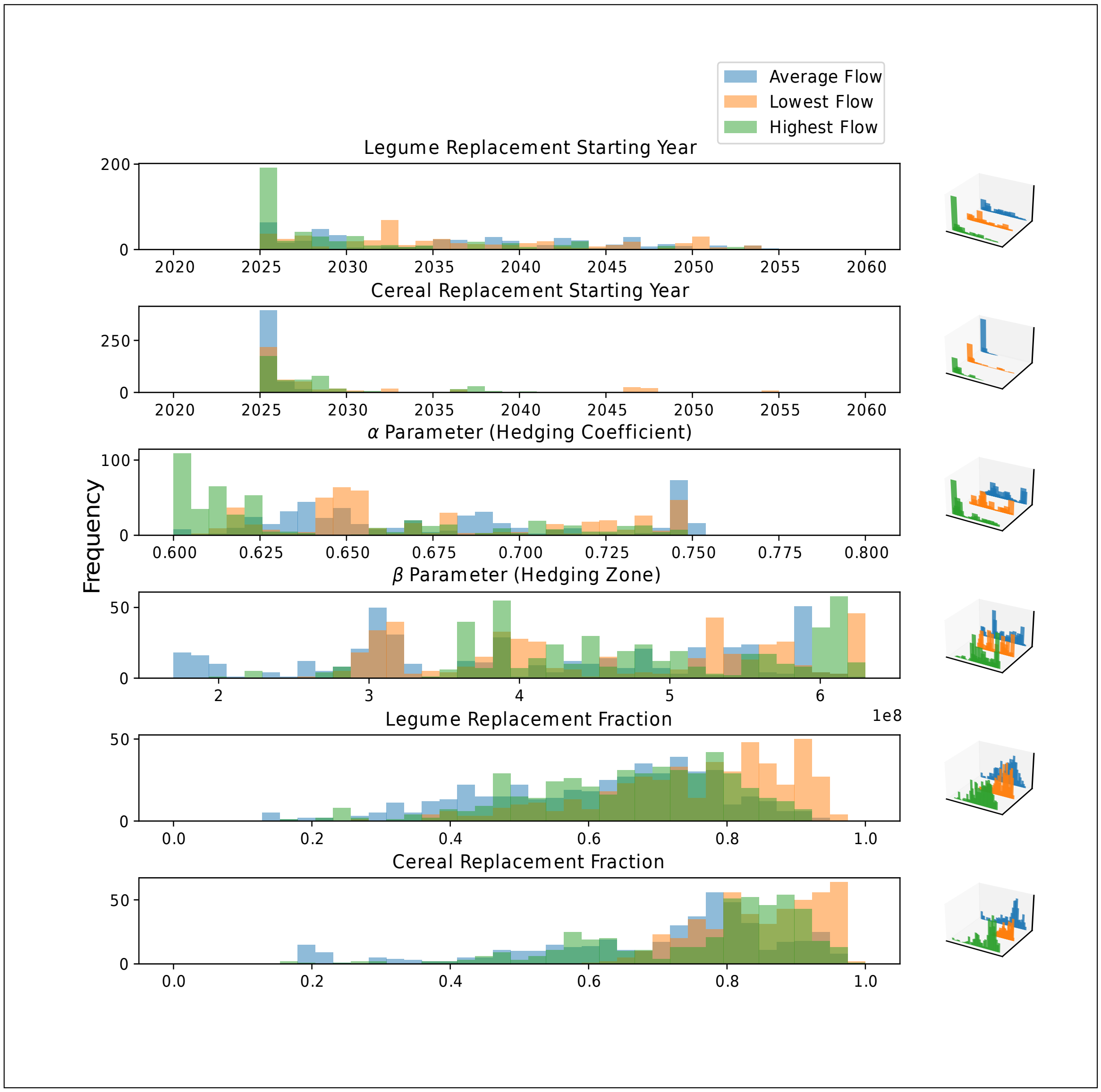


Figure 5.5. Frequency histogram of input variables for the three representative climate change scenarios selected: the one with the lowest average flow in Armerillo Station in orange, the one closer-to-average in blue and the highest in green. The accumulated frequency sums 463 for each scenario; which is the amount of portfolios generated.

The Lowest Flow scenario concentrates most of the crop replacement near to the total fraction of it; given the increased shortage and water scarcity it is logical to assume that in favor of water efficiency almost every crop tends to be replaced and within a time period of no more than 10 years for legumes, and almost exclusively on the first available year (2025) for cereals. This scenario also considers quite a reduction in the hedging coefficient, from 0.8 (current reservoir operation) to 0.65 in most portfolios; alongside an almost even distribution from the hedging zone's perspective. The Average Flow Scenario, while also with a tendency to replace the majority of the crops as soon as possible, doesn't concentrate as much in legumes as it focuses on cereal; with a more evenly distributed α parameter selection. The Highest Flow scenario, given the increased level of inflow, tends to select the lower available hedging coefficient, with higher hedging zone values; with a more evenly (though still predominantly high) distributed crop replacement.

Hedging strategies imply a trade-off between short-term shortages and long-term prolonged deficits, restraining reservoir releases for periods of increased deficit. As Figure 5.6 shows, when having higher flows the operation rules tend to restrain in higher proportion the releases, hence selecting a lower coefficient and bigger hedging zone. The higher resilience (and hence lower failure duration) comes in this scenario, however at higher vulnerability levels when compared to the average scenario; which concentrates a higher coefficient selection and a lower hedging zones and contain less variability in the registered flow values, while the Higher Flow registers more extreme events that result in higher vulnerability levels.

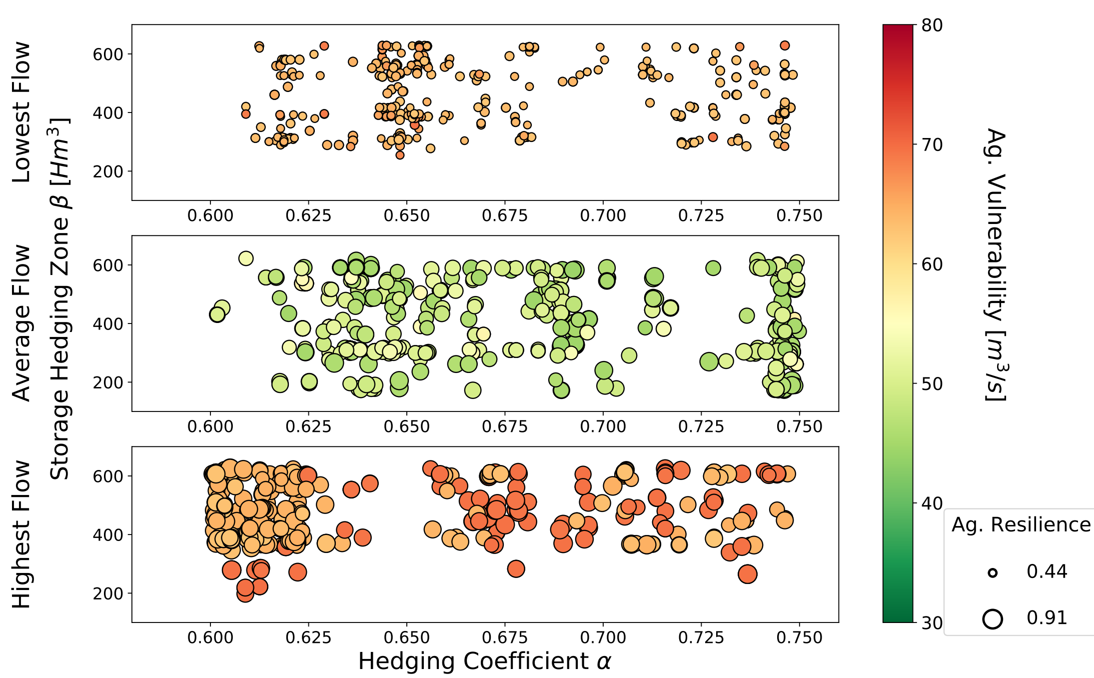


Figure 5.6. Portfolio distribution of hedging variables (α and β) over two agricultural system performance indicators (resilience and vulnerability), for the three representative scenarios considered: the one with the lowest average flow in Armerillo Station, the one closer-to-average and the highest.

The portfolio distribution can be seen in Figure 5.7 for the three representative scenarios, where the objectives have been separated in two groups including the agricultural system performance ones, and the financial, environmental and energetic ones. There are objectives with direct correlation, such as the yearly hydropower generation and the net benefits, given that the former are included in the Total Benefit Equation 4.24. Lesser outflow levels are also indicators of less input flow for hydropower plants (prioritized for crop consumption), another correlation factor.

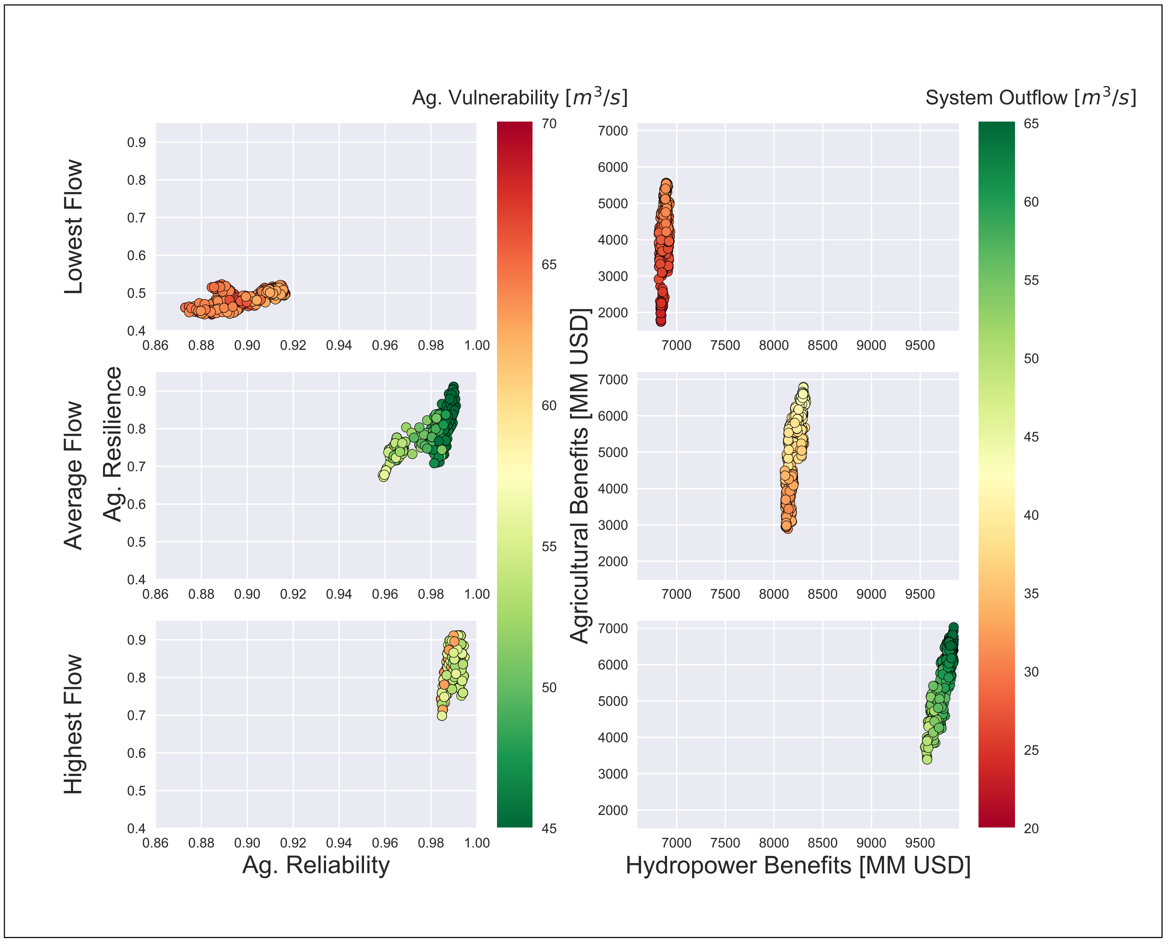


Figure 5.7. Multi-Objective Evolutionary Algorithm generated portfolios distribution along system performance indicators, for the three representative scenarios considered: the one with the lowest average flow in Armerillo Station, the one closer-to-average and the highest.

In terms of total benefits, there is a stable ratio between scenarios that indicate a balanced growth, where almost two thirds of the total benefits come from Hydropower Production, shown in Figure 5.8. However, it is important to consider that the benefit for every hectare of cereal, legume, fruit and vineyard wasn't considered in net terms, but rather in marginal ones, so in reality the benefits from agriculture are higher than the ones estimated in this research.

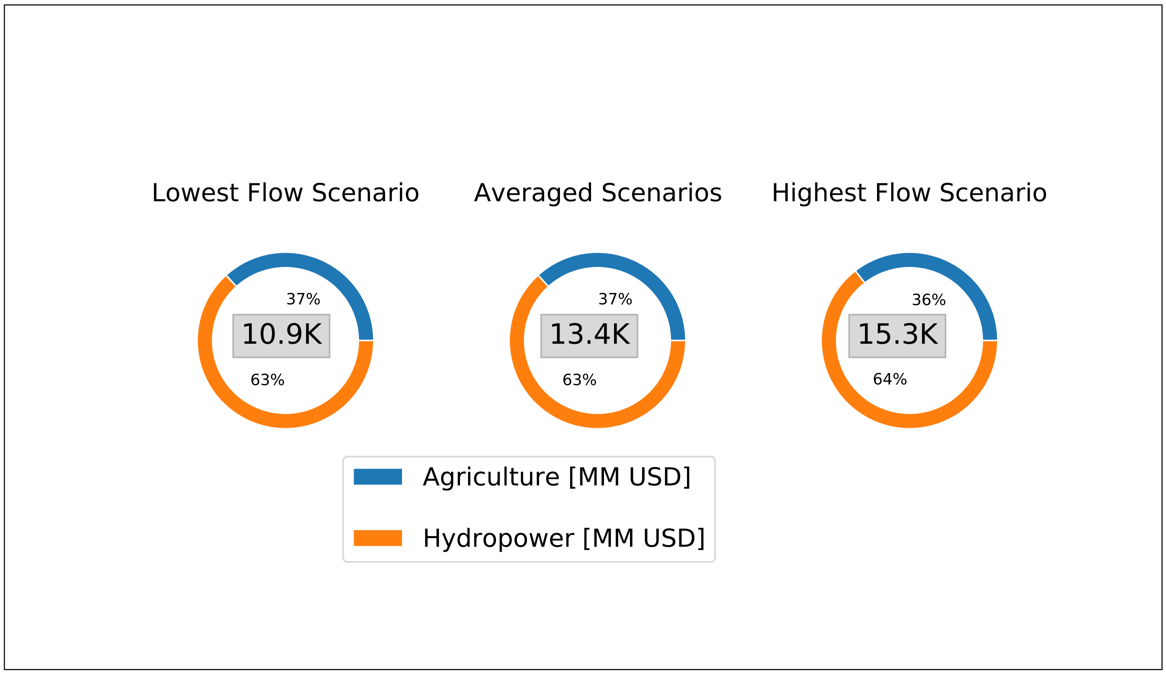


Figure 5.8. Distribution of the total benefit according to activity, agriculture being the summed base and replacement benefits while hydropower the total hydropower production benefits, for the three representative scenarios considered: the one with the lowest average flow in Armerillo Station, the one with the highest and the 14 averaged scenarios

5.4. Decision Making Process

The methodology and considered algorithms exhibit not a single solution, but rather different portfolios of possible adaptation strategies to be considered, depending on the stakeholder's many interests and/or purposes. There is a balance to be kept, in this case manifested historically in trade-offs between productive activities and environmental welfare (Suen & Eheart, 2006; Tinoco, Willems, Wyseure, & Cisneros, 2016; L. Yu et al., 2021), while increased system performance also induces a higher financial benefit. In order to represent the different competing objectives, a Parallel Coordinates graph is adequate for visualization of the different trade-offs between objectives. Figure 5.9 shows Lowest Scenario Parallel Coordinates graph, with the same objectives measured in the case without adoption strategies.

The main trade-off occur between the agricultural system performance and the outflow, as increased irrigation decreases the outflow levels; while the hydropower production and reliability hold a direct proportionality; as opposed to the inverse one between the resilience level and vulnerability. As seen, the situation without adaptation strategies is considerably less desirable, only performing better that some portfolios in the vulnerability objective but having much lower performance levels on the rest. It is then backed up to say that the adaptation strategies considered incur in an effective water resource management, even in the most pessimistic of scenarios (such as RCP8.5).

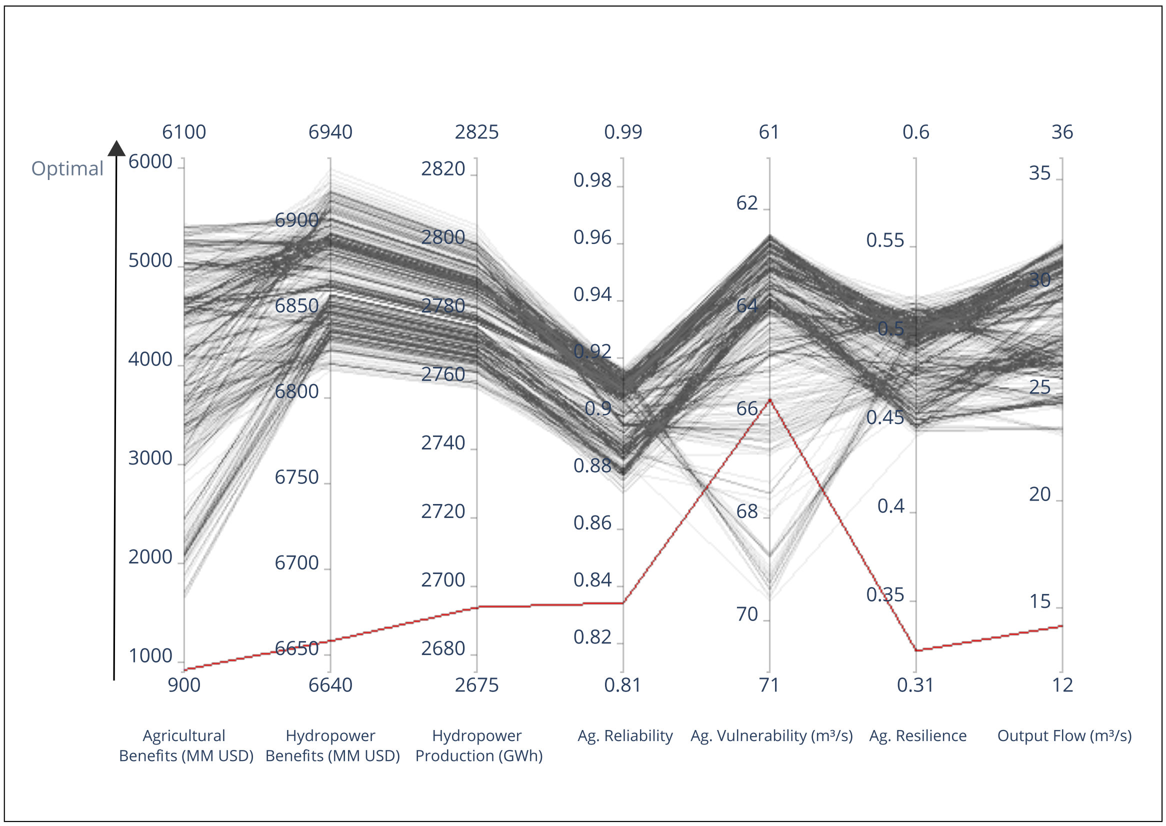


Figure 5.9. Parallel axis graph of the different performance indicators for the scenario with the lowest average flow in Armerillo Station. Each path represents a different portfolio of the pareto frontier, and in red, the no-adaptation strategies case. The higher the line, the more optimal the value for the objective.

One of the principal obstacles to the proposed analysis is the uncertainty of the future and to which proposed scenario will reality adjust, as each portfolio generated considers a deterministic approach to a known flow. In order to manifest the averaged results for this deterministic futures, and illustrate the averaged trade-offs of all uncertain futures, Figure 5.10 illustrates the Parallel Coordinates for both the higher flow and lower flow scenarios, including as an aggregated the average portfolio values for all 14 scenarios. Stakeholders can limit portfolio boundaries by establishing desired minimum requirements, such as ecological flows, hydropower generation of the area, or maximum amount of months allowed with water shortage in the agricultural system (calculable with resilience).

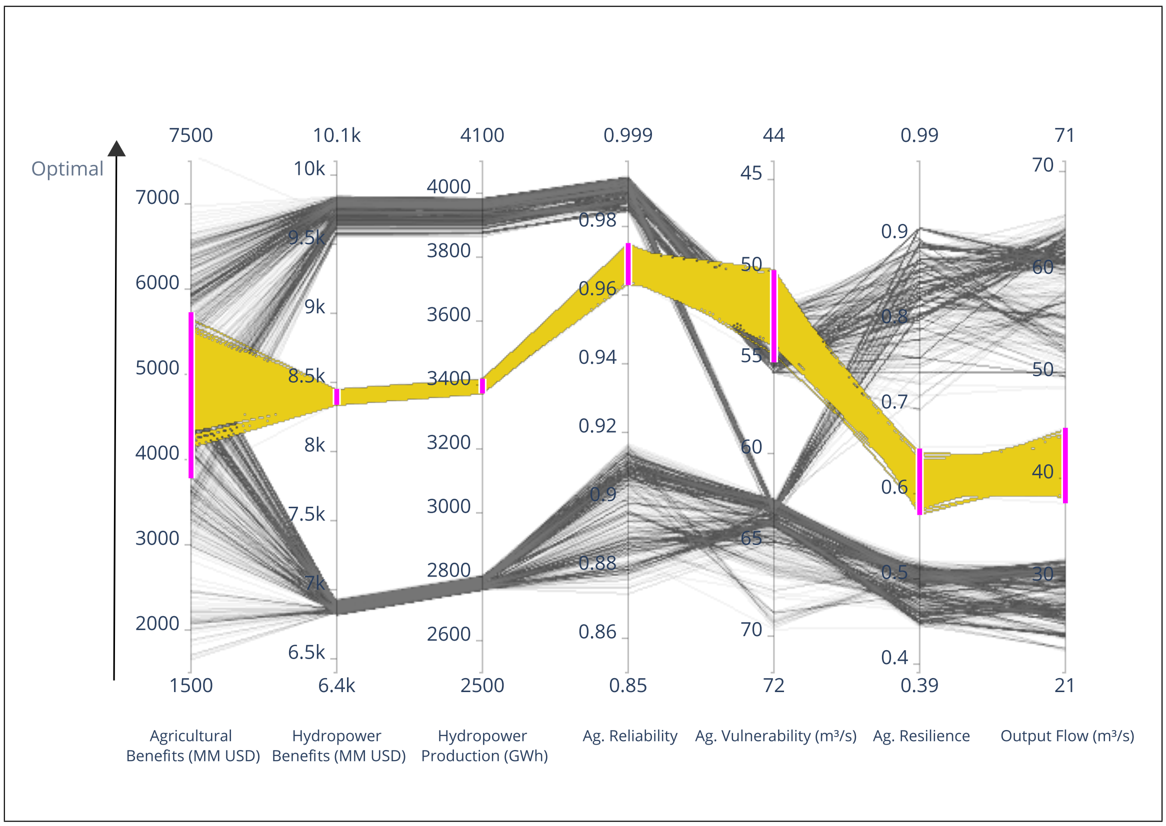


Figure 5.10. Parallel axis graph of the different performance indicators for the scenario with the lowest average flow in Armerillo Station (lower section), the highest average flow (upper section), and the 14 averaged scenarios (yellow paths). The higher the line, the more optimal the value for the objective. The purple domains indicate the upper and lower limits of the 14 averaged scenarios.

Each scenario is also assigned with a weight, w^s (preliminary equal for each scenario), to establish the probability of occurrence or relevance in decision-making, in order to displace the average portfolios depending on the input given.

6. CONCLUSIONS

Climate change will have a future impact that implies a high level of uncertainty, where no projection can be supported with total security. Faced with this challenge, it is necessary to consider different possible scenarios and analyze the potential impact that a decrease in the availability of water resources may generate. As a first conclusion, and considering two of the climate scenarios with the highest levels of greenhouse gas emissions, it is valid to state that the upper Maule basin system in Chile's main productive activities related to water resources are at risk, where there may be deficits in the water consumption need of the crops up to 170 Hm^3 per month, a considerable drop in hydroelectric production (up to 30%) and a much lower remaining flow of the system (40% of historical values); considering a timelapse until 2060. The lowering of this indicators affects negatively on a large scale to several agents in Chile, due to the high level of relevance that these activities contribute to the national total.

In the context of a reduced availability in water resources, it is essential to analyze the possibility of improvements for efficient use of water, especially in basins with the Water-Energy-Food nexus, where water allocation is generally regulated by reservoirs and passes through productive processes that have associated efficiencies. As a second conclusion, in the upper Maule basin there is a potential for unexplored management strategies, such as the massive technification of irrigation systems to increase efficiency, and reservoir release policies that consider extended periods of future water scarcity. The irrigation efficiency levels are around 45%, and the reservoir buffer zone allows up to 80% of its discharge, which can be altered to analyze the possibility of reducing the future deficit based on an operation that further restricts the level of releases.

The vast amount of repositories, optimization algorithms and computational modeling software allows an accurate representation of a hydrological system or basin, with its regulatory, physical and productive aspects. Being able to articulate multi-objective tools to these systems provides a third conclusion, which is the possibility of generating a win-win scenario for all productive agents in a basin with a Water-Energy-Food nexus if an integrated management of the water resource is carried out, where the objectives of all parties can be placed with a respective directive. Linking the increase in irrigation efficiency with a decrease in allocated water rights and static amount of irrigated area, for example, avoids the traditional Jevons Paradox, and allows generating economic benefits for both irrigators and hydropower producers. As a consequence, almost every portfolio generated for each scenario doesn't imply a trade-off between hydropower and agricultural benefits, on the contrary; they are generated as directly proportional outputs.

Each proposed strategy involves supply-side or demand-side water management, with expected effects that manifest themselves in different ways on the objectives. Since these objectives may compete with each other, there is generally always a level of trade-off associated with these multiple-use systems such as Water-Energy-Food basins. As a fourth conclusion, hedging measures generate a trade-off between the levels of agricultural resilience and vulnerability, given that it is linked to prioritizing water storage focused on periods of considerably higher deficits. On the other hand, irrigation technification is practically immediate and almost total, considering that it does not generate negative trade-offs in its implementation. The main trade-off, as usually occurs in basin systems of the Water-Energy-Food type, is between the remaining flow of the system (environmental measure) and hydroelectric and food production (productive measures), where on average each cubic meter per second of output for 40 years (2020-2060) is traded at a rate of 277 million dollars.

However, this study has a couple of limitations, such as considering a reduced number of climate change scenarios, working with future scenarios in a deterministic and not stochastic approach, a large number of agricultural assumptions (constant area, linear production and profit functions, and projections based on historical data), not considering the interaction of surface-groundwater flow, not considering groundwater rights, limiting the change in crop pattern to the availability of information when in fact it could be a technification of crops as such instead of substitution, performing a linear hedging, considering the environmental objectives as a simple outflow, among others. Each one of these limitations is presented as a challenge to develop a model with a higher degree of sophistication, and to represent in an even more complex way what Integrated Water Resources Management is.

Water-Energy-Food Nexus basins are of particular interest for a multi-objective approach, as each agent of one of the three parties can argue the relevance and prevalence of their own interests, however, real life decisions are far more complex than ”maximizing benefits”, and certainly not as one-sided. In the context of water and the productive uses it has, an Integrated Water Resources Management approach is imperative to face the uncertainties and negative impacts of the imminent climate change; and generate collaborative solutions that consider the regulators, economic and normative agents, the system limitations and the environmental welfare.

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APPENDIX

A. AGRICULTURAL INFORMATION UPDATE

Before proposing an adaptation strategy that deals with irrigation technification and crop renewal, it is necessary to visit the irrigation efficiency concept, and also estimate the actual crop distribution in the zone of interest, the irrigation methods used, and the historical growth in order to determine the implications of this technological update.

Crop irrigation is a complex subject, as it has many techniques, methods and variability within. Nevertheless, whenever crop irrigation area has a considerable magnitude (hectare order), its certain that not every flow unit of allocated water will be effectively translated as an evapotranspiration unit. One key concept to understand this difference, established by the National Irrigation Commission, is the Irrigation Efficiency (ϵ); defined as the fraction of allocated water that evapotranspires. This efficiency has four main components, established in Equation A.1 (CNR, 2014).

$$\epsilon = \epsilon_{ap} \cdot \epsilon_s \cdot \epsilon_{un} \cdot \epsilon_{con} \tag{A.1}$$

With each term referring to:

- ϵ : Irrigation Efficiency
- ϵ_{ap} : Application Efficiency
- ϵ_s : Storage Efficiency
- ϵ_{un} : Uniformity Efficiency
- ϵ_{con} : Conductive Efficiency

The four types of efficiency are linked to different properties of the particular crop and irrigation technique, where application refers to the fraction of water applied in crop terrain that is retained in the radical zone, storage to the fraction of water applied in comparison to the field capacity, uniformity to the deviation of the soil profile water content and conductive to the fraction of allocated water by irrigation channels, or other conductive means, that reaches the crop (INIA, 2009).

The technification of irrigation methods is associated with different levels of application efficiency, given the different water-delivery mechanisms and how localized they can be. Table A.1 shows the different average application efficiencies that common irrigation methods contain (Brouwer, Prins, Kay, & Heibloem, 1988).

Table A.1. Application efficiency by irrigation method (Brouwer et al., 1988)

Irrigation Method	**Application Efficiency (%)**
Basin	30
Furrow	45
Californian Gravitational Methods	65
Aspersion	75
Microjet	85
Microaspersion	85
Drip	90

Another relevant term in order to analyze an irrigation technification is the Net Hydric Need (NHN) that each crop has, obtained by discounting external water inputs to the gross hydric need, and in Chile usually calculated as Equation A.2 shows (TYPSA, 2015).

$$N.H.N = G.H.N. - P_e \quad [m^3/ha/year] \tag{A.2}$$

With:

- $N.H.N.$: Net Hydric Need $[m^3/ha/year]$
- $G.H.N.$: Gross Hydric Need $[m^3/ha/year]$
- P_e : Effective Precipitacion $[m^3/ha/year]$

A reservoir pre-factibility study done for the location of Longaví, approximately 50 kilometers South-West of the Colbún Reservoir, establishes NHN for different crop types, in consistency with the hydro geological and climatic regime of the region. Table A.2 shows the NHN values for each crop type (TYPSA, 2015).

Table A.2. Net Hydric Need by crop type, scaled to Maule Region. Calculated as the average NHN of all the crop types within the categories found in the study region (TYPSA, 2015).

Crop Category	**Annual NHN [m^3/ha/year]**
Cereal	9,395
Legumes and Tubers	9,592
Fruit	8,352
Vineyards	6,396
Forest Plantations	8,313
Vegetables	6,757
Seedbeds	9,782
Industrial Crops	8,048
Forages	5,220

The National Statistics Institute (INE) has conducted seven Agricultural Censuses so far, referred to as the most important source of agricultural information available nationwide; with the latter being done in 2007. Considering each demand site with a similar distribution to the whole administrative commune of location, useful information can be extracted to estimate future crop distribution.

In terms of irrigation methods, Figure A.1 illustrates the demand site's average irrigation technology distribution by total area, while Figure A.2 breaks it down by demand site.

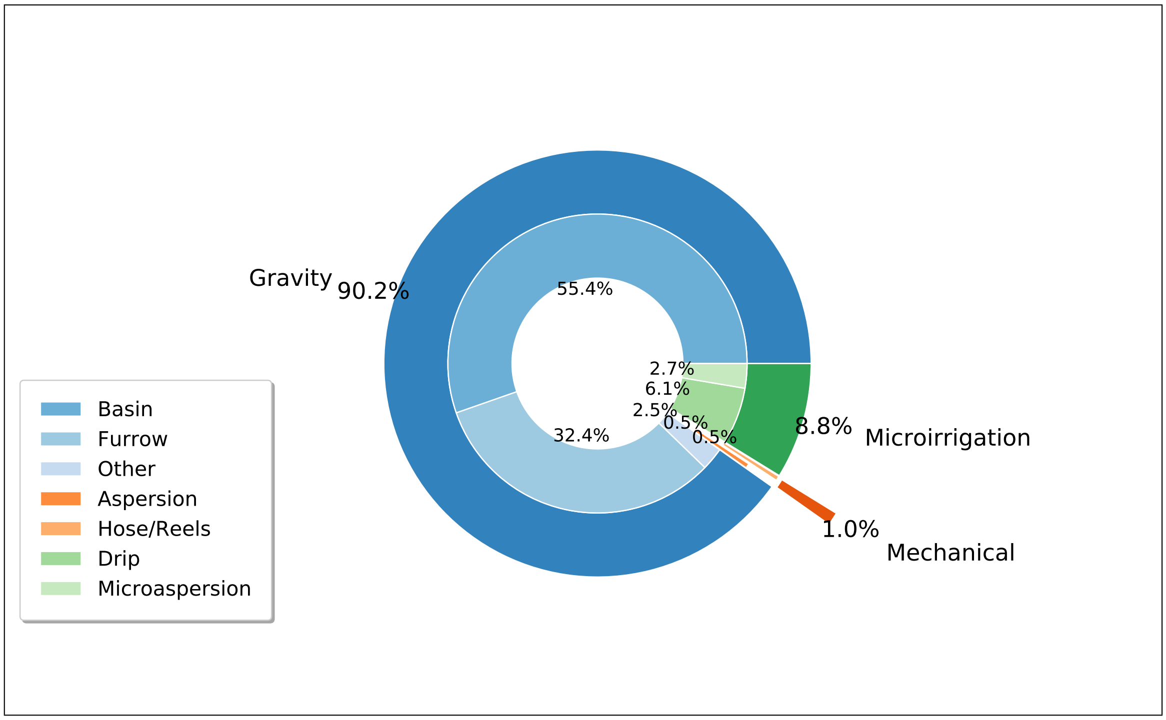

Figure A.1. Distribution of irrigation technologies in the study area, as a weighted average of every demand site, with two main categories. The first one being the main division according to technology; with gravity, mechanical and microirrigation technology types, and the second one separating by specific irrigation methods (INE, 2007).

The fact that more than 90% of irrigation methods used in the study zone are gravitational implies that the application efficiency tends to be relatively low, as this type of methods go in between 30% and 65%, in contrast to the technicized ones that go between 75% and 90%. The overall irrigation costs usually increase with technification, so the more efficient methods are often used in the most profitable crops, like fruits and vegetables (Savva, Frenken, et al., 2002), moreover as in the study zone there are no type of maintenance cost for water rights; so there is no incentive to increase the water efficiency in order to irrigate the same area with less water.

Figure A.2. Distribution of irrigation technologies by demand site in the study area. Each demand site has two categories, the first one being the main division according to technology; with gravity, mechanical and microirrigation technology types, and the second one separating by specific irrigation methods (INE, 2007).

In terms of crop distribution, Figure A.3 illustrates the demand site's average crop distribution by total area, while Figure A.4 breaks it down by demand site. These areas only consider irrigated crops, excluding rainfed ones.

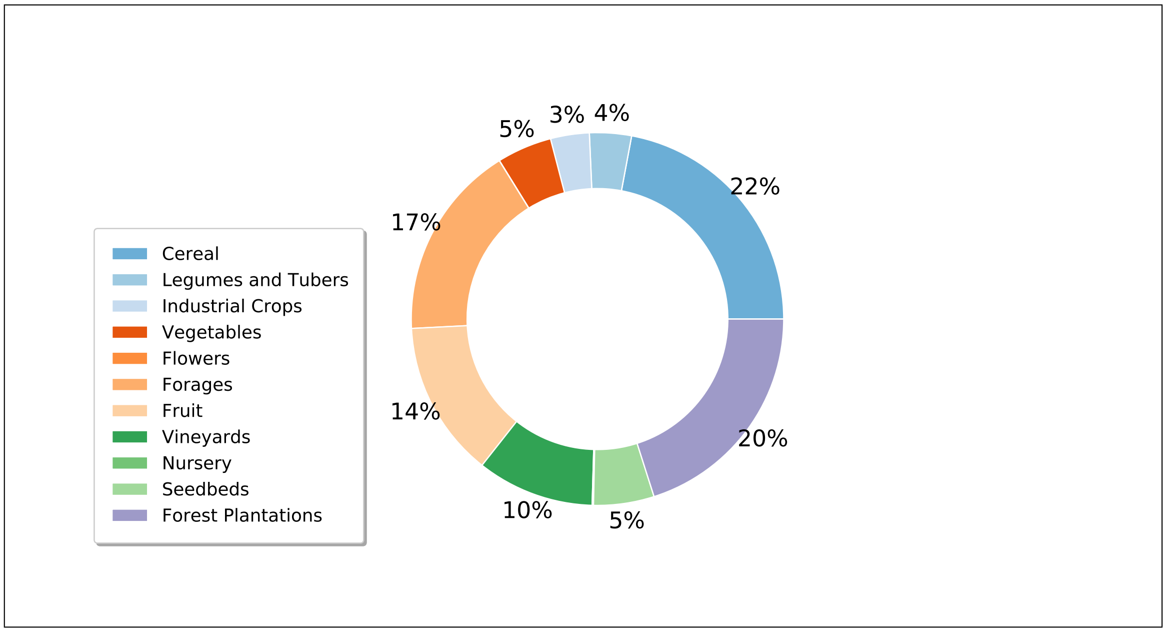

Figure A.3. Distribution of irrigated crop types in the study area, as a weighted average of every demand site, separated in the 11 main types of crops established by the Agriculture Minister (INE, 2007).

Each demand site has a considerable amount of variability between and within, however as an average trend forest plantations, cereals, forages and fruits cover more than 70% of the irrigated areas.

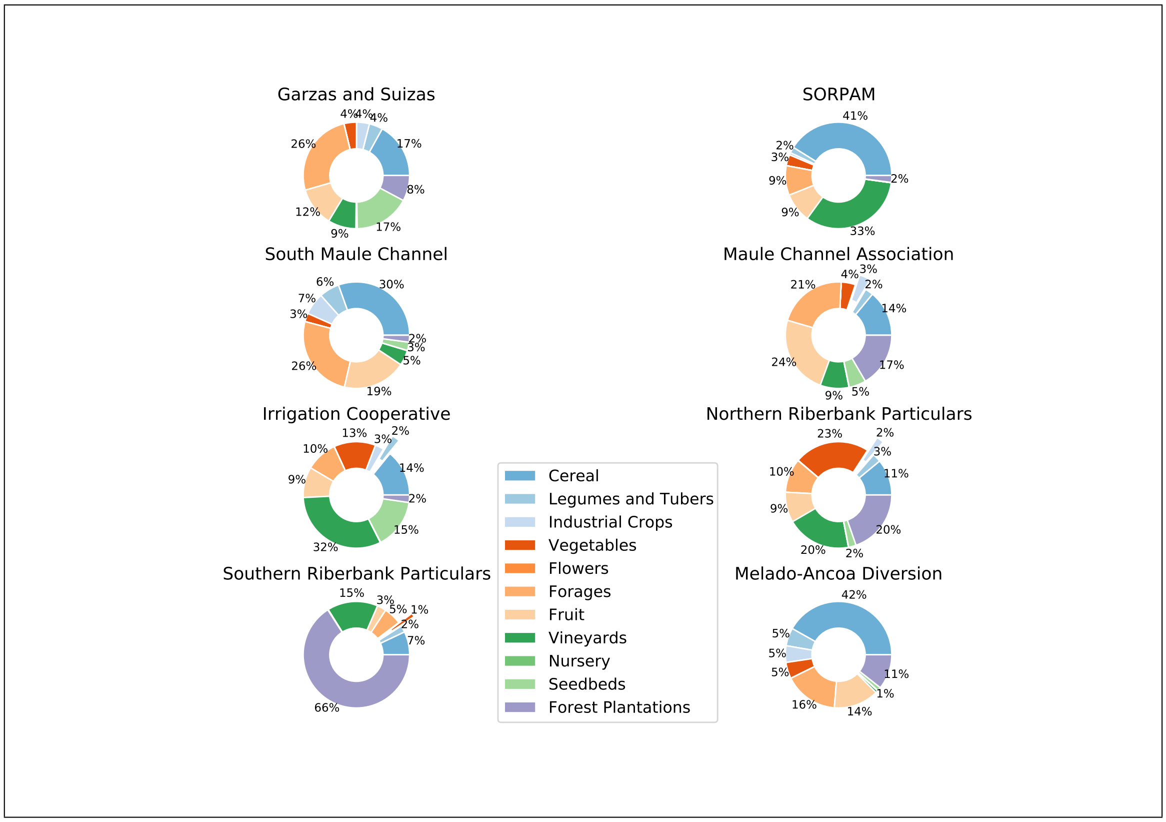

Figure A.4. Distribution of irrigated crop types in the study area, per demand site, separated in the 11 main types of crops established by the Agriculture Minister (INE, 2007).

This availability of information allows the estimation of different relevant parameters. First, the average application efficiency per demand site (ϵ_{ap}^{ds}) is calculated with Equation A.3.

$$\epsilon_{ap}^{ds} = \sum_{m=1}^{6} (f_m^{ds} \cdot \epsilon_m) \tag{A.3}$$

With:

- ϵ_{ap}^{ds} : Application Efficiency for demand site ds
- f_m^{ds} : Fraction of irrigation method m in demand site ds

- ϵ_m : Application Efficiency for method m, based on Table A.1

Another relevant term is the Net Hydric Need for each demand site (NHN^{ds}), calculated with Equation A.4.

$$NHN^{ds} = \sum_{c=1}^{9}(f_c^{ds} \cdot NHN_c) \tag{A.4}$$

With:

- NHN^{ds} : Net Hydric Need for demand site ds [$m^3/ha/year$]
- f_c^{ds} : Fraction of crop type c in demand site ds
- NHN_c : Net Hydric Need for crop type c, based on Table A.2 [$m^3/ha/year$]

Given the relationship between the evapostranspired and allocated water, it is possible to estimate each site's irrigation efficiency with Equation A.5.

$$\epsilon_t^{ds} = \frac{NHN^{ds}}{Qal_t^{ds}} \tag{A.5}$$

With:

- ϵ_t^{ds} : Irrigation Efficiency of demand site ds in timestep t
- NHN^{ds} : Net Hydric Need of demand site ds [$m^3/month$]
- Qal_t^{ds} : Water allocated to Demand Site ds in timestep t [$m^3/month$], calculated in Equation 4.5

Besides the Agricultural Census, a more focused source of information are the different cadastres for each crop type, with a regional composition, conducted by the Office of Agrarian Studies and Policies (ODEPA). Although not as complete as the census, particular sets of information can be obtained to analyze the evolution in crop type areas, with more frequent editions. All the available crop type evolution is shown in Figure A.5, showing downward trends in cereals and legumes/tubers, and upward trends in fruit and vineyards. This is consistent with the hectare revenue per crop type, as more lucrative crops are substituting traditional ones.

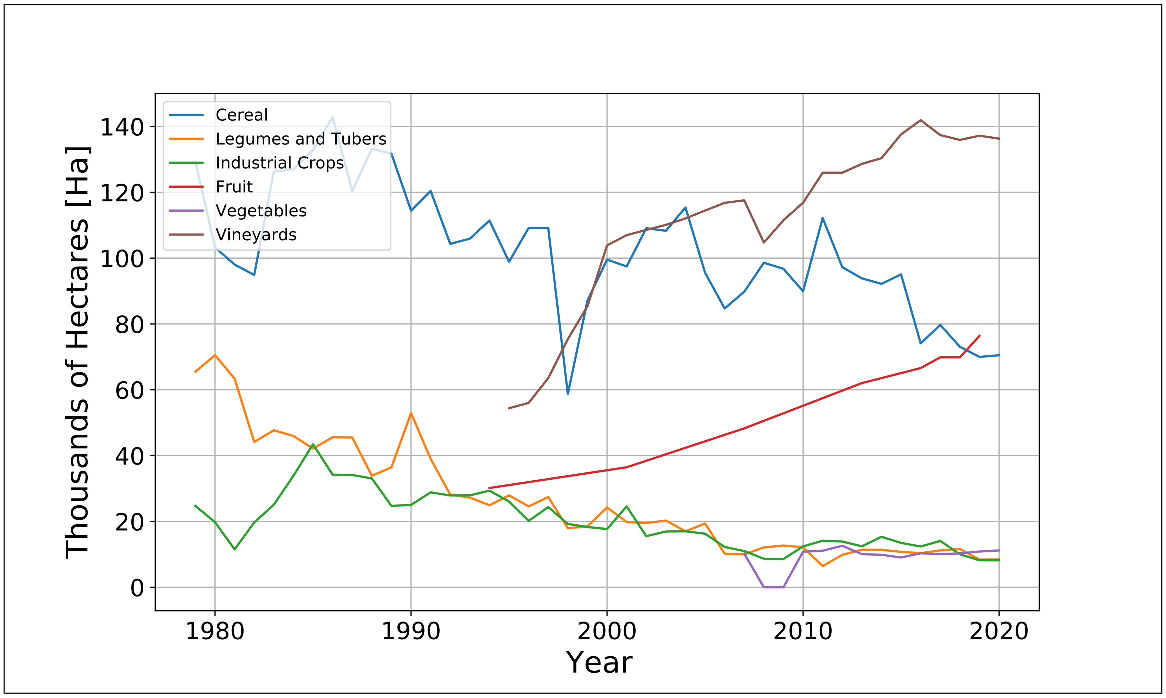

Figure A.5. Evolution of irrigated hectares, by available crop type, in the study area. Some crop types have different temporal intervals, as available information varies (ODEPA, 2020).

Based on the historical evolution of crop types, the areas in Figure A.4 can be updated for each demand site between 2007 and 2020 with the following proportions:

- Cereals : $A^{ds}_{2020} = 0.79 \ \ A^{ds}_{2007}$
- Legumes and Tubers : $A^{ds}_{2020} = 0.85 \ \ A^{ds}_{2007}$
- Fruits : $A^{ds}_{2020} = 1.58 \ \ A^{ds}_{2007}$
- Vineyards : $A^{ds}_{2020} = 1.16 \ \ A^{ds}_{2007}$

This update impacts directly on the Net Hydric Need of each demand site, as changing the crop distribution also implies a different water consumption in each demand site. Table

A.3 shows the NHN values for both 2007 and 2020, with a downward trend based on the lesser Annual NHN that fruits and vineyards present over cereals and legumes/tubers.

Table A.3. Annual Net Hydric Needs, calculated as the weighted average of each crop fraction per demand site. Values are calculated for 2007 and then projected into 2020, as available information is used to update the indicator.

Demand Site	**Annual NHN 2007** (m^3/ha)	**Annual NHN 2020** (m^3/ha)
Garzas and Suizas	7,740	7,695
SORPAM	7,822	7,633
South Maule Channel	7,826	7,758
Maule Channel Association	7,672	7,688
Irrigation Cooperative	7,603	7,527
Northern Riverbank Particulars	7,432	7,396
Southern Riverbank Particulars	7,935	7,878
Melado-Ancoa Diversion	8,235	8,125

Considering the NHN of the year 2020, and Equation A.5, it is possible to estimate the monthly Irrigation Efficiency for each demand site, shown in Table A.4. For Garzas and Suizas demand site, the amount of water rights assigned to the site is less than the actual net hydric need of the crops, so the values are above 1.

Table A.4. Monthly irrigation efficiencies (ϵ) per demand site, 2020

Demand Site	**Irrigation Efficiency**											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Garzas and Suizas	1.07	1.19	1.07	1.11	1.07	1.11	1.07	1.07	1.11	1.07	1.11	1.07
SORPAM	0.4	0.44	0.4	0.41	0.4	0.41	0.4	0.4	0.41	0.4	0.41	0.4
South Maule Channel	0.39	0.43	0.39	0.4	0.39	0.4	0.39	0.39	0.4	0.39	0.4	0.39
Maule Channel Association	0.64	0.71	0.64	0.67	0.64	0.67	0.64	0.64	0.67	0.64	0.67	0.64
Irrigation Cooperative	0.39	0.43	0.39	0.4	0.39	0.34	0.39	0.39	0.4	0.39	0.4	0.39
Northern Riverbank Particulars	0.61	0.68	0.61	0.63	0.61	0.63	0.61	0.61	0.63	0.61	0.63	0.61
Southern Riverbank Particulars	0.25	0.27	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Melado Ancoa Diversion	0.22	0.25	0.22	0.23	0.22	0.23	0.22	0.22	0.23	0.22	0.23	0.22

In terms of irrigation methods, available information is more limited. Only the historical evolution of irrigation methods for fruit crops is available, displayed in Figure A.6.

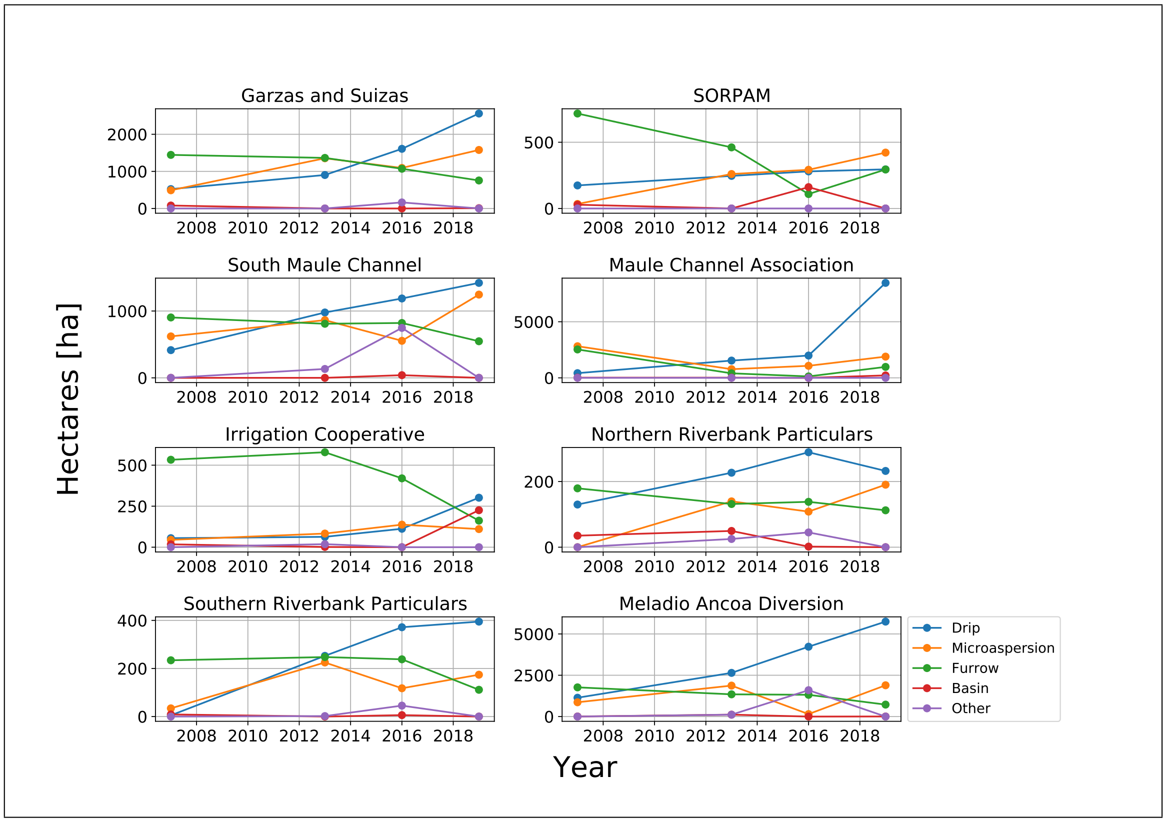

Figure A.6. Temporal evolution of fruit irrigation methods according to different hectare occupancy in the study area, by demand site.

However, it is possible to estimate the increase in application efficiency, by assuming that the fruit and vineyard expansion has replaced the entirety of the cereal and legume area, so the net change in irrigation methods for fruits scaled down to the total fruit proportion represent the net change to the whole demand site. Equation A.6 illustrates this estimation.

$$\epsilon_{ap,2020}^{ds} = \epsilon_{ap,2007}^{ds} + \Delta\epsilon_{ap,fr}^{ds} \cdot f_{fru,vin}^{ds} \tag{A.6}$$

With:

- $\epsilon_{ap,y}^{ds}$: Application Efficiency in the year y, for demand site ds
- $\Delta\epsilon_{ap,fr}^{ds}$: Application Efficiency variation between 2007 and 2020 in demand site ds
- $f_{fru,vin}^{ds}$: Fraction of fruit and vineyard areas in demand site ds in the year 2020

Given the increasing relevance in fruits, both irrigated area and technicized methods increase substantially, and impact considerably on the application efficiency per demand site between 2007 and 2020, as Table A.5 shows.

Table A.5. Application efficiencies per demand site in the study area, calculated for 2007 and then projected to 2020 considering the irrigation technification.

Sitio de Demanda	ϵ_{ap} **2007**	ϵ_{ap} **2020**
Garzas and Suizas	0.45	0.51
SORPAM	0.46	0.56
South Maule Channel	0.43	0.48
Maule Channel Association	0.48	0.56
Irrigation Cooperative	0.48	0.54
Northern Riverbank Particulars	0.48	0.55
Southern Riverbank Particulars	0.48	0.55
Melado Ancoa Diversion	0.45	0.49

Having estimated both the irrigation and application efficiency, it's possible to calculate the rest of the efficiencies in Equation A.1, and establish them as a constant parameter that will remain on value in the proposed strategies. The denominated C parameter is then calculated as Equation A.7 shows.

$$C_t^{ds} = \epsilon_{un} \cdot \epsilon_{con} \cdot \epsilon_s = \frac{\epsilon_t^{ds}}{\epsilon_{ap}^{ds}} \tag{A.7}$$

The resulting monthly C parameters for each demand site are shown in Table A.6.

Table A.6. Parameter (C) to represent the additional components of irrigation efficiency (conduction, uniformity and storage values), per demand site. As efficiency depends on the allocated flow, each month has a different value.

Demand Site	***C* Parameter**											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Garzas and Suizas	1	1	1	1	1	1	1	1	1	1	1	1
SORPAM	0.7	0.78	0.7	0.73	0.7	0.73	0.7	0.7	0.73	0.7	0.73	0.7
South Maule Channel	0.82	0.9	0.82	0.84	0.82	0.84	0.82	0.82	0.84	0.82	0.84	0.82
Maule Channel Association	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Irrigation Cooperative	0.71	0.79	0.71	0.73	0.71	0.73	0.71	0.71	0.73	0.71	0.73	0.71
Northern Riverbank Particulars	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Southern Riverbank Particulars	0.45	0.49	0.45	0.46	0.45	0.46	0.45	0.45	0.46	0.45	0.46	0.45
Melado Ancoa Diversion	0.45	0.5	0.45	0.47	0.45	0.47	0.45	0.45	0.47	0.45	0.47	0.45