From risk assessment to adaptation pathways: an improvement of the Climate Risk Informed Decision Analysis for the Limari basin in Chile

Submitted by: Christianne Luger

Supervised by:
Saket Pande[1]
Edo Abraham[1]
Boris van Breukelen[1]
Ad Jeuken[2]
Andrew Warren[2]
Koen Verbist[3]

[1] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands
[2] Water Resources and Delta Management Department, Deltares, Boussinesqweg 1, 2629 HV Delft, Netherlands
[3] Division of Water Sciences, UNESCO – IHP, 7 place de Fontenoy, F-75352 Paris 07 SP, France

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1. Executive Summary

Until recently, planners and engineers assumed a relatively stable climate and have designed water resource systems (i.e. utility, distribution and storage of water) to function optimally under an identified range of conditions within the historical envelope with an applied safety factor. With conditions shifting away from this envelope, systems are increasingly under stress causing economic and human losses in sensitive regions. Therefore, planners require a new approach to water resource planning that does not rely on empirical observations of climate to dictate the design specifications and one that can account for the unknowable uncertainty of future conditions under climate change. To address this need, the Climate Risk Informed Decision Analysis (CRIDA) framework was developed to incorporate the uncertainties of climate change that impact project planning, socioeconomic justification, and engineering design into a step-wise and collaborative planning process to guide an analyst to low-regret risk- and cost-effective solutions. This new approach combines climate science tools such as the Decision Scaling bottom-up risk assessment methodology by Brown et al. (2012) and the Dynamic Adaptive Policy Pathways by Haasnoot et al. (2013). Essentially, CRIDA links a bottom-up approach for risk assessment to the generation of low regret adaptation strategies that may be adapted over time as new information becomes available or if there are rapid shifts in circumstances. However, CRIDA as a new approach, still requires reviews and case study applications to identify its gaps. Therefore, the purpose of this research is (1) to review and identify gaps in the current methodology in terms of its usability, defined here as the clarity of steps, ease of use and repeatability, and propose additional tools and guidelines to improve these aspects; and (2) to demonstrate the application of CRIDA with the additional tools and guidelines to a case study as a 'proof of concept'. The scope of the research is limited to the first three steps of CRIDA namely the definition of the decision context, the vulnerability assessment and the formulation of actions. For more information on these steps of CRIDA refer to section 3.4 of this report.

To achieve the first purpose of this research, research questions are developed to resolve each gap identified in the review of the methodology and additional guidelines and tools are proposed to achieve this aim. The review of CRIDA and its previous case study applications led to the identification of three key gaps and thus additional guidelines and tools for the CRIDA framework. First, it is assumed in the original risk assessment aspect of CRIDA that modelling system response to scaled and shifted historical precipitation and temperature series is representative of the system response under climate change. However, the validation of this assumption in this research revealed that this assumption only applies to time independent metrices in the system model. Therefore an additional requirement of time independence is proposed for defining key performance metrics (KPMs) which represent the vulnerability of the case in the decision context stage of CRIDA. Second, the level of concern classification, a function of analytical uncertainty, impact and plausibility of failure, which ultimately guides the analyst towards the appropriate low regret strategy is found to be subjective and challenging to interpret. Thereby, introducing significant individual analyst bias in the strategy recommendation. To improve clarity and remove analyst subjectivity (1) additional guidelines are developed based on literature to offer analysts clearer justifications of analytical uncertainty in identified sources such as threshold definitions, system model and climate projections as well as how different sources of uncertainty are prioritized and combined for the

integrated analytical uncertainty assessment; and (2) stakeholder risk perceptions are introduced in the risk assessment step, essentially replacing analyst subjectivity with stakeholder subjectivity thereby also strengthening the co-design aspects of CRIDA. Finally, a new approach linking the vulnerability assessment to generating adaptation strategy pathways is developed utilizing stakeholder risk perceptions for the tipping point of strategies. These additional guidelines and tools aim to improve on the scientific basis of the risk assessment by ensuring that the stress test is representative of future conditions and that multiple RCPs are represented in the assessment. Furthermore, additional guidelines that strengthen the numerical basis of the risk and analytical uncertainty assessments aim to make these assessments more straight forward for analyst thereby removing subjectivity and ensuring that the same results are achieved by different analysts. The incorporation of stakeholder risk perceptions in the risk assessment step and the development of adaptation strategy pathways aims to shift analyst subjectivity to stakeholder subjectivity further improving the repeatability of these assessment and in addition improves co-design aspects of the method ultimately resulting in more acceptable pathway recommendations.

To achieve the second purpose of this research, CRIDA with its new guidelines and tools are applied to a water security case study as a proof of concept. It is specifically stated here as a proof of concept as it is recognised there are limitations in the model and data sources that can affect the final recommendations. The case study presented should therefore only be referred to as a demonstration of CRIDA and the added guidelines and tools. The framework is applied to the Limari Basin in Chile which has experienced an increase in drought frequency and severity over the last decades. The area is in a semi-arid region with its water supply primarily sourced from snow-melt in the Andes. The combined effects of (1) increased water insecurity in the future, (2) an economic reliance on agriculture, (3) the limited capacity of farmers to adapt due to overdevelopment of irrigation infrastructure and (4) a complex market-based water governance system caused this basin to have some of the highest vulnerability to climate change in the country. The decision context and the vulnerability assessment steps of CRIDA has been completed in a 2016 study but is adapted in this research according to the added tools and guidelines as well as additional information gathered from the field visit in 2019. The case study is extended to the formulation of actions in the form of adaptation strategy pathways.

In the decision context definition step of CRIDA, the KPMs that reflect the vulnerabilities of the basin is the inflow to the La Paloma Reservoir, hereafter referred to as KPM1 the unmet irrigation demand in the Grande Region, hereafter referred to as KPM2, which satisfy the novel time independent requirement for KPMs. In the next step of CRIDA, the risk of failure and the analytical uncertainty in the analyses are defined following the newly developed guidelines to identify an appropriate no-regret general strategic approach. The risk of failure is essentially the plausibility and impact of the KPMs breaching their critical threshold which would result in system failure. The assessment of the plausibility of failure (%) follows a collaborative and semi-quantitative approach using the decision scaling method on the WEAP system model with projections generated by the SIMGEN weather generator and the risk perceptions of stakeholders. The assessment of the impact of failure for this case study is purely qualitative due to limitations in the system model. The analytical uncertainty in the risk assessment is determined explicitly for identified sources of uncertainty, namely the critical threshold definition, the system model and the projections. The risk and analytical uncertainty assessments resulted in a high future risk rating and medium-high analytical uncertainty rating for each KPM, guiding the analyst to recommend robust actions (i.e. building reservoirs) supplemented by flexible actions (i.e. crop pattern changes) as the general strategic approach.

The final step within the scope of this study is to formulate actions. Specifically, for this case, a combination of flexible and robust actions is recommended. Acceptable actions were compiled through interviews and a workshop with the stakeholders and by reading through local and national plans as well as literature describing historical responses to drought in the area and in similar arid regions. Among the most popular actions historically is for farmers to reduce cultivated areas, practice deficit irrigation, trade water rights in the market, extract groundwater often illegally and improve irrigation efficiency. As for the future, popular actions among the stakeholders are technocentric that is to further improve irrigation efficiency, recharge aquifers and construct additional reservoirs. From the compiled actions, 9 unique actions are chosen to be tested based on the availability of data in the literature to justify their parameterization in WEAP and the ability of WEAP itself to incorporate these actions. These 9 actions are namely, (D1) deficit irrigation, (D2) replacing permanent crop acreage to annual crops with lower water requirements, (D3) replacing currently grown annual crops to annual crops with lower water requirements, (D4) altering crop planting schedules, (D5) reducing plant transpiration through meshes, (S1) improving irrigation efficiency, (S2) improving canal delivery efficiency, (S3) building reservoirs, and (S4) injecting an additional source (e.g. desalination plant, waste water re-use or water highway). Through an extensive literature review, an adaptation action toolbox is created detailing the parametrization of each action in WEAP. Each action is incorporated into the WEAP model as scenarios and a fast-track decision scaling method is iterated for each action to determine the resulting numerical plausibility of failure (%) of the system. A satisfactorily effective action is one that is capable of reducing the future risk rating which is currently at high if business as usual continues in the future. To achieve this in the Limari case, the plausibility of failure must be reduced to low which based on stakeholder perceptions is <40%. This link in the assessment of effectiveness of actions to stakeholder perceptions is a novel addition of the proposed guidelines.

The results of the fast-track decision scaling method showed that no single action is capable of reducing the plausibility of failure (%) of both KPMs to <40% for decades into the future. The system under historical conditions is already in a critical state due to persistent droughts therefore many strategies are not able to reduce the plausibility of failure (%) satisfactorily as conditions worsen. Furthermore, the projected decreasing flow to the basin from snow-melt in the Andes would be unable to fill the capacities of existing and additional reservoirs. Thus, this rather popular action does little improve water security in the future. The limited portfolio of effective actions suggest that the reliance on agriculture for the local economy is not sustainable in the future and other livelihood and sources of income must be considered. But if agriculture is to be maintained as the main economic activity in the basin, an additional water source is necessary in combination with flexible measures for managing demand (i.e. implementing agricultural meshes and improving irrigation efficiency). Therefore, individual actions were packaged based on their acceptability, compatibility as some actions have negative feedbacks, and how effective they are at reducing the plausibility of failure individually. Using the action packages, adaptation strategy pathways are created. The tipping point of each package signaling transition to an alternative, is the decade in which this package is no longer able to maintain the plausibility failure to <40%. This novel approach linking plausibility assessment directly to the generation of adaptation strategy pathways while strengthening co-design by incorporating stakeholder risk perceptions is one of the significant contributions of this research to streamline and connect the different steps of CRIDA.

The Limari case is already critical therefore there is only a limited number of possible pathways that can be recommended by the analyst. In other cases, where multiple options exist, the initial pathway recommendation would be in consultation with stakeholders. The recommended pathway would then be evaluated economically in the next step of CRIDA and this information would feedback into the pathway development as an iterative process. The economic evaluation of action falls beyond the scope of this research.

The study demonstrated the functionality of CRIDA for planning and design under climate change uncertainty. While the added guidelines required more processing time, subjectivity in the method is reduced thus also reducing possible bias introduced by the analyst. In addition, overall acceptability of the proposed strategies is improved by incorporating stakeholder risk perceptions and opinions explicitly in the process. Another key outcome of this study is that the risk assessment is directly linked to adaptation strategy development. This is the first CRIDA case study which demonstrated CRIDA novelty in linking a bottom-up decision-making approach to the development of adaptation strategy pathways. Further research and case studies applying CRIDA with the additional guidelines is required to validate its functionality in different contexts.

2. Introduction

Worldwide, water management systems designed to support many socio-economic activities are under increasing stress due to climate change. There is evidence of alterations in hydrological processes over the last decades caused by the rise in global temperatures and greater climate variability – that is, the increase in the frequency and intensity of extreme events (i.e. floods and droughts) (IPCC, 2014). As a result, water quantity and quality values are shifting outside the range of historical observations which dictate the design contexts of current systems under traditional planning principles.

Until recently, planners and engineers assumed a relatively stable climate and have designed systems to function optimally under an identified range of conditions within the historical envelope (Stakhiv, 2011). With conditions shifting away from this envelope, systems are increasingly under stress causing economic and human losses in sensitive regions. The projected continuation of climate change into the 21st century coupled with unprecedented global economic growth suggests that future conditions will continue to shift further away from the envelope of historical observations (Milly et al., 2008); possibly amplifying system stresses where they exist and pushing more water systems worldwide into stressful conditions. Therefore, the appropriate response of water managers and engineers is to assess the potential effects of climate change on their systems and make new plans and investments to adapt their systems in response to increasing uncertain future risks. But they require a new approach to water resource planning that does not rely on empirical observations of climate to dictate the design specifications and one that can account for the unknowable uncertainty of future conditions under climate change (Hallegatte et al., 2012, Milly et al., 2008).

To address this need, the Climate Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018) method was jointly developed by the US Army Corps of Engineers (USACE), the International Center for Integrated Water Resources Management (ICIWaRM) under the auspices of UNESCO and Deltares. The framework was published only recently in November 2018 by the UNESCO and ICIWaRM Press. CRIDA uses the latest scientific tools in the climate change field - including decision scaling (Brown et al., 2012) and adaptation pathways (Haasnoot et al., 2013)- to incorporate the uncertainties of climate change that impact project planning, socioeconomic justification, and engineering design; into a step-wise and collaborative planning process to guide the analyst to risk- and cost-effective solutions; while remaining compatible with international guidelines of Integrated Water Resources Management (IWRM) (Gilroy and Jeuken, 2018). It focuses on the early feasibility stages of project planning when vulnerabilities are assessed and options are devised and formulated. CRIDA is essentially a client-advice style of policy analysis according to the framework of Mayer et al. (2013) as it is mainly design and solution oriented and ultimately aims to present the analyst with clear choices for strategies to achieve a defined set of common objectives amongst stakeholders. The success of this type of policy analyses lies in its usability for the analyst and its ability to clearly communicate/present the advice; as well as the 'workability' of the advice it recommends in the complex environment it is situated.

2.1. Thesis Approach and Objectives

As a novel approach, the developers of the methodology recognize that case studies need to be conducted so that gaps may be identified, and necessary revisions or additional guidelines may be incorporated to ensure the success of the methodology. This research will continue the application of the first three steps of CRIDA, namely STEP 1: the decision context, STEP 2: the climate change vulnerability assessment and STEP 3: formulating adaptation actions, on a water security case study in the Limari Basin, Chile which was started in 2016 by UNESCO and CAZALAC. Alongside the application following steps of the official publication, the methodology is reviewed from the perspective of an analyst with a background in civil engineering (water management) to identify aspects that was not straightforward and vague to apply. These aspects of CRIDA are also defined in collaboration with the developers of the methodology based on their experiences in previous case studies.

Guidelines or revisions for the methodology are then proposed in this research with the aim of improving the 'usability' of the methodology which determines the success of this client-advice style method according to Mayer et al. (2013). Usability is defined here as the clarity of steps, ease of use and repeatability. These guidelines are developed essentially by writing down in a step-wise manner the reasoning of the analyst on how the outcomes of the different aspects of CRIDA are achieved and logically justifying the results, supported by academic literature where available, and under what conditions these results would vary. This was an iterative process with each outcome feeding into what information is needed in the preceding steps and what additional information can be used in the following steps to better transition and link information between the steps.

The newly developed guidelines defined in Chapter 5 are demonstrated as on a water security case study in the Limari Basin, Chile. To satisfy the collaborative aspects of CRIDA, interviews and a workshop were conducted at the case study area to revisit the decision context, gather information on the risk perceptions of stakeholders used in STEP 2 in the revised CRIDA and compile a library of actions and characteristics of actions that are used in STEP 3. Aside from the direction application of CRIDA and its revised guidelines, several tools were used in the case study to generate data for the application. Within STEP 2 of CRIDA, a validated WEAP model is used to simulate the system response to changes in temperature and precipitation to create a response surface and identify the vulnerability domain. WEAP iterations are automated through its Application Programming Interface (API) in python. The SIMGEN weather generator is used to generate climate projections that are overlaid onto the response surface of the system and a Kernel Density Estimation python script is written to determine the 2-dimensional probability distribution of projections within the vulnerable domain of the response surface. The WEAP model is used again in STEP3 of CRIDA for testing the effectiveness of adaptation actions whose parameterizations in WEAP are justified through an extensive literature review. The WEAP API is again used in this step to automate the changes in WEAP parameterization for each action and the iterations to recreate the response surface of the system with the strategies applied. The use of these tools and how they complement CRIDA are detailed further in Chapter 6.

2.2. Thesis Structure

The thesis is structured in the following manner. In the next chapter, a brief background is presented on the broader literature of water resource planning under climate change and how CRIDA fits into this broader science. In the same chapter, CRIDA is elaborated with examples taken from its initial application in the Limari Basin. In Chapter 4, CRIDA is reviewed and the issues identified which inform the research questions. Chapter 5 presents the proposed new or additional guidelines to address issues identified for the first three steps of the CRIDA which are applied in the Limari Basin Case study in Chapter 6. Chapter 7 discusses the results of the application of CRIDA on the Limari Basin and how the newly developed guidelines improve the overall methodology as well as concludes the research and recommends opportunities for future research.

3. Research Background

This chapter begins with a description of the contemporary approach to water resource planning and management. Then transitions into a discussion of the shortcomings of current practices when planning for climate change. The popular ideas for planning under uncertainty are then presented followed by a description of the scientific tools which form the basis of the main elements of CRIDA. Finally, this chapter will end with a brief description of aspects of the CRIDA method relevant to this study.

3.1. Contemporary Decision Making in Water Resource Management

Contemporary water management decisions are based on the multi-objective planning paradigm pioneered by the Harvard Water Program (Maass et al., 1962) in the mid-twentieth century. It is recognized that designing or planning for water resource management projects requires decisions that could potentially impact individuals, industries, communities, regional economies and the environment in different ways. Therefore, the program advocated a strong interdisciplinary and collaborative approach to planning; recommending that the first step in any planning effort is to reach an agreement on planning objectives encompassing the broader socio-economic and environmental consequences of the design. A decision to implement a specific water management design is then justified through a complex set of cost-benefit procedures that reflect the balances and trade-offs between the defined objectives for the project. This is the general planning process underpinning international guidelines for sustainable development and integrated water management (IWRM, UN-Water 2014).

The justification of water management projects is however further complicated as planners must ensure that the trade-offs among objectives are accepted under a variety of socio-economic and natural scenarios. It is this uncertainty in operational circumstance that requires a risk-based approach to decision-making where the consequences of alternative actions under a specific future state are weighted by their probabilities. Traditionally, it is the strategy that gives on average the best value across all futures that is recommended for application (optimum expected utility) (Lempert, 2003). At the core of these procedures in water management is a reliance on hydrologic frequency analysis based on historical data to generate a single probability distribution for future natural states specifically (Stakhiv, 2011). In this rational style of decision making, it is assumed that decisions can be made according to empirical evidence assuming some form of stationarity in conditions and that uncertainties can be reduced by gathering more empirical evidence to enhance the stochastic processes (Mayer et al., 2013, Milly et al., 2008). As a result of this process, the justification of modern projects is based on their performance under conditions within the range of historical observations and climate non-stationarity undermines the validity of this approach (Milly et al., 2008). Ironically, this focus on risk analysis and the addition of numerous societal and cultural objectives to justify projects has lead to what has been termed by Hashimoto et al. (1982) as 'brittle solutions'. Much of the redundancies and safety factors historically engineered into the designs have been reduced and these projects are more likely to fail when the climate shifts outside of the historical envelope that these systems were designed for (Stakhiv, 2011). A new standard to water resource decision making and planning is needed that does not rely on empirical observations of climate to dictate the design specifications and one that can account for the unknowable uncertainty of future conditions under climate change.

3.2. Decision-Making under Deep Uncertainty

Decision challenges that relate to climate change are under conditions of “deep uncertainty” which means that the uncertainties about the future cannot be reduced by gathering more empirical information. In this situation, there are multiple possibilities for future scenarios without being able to rank the likelihood of these (Kwakkel et al., 2010). Identifying a probability distribution of the future states for the traditional optimised utility approach becomes controversial with different experts likely gravitating towards different conclusions. Even if there is consensus for one, it can encourage analysts and decision makers to be overconfident in their estimates of uncertainty (Groves and Lempert, 2007). Hence, a study by Lempert and Collins (2007) revealed robust strategies that sufficiently meet objectives across a wide range of plausible future states are more appropriate. This concept has formed the basis of the Robust Decision Making (RDM) framework (Lempert, 2003). RDM is an iterative process of stress testing alternative plans under multiple futures to identify one that meets the objectives satisfactorily across the broadest range of futures.

Aside from robustness, Haasnoot et al. (2011) argues that a sustainable strategy should also be flexible enough to be adapted over time as new information becomes available or if there are rapid shifts in circumstances. Near-term actions are preferred with little dependencies so that there is an option to modify, extend or alter plans in the future. This is in line with the definition of sustainable development: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland et al., 1987). Decision-making approaches that incorporate this idea are the Dynamic Adaptive Planning (DAP) approach introduced by Walker et al. (2001), which in addition to proposing an adaptation plan, identifies alternatives when the proposed plan is found to have become vulnerable by continuous monitoring. Expanding on this concept is the Dynamic Adaptive Policy Pathways (DAPP) approach developed by Haasnoot et al. (2013). This approach organises alternatives in adaptation pathway maps which visualizes sequences of possible actions through time by examining how the strategies perform over transient scenarios. These flexible pathways include transfer points in time to other strategies to ensure that the system can be adapted if future conditions vary from those expected. An example of an adaptation pathway maps is on Figure 3.2.1.

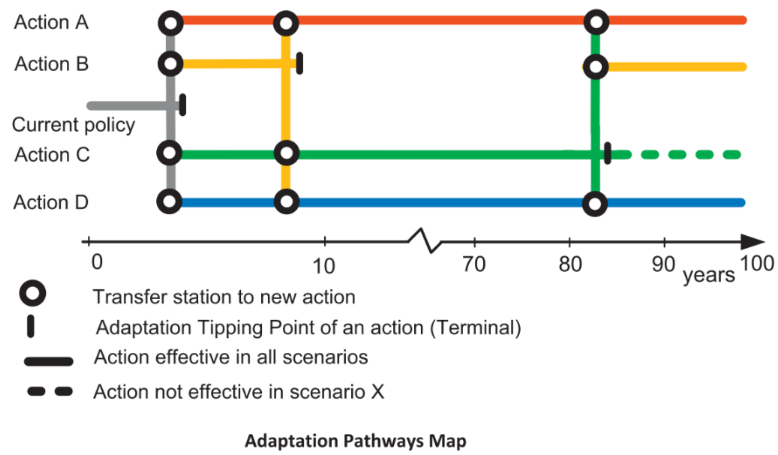

Figure 3.2.1 Example of Adaptation Pathways Map (Haasnoot et al., 2013)

3.3. Climate Change Risk Assessments

Decision makers use risk assessments to make sound judgements about the resources they should allocate to address them. In climate change science, different risk assessment methods are often segregated into top-down and bottom-up approaches. These method groups use data tools differently and begin the impact and vulnerability assessments from different directions (Figure 3.3.1).

The former "top-down" approach uses climate projections from Global Circulation Models (GCMs) following different economic and social trends or Representative Concentration Pathways (RCPs)(AGWA, 2013). These projections, downscaled to the local level, are used to drive system models in order to estimate the climate change impacts on variables of societal interest for the risk assessment. In other words, GCMs become the input for future climate conditions in the traditional expected utility theory. This approach is scenario-based, and the system risk is only assessed within the defined set of scenarios following GCMs trends and conditions outside the GCMs projections are not considered. This is an issue because GCMs have uncertainties such as uncertainty in model input and parameters as it aims to simulate hard-to-predict human behavior and uncertainty in the model structure due to uncertainties in the underlying science). GCMs are also unable to appropriately represent the two dimensions of risk in a system; impact and probability. GCMs only provide a range of mean future climate conditions without providing any insight into climate extremes (i.e. floods and droughts) which are most important for water resource projects. As a result, the analyst gains little insight into the full range of future states, their impact into the system and plausibility of occurrence. Second, GCMs are only considered spatially credible at coarse grids (>100 km) and temporally credible at a monthly time-step. This issue of scale is not resolved by downscaling techniques and adds considerable uncertainty in applications at the local scale. Finally, uncertainties that are related to the underlying science of GCMs will be the same in different models. Therefore, individual GCMs cannot be assumed to be independent from each other and a distribution of their outcomes does not necessarily indicate accuracy of the projections or provide the analysts with a probability estimation for a future state. (García et al., 2014, Ray and Brown, 2015, AGWA, 2013, Stainforth et al., 2007)

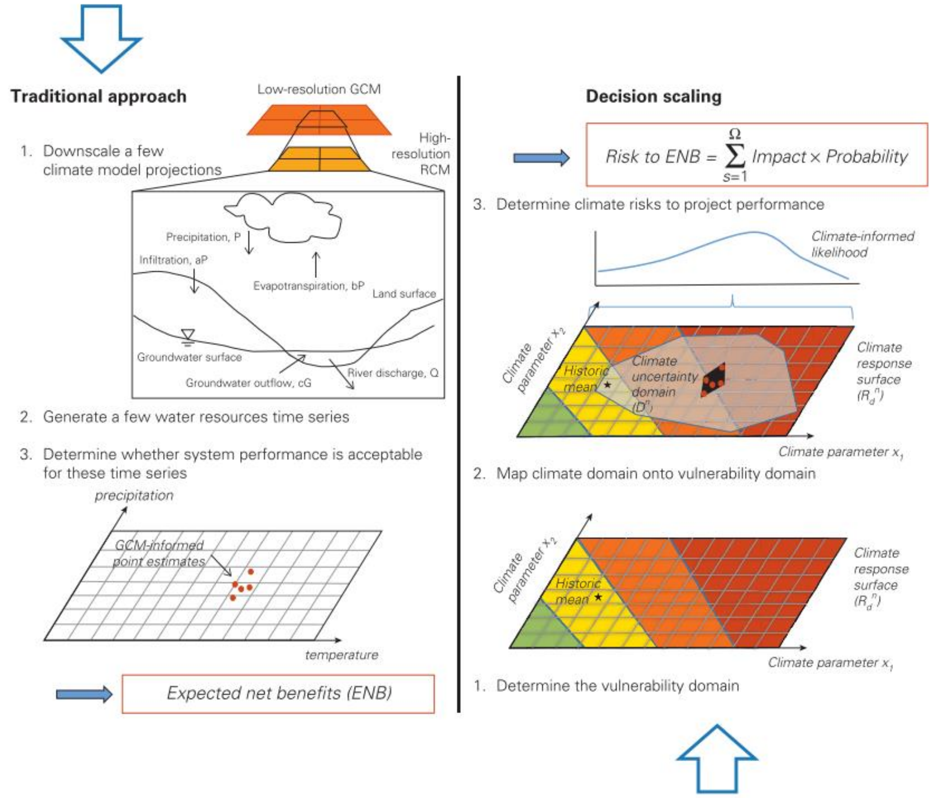

Figure 3.3.1 Top-Down 'Traditional' and Bottom-Up 'Decision Scaling' Approach

Instead, there is growing support for a "*bottom-up*" approach. A particular example of this approach is the 'decision scaling method' by Brown et al. (2012). This approach begins with stakeholder consultations to define future objectives, system vulnerabilities, the performance thresholds that would shift the system into a vulnerable state and the impacts of this shift. A system model is then used to simulate system performance through a wide range of climate conditions outside the predictions of GCMs to identify the vulnerable domain. This process is called the 'stress test'. The stress test is iterated with different strategies incorporated into the system model. GCMs are only used in the last stages of the approach to estimate risk by informing on the probability that the future falls in this vulnerable domain. By doing so, the specificity required from GCMs is reduced and the results may be more reliable (Mastrandrea et al., 2010b). This method changes the question posed by the traditional top-down approach of ''what will the future climate be?'' which is deeply uncertain, to ''is the climate that favors action A more or less likely than the climate that favors action B?''. The results do not identify the optimal solution in a traditional decision-making sense. Instead, it recommends the most robust solution which reduces the probability that the future falls within the vulnerable domain.

Ultimately, the decision scaling methodology is more in line with the recommendations for decision-making under deep uncertainty as it recommends robust over optimal strategies. Furthermore, it recommends that the first step in the process is to define common objectives among stakeholders which are complementary with international standards of sustainable and integrated water management.

3.4. Climate Risk Informed Decision Analysis (CRIDA)

The Climate Risk Informed Decision Analysis approach combines the latest climate science tools such as Decision Scaling by Brown et al. (2012) and Dynamic Adaptive Policy Pathways by Haasnoot et al. (2013) to guide the analyst with a technical background in water resource management through a collaborative process to evaluate, design and implement strategies to reduce climate change risk. The justification of these strategies is risk-based which aligns with traditional methods of strategy justification to decision makers. Furthermore, CRIDA is compatible with international guidelines of sustainable and Integrated Water Resources Management in that it emphasizes starting the process with the negotiation of multiple interests and the inclusion of multiple system stresses across the social, environmental and economic sectors (Gilroy and Jeuken, 2018). CRIDA is broken down into five iterative steps (Figure 3.4.1).

The following sections briefly introduce the first three steps of CRIDA which are reviewed and applied in this research. Step 1, the decision context and part of Step 2, the bottom-up vulnerability assessment has been applied to the Limari Basin water security case study by UNESCO and CAZALAC in 2016. The results of their applications are included in the CRIDA steps description where available. For more details on the initial Limari Basin application and a description of the remaining steps, the reader is referred UNESCO and CAZALAC (2018) and Mendoza et al. (2018) respectively.

3.4.1. STEP 1: Decision Context

Step 1 of the CRIDA framework aims to create a full description of the current holistic state of system which will be used in the following steps to assess the impact of drivers and/or uncertainties on the system and the relative benefits of adaptation strategies applied to mitigate these impacts. The decision context is defined through collaborative workshops and modelling attended by stakeholders and decision makers with support from technical experts. This ensures that the technical analysis is aligned to decision maker and stakeholder needs.

The process follows a framework on Figure 3.4.1 and starts with a problem statement definition which identifies the water security vulnerabilities and should encompass economic, social and environmental objectives to allow for identifying broad and sustainable solutions. The problem should not preclude the consideration of all potential alternatives to solve the problem or aim to implement specific alternative as it may limit the comprehensive examination of alternative adaptation strategies. From the problem definition, key drivers of change exacerbating the problem can be identified. Drivers can be climatic, such as temperature and precipitation changes, or socio-economic, such as population growth. The relative importance of climate change compared to other drivers such as population growth cannot be generalized for every case (Ray and Brown, 2015). Therefore, each unique case would require an evaluation to determine relevant drivers.

Figure 3.4.1. CRIDA steps (Mendoza et al., 2018)

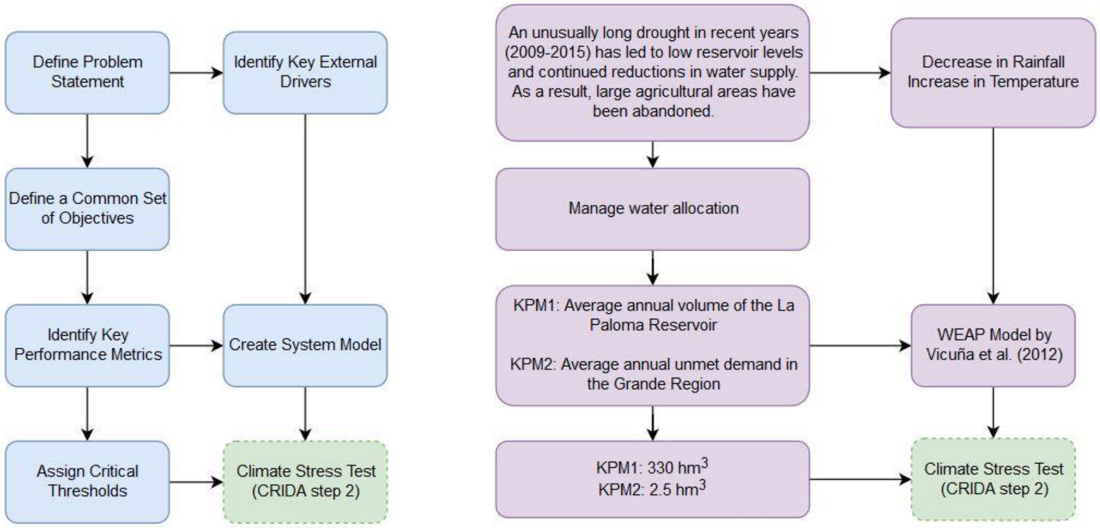

Figure 3.4.2. Left: Decision Context definition framework. Right: Decision Context Definition of the Limari Basin water security case study (UNESCO and CAZALAC, 2018).

A common set of objectives among stakeholders is then defined within the context of the problem statement. A maximum of two core objectives is ideally specified to ensure clarity in the decision-making process. Key performance metrics (KPMs) that represent vulnerable areas of the watershed with respect to the overall water security are selected in order to quantify progress towards the defined objectives. The choice of indicator deeply affects the analysis and should have direct, monotonic relationships with the external drivers. Critical thresholds are linked to each indicator which is defined as the quantified unacceptable level of performance or reliability which may be based on formal documents and agreements, such as design standards, or on stakeholder’s experience. In the climate stress step of CRIDA (Step 2), a comparison of indicator reactivity to changes in the drivers against their critical thresholds is done to indicate the system’s reliability, resilience, and robustness which are standard evaluating decision criteria when high climate uncertainty and variability are relevant.

Finally, a model of the water resources system is created to be used in the following CRIDA steps for stress testing and to evaluate adaptation strategies. The model is designed so that the identified KPMs are the primary outputs and adjust to changes in the external drivers and adaptation strategies which act as the primary inputs. The model must also reflect the physical system as well as regulatory constraints such as priority water allocation and ecological flow requirements.

3.4.2. STEP 2 :Bottom-Up Vulnerability Assessment

The second step of CRIDA is a vulnerability assessment that leads the analyst to a general strategic approach (GSA) given the level of risk of failure and uncertainty in the analysis. The GSA informs the analyst on appropriate low-regret actions for the case. The level of the risk of failure is assessed following traditional definitions of risk as a function of the plausibility and impact following partly the 'Decision Scaling' methodology by Brown et al. (2012).

3.4.2.1. Future Risk Estimation

Risk is determined qualitatively through a matrix on Figure 3.4.3. The y-axis is the plausibility that future conditions will result in KPMs exceeding their critical threshold; and the x-axis is the level of impact (consequence) when this critical threshold is surpassed. To assess the plausibility of unacceptable performance, CRIDA recommends integrating theory, historical climate observations, system sensitivity, and projections. A trend analysis is recommended for short project lifespans. While for longer lifespans, climate projections are used. These are overlaid onto the system response surface of a KPM (Figure 3.4.4) created through a stress test, in order to identify the proportion of plausible futures falling in the vulnerable domain following the decision scaling method by Brown et al. (2012). The vulnerable domain on the response surface encompasses the driver conditions that have resulted in KPMs exceeding their critical thresholds. An example of such analysis is shown on Figure 3.4.5. Each point on this figure is a temporally averaged climate projection. Climate projections are created using a multi-variate stochastic weather generator, SIMGEN (see Appendix A), informed by the long-term trends of an ensemble of GCMs at RCP 8.5. A mild, medium and strong trend is inferred by taking the 10^{th}, 50^{th} and 95^{th} percentiles of the distribution of the trends from this ensemble. GCMs are not used directly because they do not provide any insight into climate extremes and they cannot resolve the heterogeneity of climate change at this physiographically complex basin at their current scale (Falvey and Garreaud, 2009, Vicuña et al., 2012).

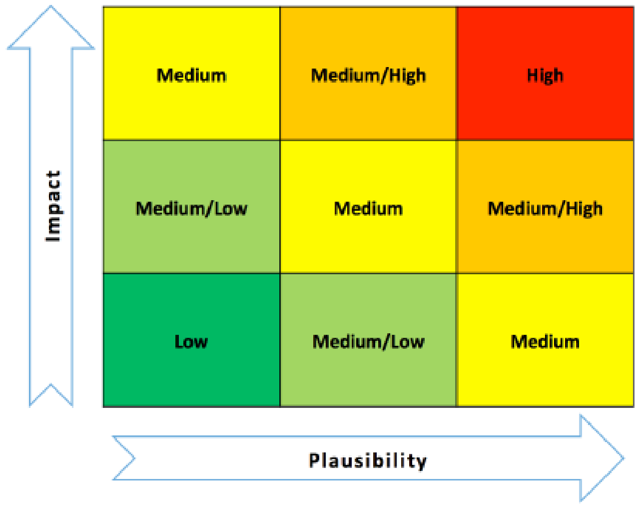

Figure 3.4.3 Future Risk Matrix

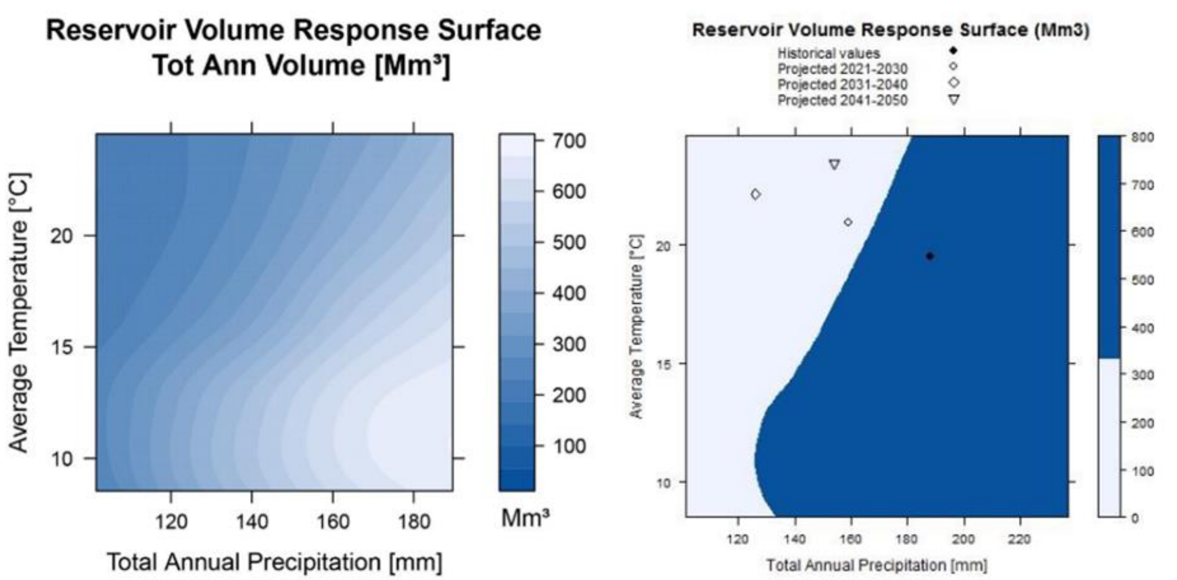

Figure 3.4.4 Left: Response Surface for KPM1 from the Limari Basin water security case study. Right: Vulnerable domain of climate conditions [dark blue] with the KPM critical threshold at 330 hm^3. (UNESCO and CAZALAC, 2018)

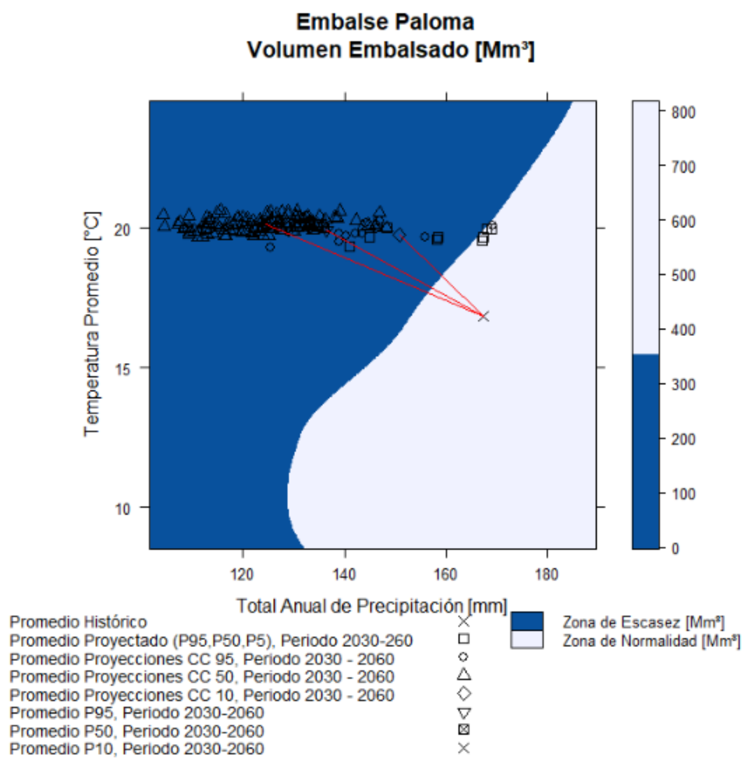

Figure 3.4.5 The temporally averaged observed (1980-2010) and projected conditions (2030-2060) of precipitation and temperature overlaid on the response surface of KPM1 for a mild (P10), medium (P50) and strong (P95) climate change trend. The red lines show the transects from the past observed to the averaged mild, medium and strong projected climate conditions. (UNESCO and CAZALAC, 2018)

A transect is drawn to the average future climate conditions of the mild (10^{th} percentile), medium (50^{th} percentile) and strong (95^{th} percentile) scenario. Plotting the change of the KPM along this transect with respect to any of the two climate drivers informs on the sensitivity of the system (See Figure 3.4.6 for an example). A system that is more sensitive to external drivers has a higher likelihood to be affected by shifts in that driver's variability.

Figure 3.4.7 illustrates the determination of plausibility of failure by combining information regarding historical observations, system sensitivity and future projections. The red line is the KPM sensitivity to the drivers. The GCM range is informed by the points of future projections plotted on top of the response surface. In variation A, climate projections suggest that the climate will become more stressful, while short-term trends suggest climate is in fact becoming more stressful. GCM models support these forecasts, while modeling suggests that the system's performance is very sensitive. For this situation, the analyst is likely to determine that there is high plausibility that the critical threshold will be surpassed in the planning horizon. In the variation B, all the climate data components are the same, but the system is less sensitive within the evidence domain, so it may be categorized as having low plausibility for surpassing a threshold. Variation C is analogous to A, but the range of GCM forecasts is far broader. This figure could suggest that there is plausibility that the performance threshold will be surpassed but because of the broad domain of the forecast information, the analyst faces a higher level of analytical uncertainty, a situation discussed in the following section.

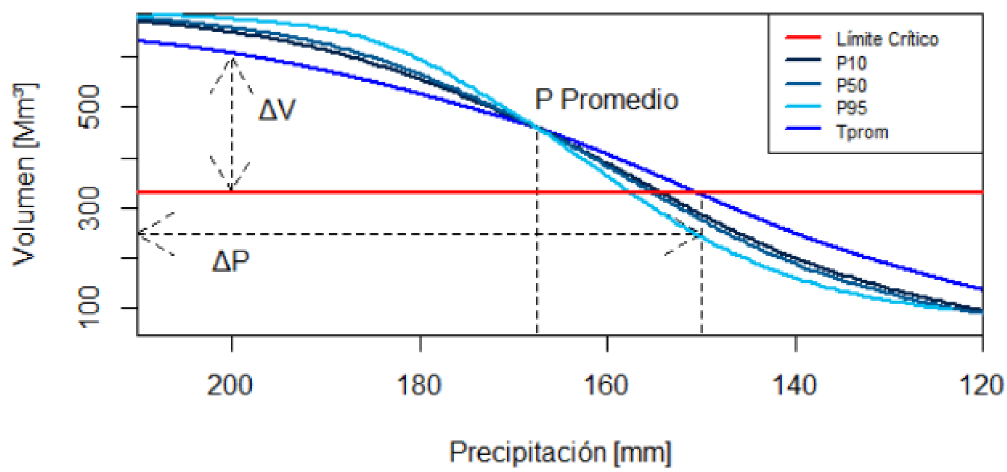

Figure 3.4.6 Sensitivity of KPM1 to precipitation changes for a mild (P10), medium (P50) and strong (P95) climate change trend. Tprom represents the average behaviour across all trends. (UNESCO and CAZALAC, 2018)

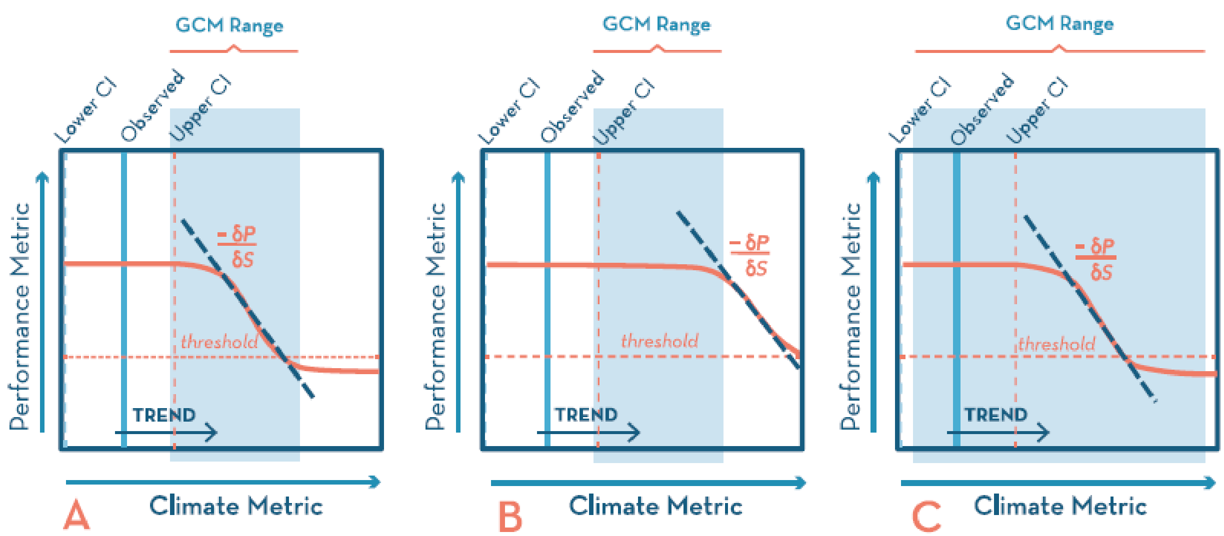

Figure 3.4.7. Examples of integrating climate information and system sensitivity to assess the plausibility of surpassing acritical threshold.

For the Limari case study, the analyst concluded a Medium/High Future Risk for KPM1 because the analysis revealed the system at a critical state has a:

- High Impact. Surpassing the critical threshold will cause significant economic damages according to stakeholders.
- Medium-High Plausibility. Most climate projections fall in the vulnerable domain of the response surface (see Figure 3.4.5) and there is a clear decay in reservoir volume with increasing temperatures and decreasing precipitation (see Figure 3.4.6) indicating that this KPM is highly sensitive to changes under plausible futures.

3.4.2.2. Level of Concern Analysis

The level of concern (LOC) analysis characterizes a climate change vulnerability (defined as key performance metrics (KPMs)) into 4 quadrants based on its determined future risk (see section 3.4.2.1) and analytical uncertainty (Figure 3.4.8). While future risk considers the uncertainty of the future, analytical uncertainty indicates the confidence in the quality of the underlying information and thus the risk of poor or ineffective analysis. There are guidelines listed in CRIDA on how to determine the level of analytical uncertainty which is based on:

- Consistency of information;
- Spread of projections;
- Quality of the system model;
- Availability of relevant data for the analysis and modelling;
- Certainty in assumed future activities (economic, land use etc.);
- Hydrological complexity of the area; and
- Agreement among decision makers.

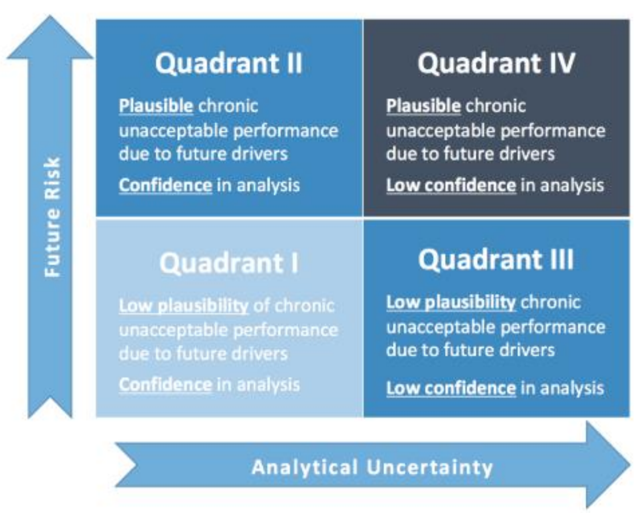

Figure 3.4.8. Integrating future risk and analytical uncertainty to establish a "level of concern" for the planning process.

3.4.3. STEP 3: Formulate Robust and Flexible Actions

The LOC characterisation from step 2 is used to suggest a General Strategic Approach (GSA) for the case. Specific adaptation measures that fit the general strategy are then assessed in three dimensions; acceptability, effectiveness and completeness. Acceptability emphasizes satisfaction and stakeholder buy-in, effectiveness is the efficacy of reducing the vulnerability of the system the stressors and completeness is assessing whether other necessary actions are needed to support the 'core' solution. The output of this step is a set of robust and flexible plans based on risk reduction, comprehensiveness and completeness, effectiveness in meeting planning objectives, and stakeholder acceptability.

3.4.3.1. Identifying the General Strategic Approach

The GSA may be (1) to continue standard planning practice, (2) implement robust actions, (3) implement flexible actions or (4) implement a combination of robust and flexible actions (Figure 3.4.9). A high future risk and/or analytical uncertainty rating from the "level of concern" analysis in Step 2 supplies a clear cause and justification to deviate from standard planning towards applying more robust and/or flexible solutions.

Robust solutions are designed to encompass a broad range of uncertainty which usually implies more costs. These solutions are often also irreversible which limits adaptation options in the future. These solutions are preferred when the LOC of a KPM falls in Quadrant II characterized by low analytical uncertainty and high future risk.

Flexible solutions can evolve around emerging conditions but usually require long-term commitment to monitor, apply and maintain several options simultaneously and may not always result in timely problem solving. Therefore, these solutions are preferred when the LOC of a KPM falls in Quadrant III characterized with high analytical uncertainty and low future risk (Quadrant III).

If a KPM's LOC is characterized with both high analytical uncertainty and high future risk actions (Quadrant IV), a combination of robust and flexible actions is recommended.

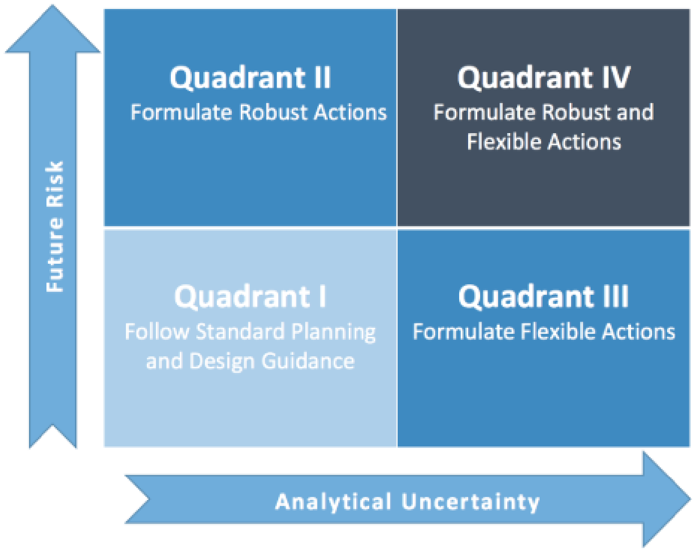

Figure 3.4.9. General Strategic Approaches for the 'level of concern' characterisation.

3.4.3.2. Formulating Diverse courses of Actions

The next step is to compile a broad and inclusive portfolio of structural and non-structural actions which comply with the general strategic approach and objectives of the case. The formulated actions must further be acceptable, effective, and complete. Acceptability emphasizes satisfaction and stakeholder buy-in, effectiveness is the efficacy of reducing the vulnerability of the system to the stressors and completeness is assessing whether other necessary actions are needed to support the 'core' solution in achieving the case objectives.

3.4.3.3. Evaluating Courses of Actions

A portfolio of actions is then be assessed for their acceptability, completeness and effectiveness. For an evaluation of effectiveness, the actions in the portfolio are incorporated into the system model created in Step 1 of CRIDA. A sensitivity analysis is iterated for every action to assess the changes affected by the action to the system limits and model performance across a range of plausible futures. The sensitivity analysis may be simple, only considering a few alternate climate states, which is recommended as an initial analysis, or a full-scale stress test may be performed.

3.4.3.4. Developing Adaptation Pathways

This step uses concepts from Haasnoot et al. (2013). Adaptation pathways are created by combining the better performing and most accepted individual strategies identified in the previous step to offer alternative actions in the mid and long term if the initial effort proves insufficient (See Figure 3.2.1). The point of transition to an alternative action, called the adaptation tipping point (ATP), is informed by the transition from the non-critical to critical domain.

4. Research Questions

A review of STEP 1-3 of the CRIDA methodology based upon earlier experiences in applying the method, discussion with the authors and its initial application on the Limari Basin water security case study resulted in the identification of aspects of the method that could benefit from additional guidelines and tools to improve its ‘usability’ for the analyst. Usability is defined here as the clarity of steps, ease of use and repeatability. Essentially, this review list aspects of the method that was not clear or straightforward for the researcher to follow and apply. These aspects are shown in red below to situate them in the steps of CRIDA (Figure 3.4.1) and are further discussed in the following sections.

Step 1: Decision Context

Step 2: Bottom-up Vulnerability Assessment

2.1: Performance limits are identified by stress test

2.2: Future risk of unacceptable performance determined

Compatibility of stress test results to conditions under the projected climates (Section 4.1)

Classification of future risk as a dimension of the level of concern (Section 4.2)

2.3: The effect of analytical uncertainty on decision making is determined

Classification of analytical as a dimension of the level of concern (Section 4.2)

2.4: Determine the “Level of concern” to inform a strategic approach

Step 3: Decision Context

3.1: Develop robust plans

3.2: Develop adaptation management pathways

Adaptation Tipping points under transient futures (Section 4.3)

3.3: Compare completeness, effectiveness and acceptability

4.1. Compatibility of Stress Test Results to Conditions under the Projections

The plausibility of unacceptable performance is informed in part by overlaying future projections onto the response surface of the stress test (See section 3.4.2.1). This exercise assumes that the response surface, created from scaled and shifted historical precipitation and temperature records, is representative of the conditions under the projected series. However, extreme events are effectively smoothed out when scaling precipitation series whereas these events are preserved in the projected series. This may cause inconsistencies between the conditions presented on the response surface and the actual conditions under the projected climates.

To assess whether the response surface is representative of conditions under the projected time series, the projections were used to drive several iterations of the system model and the resulting KPM conditions overlaid on top of the response surface. Figure 4.1.1 shows the results of this assessment for KPM1 of the Limari Basin water security case study. Ideally, the colours within the circles should match the colours of the response surface. However, this assessment shows that:

1. There are significant inconsistencies between the response surface values and the actual values that the model calculates using the projected precipitation and temperature time series; and
2. A lower average annual precipitation do not always result in lower reservoir levels among the results generated from the weather generator projections as would be expected.

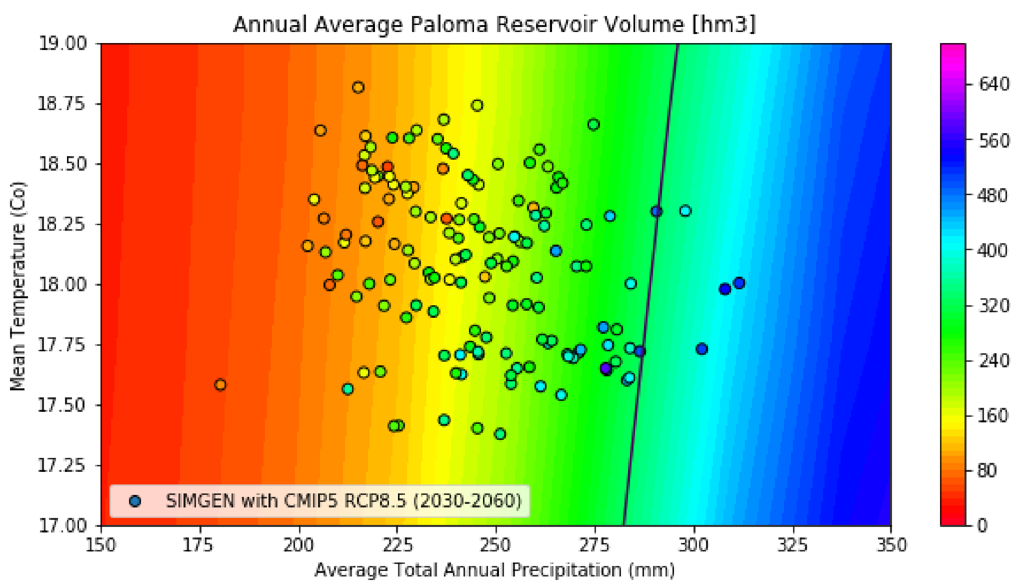

Figure 4.1.1. KPM1 output of the Limari Basin Case Study from the model ran with projected precipitation and temperature times series created using the weather generator, overlaid on the response surface resulting from the stress test. The response surface and circle colours have the same scale.

A histogram of the differences (response surface value minus the output from the model driven by the project series) (Figure 4.1.2.a) shows a maximum absolute difference of 288.7 hm^3 and a mean difference of -94.67 hm^3. The absolute percentage difference (difference/output from the model) histogram (Figure 4.1.2.b) shows that the difference can be up to 96% of the modelled reservoir volume output with a mean percentage difference of 36%. It is also evident from the histograms that the KPM model outputs driven by the projected time series primarily predicts higher reservoir volumes than what the response surface indicates.

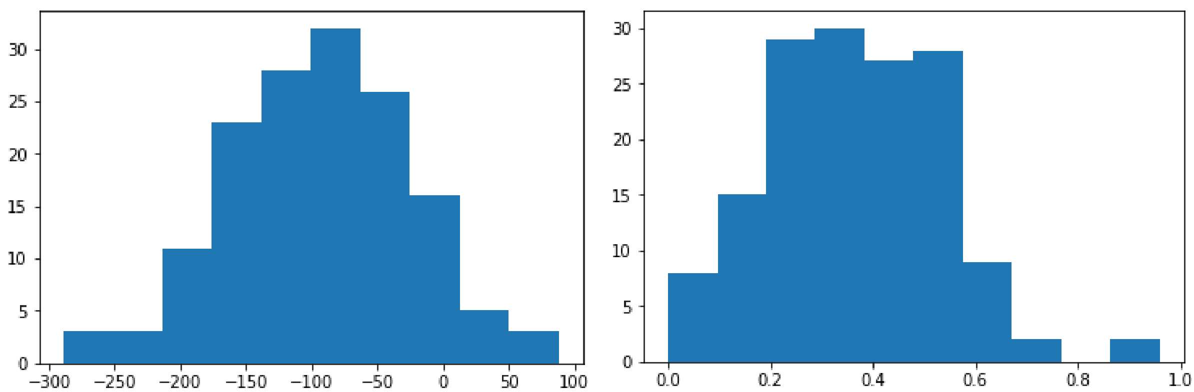

Figure 4.1.2. (a) Left: Frequency distribution of the difference between the response surface and modelled output. (b) Right: Frequency distribution of the absolute percentage difference between the response surface and modelled output.

To understand the discrepancy, it must first be noted that reservoir volumes at a particular timestep, t, is a function of the water supplied into the reservoir by flow and precipitation (S_t), the water losses due to downstream demand, evaporation and leaks (L_t) and the dammed volume at the previous timestep (V_{t-1}). S_t and L_t are dependent on the precipitation and temperature variables.

$$V_t = V_{t-1} + S_t - L_t$$

The response surface on Figure 4.1.1 shows that changes in temperature has a limited effect on KPM1, therefore the following analysis is focused on the effect of precipitation. Consider two precipitation time series on Figure 4.1.3. Both time series have similar precipitation averages from May 2030 to April 2060 but have resulted in significantly different reservoir volume averages. Regime A generally has higher peaks but more consecutive dry days, while Regime B has lower peaks occurring at higher temporal frequency. The rainfall peaks in Regime B do not contribute to an increase in storage because all inflow is used up to meet demand outflow, hence the resulting average reservoir volume is low. On the other hand, the high rainfall peaks of Regime A is able to meet the demand and also increase the storage of the reservoir to meet demand during “drier days” which results in a higher average reservoir volume. Ultimately it is the differences in the intra-annual and inter-annual regime (specifically the magnitude of the peaks and number of consecutive “low” rainfall months) of the precipitation series that causes differences in reservoir volume. Creating a response surface for the reservoir volume with average annual precipitation as an axis is inaccurate as this average statistic is not representative of the rainfall regime characteristics.

This explains why a lower average annual precipitation value does not necessarily result in lower reservoir levels among the results generated from the projected series (i.e. the circles in Figure 4.1.1) as the projected series have random regimes. The relationship is more evident on the response surface as the scaled series reduces peaks but preserves regimes. The difference between the response surface and the results from the projected series may also be attributed to differing regimes.

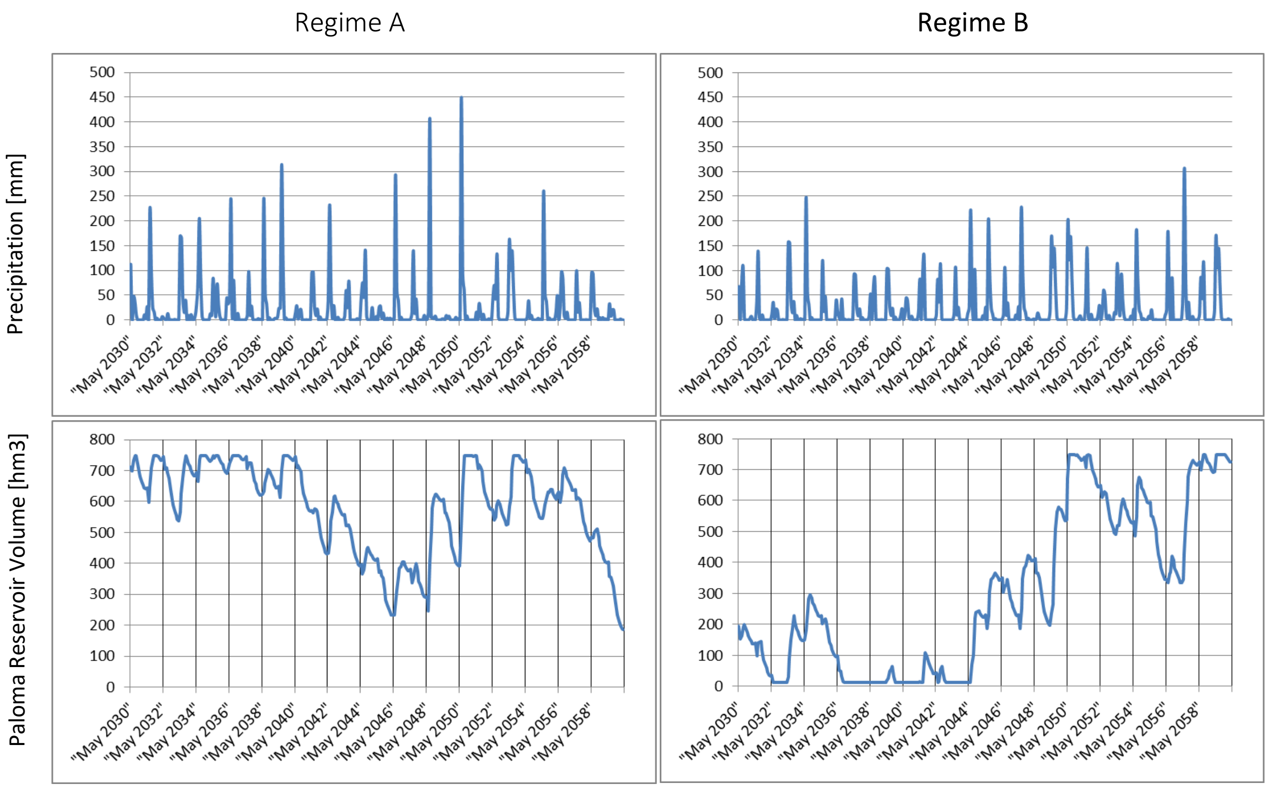

Figure 4.1.3. Two SIMGEN generated precipitation regimes and their associated Paloma Reservoir Volume output when routed through the WEAP model.

4.2. Classification of the Level of Concern Dimensions

The LOC analysis (see section 3.4.2.2) communicates to analysts and stakeholders the appropriate general strategic approach for the case. It does so by classifying the case KPMs into a 4-blockmatrix based on the qualitative assessments of climate change risks and analytical uncertainty (Figure 3.4.8). Another 9-block qualitative matrix is used for the classification of the climate change risk (Figure 3.4.3) with the plausibility and impact of failure as dimensions.

This aspect of the methodology is found to be subjective and challenging for the analysis to interpret (Gilroy and Jeuken, 2018). Specifically, in that the LOC is determined through a matrix with 2 risk classifications whereas the risk assessment matrix provides 3 classification of risk. CRIDA further lacks guidelines for the translation of the often-quantitative assessments of the dimensions of the LOC to the qualitative categories of the matrices. For example, the method recommends that the plausibility of failure is informed by historical trends, system sensitivity and the proportion of projections falling in the critical domain of the response surface. However, there are no clear boundaries on what trends or proportions would be classified as low, medium and high plausibility or what weights these three information sources would have in the conclusion. The classification is thus subject to the biases of the analyst and may differ depending on the person doing the assessment even if the same data is used. For example, analyst 1 may conclude medium plausibility of failure if 50% of projections lie in the critical domain, while analyst 2 may conclude a high plausibility of failure for the same statistic. On the other hand, there is very little guidelines within CRIDA on how the analyst may assess the impact of failure leaving the analyst to decide on the method of this assessment.

For the final dimension of the LOC, the analytical uncertainty, CRIDA only broadly lists indicators (See section 3.4.2.2) such as the consistency of information, spread of projections and the quality of the system model. However, it lacks guidelines on how these individual indicators would be assessed, how this individual assessment may be integrated for the overall assessment and how this assessment is translated to a qualitative rating for analytical uncertainty.

More guidelines and compatible tools need to be included in the methodology to ensure that:

1. A more consistent LOC result is achieved when the exercise is repeated for the same case study by different analysts.
2. The analysis is more straightforward, easy and quick to conduct for the analyst.
3. The results become more justifiable when presented to decision makers.

4.3. Adaptation Tipping Points under Transient Futures

Adaptation tipping points (ATP) specifies the conditions under which applied actions become insufficient and additional or complementary alternatives are required to maintain acceptable performance. This point is often expressed in terms of time or a metric such as in a previous case study of CRIDA (Gilroy and Jeuken, 2018). Under transient futures the action sell-by date may be translated to a metric of time by taking the median or quartile values of the distribution of performance across all futures according to Haasnoot et al. (2013)— stating for example, ‘‘on average the tipping point will be reached within 50 years”. The translation of this statement to the terms used in CRIDA would be that “50% of the scenarios lie in the critical domain of the response surface in 50 years”. There is an unexplored opportunity to link CRIDA risk assessment directly to the definition of ATP.

4.4. Research Questions

The research questions are formed to solve the specific issues found in the review of the CRIDA.

Research Question 1

How can the coherence between the response surface and the modelled future conditions using the projected series be improved?

Research Question 2

How can the assessments of impact of failure, plausibility of failure and analytical uncertainty be less subjective?

Research Question 3

How can the CRIDA risk assessment be linked to the definition Adaptation Tipping Points to create adaptation strategy pathways?

5. CRIDA proposed revisions

This section describes the additional guidelines proposed for the CRIDA method to resolve the research questions posed.

5.1. Revision to STEP 1: Decision Context

To resolve Research Question 1

In section 4.1 it is identified that there is little coherence between the KPM values on the response surface and the model outputs ran using the projected timeseries. Two options are proposed to improve this coherence: (1) Replace the x-axis of the response surface, the average Total Annual Precipitation measure, by some parameter that characterizes the rainfall regime or (2) Replace the KPM with a measure that is independent of its previous value.

Option 1 may not be feasible as it is difficult to characterise the rainfall regime with one parameter. The standard deviation of the regime gives no indication on the number of consecutive "low" rainfall days (i.e. days where the rainfall does not meet demand) and fitting a sine function through the regime results in a too rough characterisation of both the peaks and consecutive "low" rainfall days. Therefore option 2 is recommended. It is proposed to include the criteria of considering time independence in the CRIDA guidelines for the selection of appropriate KPMS if the average precipitation is used on one axis of the response surface. The analysis from section 4.1 is repeated with a KPM that is independent of its previous value. The results on Figure 5.1.1 and Figure 5.1.2 show better coherence between the KPM values on the response surface and the model outputs ran using the projected timeseries.

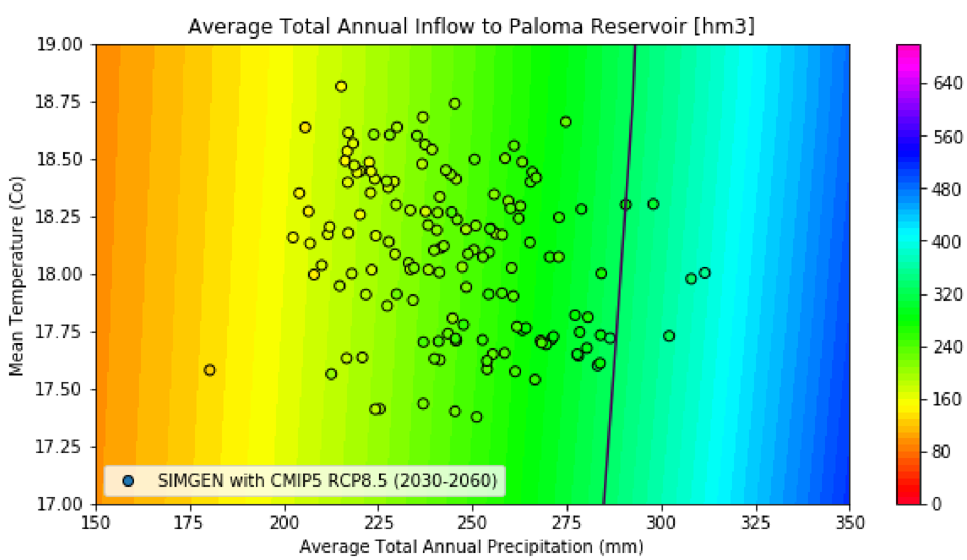

Figure 5.1.1 Revised KPM output of the Limari Basin Case Study from the model ran with projected precipitation and temperature times series created using the weather generator, overlaid on the response surface resulting from the stress test.

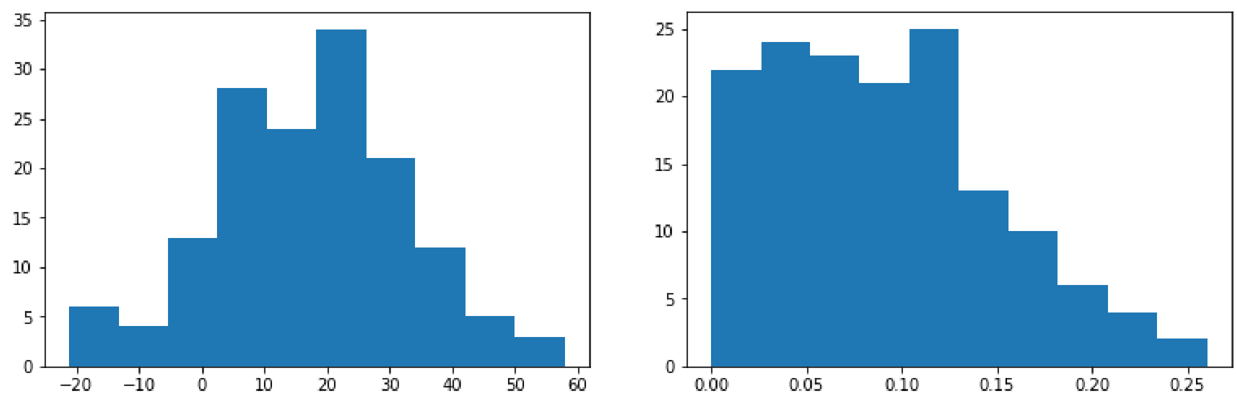

Figure 5.1.2 (a) Left: Frequency distribution of the difference between the response surface and modelled output. (b) Right: Frequency distribution of the absolute relative difference between the response surface and modelled output.

5.2. Revision to STEP 2: Bottom-up Vulnerability Assessment

To resolve Research Question 2 and 3

The proposed method follows a participatory semi-quantitative to determining the LOC. It provides additional guidelines for the quantitative assessments of risk, plausibility and analytical uncertainty as well as their conversion to the qualitative ratings compatible to the Future risk and LOC matrices. This more step-wise and methodological assessment aims to improve consistency in the application and remove analyst' subjectivity to resolve research question 3. Research question 2 is resolved by considering different RCPs in the assessment of plausibility and recommending separate pathways for each RCP when the planning horizon exceeds a specific year.

5.2.1. Future Risk

The proposed method for the future risk classification preserves the original procedure of CRIDA by categorizing the KPM according to the plausibility of failure and the impact of failure. However, it provides clearer guidelines for the assessment and the integration of different information sources. Furthermore, stakeholder defined thresholds are used to convert quantitative assessments to the qualitative rating compatible with the matrix. By doing so, the personal bias of the analyst in the assessment is removed while introducing the general risk perceptions of the stakeholders. In other words, this method shifts the subjectivity introduced from that of the analyst to those of the stakeholders in the selection of a strategy which will further improve its acceptability. A culture that is risk averse is likely to set more conservative thresholds which eventually favors robust measures. If a culture's risk-aversion is not considered and a flexible strategy is then proposed, there is a higher risk that the proposal will not be implemented as it no longer aligns with their overall perception. So rather than correcting for risk-aversion, this step embraces risk perceptions of the stakeholders by allowing stakeholders to co-design the categorization of future risk.

5.2.1.1. Stakeholder Risk Perception

Stakeholder risk perceptions are incorporated in the risk assessment by engaging them when defining thresholds to convert quantitative values of plausibility of failure and consequences of failure [impact] to qualitative ratings of low, medium and high.

For the plausibility of failure dimension, the stakeholders are asked to imagine 100 possible futures where a critical failure of the system may or may not occur. Their individual high plausibility of failure threshold is the number of critical failure scenarios; out of the 100, that would inspire the stakeholders to take immediate action. Their individual medium plausibility of failure is the number of critical failure scenarios that would inspire discussion about possible actions. Their individual low plausibility of failure is the number of critical failure scenarios that they are able to tolerate assumed be below the medium threshold. Answers from the stakeholders are averaged to obtain a representative estimate of the thresholds.

For the impact dimension, the stakeholders are first asked to identify a set of impact indicators then estimate qualitatively for each indicator the degree of impact if the critical threshold of a KPM is breached in terms of low, medium and high. A high impact rating would inspire immediate action. A medium impact rating would inspire discussion about possible actions. A low impact rating would be tolerated.

5.2.1.2. Plausibility

The proposed method for assessing the plausibility of a future state violating a critical performance threshold is determined from historical data (Has this threshold been breached historically and is there a clear trend towards the threshold?) and projected future states (What is the plausibility of failure in the future?). The planning horizon (near or long term) of the project determines how each of these analyses are integrated to a final plausibility rating (Table 5.2.1).

Table 5.2.1. Plausibility analysis according to planning horizon.

PLANNING HORIZON	ANALYSIS ON:
$< T_{CURRENT} + 5$	Historical Records
$> T_{CURRENT} + 5$	Projected Future States (Single RCP)

Plausibility analysis based on historical records only:

Historical records can provide insights into current or past climate, but due to non-stationarity in climate conditions these cannot be used with certainty to inform future states (UNESCO and CAZALAC, 2018, Blöschl and Montanari, 2010). Therefore, using historical records for assessing future plausibility of system failure under climate change is only applicable for very short planning horizons (<5 years from current year). The plausibility of failure is assessed qualitatively based on whether the critical threshold has been reached in the past and whether a trend analyses confirms a significant (p=0.05) trend towards the critical threshold (Figure 5.2.1).

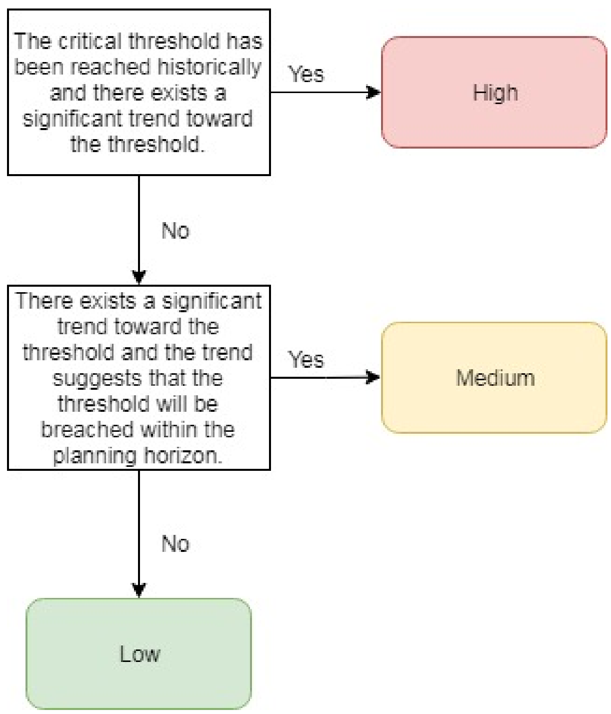

Figure 5.2.1. Framework for qualitative assessment of plausibility of failure based on historical records.

Plausibility analysis based on projected future states:

In the context of planning for climate change risks, planning horizons are likely to exceed 5 years. In many cases therefore, the plausibility of a future state violating a critical performance threshold is informed by the domain (critical or non-critical) on which possible future states plot on the response surface generated from the climate stress test. Multiple projections can be generated for example by using a weather generator. The temporal resolution of the projections (i.e. yearly or decadal) will vary according to the weather generator used and how the analyst post-processes the projections. Each data point of the projections plots at an x,y location on the response surface representing the system state, either critical or non-critical, for a certain year or decade. Plotting multiple projection series onto the response surface results in a scatter of states for a particular in timestep. For each timestep, the continuous probability distribution of the future states on the 2-dimensional response surface is calculated using a multivariate Kernel Density Estimation (KDE). The plausibility of failure (%) is then the area under the multivariate curve that is in the critical domain. By repeating this analysis per time-step, the result is the time-varying plausibility of failure at the resolution of the projections used. The value at the case planning horizon is converted to its low, medium and high qualitative rating based on the thresholds the stakeholders have defined (See section 5.2.1.1).

Historical records are not used explicitly in this plausibility of failure assessment however do contribute implicitly if the means of creating projections is chosen correctly. Weather generators such as SIMGEN (Appendix A) extend the current records with a climate change trend while incorporating historical inter-, intra-annual and decadal variations. If the starting point is already in a critical or close to critical state, in other words the critical threshold has been breached in the past, projections with trends to more stressful conditions will push the future states faster and further into the critical domain compared to a starting point where conditions have not breached the critical threshold.

5.2.1.3. Impact

The first step in this proposed method of impact assessment is to identify and prioritise measurable (quantitative or qualitative) consequences of surpassing the critical threshold through collaboration with stakeholders. An important consideration when defining the impact indicators is that they must be applicable to all key performance metrics defined in the initial step of CRIDA to ensure that the level of impact is comparable between the key performance metrics.

The definition of impact in the risk framework of the 5th Assessment report of the IPCC may serve as a guide for identifying appropriate indicators. In this report, they define the assessment of impact to consider the vulnerability and exposure to the hazard. Vulnerability is defined as the propensity or predisposition to be adversely affected which can encompass a variety of elements including sensitivity or susceptibility to harm and lack of capacity to cope. While Exposure is defined simply as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. Table 5.2.2 serves as a guide for identifying indicators.

Table 5.2.2. Guide for identifying impact indicators when a critical threshold is surpasses with example indicators for a scenario that the Paloma Reservoir surpasses its critical threshold.

SECTOR		INDICATOR
ECONOMIC	Vulnerability	e.g. Annual Industry Losses
	Exposure	e.g. Number of industries affected
ENVIRONMENTAL	Vulnerability	e.g. Reduction in Ecosystem Services
	Exposure	e.g. Area affected
SOCIAL	Vulnerability	e.g. Loss of livelihood
	Exposure	e.g. Number of People Affected

The next step is to estimate the consequence of critical failure (the point when the critical threshold is exceeded) using models or other tools in terms of the impact indicators identified. It is assumed that the impact is constant in the critical domain regardless of any further changes in the key drivers. These estimates are then converted to qualitative ratings of low, medium and high using the thresholds defined by the stakeholders. Where multiple indicators are identified, the ratings are averaged or combined according to weights assigned to each in the prioritisation.

5.2.2. Analytical Uncertainty

The proposed methodology focuses on sources of analytical uncertainty that are identified in this research, namely, the critical threshold definition, system model, projected variables and risk perceptions of stakeholders (Figure 5.2.2). The significance of the latter is reduced by including risk perceptions of stakeholder within the LOC analysis. The following sections describe how the uncertainty in each source may be assessed following where possible the IPCC recommendations for assigning the level of certainty based the robustness of evidence, if there are multiple, consistent independent lines of high-quality evidence, and the agreement amongst evidence (Mastrandrea et al., 2010a). The overall uncertainty rating in the analysis is the highest uncertainty rating of the individual assessments.

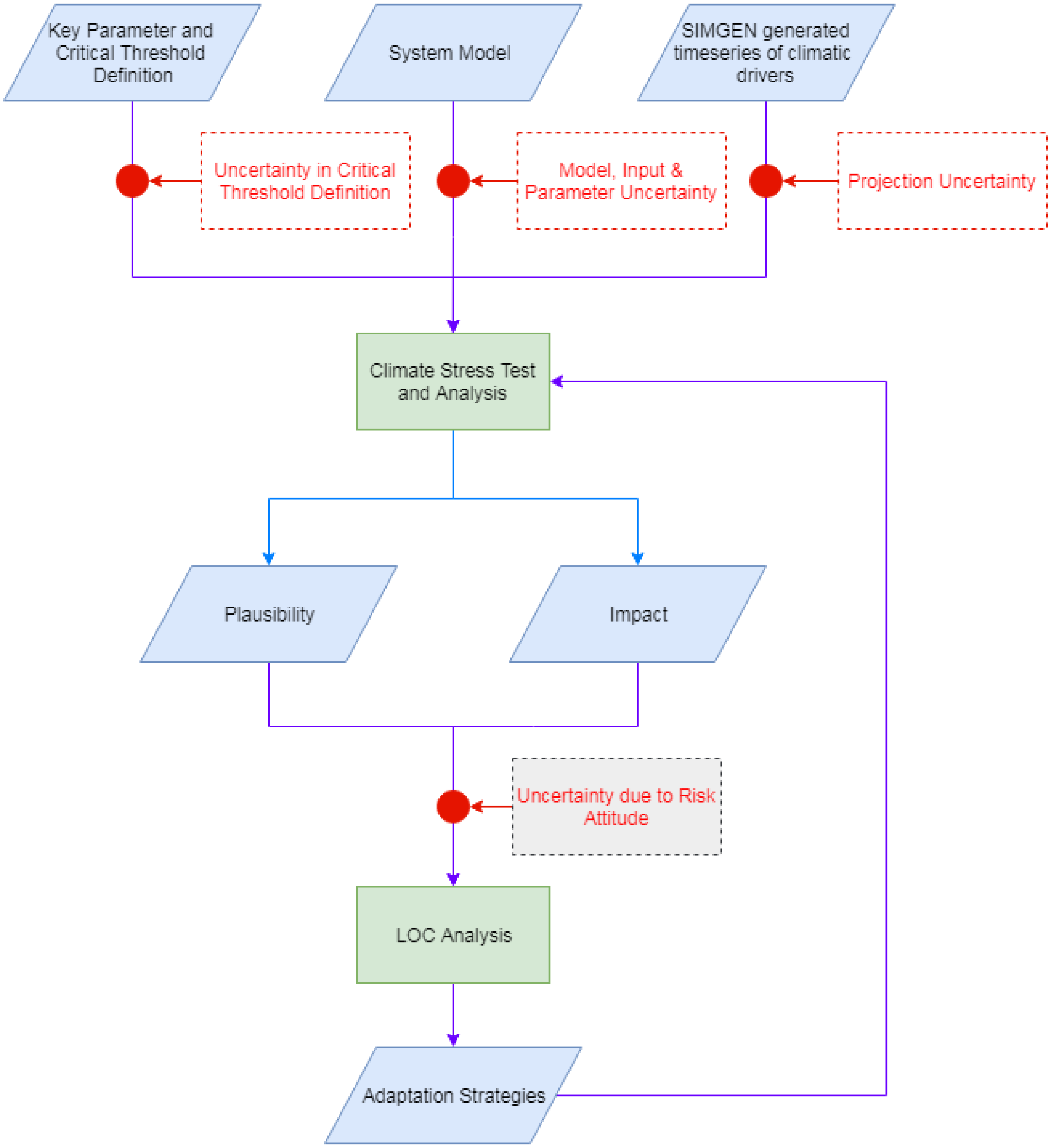

Figure 5.2.2. Uncertainty Propagation in CRIDA.

5.2.2.1. Critical Threshold Definition

In the decision context step of CRIDA, key performance metrics are defined along with a critical threshold which when surpassed, results in system failure. The threshold is used in the methodology to directly assess the plausibility of system failure indicating the level of future risk of the climate change impact. Any changes in the critical threshold will significantly affect the stress test analyses assuming that the critical threshold is surpassed in some of the climate change scenarios. The closer the current system is to the threshold, the more sensitive the analyses will be to the critical threshold definition. The proposed methodology for assessing the confidence in the critical threshold definition roughly follows the scales of confidence used be the IPCC to communicate uncertainty. The analytical uncertainty is can be classified as:

- Low - There is full agreement that a breach of the critical threshold defined has led to a significant reduction in system performance or system failure.
- Medium - There is consensus that a breach of the critical threshold defined will lead to a significant reduction in system performance.
- High - There is limited evidence/studies and/or little agreement in studies that suggest a breach of the critical threshold defined will lead to a significant reduction in system performance.

Note that agreement and consensus encompass both statistical evidence as well as stakeholder experiences. It is recognized that the reality is often not represented by recorded observations, hence stakeholder experiences are equally as important when justifying a critical threshold for the system.

5.2.2.2. System Model

The system model is used in the stress test to create the system response surface for the level of concern analysis and to test the effectivity of adaptation strategies in the following steps of CRIDA. The output from the system model is critical to determining the level of concern and test adaptation strategies. High uncertainty in the system model will thus result in high analytical uncertainty in the overall analyses.

There are several uncertainties within models identified by Walker et al. (2003) (i.e. context, model uncertainty, inputs and parameter uncertainty) which are accumulated in the model outcome uncertainty. Instead of looking at the analytical uncertainties of each input and parameter used in the model, the collective uncertainty may be determined from the model outcome uncertainty rating. The recommended quantitative statistics to evaluate models are the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). In general, model simulations can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 25 % for streamflow (Moriasi et al., 2007).

In addition to uncertainties in the model simulating current conditions, there is additional uncertainty when a model is used to forecast system response. Rainfall-runoff models when calibrated using historical datasets can generally only be used for forecasting where the future mean annual rainfall is no more than 15% drier or 20% wetter than the mean annual rainfall in the model calibration period (Vaze et al., 2010).

Considering the models ability to simulate current conditions and to forecast system response the analytical uncertainty where it relates to the system model in the analysis may be classified according to the framework on Figure 5.2.3.

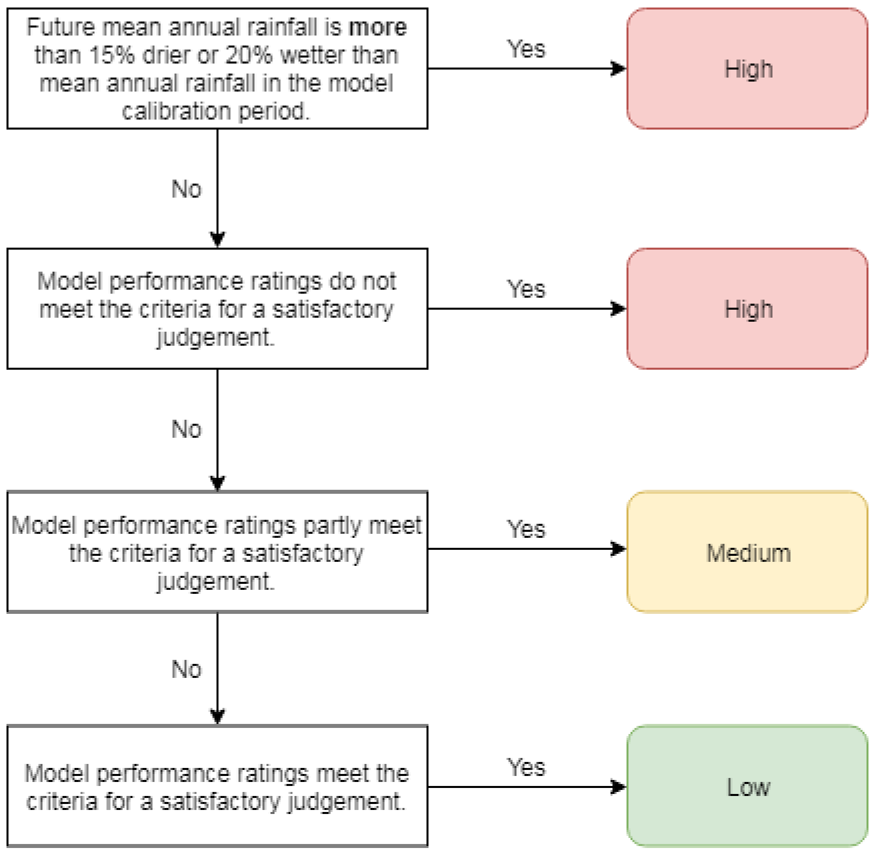

Figure 5.2.3. Framework for assessing analytical uncertainty in the system model.

5.2.2.3. Projections

Uncertainty in projections cascades onto the plausibility assessment which eventually leads to uncertainty in the LOC rating. However, the assessment of the level of uncertainty in the projections presents a large challenge as there are no observations for comparison. GCMs still remain the best source of information for future climate trends. But it is understood that using GCMs to extrapolate climatic variables into the future is attached with high analytical uncertainty due to uncertainties in the model inputs and parameters, uncertainties in the underlying science of the model structure and uncertainties due to downscaling. Furthermore, measuring uncertainty based on coherency of the projected monotonic trend and the range of projections cannot be done because GCMs are not independent (Tebaldi and Knutti, 2007). Due to climate non-stationarity historical trends also cannot be used to assess the uncertainty of projected trends of the future. While agreement amongst the projections and with historical trends can vary from high to low, the robustness of evidence remains low because of climate non-stationarity and GCM dependencies and inherently low-quality. This relationship in the data translates to very low to at most a medium confidence in projections (Mastrandrea et al., 2010a). The consequence of such an assessment is that any case which uses projections falls in the two right quadrants of the LOC matrix. The downside of this, is that uncertainty may be over-estimated because uncertainty in the projections does not have the same significance for all cases. To explain this statement, it is iterated that projections are plotted on top of the response surface to calculate the distribution of projections within the critical domain as the plausibility of failure (%). These projections are anchored essentially to current conditions. In other words, current conditions are the starting point of projections. On the response surface therefore, the scatter of projections cluster close to the point of current conditions and its distance from the point of current conditions is limited by what is physically possible, in terms of how drastic the climate can change in the future. Temperature cannot increase by 10^{o}C for example in a decade. Hence, the closer current conditions are to boundary of the critical and non-critical domain, the more significant uncertainties in projections become. For example, if current conditions plot far enough into non-critical domain, all projections will fall in the non-critical domain as well, regardless of any uncertainties in the projections that would shift the points within a reasonable range. The uncertainty in the projections become significant if current conditions are close to the boundary of the critical and non-critical domain. Hence the sensitivity of the analysis to the projections is considered when assigning analytical uncertainty.

The framework for assessing analytical uncertainty related to the projections are shown in on Figure 5.2.4. In rare cases where only historical data is used for the plausibility of failure assessment (see Table 5.2.1), the uncertainty attached to projections does not exist. If projections are used, then the sensitivity of the analysis to the projections is considered. A sensitive analysis is one that shifts in the qualitative rating of plausibility in time. In section 5.2.1.2, it is explained that the outcome the plausibility assessment is a plausibility of failure (%) per timestep. This percentage is translated to its qualitative risk rating (low, medium or high) per timestep using stakeholder risk perceptions. An analysis which shifts in this qualitative rating from current conditions to the planning horizon and reasonable timesteps afterwards would be considered sensitive. However, one that remains at the same qualitative rating from current conditions to the planning horizon and reasonable timesteps afterwards would not be considered sensitive.

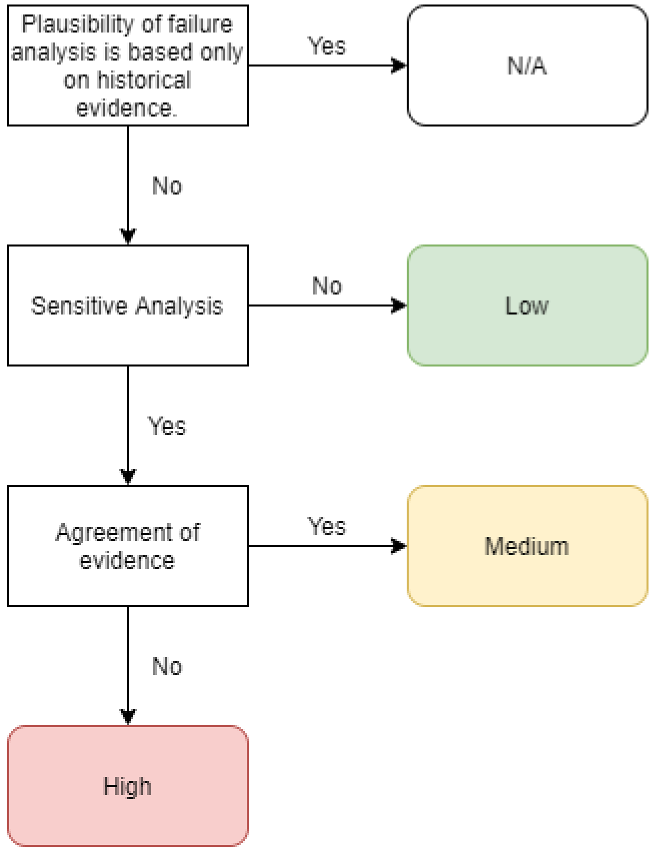

Figure 5.2.4. Framework for assessing analytical uncertainty in plausibility of failure analysis.

5.3. Revision to STEP 3: Formulating Robust and Flexible Actions

To resolve Research Question 4

The proposed method follows the same general steps described in the CRIDA methodology, however links the risk assessment to the development of adaptation strategy pathways in the final stage.

To develop adaptation strategy pathways more explicitly, the first step is to evaluate the effectiveness of each action. This is done by to repeating the plausibility of failure assessment described in section 5.2.1.2 with each action incorporated into the system model. The result is the temporally varying plausibility of failure percentage of the system with individual actions incorporated.

The next step is to define the ATP of an action in terms of the plausibility of failure percentage. Stakeholders have defined what they consider to be a low, medium and high plausibility of failure during the bottom-up vulnerability assessment stage of CRIDA as discussed in section 5.2.1.1. The analyst then chooses the appropriate threshold enough to reduce the future risk rating to low using the matrix on Figure 3.4.3. For example, if the impact classification is low, a plausibility rating reduced to medium is sufficient. On the other hand, with an impact classification at high, the plausibility rating should be reduced to low.

An action is sufficient up to the time it is no longer able to keep the plausibility of failure percentage below the threshold defined in the previous step. At this point, the pathway should shift to an alternative action or add a complementary action to maintain the plausibility of failure percentage below the threshold.

6. Case Study: The Limari Basin

In this chapter, CRIDA is applied onto the Limari Basin case study with the additional guidelines presented in Chapter 5 as a 'proof of concept'. To supplement the participatory aspects of the methodology, a field visit was organised to gather information regarding the decision context, stakeholder risk perceptions and acceptable adaptation strategies in the basin. More information regarding this visit is on Appendix C.

6.1. Case Study Background

The Limari basin covers an area of 11,800 km^2 and is located in a semi-arid area west of the Andes mountain range in the Coquimbo region of Chile (Figure 6.1.1) (Corporación Regional de Desarrollo Productivo, 2016). At its highest points (>5000 m ASL) total annual precipitation is 300 mm which decreases to 100 mm closer to the coast subject to significant inter-annual and decadal variability linked to the ENSO and the pacific decadal oscillation (Vicuña et al., 2011, Urquiza and Billi, 2018). More than 80% of rainfall falls between May and August (austral winter) and is stored as snow above the zero isotherm at high altitudes which feed the tributaries of the Limari river (Vicuña et al., 2012). This regime has a peak flow during spring/early summer and very low flows from late summer to late fall (Vicuña et al., 2011).

An innovative market-based water governance (Appendix B.1) and the Sistema Paloma (Appendix B.2), a complex system of infrastructures for water (superficial and subsurface) distribution and storage, have allowed the agricultural sector to develop in this semi-arid region. It is currently the primary economic sector and uses the majority of the water resources (517.0 hm^3/year). Other consumptive water uses are for potable demand (11.9 hm^3/year) and mining (1.2 hm^3/year). Refer to Appendix B.3 for more information regarding the water use and water management system of the Limari Basin.

While drought is a natural occurrence in the basin, historic data shows evidence of an increase in drought frequency, duration, and severity as well as progressing desertification (Vicuña et al., 2014, Meza, 2013, Meza et al., 2010, Valdés-Pineda et al., 2014). For example, the recent mega-drought lasted from 2003-2015 which is significantly higher than the common drought cycle of 4 years. Climate projections further suggest a drier and warmer future climate indicating that water scarcity will be a recurring problem in the area (Vicuña et al., 2011, Held and Soden, 2006, Fuenzalida et al., 2007, Vicuña et al., 2014). Semi-arid basins with snow-melt driven hydrologies, such as the Limari Basin, are extremely sensitive to climate change because the already scarce water resource depends on both precipitation and temperature (Barnett et al., 2005, Mishra and Verbist, 2017). An increase in temperature and a reduction in precipitation would increase snow melt and reduce snow accumulation at high altitudes (Vicuña et al., 2011, Held and Soden, 2006, Fuenzalida et al., 2007). In the short term, the increased snow-melt adds water to streamflow increasing the annual water flow and reservoir storage while shifting seasonal maximums to earlier periods (Ribbe et al., 2018). In the longer term, however, snow melt as an additional source of water may disappear translating to a reduction in annual flow (Vicuña et al., 2012, Vicuña et al., 2011). At lower altitudes, the change in climate would theoretically increase evapotranspiration, reduce soil moisture content, reduce aquifer recharge and increase in erosion (Muck et al., 2013). The compound effects of climate change at high and low altitudes will ultimately result in an increase in demand (due reduced irrigation coverage) and a decrease in supply from the superficial (due to reduction in total annual flow) and subsurface sources (due to reduction in aquifer recharge) indicating a more water stressed future.

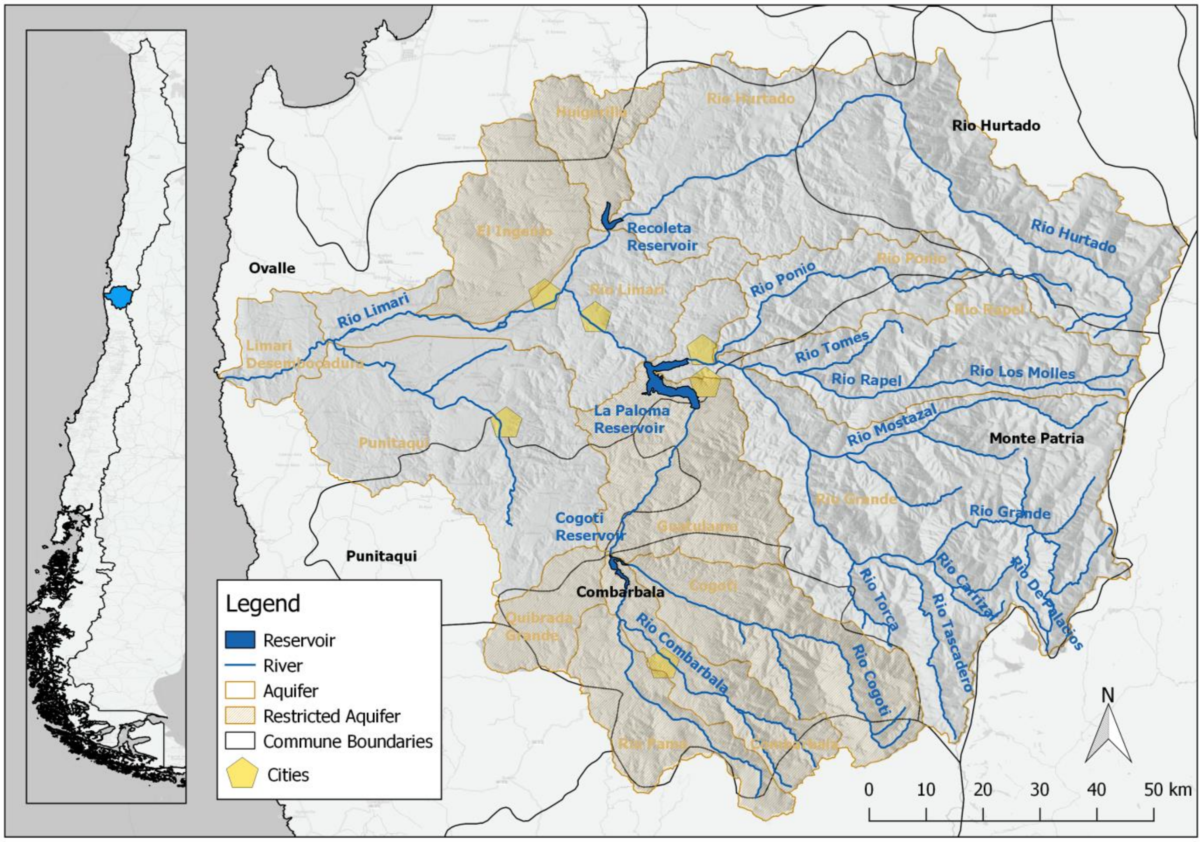

Figure 6.1.1. Physical features of the Limari Basin.

The portfolio of options available to farmers to accommodate these increasingly stressed conditions are becoming more limited as farmers continue to increase farmed acreage devoted to high value permanent crops with the improvement in irrigation infrastructure and technology. This is a typical consequence of basin closure, as stated by Molle et al. (2010), where the slack in water resources availability is reduced due to basin overdevelopment. The basin aquifers have also since been declared '*Restricted*', limiting the water rights allocated for legal groundwater extraction (Vicuña et al., 2014).

Due to the joint effect of water insecurity in the future, the basins economic reliance on agriculture, the overdevelopment of irrigation infrastructure and the lack of structural arrangements determining how the existing water is organized, distributed and employed, the Limari Basin has some of the highest agri-business vulnerability to climate change settlements in the country (Ferrando and Francisco, 2003, Peña et al., 2004, Urquiza and Billi, 2018)

6.2. STEP 1: The Decision Context

The Limari Basin decision context is shown on Figure 6.2.1. In grey are the original definitions from the 2016 study that have been revised. The following sections describe the justifications for these revisions.

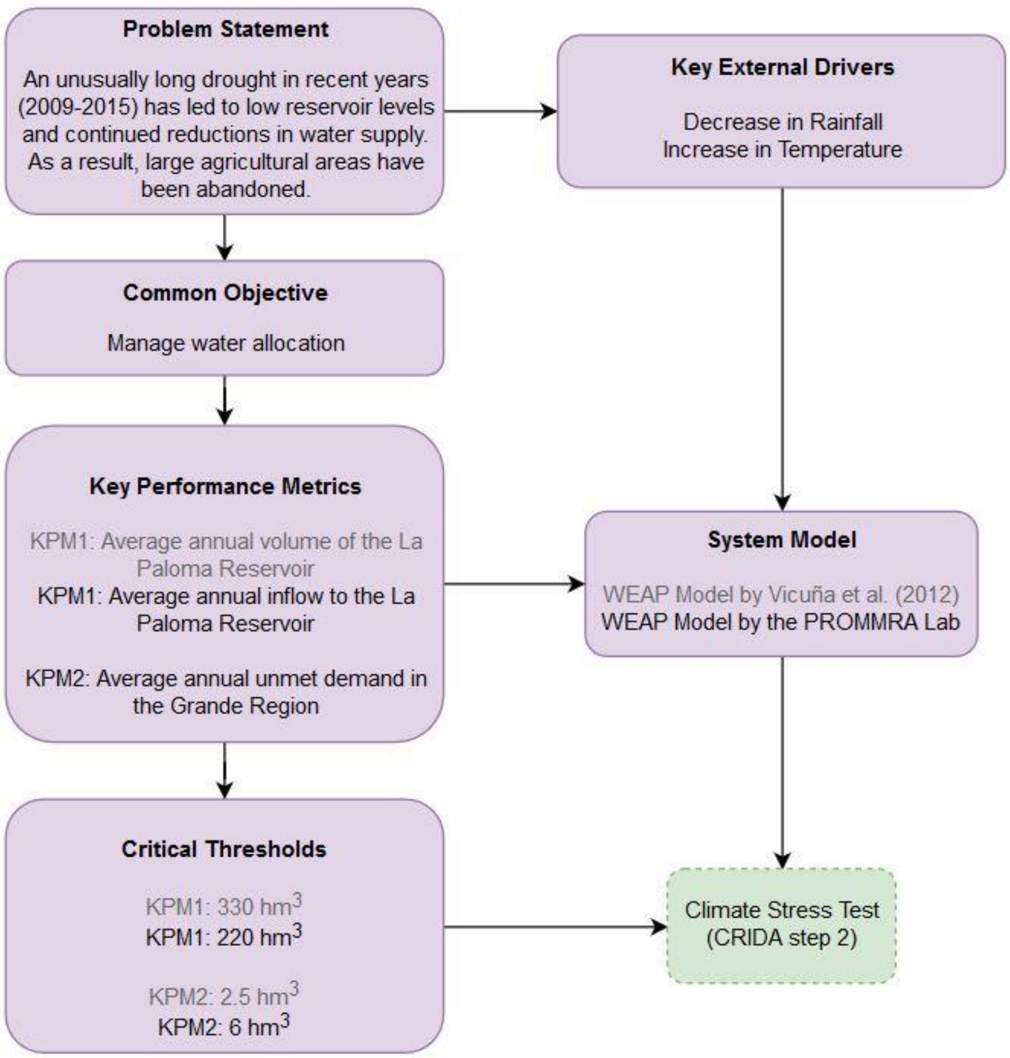

Figure 6.2.1 Revised Decision Context Definition for the 2018 Limari Basin water security case study. In grey are the original definitions from the 2016 study that have been revised.

6.2.1.Revised System Model

The system model must be accurate in representing the elements of the system listed by Mendoza et al. (2018). However, a review detailed in Appendix B, found that the WEAP model by Vicuña et al. (2012) does not represent current conditions in the area, particularly when it comes to the agricultural conditions which uses 97% of the consumed water in the area. The patterns represented is similar to the patterns reported before the construction of the Sistema Paloma. After the constructions of the irrigation network, farmers have shifted much of their annual crops, such as cereals and alfalfa to more high value permanent crops such as vineyards and citrus trees. Therefore, another WEAP model was sourced from the Laboratorio de Prospección, Monitoreo y Modelación de Recursos Agrícolas y Ambientales (PROMMRA Lab) associated with the University of La Serena's Department of Agronomy. WEAP is an initiative of the Stockholm Environment Institute (SEI) that operates on basic principles of water accounting. It allows for an integrated model of the water resources system by simulating natural hydrological processes as well as anthropogenic activities superimposed on the natural system. The WEAP model from PROMMRA consists of 7 upper basin models to model the snow-melt driver hydrology of the basin. The flow output from these upper basin models are then used as the input for the main model which is used for the stress test and solution testing (Figure 6.2.2). The limitation of the current PROMRRA lab model and the changes made to this model in this study is also discussed further in Appendix B.

6.2.2. Revised KPM

During the workshop held on the 9th of November 2018, the primary vulnerabilities in the basin were revisited to set the context for discussions regarding the next steps of CRIDA. These discussions resulted in the identification of a different set of KPMs for the analysis:

- Ground water depth at Romerlacillo (-25 m [below ground level])
- Average annual volume of the La Paloma Reservoir as it relates to drinking water (12.5 hm^3)

Ground water depth as a KPM cannot be implemented in this study because no comprehensive groundwater study currently exists in this basin to inform a groundwater water model. It is recognized however in this report as an important KPM to consider as rural communities such as at Romerlacillo that rely on groundwater for substinence farming are identified as being the most vulnerable in the basin (Meza et al., 2010, Roco et al., 2016). While this is beyond the scope of this research, a groundwater study should be prioritized in future work to properly represent the vulnerability of rural communities to climate change.

While both stakeholder groups in 2016 and 2018 identified the volume in the La Paloma Reservoir as a KPM, the groups focused on different sectors (2016; Agriculture and 2018; Potable Demand) which resulted in a different definition of the critical threshold. As the La Paloma Reservoir is the source for both irrigation and potable water, the conservative estimate of the critical threshold based on irrigation demand is used in this study to consider both functions.

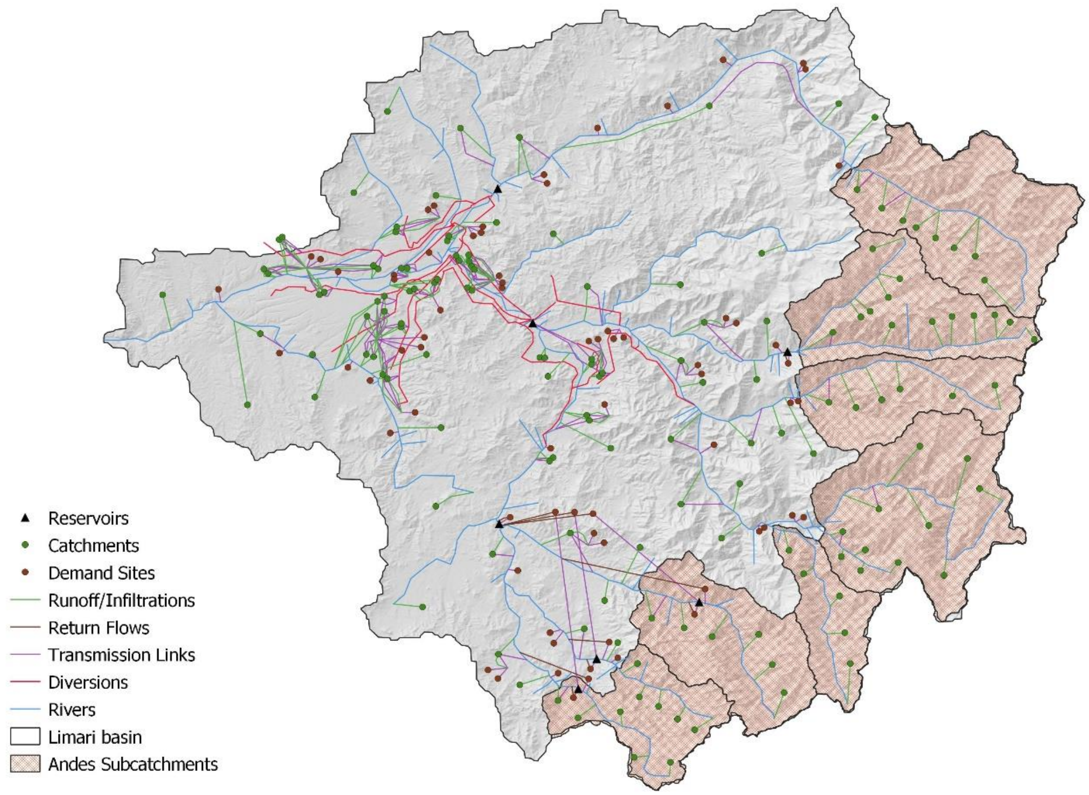

Figure 6.2.2 WEAP model of the Limari Basin courtesy of the PROMMRA Lab. Note that the adaptation solutions have already been added in this image.

The Annual Average Volume of the Paloma Reservoir as a KPM is however ultimately replaced with the Annual Total Reservoir Inflow to the Paloma Reservoir in accordance to the recommendations in section 5.1. The latter has less dependence on its value from the previous time step and is thus less dependent on precipitation regime. This holds for the WEAP model used in the Limari Basin case study but may not hold for other models as they may have a storage factor.

The assessment of whether the response surface is representative of conditions under the projected time series shown in section 4.1 is repeated with the revised KPM. The results on Figure 6.2.3 shows better coherence between them. The histogram of differences (Figure 6.2.4.a) and absolute relative differences (Figure 6.2.4.b) also support a conclusion that the modelled outputs and the response surface are more similar when using the Annual Total Reservoir Inflow to the Paloma Reservoir as the KPM. The maximum difference is 57.8 hm3, the mean difference is 17.13 hm3, the maximum absolute difference is 26% and the mean absolute difference is 9%. The cause of the inaccuracies is likely due to snow melt, which influences the inflow, relying on past events (i.e. how much snow has accumulated is a function of temperature and precipitation).

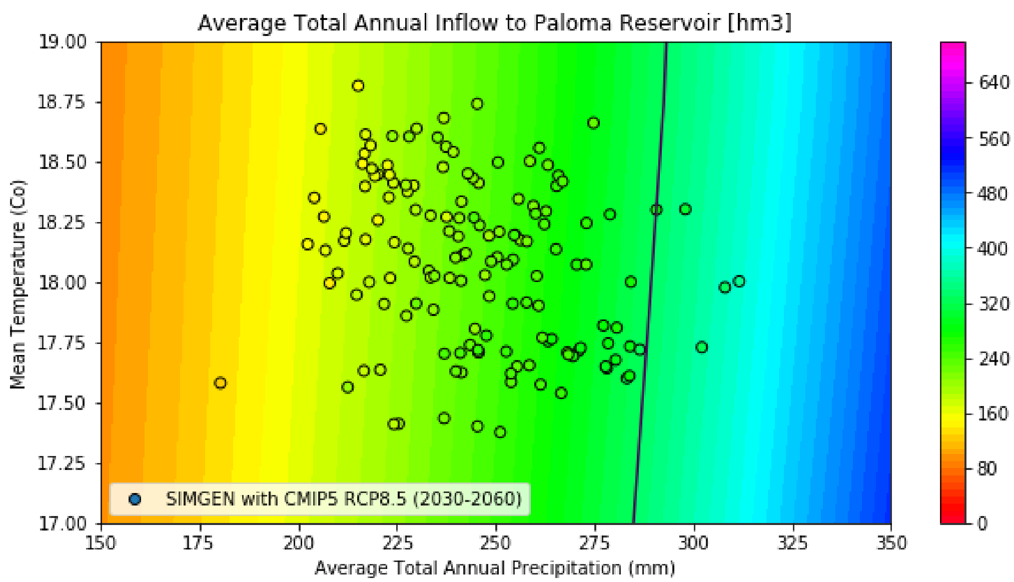

Figure 6.2.3. Revised KPM output of the Limari Basin Case Study from the model ran with projected precipitation and temperature times series created using the weather generator, overlaid on the response surface resulting from the stress test.

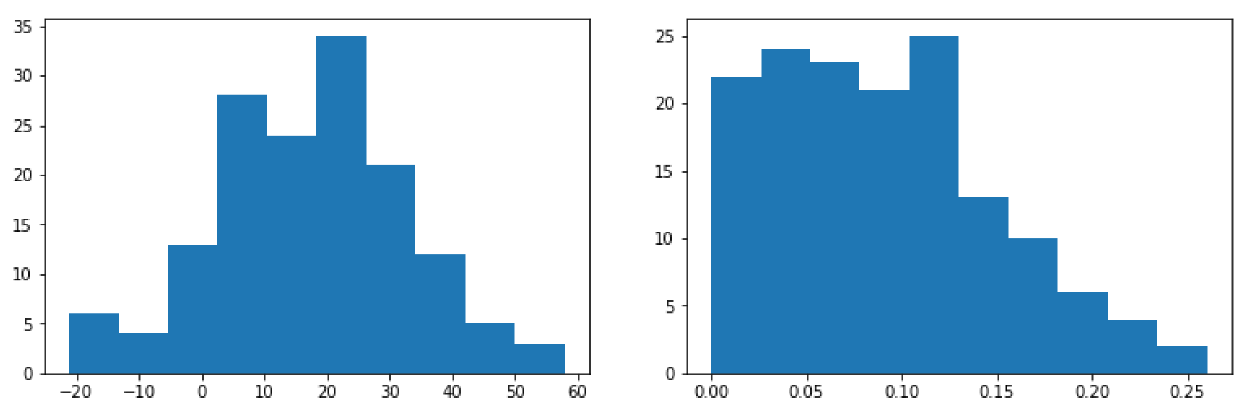

Figure 6.2.4. (a) Left: Frequency distribution of the difference between the response surface and modelled output. (b) Right: Frequency distribution of the absolute relative difference between the response surface and modelled output.

6.2.3. Revised KPM Critical Thresholds

The thresholds for both KPM's have also been modified. After consultation with the author of the 2016 study, the threshold for KPM, Average annual inflow to the La Paloma Reservoir, is revised to 220 hm^3 so that the threshold is representing a more critical scenario. The threshold for KPM: Average annual unmet demand in the Grande Region is revised to 6 hm^3. The original threshold was based on the 10^{th} percentile historical annual unmet demand simulated with the WEAP model of Vicuña et al. (2012). As this application of CRIDA uses a different model than the 2016 previous study, a new threshold is defined.

6.3. STEP 2: Bottom-Up Vulnerability Assessment

6.3.1.The Climate Stress Test

Following the guidelines of CRIDA, the climate stress test is performed through an iterative manipulation of the identified key external drivers of the system model to generate different key performance [metric] outcomes.

A 25- year (1990-2015) time series of the drivers are taken from station records. The temperature series is shifted by from t-1 to t+3ºC in 1ºC increments and the precipitation series is scaled by 10% to 140% in 10% increments. The range of testing is informed by the range of the future projections generated by the weather generator. Every combination of the temperature and precipitation series (56 iterations) is routed through the system model to generate the key performance metric series. This is automated by a python script accessing WEAP API.

The temporal averages of the drivers and performance metric over the 15-year period (2000-2015) are calculated for each iteration and plotted as a point on the 3-dimensional response surface. The first decade is excluded to allow the model to stabilize when solutions are being tested (i.e. reservoir filling). The performance metric is interpolated between the points to generate a continuous contour of the system response.

Figure 6.3.1 shows the response surface for the KPMs defined in the decision context. The y-axis is the spatially (across Las Ramadas and Ovalle weather stations) and temporally (across 2000 – 2015) averaged temperature series in the basin. The x-axis is the spatially (across all stations) and temporally (across 2000-2015) averaged annual precipitation in the basin. The response surfaces of both KPMs indicate that the historical conditions in the basin fall in the critical domain reflecting the sustained drought in the area since the start of the century.

The contours on the response surface indicate that precipitation dominates temperature in driving changes for both KPMs. This biased sensitivity is partly attributable to the KPMs being total annual measures. Precipitation is found to affect streamflow magnitude while temperature causes shifts in the seasonal mean

Vicuña, Garreaud et al. (2011). When up-sampling the metrics to the annual scale the effects of temperature are smoothed. Furthermore, the biased sensitivity may be exacerbated because the model only considers temperature variations due to climate change when calculating snow melt and ignores this factor in other processes such as evaporation and transpiration.

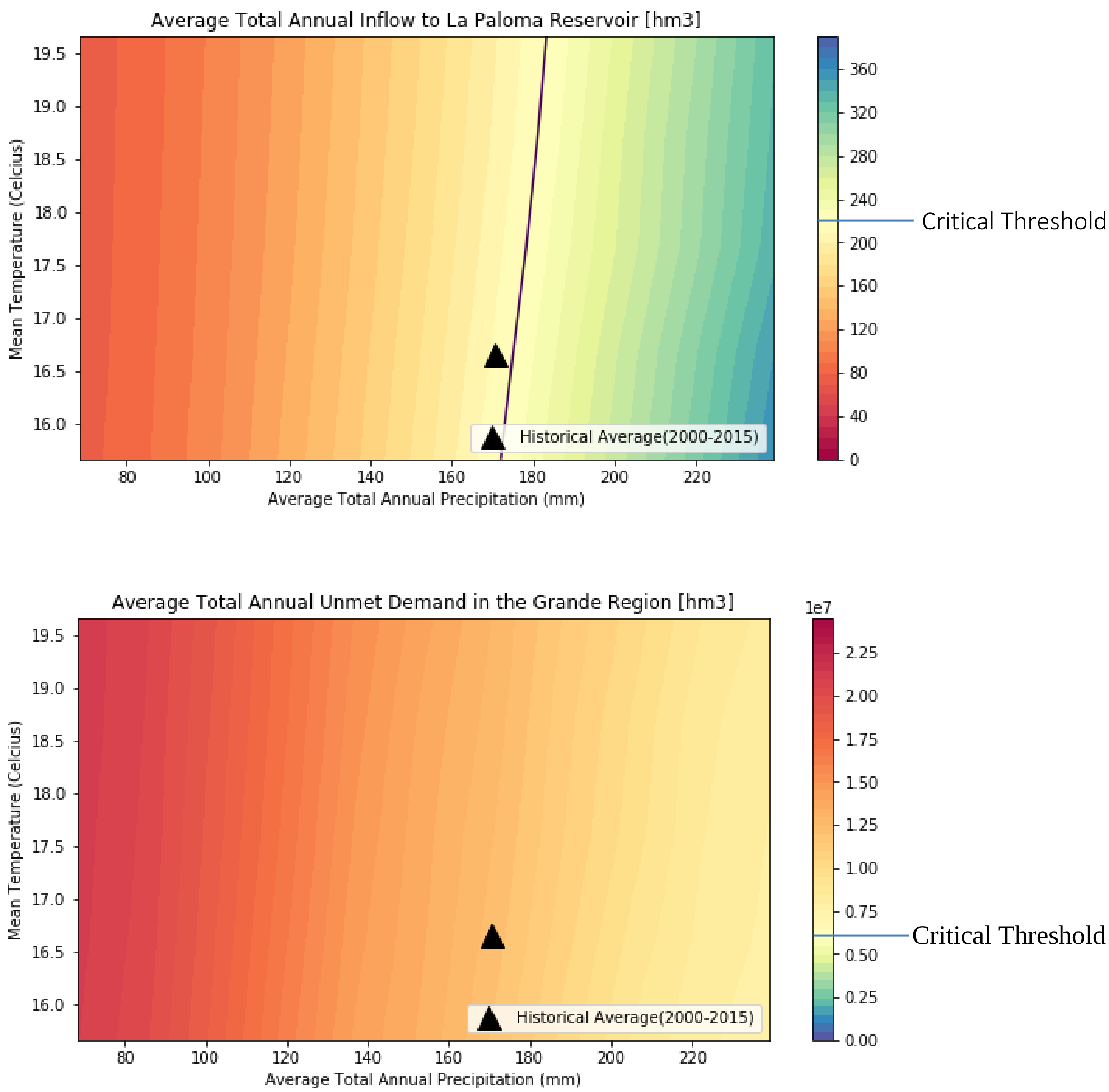

Figure 6.3.1. Response Surface of (A) Total Annual Inflow to La Paloma Reservoir and (B) Total Annual Unmet Demand in the Grande Region

6.3.2. The Level of Concern Analysis

The LOC analysis for each KPM is discussed in the following sections. However, the results are summarised on Figure 6.3.2 LOC Analysis Results for KPM1: Total Annual Inflow to La Paloma Reservoir and KPM2: Total Annual Unmet demand in the Grande Region. The assessment resulted in a high future risk rating for both KPMs considering that the plausibility of failure and impact of failure was determined to be medium-high. The Analytical Uncertainty Rating for KPM: Total Annual Inflow to La Paloma Reservoir is medium attributable mainly to the system model uncertainty. On the other hand the Analytical Uncertainty Rating for KPM: Total Annual Unmet demand in the Grande Region is High due to uncertainty in the critical threshold definition.

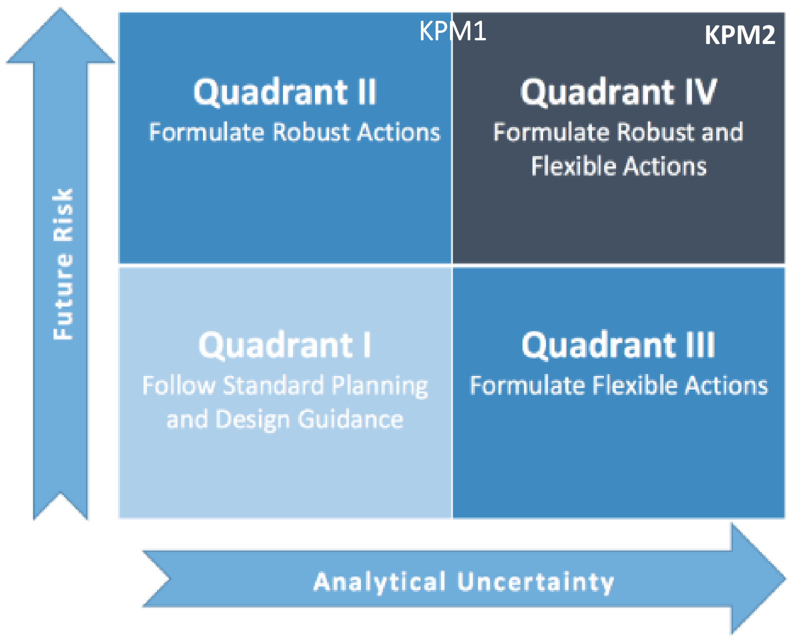

Figure 6.3.2 LOC Analysis Results for KPM1: Total Annual Inflow to La Paloma Reservoir and KPM2: Total Annual Unmet demand in the Grande Region.

6.3.2.1. Future Risk

Stakeholder Perceptions

During the workshop and survey held on the 9th of November 2018, the stakeholder risk perceptions was gathered. Appendix 0 details the workshop, survey and stakeholder attendance. Stakeholder identified the impact indicators appropriate for this case; namely Migration, Level of Poverty and Loss in Productivity and attached a low, medium and high rating for each indicator under the conditions that the critical threshold of a KPM is breached. Their responses are summarised on Table 6.3.1. Assuming equal weights to all indicators, the consequence of the KPMS breaching their critical threshold is Medium-High. The KPMs however used in this exercise differ from the KPMs used in the final analysis. The questionnaire with the corrected KPMs was forwarded onto stakeholders but no responses were received. Therefore, for the purpose of this proof of concept, a medium-high rating is used for both corrected KPMs.

In the same questionnaire, the stakeholders were asked to define thresholds for low, medium and high plausibility of failure. Their responses are summarized on Table 6.3.2.

Table 6.3.1. Stakeholder perceptions on the consequence of failure for each KPM.

	STAKEHOLDER 1	STAKEHOLDER 2	STAKEHOLDER 3	STAKEHOLDER 4	AVERAGE
KPM: VOLUME OF THE PALOMA RESERVOIR AS IT RELATED TO DRINKING WATER AVAILABILITY					Medium-High
MIGRATION	Medium	High	Medium	Medium	
LEVEL OF POVERTY	Medium	High	Medium	High	
LOSS IN PRODUCTIVITY	High	High	Medium	High	
KPM: UNMET WATER DEMAND IN RURAL COMMUNITIES					High
MIGRATION	High	High	Medium	High	
LEVEL OF POVERTY	High	High	Low	High	
LOSS IN PRODUCTIVITY	High	High	Medium	High	

Table 6.3.2. Stakeholder perceptions of low, medium and high plausibility of failure.

	LOW	MEDIUM	HIGH
STAKEHOLDER 1	<50	50-85	>85
STAKEHOLDER 2	<20	20-30	>30
STAKEHOLDER 3	<50	50-80	>80
STAKEHOLDER 4	<40	40-70	>70
AVERAGE	<40	40-66	>66

Plausibility

The planning horizon is 2030 in this case based on the Estrategia Regional de Recursos Hidricos por Cuenca by CAZALAC. This case therefore requires the assessment of the plausibility of failure of the system to be based on future projections according to Table 5.2.1.

Future projections of precipitation and temperature at all stations within the basin are generated using a multi-variate stochastic weather generator, SIMGEN (see Appendix A), because GCMs, at their current scale, cannot resolve the heterogeneity of climate change at this physiographically complex basin (Falvey and

Garreaud, 2009, Vicuña et al., 2012). SIMGEN outputs are time series at a station-level monthly scale with climate change trends inferred from an ensemble of GCMs assuming RCP 8.5. Only a single RCP is used in this analysis since the projection of the different RCPs are similar until the year 2035 (IPCC, 2012). To ensure that all possible futures are considered, the extremes as well as the moderate trends (i.e. trends at the 10th, 50th and 95th percentile of the distribution shown on Figure 6.3.3) in the GCM ensemble are used in the analysis. The spatially (across stations) and temporally (by decade) averaged projections are plotted on the response surface of each KPM as shown on Figure 6.3.4 and Figure 6.3.5.

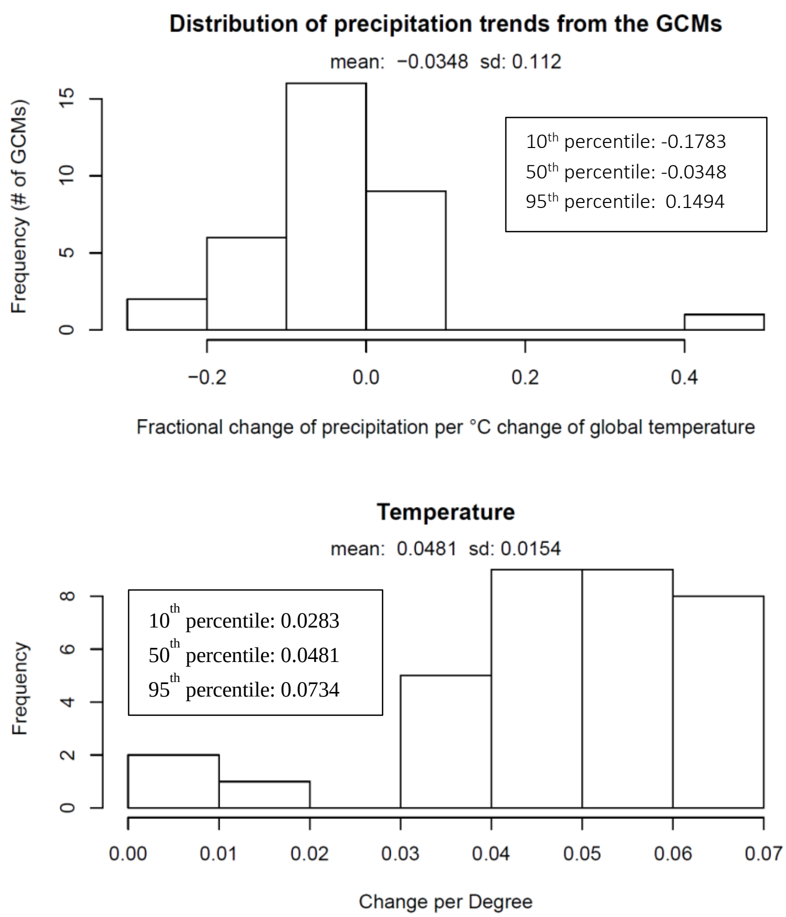

Figure 6.3.3. Distribution of precipitation and temperature trends from the GCMs

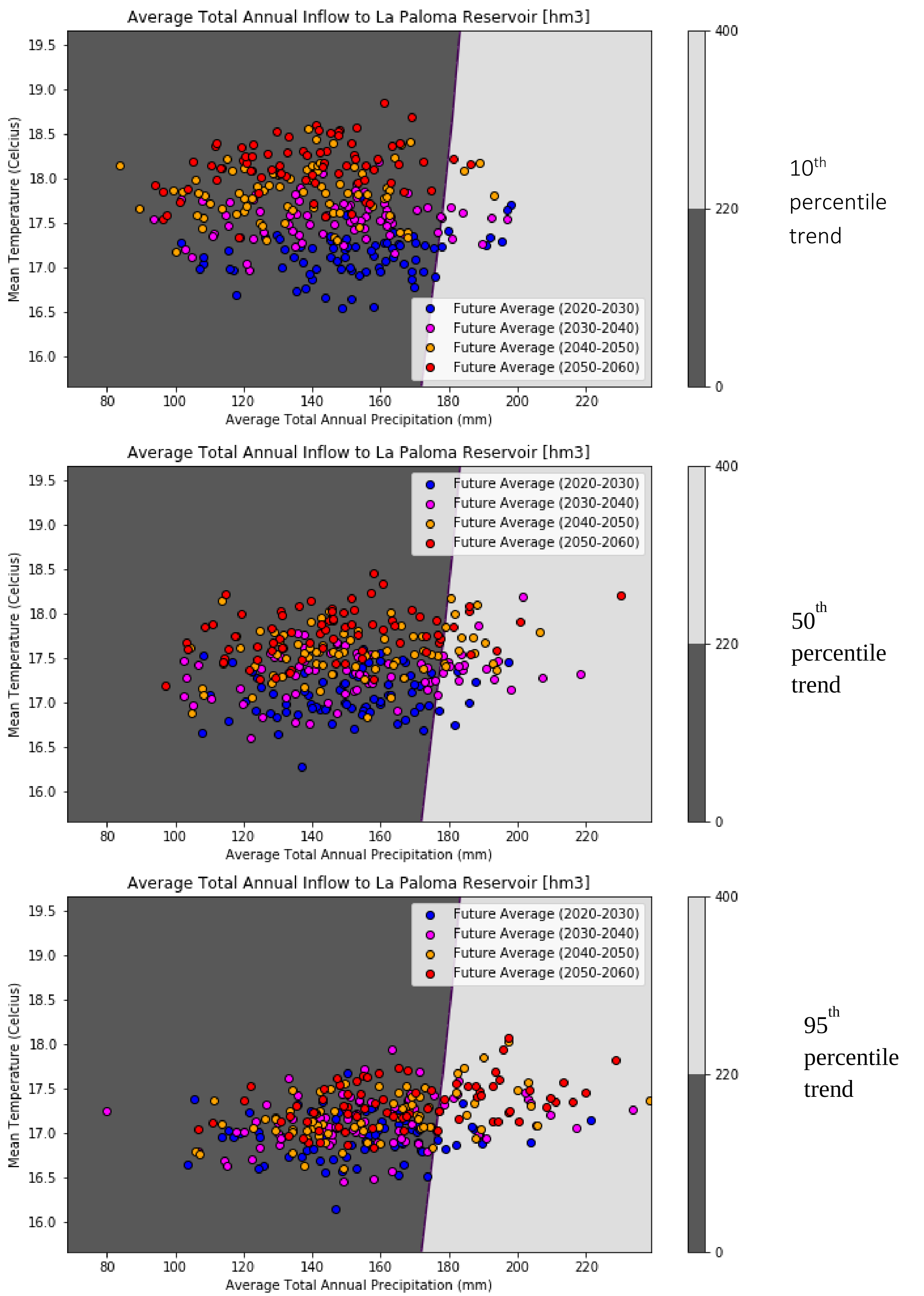

Figure 6.3.4. Projected future states plotted on top of the response surface of KPM: Total Annual Inflow to La Paloma Reservoir. The critical domain is the area in grey.

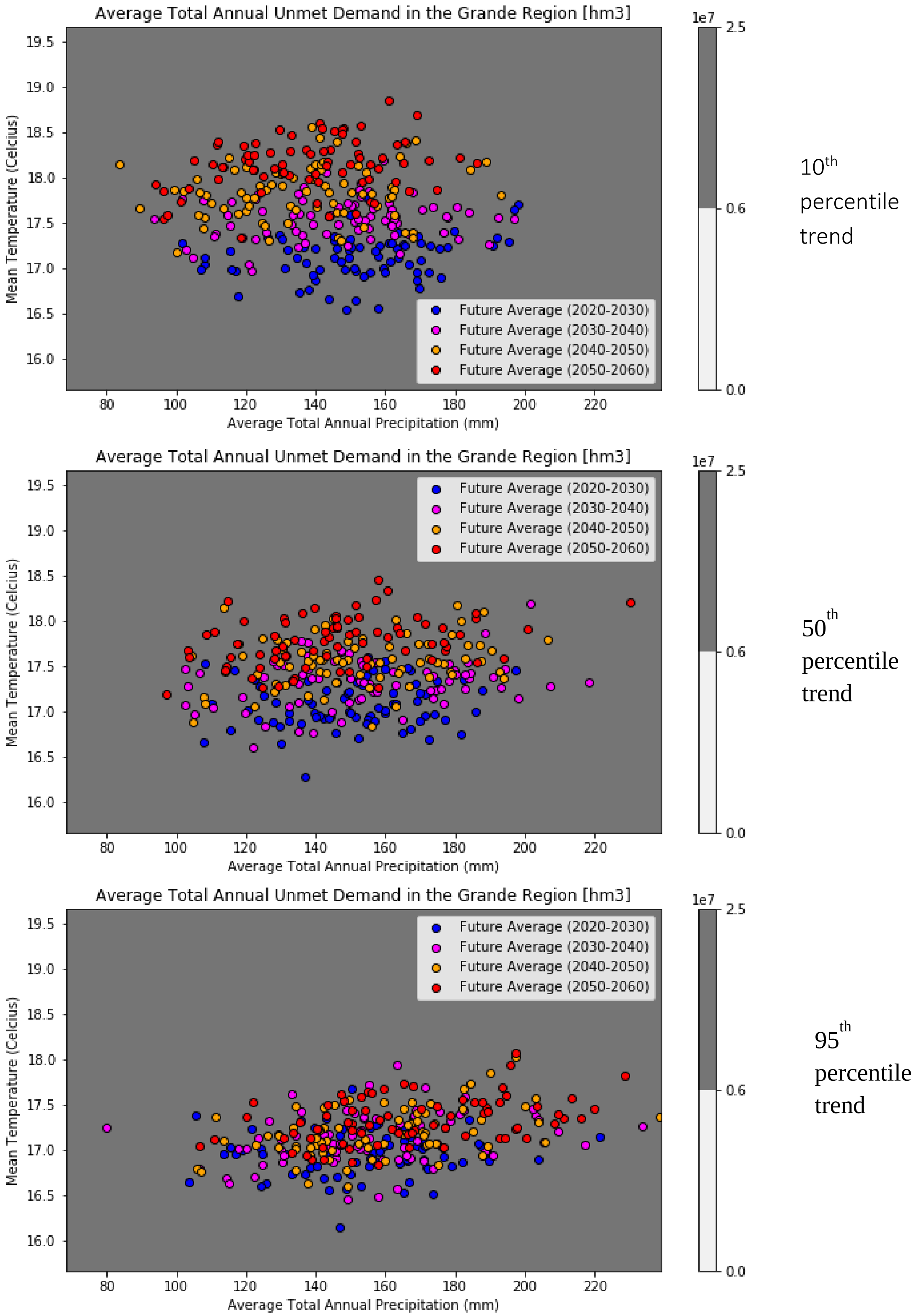

Figure 6.3.5. Projected future states plotted on top of the response surface of KPM: Total Unmet Demand in the Grande Region. The critical domain is the area in grey.

The continuous probability distribution of the future states on the response surface of each KPM is calculated using a multivariate Kernel Density Estimation (KDE) so that the plausibility of failure for each decade [and percentile] is the area under the multivariate curve that is in the critical domain (Appendix E). Figure 6.3.6 shows the result of this process.

Based on the average perspectives of the stakeholders, all scenarios from 2020 to 2060 fall in the critical domain for the KPM: Total Unmet Demand in the Grande Region while plausibility of failure remains high [according to the stakeholder defined threshold] throughout this period for the KPM: Total Annual Inflow to the Paloma Reservoir. For the latter KPM, the plausibility of failure decreases with time under the 95th percentile trend because the dominant driver, precipitation, increases under this trend (Figure 6.3.3). Under the 50th percentile, the trend is not monotonic throughout the period. Under this percentile the trend, in the dominant driver, precipitation is small, hence in the near term annual to decadal variations dominate randomising the trend slightly.

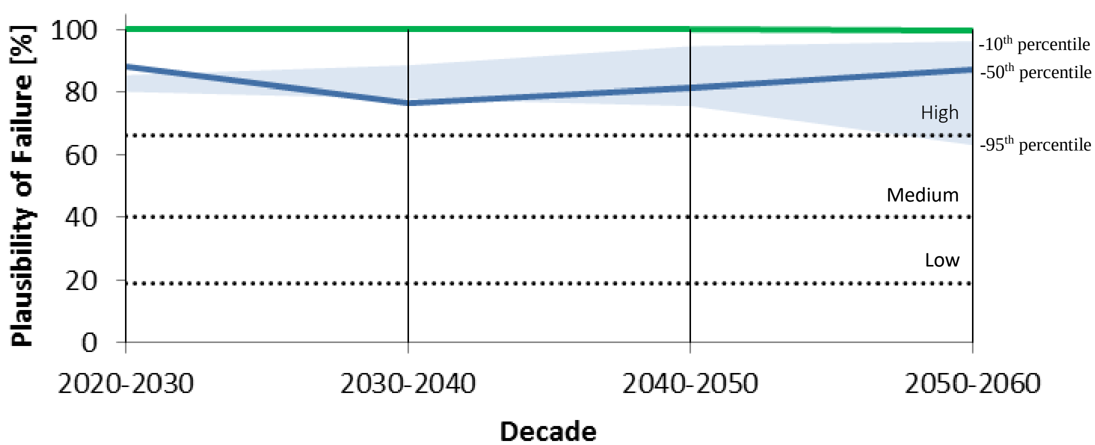

Figure 6.3.6. Plausibility of Failure per decade for KPM: Total Annual Inflow to La Paloma Reservoir in (Blue) and KPM: Total Annual Unmet Demand in the Grande Region (Green). The stakeholders defined thresholds for low, medium and high plausibility of failure are the dotted black lines on the graph.

6.3.2.2. Analytical Uncertainty

Critical Threshold

For the critical threshold attached to the KPM: Total Annual Inflow to La Paloma Reservoir, there is historical evidence through fluviometric data that a breach of this threshold has led to a significant reduction in system performance during the mega-drought period (2000-2015). Furthermore, the threshold definition has a basis on the annual water requirements in the basin [110 hm^3] and the threshold at 220 hm^3 ensures that there is enough water stored in the reservoir to supply activities for two years. Therefore, it may be concluded that this critical threshold has low analytical uncertainty.

On the contrary, the threshold attached to the KPM: Total Annual Unmet Demand in the Grande Region is taken from the historical simulation of the system model and there is no observed dataset to support the value chosen. Therefore, it may be concluded that this critical threshold has high analytical uncertainty.

System model

For this case, the decade averaged future precipitation conditions forecasted by the weather generator, SIMGEN, is within 15% drier than the historical series [2000-2015] expect for decades after 2040 under the 10th percentile trend (Table 6.3.3). The performance ratings (NSE, RSR and PBIAS) to assess the model's ability to simulate current conditions partly meet the criteria for a satisfactory judgement (Table 6.3.4). Considering the two previous statements, the analytical uncertainty where it relates to the system model is Medium according to the framework on Figure 5.2.3 up until the planning horizon (2030). CRIDA must be iterated in the future with a system model calibrated for the drier conditions so that adaptation strategies may be tested for decades after 2040 under the 10th percentile trend.

Table 6.3.3. Percentage difference of the decade averaged future precipitation conditions forecasted by the weather generator, SIMGEN, and the historical series averaged from 200-2015.

DECADE	TREND		
	10th percentile	50th percentile	95th percentile
2020-2030	-10.50	-11.17	-8.53
2030-2040	-13.72	-9.25	-7.84
2040-2050	-19.29	-10.56	-7.03
2050-2060	-18.89	-13.47	-1.54

Table 6.3.4. Model Validation at fluviometric stations in the basin.

NAME OF FLUVIOMETRIC STATION	NSE	RSR	PBIAS
CRITERIA	*>0.50*	*≤ 0.70*	*± 25 %*
RIO COGOTI EN FRAGUITA	0.81	0.43	0.11
RIO COGOTI ENTRADA EMBALSE COGOTI	0.87	0.36	-2.84
RIO COMBARBALÁ EN RAMADILLAS	0.81	0.44	19.12
RIO GRANDE EN LAS RAMADAS	0.90	0.32	-4.16
RIO GRANDE EN CUYANO	0.71	0.54	-32.88
RIO GRANDE EN PUNTILLA SAN JUAN	0.69	0.56	-33.58
RIO GUATULAME EN EL TOME	0.59	0.64	-31.78
RIO HURTADO EN SAN AGUSTÍN	0.69	0.56	-2.17
RIO HURTADO EN ANGOSTURA DE PANGUE	0.46	0.74	-6.53
RIO LIMARÍ EN PANAMERICANA	0.47	0.73	-49.53
RIO MOSTAZAL EN CUESTECITA	0.67	0.58	-26.22
RIO MOSTAZAL EN CARÉN	0.36	0.80	-38.47
RIO PAMA EN VALLE HERMOSO	0.48	0.72	11.22
RIO RAPEL EN JUNTA	0.75	0.50	6.85
RIO TASCADERO EN DESEMBOCADURA	0.71	0.54	-10.75

Projections

Due to the planning horizon, the analysis relied on future projections which are inherently uncertain to determine the plausibility of failure. The change in the plausibility of failure (Figure 6.3.6) however shows little sensitivity for both KPMS. Therefore, the analytical uncertainty related to the plausibility assessment for both KPMs is low.

6.4. STEP 3: Formulate Robust & Flexible Actions

6.4.1. Identifying the general strategic approach

The general strategic approach is informed by the LOC analysis which resulted in a high future risk rating for both KPMs and medium [high] analytical uncertainty rating for KPM: Total Annual Inflow to La Paloma Reservoir [KPM: Total Annual Unmet demand in the Grande Region]. This assessment puts both KPMs in quadrant 4 of the LOC matrix (Figure 6.3.2) for which CRIDA recommends the analysts to implement both flexible and robust actions.

To reduce the LOC rating so that both KPMs plot on quadrant 1 of the matrix, the adaptation strategies implemented must target to reduce the uncertainty in the critical threshold definition for KPM: Total Annual Unmet Demand in the Grande region and the future risk for both KPM's. Due to modelling and information constraints, strategies to reduce the consequence [impact] of failure could not be tested in this proof of concept. However, a low future risk rating may still be achieved if plausibility of failure can be reduced to low.

6.4.2. Compiling the adaptation action library

A portfolio of adaptation measures (Table 6.4.1) targeting both dimensions of the LOC and following the general strategic approach recommended in the LOC analysis is compiled through stakeholder interviews, a review of previous strategies employed in the basin, a review of climate adaptation plans, and a review of literature. See Appendix B.4 and B.5 for historical responses and adaptation plans drafted in the basin respectively. The strategies targets agricultural water supply and demand mainly as this sector makes up 97% of the consumptive water use in the basin. It is noted that the most popular strategies mentioned during the interviews are an improvement in irrigation efficiency, recharging aquifers and building reservoirs. 5 additional reservoirs of capacities ranging from 5-50 hm^3 are proposed with 3 already under construction in the basin. Previous strategies in the basin such as cutting down fruit trees and reducing cultivated area are not tested as these are not considered adaptation strategies since they result in a large reduction of income.

Each action is individually evaluated in the next step for their acceptability, effectiveness and completeness in reducing the future risk of climate change in the basin. Past actions which likely would have resulted in economic losses and illegal actions were excluded from the test. Furthermore, a number of actions could not be tested due to either model, parameter and information constraints and future work should focus on research or model improvements to allow for testing a broader range of actions in this basin.

Table 6.4.1. Adaptation Strategy Library

Strategy	General Strategic Approach	Test Reference
Analytical Uncertainty Dimension		
Research Critical Threshold Definition for KPM: Total Annual Unmet in the Grande Region	-	-
Impact Dimension		
Improve insurance mechanisms and monetary compensations schemes[1].	Flexible	-
Diversification of economic activities[1].	Flexible	-
Improve service for water delivery during drought[1].	Flexible	-
Plausibility Dimension		
Demand Side		
Deficit Irrigation	Flexible	D1
Replacing permanent crop acreage to annual crops with lower water requirements • 25% of area • 50% of area • 75% of area	Flexible	D2 D2.1 D2.2 D2.3
Replacing currently grown annual crops to annual crops with lower water requirements • 25% of area • 50% of area • 75% of area	Flexible	D3 D3.1 D3.2 D3.3
Altering the Crop Schedule	Flexible	D4
Reducing plant transpiration	Flexible	D5
Switching to alternative crop cultivars[2]	Flexible	-
Improving soil quality[3]	Flexible	-
Supply Side		
Improving Irrigation Efficiency	Flexible	S1
Improving Canal Delivery Efficiency	Flexible	S2
Building Reservoirs	Robust	S3
Additional source from waste water reuse and treatment, desalination plant or water highway • 1.5 m^3/s • 2 m^3/s • 2.5 m^3/s	Robust	S4 S4.1 S4.2 S4.3 S4.4

• 3 m^3/s		
Rain Water Harvesting[4]	Flexible	-
Aquifer Recharge[5]	Flexible	-
Changing water allocation rules[6]	Flexible	-

[1] The system model does not support the simulation of how these strategies reduce the consequence [impact] of failure measured using the impact indicators.

[2] Limited information to the researcher regarding crop factor values of different crop cultivars.

[3] Limited information to the researcher regarding soil types in the basin.

[4] There is very little rain in this basin so this strategy is not applicable in this case.

[5] Limited information regarding the ground water flows in the area

[6] Very complex interaction and will likely require a separate study beyond the scope of this research.

6.4.3. Adaptation Strategy Evaluation

6.4.3.1. Evaluation based on Acceptability

Strategies are assessed for acceptability according to the acceptability criteria gathered from interviews with the stakeholder:

A. Maintain or improve income (even during drought years)

In this basin, where water is treated as a commodity and owned by 'water users', federal institutions have limited influence to enforce best practices on the industries (Valdés-Pineda et al., 2014, Hurlbert, 2018). Therefore, the strategy must benefit the users economically to increase the likelihood of adoption. For example, the crop pattern in the area is naturally optimised to economic returns; recommendations to alter the pattern will likely incur losses to the farmers.

B. Micro-level strategies (i.e. motivated by individual economic agents)

Agrarians through their water associations hold considerable influence on the management of the resource through their water rights. As they own the water it is difficult to implement federal policy that dictates how these users specifically use their water. These organisations however are described by Urquiza and Billi (2018) as having poor vertical and horizontal coordination which leads to conflicts in the management and use of the resource and limits the collective decision-making needed for an integrated water management. Therefore, particularly for the short term, small to medium scale strategies could be recommended so that they may be implemented by individual farmers and organisations.

The climate change plan for agriculture further promotes the focus on small to medium scale strategies to reduce the vulnerability of subsistence farming which are recognised to be the most vulnerable in the area.

C. Applicable with current technical knowledge/capacity in the basin

Information regarding the water cycles, balance and storage (in the aquifers and the Andes mountains) in the Limari Basin is limited (Urquiza and Billi, 2018). Furthermore, the records of water rights are fragmented across institutions making the total amount of legal extractions uncertain. In addition there are a lot of illegal extractions in the basin that may rival legal extractions in magnitude. Therefore the employment of strategies which rely on knowledge of the water availability and hydrology of the region (i.e. ground water extractions and recharge) should be minimised.

Information regarding the effect of climate change on crop life stages and empirical studies on adaptation strategies to maintain crop productivity and income (i.e. using meshes/screens, deficit irrigation, and changing crop schedules) is also limited in the basin. These strategies are tested in this case study using parameters from experiments in similar climatic conditions (See Adaptation Strategy Library). However, aside from the climate, soil type and specific species may have a considerable influence on the effectiveness of these strategies. Hence such strategies should not be implemented in the basin until further studies confirm their effectiveness and correct best practices.

D. Compatible with current water management laws and policies

The laws and policies that dictate the management of water in the basin may limit the effectivity of some measures. Policies identified in the literature review and interviews which limit certain strategies are described below.

- Improving irrigation efficiency does not reduce water demand as the water law and policies encourage irrigating more crop acres with the water saved (Vicuña et al., 2014).
- Improving delivery efficiency does not reduce water demand as water associations which manage the delivery canals are not required to distribute the additional water to farmers. Instead, the additional water may be sold for the economic benefit of the associations.
- Water rights are tied to a specific location of extraction. This is particularly relevant where aquifer recharge as a solution is proposed. The water injected by users at a specific location may flow away from the location where they hold rights. Hence the policy needs to be amended before such strategies are employed.

E. Quick application

At the macro-level, there is the tendency of every new government to discontinue and modify policy introduced by the previous administration to the extent of discontinuing programs and trainings halfway (Urquiza and Billi, 2018). Hence projects that can start within a term of government (4 years) is preferred. Where research is needed, it should be considered whether the research and application is possible within a government term.

F. Low Memory

Strategies implemented in the past tend to be re-active and stop when the droughts end (Urquiza and Billi, 2018). Optimised strategies that may be applied reactively are likely to have higher adoption rates as they are already applied to some degree in the basin.

6.4.3.2. Evaluation based on Effectiveness

The strategies are individually incorporated into the WEAP model as scenarios following the parameterisation described in Appendix F, then iterated through a fast track stress test. The fast track stress test has less iterations to create the response surface so that compute time is reduced. The iterations are for future states where precipitation is at 40%, 90% and 140% of the historical series and temperature is at -1^{0}C and +3^{0}C of the historical series. The iterations model more precipitation future states than temperature since the system was found to me more sensitive to precipitation through the climate stress test.

For each individual action, a new [lower resolution] response surface is generated and the plausibility of failure for each decade recalculated using the same method as in the Level of concern analysis. Since the impact dimension of future risk cannot be reduced due to model and information constraints, the effectivity of a solution is measured based on whether it is able to reduce the plausibility of failure for both KPMS to a low rating which was defined by stakeholder to be <40%.

6.4.3.3. Results – Individual Measures

This section presents the results of the individual adaptation measures evaluated for their acceptability based on how they meet the criteria (Table 6.4.2) and effectiveness (Figure 6.4.1) based on howthey reduce the plausibility of failure percentages. Appendix G shows the changes on the response surface with the individual strategies implemented.

Table 6.4.2 Compliance of individual measures to the acceptability criteria.

TEST	COMPLIANCE WITH ACCEPTABILITY CRITERIA [Y/N]					
REFERENCE	A	B	C	D	E	F
D1	Y	Y	N	Y	Y	Y
D2	N	Y	Y	Y	Y	N
D3	N	Y	Y	Y	Y	Y
D4	Y	Y	N	Y	Y	Y
D5	Y	Y	N	Y	Y	Y
S1	Y	Y	N	N	Y	N
S2	Y	Y	N	N	Y	N
S3	Y	N	Y	Y	N	N
S4	Y	N	Y	Y	N	N

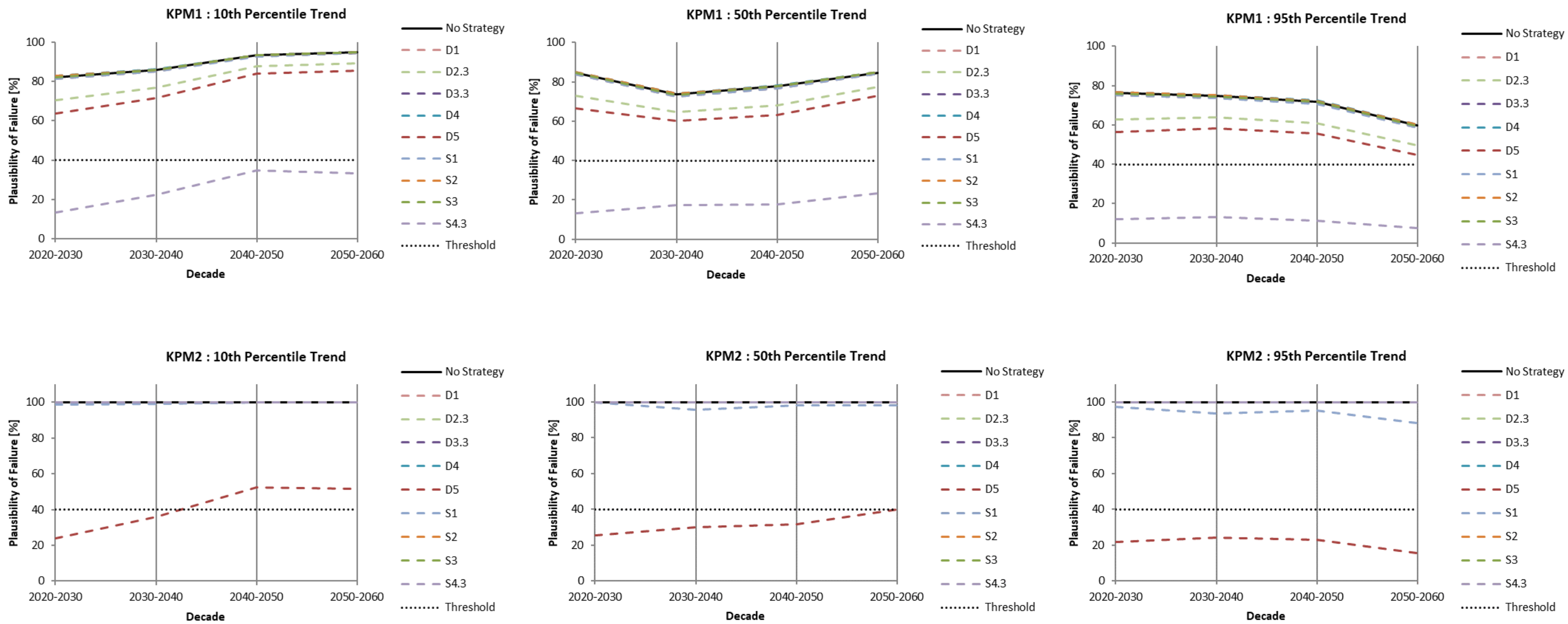

Figure 6.4.1 Plausibility of failure per decade for KPM1: Total Annual Inflow to La Paloma Reservoir and KPM2: Total Annual Unmet Demand in the Grande Region with individual measures applied in the system under the 10th, 50th and 95th percentile climate change trends.

The results show that most individual strategies were unable to reduce the plausibility of failure for both KPMs sufficiently to a low rating. The exception to this is the iteration with an additional source supplying at least 2.5 m^3/s of water at the mouth of the La Paloma Reservoir. There is less activity upstream of the La Paloma reservoir; therefore, any adaptation actions implemented upstream does little to offset the reductions in stream flow caused by climate change. The strategies have more impact in reducing the unmet irrigation demand in the Grande Region which is apparent when looking at the response surface changes (Appendix G), however, this is not reflected in the plausibility of failure calculated based on this KPM because the original situation is already far into the critical domain (Figure 6.3.1). The following paragraphs discusses how each strategy reduces the plausibility of failure for each KPM and justifies the evaluation of their compliance to the acceptability criteria.

D1: Deficit Irrigation

Water demand for irrigation is reduced in this strategy. This demand is more easily met than in the current situation and therefore less water abstracted from the rivers.

The deficit irrigation regime depends on climate, soil type, crop and also the specific genotype of crop. Since local studies were not found during the literature review, deficit irrigation regimes for the main crop types in the basin is modelled based on best practices from published work with study areas of similar climates (i.e. semi-arid to arid). But local studies are required before application to draft the optimal irrigation pattern to ensure little to no losses in production.

D2: Replacing permanent crop acreage to annual crops with lower water requirements

Reducing permanent crop acreage increases the inflow to the La Paloma reservoir, however this effect is due to the reduction in irrigation efficiencies which means more water returns to the river (as annual crops are often irrigated at lower efficiencies in the model). For the KPM: Total Annual Unmet Demand in the Grande Region, this adaptation strategy has a negative effect. A reduction is irrigation efficiency offsets the reduction is crop water demand and increases the required water extraction from the river which is how WEAP models unmet demand.

Farmers may be reluctant to follow this strategy as it may reduce earnings without some compensation/ intervention from the government. Furthermore, farmers are also likely to revert back into permanent crop after droughts are over.

D3: Replacing currently grown annual crops to annual crops with lower water requirements

Alfalfa has a high crop water demand and is one of the most grown crops in the basin. This crop is irrigated at the lowest efficiency in the model because it requires flooding in its early growth stages. In this adaptation strategy, the alfalfa crops are replaced by vegetable and cereals which have lower water requirements and are also irrigated at higher efficiencies. Therefore, while water diverted from the rivers to meet demand is lower, the return flow from runoff is also lower because overall efficiency is improved as the model assumes that all water lost during irrigation flows back into the rivers. Hence inflow to the reservoir is unchanged because the reduced water demand and hence extraction is offset also by the reduced return flow. Furthermore, where water flows are low (unable to meet the old and new demand), the improved irrigation has a negative effect (causing less water to return to the river). However, it is not the case that all water lost in irrigation returns to the rivers, parts it either infiltrates into the groundwater, evaporates or pools into lakes, therefore the model likely underestimates the effectiveness of this strategy in improving inflow to reservoir. The effectiveness of this strategy is more apparent in the KPM: Total Annual Unmet Demand in the Grande Region, a lower crop water demand and higher efficiencies (which make up the total water demand) means less water is required and is met more easily during periods of low flow.

Farmers may be reluctant to follow this strategy as it may reduce earnings without some compensation/ intervention from the government.

D4: Altering crop schedule

Altering crop schedules by shifting the planting period one month forward causes a reduction in unmet demand and a slight reduction in inflow to the La Paloma Reservoir. Since maximum crop water demand is more in line with peak flows, demand is met during these periods but more of peak flows are now abstracted to meet the plants at their highest demands causing a decrease in reservoir inflow.

Further research is required to understand the changes in the crop life cycle with increasing temperatures and decreasing precipitation. For correct application, forecasting techniques must also be improved to adjust schedules to peak flows.’

D5: Reduce plant transpiration

This strategy reduces plant water demand hence extraction for river is reduced and demand is more easily met increasing the amount of flow reaching the La Paloma reservoir and reducing unmet demand respectively.

Changes in the reference ET under netting is also a function of the hydric properties of the specific crop and the type of netting used (Tanny, 2013). Further research is required to determine the appropriate screen or mesh characteristics suited to specific crop type so as not to affect production.

S1: Improve irrigation efficiency

Improving irrigation efficiency reduces the water demand in a catchment node and decreases the unmet demand in a catchment node. However, in periods of low flow where the water availability is also unable to meet this reduced demand, the improved irrigation efficiency has a negative effect. In these cases, the same amount of water is extracted from the river (as in the scenario with the original efficiency), but less of this water is returned into the stream.

The government provides financial aid to farmers to improve irrigation efficiency. However, the water policy in Chile requires the water user to increase its cultivated area proportional to the improvement in the efficiency so that the total water demand remains unchanged. Prior to application of this strategy the policy needs to be changed and also the farmers need to be convinced to invest in improving irrigation efficiencies without increasing their yields. Improving irrigation efficiencies at a scale where necessary to have an impact on the future security may also reduce infiltration into the groundwater reservoir and reduce water availability to communities which rely on this water source. Therefore, more research is needed in this aspect.

S2: Improve canal delivery efficiency

Improving canal efficiency decrease supply requirements in the WEAP model because there is less losses downstream. As WEAP is a demand driven model, the Cogoti Reservoir releases less water to feed into the La Paloma reservoir when canal delivery efficiency is improved therefore reducing the total annual inflow to the La Paloma reservoir but increasing the water storage in the Cogoti Reservoir. The benefit however is that the storage in the Cogoti Reservoir is higher when canal delivery is improved so it can release water to feed supply for longer during drought periods which is why we see the improvement during drought years. In addition, the decreased losses in the canals allow the demands to be met during lower flow conditions which cause a reduction in unmet demand.

There is no policy in place that requires the canalistas to distribute the added water supply to farmers and there is mistrust within the organization that the water gained may instead be sold in the water market. There needs to be a policy in place to ensure that the farmers benefit from the added water. Improving canal efficiencies at a scale where necessary to have an impact on the future security may also reduce infiltration into the groundwater reservoir and reduce water availability to communities which rely on this water source. Therefore, more research is needed in this aspect.

S3: Building reservoirs

Inflow to the La Paloma reservoir is slightly improved if future states do not vary significantly from current conditions (up until the decade 2030 there is a slight improvement). The additional water stored in the upstream reservoirs can act as a buffer supplying inflow during prolonged dry periods, therefore reducing unmet demand for a period. But this is slightly offset by the reduction in peak flows which are instead stored in the upper basin reservoir. However, there comes a point where the snow melt from the Andes is significantly reduced due to differences in precipitation and temperature that there is not enough water to fill any of the reservoirs. When this happens, the reservoirs have negative effect because any inflow from upstream is used to fill the upstream reservoirs instead of La Paloma.

S4: Building an additional source

Unmet demand is not improved because there are operating rules that limit the outflow from the reservoirs. So even with the maximum allowable water released from the reservoirs (during years with sufficient water) there is still unmet demand in the lower Grande region. Only during low water availability years does it improve the unmet demand because of the additional source.

6.4.3.4. Results – Packaged Measures

Individual strategies do not sufficiently reduce the plausibility of failure to an acceptable level for both KPMs. Therefore, these individual strategies are organised in packages summarised on Table 6.4.3 and rerouted through the fast track stress test. The results of the packaged strategies under the 10th, 50th and 95th percentile trends are shown on Figure 6.4.2.

Table 6.4.3. List of packaged strategies tested

Measures Packaged		Test Reference
D1 D3.3	Deficit Irrigation Reactively changing annual crops	P1
D2.3 S1	Reducing permanent crop acreage to annual crops with lower water requirements [75%] Improving Irrigation Efficiency	P2
D2.3 D5 S1	Reducing permanent crop acreage to annual crops with lower water requirements [75%] Reducing plant transpiration Improving Irrigation Efficiency	P3
D5 S4 S4.1 S4.2	Reducing plant transpiration Additional Source • 1.5 m^3/s • 2.0 m^3/s	 P4 P4.1 P4.2
P2 P4.1	Reducing permanent crop acreage to annual crops with lower water requirements [75%] Improving Irrigation Efficiency Reducing plant transpiration Additional Source • 1.5 m^3/s	P5

P1 is the most acceptable packaged measure because it has been applied in previous droughts however it does little to reduce the plausibility of failure in the future.

P2 consists of two complementary individual strategies namely; (1) reduction of permanent crop acreage (D2.3) and (2) improving irrigation efficiency (S1). During the testing of individual strategies, D2.3 was found to have a negative effect on KPM: Total Unmet Demand in the Grande Region because the reduction in plant water demand is offset by lower irrigation efficiencies which the model automatically attaches to annual crops. In reality, the irrigation infrastructure in place to irrigate permanent crops can still be used to irrigate the annual crops that replace these. Therefore, these two strategies were packaged to examine their combined effect. This packaged measure has resulted in a reduction on the plausibility of failure; achieving similar results as applying the strategy which involves reducing plant transpiration (D5) which is the second most effective individual strategy. However, P2 is still not effective enough to reduce the plausibility of failure to the acceptable level.

P3 consists of the most effective measures and in basin that does not require finding an additional water source. However, P3 was also unable to reduce the plausibility of failure for KPM: Total Annual Inflow to the La Paloma Reservoir to an acceptable confirming that an additional source (S4) is required in this case.

Therefore, P4 and P5 consists of the measure of an additional source (S4) supplemented by an in individual as S4 alone has a limited effect in reducing the plausibility of failure for KPM: Total Annual Demand in Grande Regions. Both of these packages are able to reduce the plausibility of failure below the threshold and thus are used in the adaptation strategy development in section

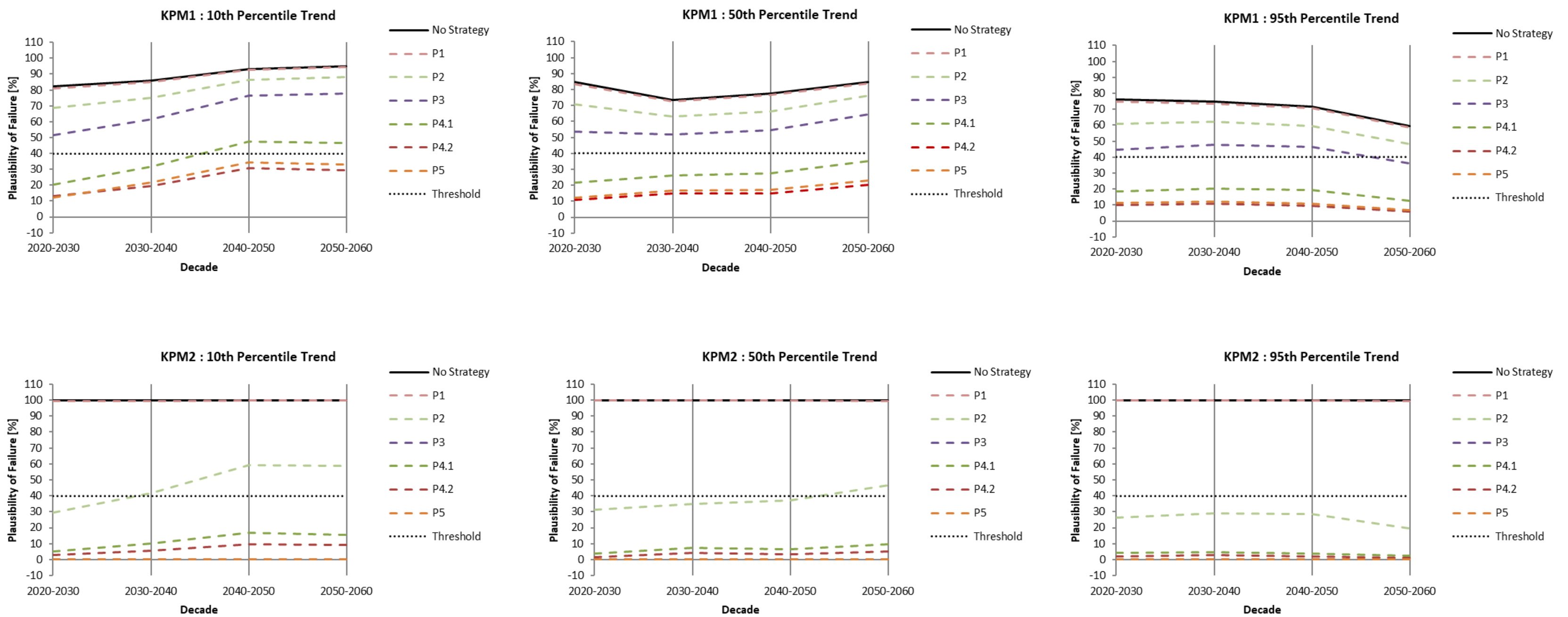

Figure 6.4.2 Plausibility of failure per decade for KPM1: Total Annual Inflow to La Paloma Reservoir and KPM2: Total Annual Unmet Demand in the Grande Region with packaged measures applied in the system under the 10th, 50th and 95th percentile climate change trends.

6.4.4. Adaptation Strategy Pathways

The adaptation strategy pathways (ASP) for this case is shown on Figure 6.4.3. A single ASP is presented as the planning horizon for this case is 2030. However, it is extended to 2050-2060 to be a proof of concept for the proposed revision in CRIDA linking the risk assessment to the ASP generation.

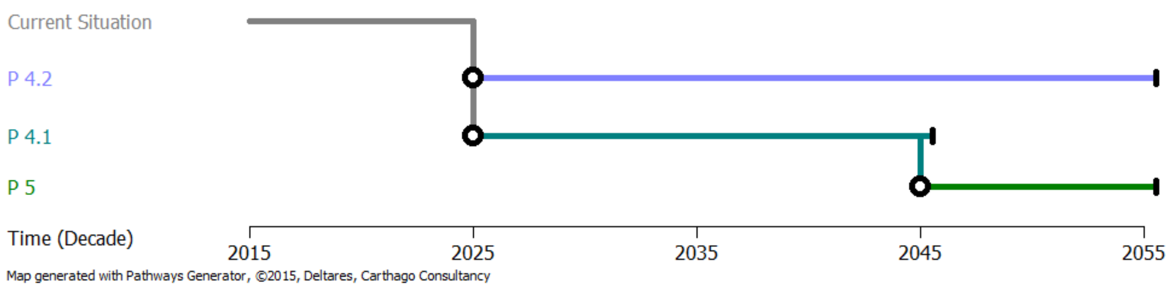

Figure 6.4.3 Adaptation Strategy Pathway for RCP8.5 Limari Case Study

The actions available are limited as the basin is already in a very critical state. All pathways involve adding an additional source into the system of varying capacity supplemented by other measures. P4.2 introduces 2.0 m^3/s of water into the system which keeps it in a non-critical state for all percentile trends until 2050-2060, the final decade in the assessment. P4.1 keeps the system in a non-critical state until 2040-2050 when the threshold is breached under the 10^{th} percentile trend only. In order to reduce future regret, the stakeholder may decide to implement P4.1 initially and supplement it with other actions to move to P5 in the future.

7. Discussion and conclusions

The discussion of this research is separated in two parts. First, the results of the CRIDA application on the Limari basin is discussed, followed by the discussion of CRIDA and the new tools and guidelines added by this research.

7.1. CRIDA results of the Limari Basin

The first three steps of CRIDA, namely the definition of the decision context, vulnerability assessment and formulation of actions, are applied to the Limari Basin water security case study as a proof of concept of the additional guidelines and tools developed in this research. The result of these steps are adaptation strategy pathways that aim to reduce the vulnerability of the basin to climate change. The adaptation pathways follow a general strategic approach recommended by the LOC classification to ensure low-regret. In this case, a high future risk rating and high analytical uncertainty rating in the LOC classification leads the analyst to recommend a combination of robust and flexible actions. Robust actions are often structural measures that reduce risk significantly, however usually implies more cost. These solutions are often also irreversible which limits adaptation options in the future. Hence, for this case, robust actions must be supplemented by flexible actions so that they may be adapted as new information becomes available or as conditions change in the future. Following the recommended general strategic approach, the adaptation strategy pathways for the Limari case are made with packaged actions which include introducing an additional water source (S4), the robust action, supplemented by flexible actions, namely; changing crop patterns (D2), improving irrigation efficiency (S1) and reducing plant transpiration through agricultural meshes (D5). The pathways show that the immediate implementation of these packaged actions is required. "Business as usual" does not sufficiently maintain the plausibility of failure of the system below what the stakeholders consider to be acceptable by the next decade (2020-2030). This is because the system is presently at a critical state due to persistent historical droughts. Historical conditions already fall in the critical domain of the response surface as seen on Figure 6.3.1.

Out of the 9 individual actions tested only S4 and D5 are able to sufficiently reduce the plausibility of failure in the future for KPM1 and KPM2 respectively. The lack of effective actions can be attributed to the current conditions in the system already falling in the critical domain as previously mentioned. Popular strategies among farmers such as (S1) improving irrigation efficiency and (S3) building reservoirs, do little to reduce the plausibility of failure in the future. S1 is further ineffective because basin development over the last decades have been technocentric, promoting improvements in irrigation efficiency. Hence, the overall irrigation efficiency in the basin is already high. S3 adds some benefit in the short term as they act as buffers supplementing additional inflow to the La Paloma Reservoir during dry periods. However, this benefit is not evident in the KPM as this addition in inflow is offset by the flattening of peak inflows during wetter months as the annually averaged inflow is used for KPM1. However, in the long term, when snow-melt from the Andes reduces due to climate change, these additional reservoirs have a negative effect. Direct water flow from the Andes fill these upstream reservoirs with little left over to run downstream to feed into the La Paloma Reservoir. Reasonings as to why other individual actions are not effective are detailed in section 6.4.3.3. Due to a limited portfolio of effective actions in the Limari case, only a limited number of packages can be combined by the analyst. A total of 5 unique packaged actions are tested with only 2 unique packages able to sufficiently reduce the plausibility of failure. These 2 unique packages are used in creating the adaptation strategy pathways. In other cases, where multiple options exist, the packages and initial pathway recommendation would be developed in consultation with stakeholders. The recommended pathways would then be evaluated economically in the next step of CRIDA and this information would feedback into the pathway development as an iterative process. This process falls beyond the scope of this research.

The strength of WEAP as a solution testing model is shown in this study. Over 250 iterations of the WEAP model was run to test the effectiveness of each individual and packaged actions in reducing the plausibility of failure. Each action required specific nodal and global parameter changes across the 149 catchment nodes and 71 demand site nodes which could be automated through WEAP API and then saved as scenarios. Furthermore, the iterations of the fast track stress test can be atomized through the API requiring minimal manual labor for the analyst after the API scripts are constructed.

In conclusion, the results do communicate to stakeholders through the LOC analysis that the Limari Basin is at a high risk of critical failure. Through the pathways, it is clearly communicated to the stakeholders that urgent action is needed if the plausibility of system failure should be reduced to their acceptable level. They also communicate that popular actions are not likely to reduce the plausibility of failure in the future and that the reliance on agriculture for the local economy is not sustainable in the future and other livelihood and sources of income must be considered. The strength of CRIDA is shown in the recommendation of the general strategic approach of combining flexible and robust actions considering the high risk but high uncertainty in this assessment for a low-regret strategy. Furthermore, the benefits of CRIDA is shown in the development of adaptation strategy pathways so that options are clearly presented to the stakeholders as conditions change in the future, a likely occurrence when planning for an uncertain future. This case study is also proof that the developed guidelines and tools in this research can be applied to a case and leads to sensible results. A discussion of the performance of the newly added tools follows in section 7.2.

7.1.1. Limitations

It is recognized that there are limitations in the assessments that can significantly affect the final pathway recommendations. For this reason, this case study is specifically stated as a proof of concept. The case study presented should therefore only be referred to as a demonstration of CRIDA and of the added guidelines and tools.

The first limitation is that the most vulnerable in the basin, recognised as the substinence farmers that rely on ground water, are not represented in the KPMs defined in the decision context. Groundwater is not modelled in the current WEAP model and thus metric representations of groundwater is not possible. The implication of this limitation is the likely underestimation of the risk of climate change in the basin, resulting in strategy recommendations that do not reduce risk sufficiently and do not target the most vulnerable in the basin.

The second limitation is that the risk perception of only 4 stakeholders are gathered in this study, which is a significant under sampling of a representative statistic in the basin. Furthermore, the risk perceptions gathered were aimed at different KPMs than the ones used in this study. One of the KPMs identified in the workshop is groundwater levels to represent the vulnerability of substinence farmers and risk perceptions were attached to this KPM. However due to model limitations, it was later concluded that groundwater levels could not be used as a metric and KPM2: the annual unmet water demand of irrigation in the Grande region, is used in its place. A follow-up survey forwarded to stakeholders to gather risk perceptions for the KPMs ultimately used in this study received no response. Therefore the risk perceptions gathered from the workshop are used to continue with this proof of concept application. This error has however, significant implications in the translation of the quantitative risk dimensions to a qualitative classification for the level of concern which ultimately guides the analyst to an appropriate no regret general strategic approach. Furthermore, there are implications in the definition of adaptation tipping points of strategies which are informed by these risk perceptions.

The third limitation is that not all actions gathered in the library could be tested. Due to either a lack of information for their parameterisation in the model or the inability of the current WEAP model to simulate the strategies. Specifically, actions tested focused in reducing the plausibility of failure dimensions of risk whereas actions that reduce the impact dimension of failure are not tested. These include actions such as diversifying economic activities and improving insurance and compensation schemes during drought. Information regarding these strategies are not available and it is beyond the scope of the current study to develop these strategies so that they may be included. It is possible that if these actions are tested, the portfolio of effective actions would increase and more options for packages and pathways can be recommended by the analyst.

The fourth limitation is that the parametrisations of the actions tested are uncertain. For example, the parameters for testing a reduction in crop transpiration by installing meshes (D5) were generalised for all crops and assumed from a study in an area with a similar climate to the case study. However, plant responses to mesh and screen instalments have many factors that are site specific including soil type and the specific species of crop. The level of uncertainty can also vary between adaptation strategies. There are less uncertain factors affecting the parameterisation of improving the irrigation efficiency (S4) for example, than reducing the crop transpiration (D5). Therefore, it becomes difficult to justify that the relative effectiveness modelled between strategies is representative to reality. The model results of D5 may show that it is significantly more effective than S4, but perhaps the parametrisation reflecting actual reality would produce worse results that S4.

The fifth limitation is that there is some error introduced by the underlying algorithms of the WEAP model. Such as feedbacks within the model that are not necessarily representative of reality. For example, as WEAP is a demand driven model, improving canal delivery efficiencies reduces the demand of a node. This results in less water release from the upstream reservoir and thus less inflow to the La Paloma Reservoir. Thereby, negatively affecting KPM1. In reality, a change in canal delivery efficiencies should not affect the water released from the upstream reservoir.

The sixth limitation is that the critical threshold definition for KPM2 is completely model driven, unlike KPM1 which is based on the annual demand in the basin defined in discussion with the stakeholders. The threshold for KPM2 situates the current system in a critical state far into the critical domain of the response surface (Figure 6.3.1(b)). As a result many individual action are unable to reduce the plausibility of failure satisfactorily and are considered ineffective and thus removed as an option for the adaptation strategy pathways. The threshold defined may be overly conservative and should be revisited with the stakeholders.

Finally, the recommended pathways after the year 2035 do not consider the full range of possible futures and falsely communicate to stakeholders the severity of the climate risks in their basin after this year. The pathways are created based on climate change trends under the most extreme scenario, RCP8.5, neglecting the possibility of trends from a stringent mitigation scenario (RCP2.6) and two intermediate scenarios (RCP4.5 and RCP6.0). Considering that the RCP trajectories before the year 2035 are not significantly different, only a single RCP was chosen for the Limari case with a planning horizon at 2030. The adaptation strategy pathways are created for decades exceeding the planning horizon as a proof of concept for using stakeholder risk perception as tipping points for strategies. But ideally, other RCPs would be considered in adaptation strategy pathways exceeding 2035. The full range of RCPs is considered by creating adaptation strategy pathways for RCP4.5 and RCP8.5 as RCP6 falls between the trends and RCP2.6 is considered unlikely to happen in the future. If under both RCPs the analyst is guided to the same general strategic approach, then the strategies within these pathways would likely be the same, differing only in the tipping points. There is a possibility that the future risk rating under the RCPs are significantly different and would result in different general strategic approach recommendations. In this case, the strategies itself may differ between the adaptation strategy pathways under RCP4.5 and RCP8.5. It is left to the stakeholders and decision makers to choose how they use the information of the two sets of adaptation strategy pathways. Do they choose to be risk averse and plan for the worst case-scenario by following the pathways created for RCP 8.5? Or do they choose to follow the pathways of RCP4.5 or a combination of both?

7.2. Improvements on CRIDA

CRIDA is reviewed in this research focusing on its usability. Essentially, this research identified aspects of CRIDA that was not clear and straightforward to apply which introduces analyst subjectivity, reducing the repeatability of an assessment for a case study. Meaning, that different analyst may reach significantly different conclusions and thus recommend significantly different strategies for the same case study making it more difficult to justify a recommendation to decision makers. Improving the repeatability by removing analyst subjectivity is important therefore to ensure the success of CRIDA. This review identified 3 gaps which this research aimed to resolve by introducing additional guidelines and tools. The additions are discussed in the following sections. While the added guidelines required more processing time, analyst subjectivity in the method is reduced and improving by extension the repeatability of CRIDA. But additional case studies need to be done to validate the repeatability of the added tools and guidelines proposed in this work and to gather opinion on its ease of use. The current application is already biased since the proof of concept was done by the same researcher that created the new guidelines and tools. Finally, the introduction of stakeholder risk perceptions in the new guidelines, result in the strategy pathway recommendations and the triggers for action to be aligned to the risk averseness or risk seeking nature of the stakeholders, improving co-design aspects of CRIDA and arguably increasing the adoption rate of the recommendations.

7.2.1. Coherence between the response surface and the modelled future conditions

It is assumed that the response surface of a KPM generated from scaled and shifted historical precipitation and temperature timeseries is representative of the KPM under the conditions of the SIMGEN generated projected series. This response surface is used in several steps of CRIDA, namely in the plausibility of failure assessment to evaluate the future risk of the basin and in testing the effectiveness of the measures applied. Inaccuracies in this step can introduce significant errors cascading through the following steps of CRIDA ultimately resulting in a wrong "general strategic approach" recommendation and wrong adaptation strategy pathway recommendations.

In the 2016 application of the first 2 steps of CRIDA for the Limari basin, this assumption has not been validated for the KPMs defined. In the reiteration of CRIDA for the Limari basin in this research, this assumption is validated for the 2016 defined KPM1: *Average Annual Volume of the La Paloma Reservoir* and is found to be false. The 2016 KPM1, as is the case for many storage metrices, is dependent on its previous value. Hence, the value at the current timestep is an integration of the climate conditions at the previous timesteps. In other words, two precipitation timeseries of varying precipitation regimes (i.e. consecutive dry days and precipitation peaks), but similar annual average precipitations, results in different KPM1 magnitudes. However, as the response surface is created with the annual average precipitation statistic on the x-axis, these two scenarios will plot on the same x-location. Temperature was found to have little effect on this KPM therefore they would also plot on the same y-location. A point on the response surface can therefore represent multiple KPM magnitudes in this case. This also means, that it cannot be assumed that the 2016 KPM1 response surface created from scaled precipitation series of a certain rainfall regime is equal to 2016 KPM1 values under the SIMGEN generated projected series of randomised precipitation regimes.

When using a KPM which is not dependent on its previous value, it is found that each point on the response surface represents only one value. By extension, it can then be assumed that there is coherence between the KPM response surface generated from scaled and shifted historical series and the KPM under projected series. Therefore, the 2016 KPM1 is changed in this reiteration of CRIDA to the Average Annual Inflow to the La Paloma Reservoir. It must be noted however that KPM2: *Annual Average unmet demand in the*

Grande Region did not undergo the same validation procedure as KPM1, but it can be justified that it is time-independent as there is no storage term involved in this metric.

The findings from this exercise led to the recommendation of adding a “time-independence” criteria when selecting appropriate KPMs in the decision context step of CRIDA. Another option for the analyst is to replace the x-axis statistic of the response surface, namely the average annual precipitation, to a statistic that can better represent the precipitation regime. Future work can focus on how to improve the response surface when using “time-dependent” KPMs by investigating other statistics or using a 4-dimensional response surface.

7.2.2. Classification of the Level of Concern Dimensions

The level of concern classification guides the analyst to an appropriate general strategic approach to ensure low-regret. This classification is informed by a qualitative matrix (Figure 3.4.9) of two dimensions; namely the future risk of failure and the analytical uncertainty. The future risk of failure dimension in itself is informed by another qualitative matrix (Figure 3.4.3) of two dimensions; the impact and plausibility of failure. The assessment for all three dimensions of the LOC in CRIDA is determined to be vague and challenging for the analyst to interpret, thereby introducing analyst subjectivity. The proposed improvements for each dimension to resolve this issue is discussed in the following sections.

Impact of failure

There are no specific guidelines within CRIDA on how the impact of failure may be assessed, leaving it to the analyst to decide on the method. In the 2016 application of CRIDA for the Limari, the analyst decided to define the impact of failure of each KPM qualitatively in collaboration with the stakeholders during a workshop. The proposed approach in this research also follows a collaborative but adds a semi-perspective to define the impact of failure. It starts with stakeholders identifying indicators of impact, which for the Limari case example is migration, level of poverty and loss in productivity. Then, stakeholders define quantitative thresholds for low, medium and high impact for each indicator. For example, a stakeholder may consider 20 people migrating as low impact, 100 people as medium and 1000 people as high. These thresholds are risk perceptions from the impact dimension of the stakeholders. The analyst then uses the system model or other tools to calculate the result for each indicator when critical failure occurs for a KPM. In other words, determine how many people would migrate if KPM1: Annual Average Inflow to the La Paloma Reservoir falls below it’s critical threshold. Then this qualitative rating would be translated to a qualitative rating based on the risk perceptions of the stakeholders. However, a tool to do such analysis for the Limari basin is not available at the time of this study and developing such a tool fell beyond the scope of this study. Therefore, the stakeholders’ qualitative estimation of whether the impact of failure for each KPM is low, medium and high for each indicator is used. It is recommended that in future applications of CRIDA, a tool or a system model able to quantify impact of failure is available. While this may cost the analyst additional time and resources the benefits are two-folds. The first benefit is that the impact of failure assessment can follow the proposed semi-quantitative approach and the second benefit, perhaps more importantly, is that actions that aim to minimize the impact of failure can also be tested in STEP 3 of CRIDA.

Plausibility of failure

CRIDA does list guidelines on how to assess the plausibility of failure. In the 2016 application of CRIDA for the Limari, the analysts followed these guidelines. However, the method used injects a significant amount of analyst subjectivity as it relies on the analyst to convert quantitative values resulting from the decision scaling methodology and the sensitivity analysis of the system to the low, medium and high qualitative classification required for the future risk matrix. Under this approach different analyst doing the same analysis for the same case study can reach significantly different conclusions making results harder to justify to decision makers. To overcome this issue in this the iteration of CRIDA for the Limari basin, the risk perceptions of the stakeholders are used to translate quantitative values to their qualitative ratings on the risk matrix. Risk perceptions for plausibility of failure are defined similarly to that of impact of failure discussed in the previous section. Stakeholders are asked through a survey to define threshold quantities for a plausibility of failure that they consider low, medium and high. The surveys used in this study to gather stakeholder risk perceptions was found to be challenging for the stakeholders to interpret. Future work is recommended to refine these surveys further.

By incorporating risk perceptions in the risk assessment, it not only improves the repeatability of an assessment, it also strengthens the co-design aspect of CRIDA. The risk assessment is used to inform the LOC classification which recommends the general strategic approach for a low-regret strategy. The added guidelines align the recommendations of the general strategic approach better to stakeholder perceptions of the risk of the system. This would likely improve the adoption of the analyst recommendation. In other words, an analysts would recommend robust actions, that are often costly and have a lot of dependencies, if through his/her own opinion the system is labelled at high risk. However, if on the contrary the stakeholders perceive the risk to be low, it would be difficult to persuade the stakeholders to follow the analyst recommendation. A recommendation that aligns to the stakeholder risk perceptions would be better received. However, the analyst must ensure that risk perceptions of a representative group of stakeholders in the basin is used for the above statements to hold. Furthermore, stakeholders may disagree significantly in their perceptions and the thresholds that they define. In this study, the average thresholds of the surveyed stakeholders are used. But while averaging is inclusive, it also arguably does not satisfy any single stakeholder completely. Further work is recommended to research how best perceptions of stakeholders are combined to inform these thresholds.

Analytical Uncertainty

For the final dimension of the LOC, the analytical uncertainty, CRIDA only broadly lists indicators (See section 3.4.2.2) such as the consistency of information, spread of projections and the quality of the system model. However, it lacks guidelines on how these individual indicators would be assessed, how this individual assessment may be integrated for the overall assessment and how this assessment is translated to a qualitative rating for analytical uncertainty used for the LOC Analysis. To resolve this issue, a structured approach for this assessment is proposed. The sources of uncertainty are identified explicitly in the steps of CRIDA preceding the LOC analysis and clear guidelines based on literature review are presented for each source to guide the analyst to a rating. The main sources of uncertainty identified are the critical threshold definition, the system model and the climate projections. The assessment of the uncertainty in the critical threshold definition is informed by whether the critical threshold has been reached in the past and there is evidence that the system failed. The assessment of the uncertainty in the system model is informed by validation statistics (such as NSE and PBIAS) of the model output against historical observations. Furthermore, as the model is used for exploratory purposes in CRIDA and not to replicate past system response, the assessment also considers how different the modelled climate conditions are to the historical conditions which the model is calibrated for. Generally, models become more inaccurate when simulating climate conditions different from the conditions used in the calibration which has not been previously recognized in the original CRIDA list of indicators. For the last identified source of uncertainty, the climate projections, it is assumed that all projections are extremely uncertain because of robust evidence does not exist. It is argued that agreement in the projections does not indicate the level of uncertainty because the GCMs which inform the trends are not independent. This goes against the original CRIDA list of indicators for the level of uncertainty (See section 3.4.2.2). Instead, the uncertainty assessment is attached to how much the plausibility of failure analysis has relied on the projected information and how sensitive the analysis is to uncertainties in the projections. Finally, after each source of uncertainty is assessed, the highest uncertainty rating of the sources is used in the LOC classification.

The guidelines presented aim to improve the repeatability of the assessment under different analysts and make the assessment more straight-forward to apply. However, the limitation in the proposed guidelines is that it does not consider the sources of uncertainty after the LOC assessment. For example, in the Limari basin case study, there is significant uncertainty in the parameterizations of the adaptation actions which should inform the general strategic approach. If the effectiveness of solutions are very uncertain, flexible strategies should have preference over robust strategies which are difficult to change and have a lot of dependencies. The guidelines can be improved by identifying the sources of uncertainty in the following steps of CRIDA and integrating these sources in the assessment of analytical uncertainty.

7.2.3. Adaptation Tipping Points under transient future

The adaptation tipping points of strategies in previous applications of CRIDA is the KPM at its critical threshold. Once a strategy is no longer able to maintain a KPM above its critical value, a transition to another strategy is invoked. Under transient futures, the tipping point can be translated to a metric of time by taking a quantile value, for example the average or 50th percentile, from the distribution of time when the threshold is reached – stating that ‘‘on average the tipping point will be reached in 20 years”. This translates in CRIDA terms to a statement that “the plausibility of failure is 50% in 20 years”. In place of the analyst determining what plausibility of failure percentage is used to translate the tipping points in time, the new guidelines recommend defining this collaboratively with stakeholders. The quantile value is essentially informed by a threshold of the plausibility of failure according to what stakeholders are able to tolerate. This is gathered through the risk perception surveys which are also used for the risk assessment in STEP 2 of CRIDA. The significance of doing so, is that the tipping points of strategies can be communicated to stakeholders as the point in time when they can no longer tolerate the risk and that another action is required. This is a stronger message arguably to justify a tipping and a call for action over an analyst selected quantile value, such as the 50^{th} percentile. The adaptation strategy pathways recommended as a result aligns better with the general risk averseness or risk seeking nature of the stakeholders in a case study.

7.3. Further work on other aspects of Steps 1-3 of the CRIDA approach

The novelty of the CRIDA approach is linking a bottom-up approach for risk assessment to the generation of adaptation strategies pathways so that strategies may be adapted over time as new information becomes available or if there are rapid shifts in circumstances. It is risk-based which aligns with traditional methods of strategy justification to decision makers and is compatible with international guidelines of sustainable and Integrated Water Resources Management. The level of concern matrix in CRIDA is a useful tool that guides the analyst to an appropriate general strategic approach based on a risk assessment and also on how certain the risk assessment itself is. This ensures a recommendation of a set of low regret strategies. The strategies are recommended based on their effectiveness in reducing the plausibility of failure. However this limits the assessment to the consideration of an actions ability to reduce the plausibility of failure only, while the other dimension of future risk, namely, the impact of failure is essentially ignored. Actions on the other hand may target either or both dimensions. For example, building a new dam may reduce the plausibility of water shortage for irrigation, while diversifying economic activities to tourism possibly reduces the impact of the reduced water supply. The current guidelines for effectiveness evaluation may influence the analyst to exclude actions that are able to reduce the latter dimension in the final recommendation. It is vital therefore to include additional guidelines in CRIDA that accounts for the reduction of the impact of failure as a measure of an action's effectiveness. The incorporation of this other dimension in the adaptation strategy recommendation was attempted in this study, however this was not possible because the system model of the case study was not able to model the impact dimension of risk to experiment with the additional guidelines.

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Appendices

A SIMGEN

A modified SIMGEN is used in this study for climate scenario generation. The algorithm is a multivariate stochastic weather generator developed by Arthur Greene at the International Research Institute for Climate and Society (IRI) and has been successfully applied in the Western Cape province of South Africa and in south-eastern South America (Greene et al., 2015, Greene et al., 2012b).

The process takes daily station data of precipitation, and temperature (minimum and maximum) and generates stochastic synthetic projections of the variable conditions. It distinguishes between three "process classes" which are (1) the forced or anthropogenic trend component; (2) a "natural" annual-to-decadal component and; (3) a sub-annual component which includes the seasonal cycles and day-to-day variations. A schematic of the SIMGEN package is presented on Figure A.1 and the processing steps are outlined in the sub-sections below.

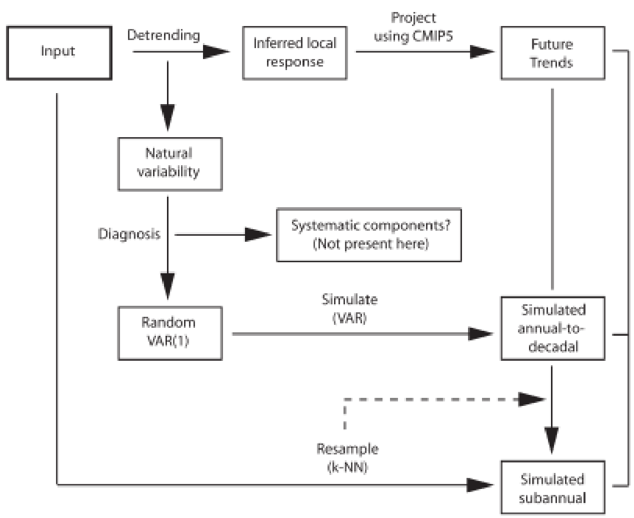


Figure A.1 SIMGEN processing components and flow (Greene et al., 2012b).

Pre-processing

This step reads in daily historical station records of precipitation and temperature (minimum and maximum) which are formatted to fulfil the requirement of the SIMGEN package. This consists of adding a specific time and date stamp as well as spatial formatting of the daily precipitation and temperature data in one file for each station. Gaps in the record are interpolated using a multivariate imputation by chained equations (MICE) developed by van Buuren and Groothuis-Oudshoorn (2011).

Anthropogenic Trend

Local temperature and precipitation trends are modelled in terms of a linear association with global mean temperature changes because they should represent a response to anthropogenic forcing. It has been shown by Ting et al. (2009) that the global mean surface temperature is an effective proxy for forced climate response. The past and future trends are modelled separately based on 20th and 21st century values respectively to account for differing trends for the past and the future. Past trends are used for detrending and future trends for projection. Spatial heterogeneity in global warming is inherently accounted for by modelling in terms of local trends (Greene et al., 2012a).

The global multi-model mean is calculated using GCMs from the CMIP5 ensemble, which are passed through a low-pass fifth order Butterworth filter having half power at 0.1 yr^{-1}. Ensemble averaging removes uncorrelated fluctuations which vary from model to model while enhancing the GCM projections to anthropogenic forcing. The smoothing on the other hand reduces residual interannual variability and effects of some short-lived transients such as volcano eruptions (Greene et al., 2012b).

For temperature, the regional or local trends are regressed on the global mean temperature signal according to:

$$T_r = \beta_O + \beta_1 T_g$$

where T_r is the regional or local temperature records, T_g is a multi-model mean, global mean temperature signal, β_O is the intercept term and β_1 represents the regional response to global temperature change. The fitted values T_r are used for detrending and β_O and and β_1 are used to project local temperature forward. For the 20th century they used annual mean temperature from local records from 1950 to 1999 compared to the global multi-model mean, and for the 21st century they used regional GCM projections compared to global GCM projections for each year from2006 to 2065 to create the scatter plot on Figure A.2. It is evident, that GCM projections of temperature are not that different. Now since, temperature was found to behave consistently across centuries, they just used the 20th century trend to also project forward the results.

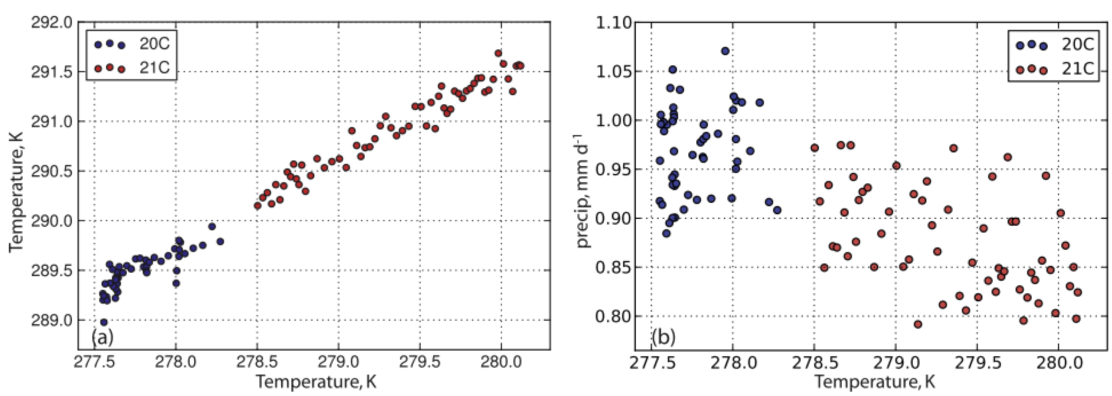


Figure A.2 Scatterplots of (a) regional mean temperature and (b) precipitation against global mean temperature, CMIP5 ensemble maens. (Greene et al., 2012b).

The fitted values of T_r appear as a scaled and shifted version of the local or regional signal as shown on Figure A.3(a). Note that this trend is not linear in time even though it is linearly dependent on the global mean temperature because warming accelerates in the later part of the century. The residual of the regression fit is now the detrended temperature record.

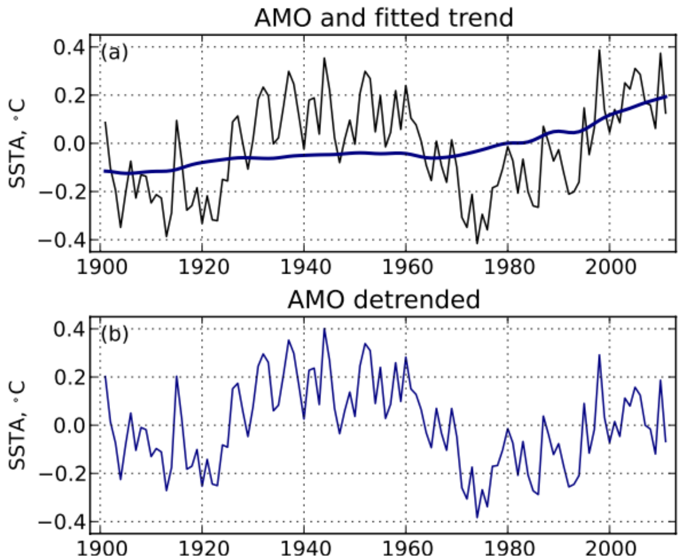


Figure A.3 Trend on local signal (Greene et al., 2012b)

The response of precipitation to changes in global mean temperature has also an indirect component, in that it depends not only on shifts in temperature, but also in changes in atmospheric circulation. Hence the scatter plot above is all over the place. Therefore projecting forward the results pf the 20th regression is less certain than is the case with temperature. Precipitation records are similarly regressed on the smoothed multimodel mean temperature but in log space (See Box 1) in order to represent precipitation projections as a fractional change per degree of global temperature anomaly. This is done separately for the 20th and 21st century values. The 20th century values use spatially (regional) averaged annual mean temperature values and the 21st century uses the GCMs which are first filtered according to a threshold correlation (0.15) with observed records to eliminate GCMs with outlying projections. A separate scatterplot is created for each GCM as shown on the figure below. Then for each GCM the percent change per temperature anomaly can be found (which is the slope of the line on the top graph of Figure A.4).

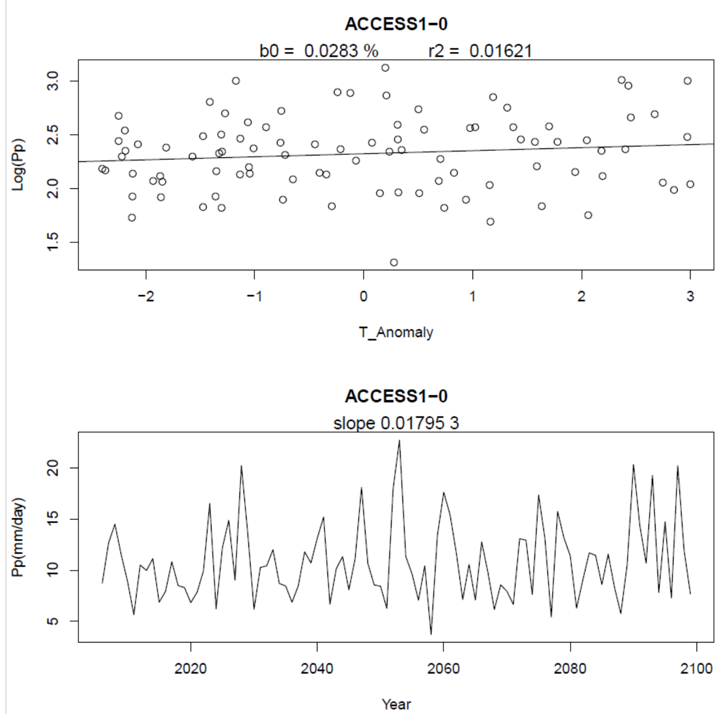


Figure A.4 Precipitation trend extracted from GCM model.

Unlike temperature regional precipitation differs significantly among GCMs so a gaussian curve is fitted on the frequency distribution of GCM projections expressed as fractional changes per degree of warming as shown on Figure A.5.

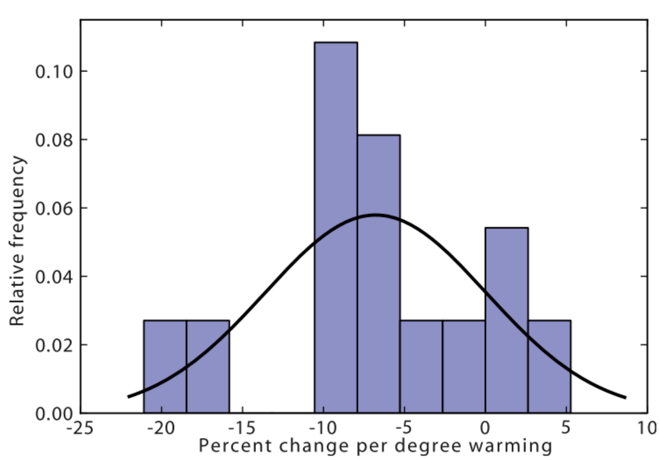


Figure A.5. Fractional Change of regional precipitation per degree of warming projected by the filtered CMIP5 ensemble. A Gaussian curve is fitted onto the data. (Greene et al., 2012b)

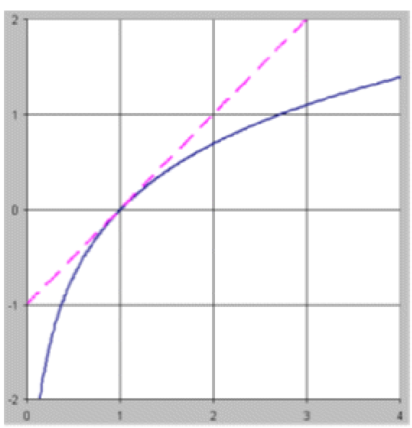
In projecting the precipitation trend, the desired quantile is specified and the corresponding fraction change in precipitation per degree warming is determined using the fitted Gaussian. Trends are then computed based on the formula:

$$T_{c21} = T_r + \alpha T_{c20}$$

Where T_{c21} is the future catchment trend, T_r the quantile based regional trend, T_{c20} the 20th century catchment trend and α sets the degree of scatter (set to 0). The catchment-averaged future trend will correspond to the imposed quantile-based value, while individual catchment trends will scatter around this value according to their 20th century behaviour. The degree of scatter, is set to 0 which results in the regional trend being applied uniformly across stations. To project, the decomposition process is reversed and T_{c21} is used per timestep to calculate the precipitation. Precipitation trend will also not be a straight line in time.

Box 1. Change in natural log ≈ percentage change.

The reason for this is that the graph of Y = LN(X) passes through the point (1, 0) and has a slope of 1 there, so it is tangent to the straight line whose equation is Y = X-1 (the dashed line in the plot below):



This property of the natural log function implies that LN(1+r) ≈ r

when r is much smaller than 1 in magnitude. Suppose X increases by a small percentage, such as 5%. This means that it changes from X to X(1+r), where r = 0.05. Now observe:

LN(X (1+r)) = LN(X) + LN(1+r) ≈ LN(X) + r

So in ln space of the precipitation axis on Figure 4, you can have the slop of percent change in precipitation per temperature increase.

Regional Annual-to-Decadal Variability

Annual-to-decadal variability is treated as ‘random’ variations. As the simulation models three variables a multi-variate generalization of a classical first-order autoregression (Vector Autoregression; VAR) is use to simulated this component of the form:

$$y_t = Ay_{t-1} + u_t$$

where y_t is the 3x1 matrix of climatic variables simulated, A is a 3x3 matrix of coefficients and u_t is 3x1 stationary white noise (error term). VAR models the evolution of a set of variable as a linear functions of not only their past values, but also the past values of other variables that are input to the model. The model is fitted to the annualized detrended series of each variable by least squares regression using the estVARXls package for the R programming language.

As SIMGEN was generated to explore decadal variability it has an additional functionality of scanning for a relatively dry or wet decade in the simulated data and slotting this series into a user-specified decade. The screening process is done by fitting a Gaussian curve onto a frequency distribution of decadal variations, and selecting a decade according to a certain percentile. This functionality is not necessary for application with CRIDA therefore default settings are used which slots a 10^{th}, 50^{th}, and 95^{th} percentile decade into the time series starting from 2010. The series is then superimposed on the projected trends as a way of combining contributions of natural and forced variations. This means, that the 10^{th} percentile anthropogenic trend series will have a 10^{th} percentile decade starting in 2010, the 50^{th} percentile anthropogenic trend series will have a 50^{th} percentile decade starting in 2010 and finally, the 95^{th} percentile anthropogenic trend series will have a 50^{th} percentile decade starting in 2010. This is not expected to affect the results of the study as the resulting series remains within the expected variability of climatic drivers and follows the same stochastic directions after the decade is sliced in.

Reassemby & Downscaling

The anthropogenic trend and annual-to-decal components are combined variable by variable resulting at this stage to a domain-scale simulation that is temporally resolved to the annual level (Referred to hereafter as SIMULATION A). This signal is downscaled to individual stations using the regression coefficients of the de-trended station-level variables on the corresponding de-trended spatially averaged variables. Uncorrelated noise is added at the station level to imitate observed variability on the annual-to-decadal scale (Greene et al., 2012a). This output is referred to hereafter as SIMUALTION B.

Sub-annual Variations

Sub-annual values are generated by resampling observations in 1 year blocks over the entire domain to preserve spatial coherence, using a modified K-NN scheme by Rajagopalan and Lall (1999). It consists of searching within the observed record for a (k=5) number of years whose regional means are "nearest neighbours" to the vector of the year being simulated along the sequence of SIMULATION A. A mahalanobis distance metric is used to identify these candidates with weights of (2/3, 1/6,1/6) for precipitation, maximum temperature and minimum temperature. The resampling year is chosen from among the k candidates, with a monotically decreasing resampling kernel with probabilities 1/n, n = 1,2,...5 (normalized) to select from among the nearest neighbours. Since year-to-year dependencies are already accounted for by the VAR, the station level sub-annual pattern of the year chosen from among the candidates are appropriated for the year being simulated. These station level records are then rescaled to match the station level trend and variations of SIMULATION B.

B Additional Background Limari Basin

B.1. Water governance and management

Chile is the country with the highest diversity of administrative authorities related to water resource management (Table B.1). The main government organizations in charge of water resources in the country is the Ministry of Public Works, having under its umbrella the General Directorate of Water Resources (DGA), the Directorate of Hydraulic Works (DOH, 2010), and the Superintendence of Water and Sanitation Services (SISS) (Valdés-Pineda et al., 2014). The DGA further does the research to inform the Dirección de Obras Hidráulicas (DOH) and the Comisión Nacional de Riego (CNR) which are federal institutions that are mandated to construct, implement and coordinate hydraulic works (i.e. irrigation) and are enabled to promote the efficient us of water resources. Climate change adaptation plans in the water context are under the mandate of the Ministerio del Medio Ambiente (MMA). INDAP is another federal institution with high interest to climate change adaptation and has specialized programmers to build capacities of small farmers and peasant family agriculture.

Table B.1. Federal Institutions directly linked to water resources management. Source: Valdés-Pineda et al. (2014)

Ministry	Department	Function
MOP	DGA	Promote the management and administration of water resources. Provide and disseminate the information generated by the hydrometric network contained in the Public Water Cadaster, Monitoring and control of the quantity and quality of the resource in its natural sources
MMA	SMA and SEREMI-MMA	Environmental protection and conservation of water resources. Implementation of environmental regulations related to water resources
MOP	DGA	
MDN	DIRECTEMAR	
MOP	SISS PAPR-DOH	Regulation of Water Drinking and Sanitation Services
MINAGRI	CNR and INDAP	Foment and Development of Irrigation Activities, and Water Infrastructure
MOP	DOH	
MINAGRI	SAG	Supervision and Control of water quality with specific objectives
MINSALUD	SNS	
MEFT	SERNAPESCA	
MEFT	SUBPESCA	
MOP	SISS	Supervision and control of effluents
MINSALUD	SNS	
MOP: Ministry of Public Works, DGA: General Directorate of Water Resources, MMA: Ministry of Environment, SMA: Sub-secretary of Environment, SEREMI-MMA: Ministerial Regional Secretary of		

Environment, MDN: Ministry of National Defense, DIRECTEMAR: General Directorate of Maritime Territory and Merchant Marine, SISS: Superintendence of Sanitary Services, PAPR: Rural Drinking Water Programme managed by DOH, MINAGRI: Ministry of Agriculture, CNR: National Commission of Irrigation, DOH: Directorate for Hydraulic Works, SAG: Agricultural and Livestock Service, MINSALUD: Ministry of Health, SNS: National Service of Health, MEFT: Ministry ofEconomy, Foment and Tourism, SERNAPESCA: National Service of Fishing, SUBPESCA: Sub-Secretary of Fishing.

Water users within the context of the water markets also hold considerable power in the management of water. There are three types of water users defined according to their ownership of water rights which gives a user the right to be allocated a portion of available water at a specific source (i.e. natural river, canal or aquifer) for consumptive (i.e. irrigation) or non-consumptive use (i.e. hydropower generation)(Valdés-Pineda et al., 2014) (1) *Users with water rights*; (2) *Users with traditional land ownership*; and (3) *Users without water rights*. The water rights are initially allocated by the DGA and are then redistributed among water users through the water market (Hurlbert, 2018).

If two or more users hold the right to extract from the same body of water, the users form organizations which are charged distributing water and enforcing its correct use by its members, and with collecting fees for the construction, maintenance and administration of irrigation infrastructure (Ribbe et al., 2018, Hurlbert, 2018). Within the Limari Basin, there are 318 organizations are registered *(Geohidrología Consultores LTDA, 2014).* These organisations of water users (OWUs) OWUs enforce the guidelines for management reported by the Dirección General de Aguas (DGA) whom together manage the water resources in the basin in a fragmented manner.

B.2. Water Infrastructure

The core of the water infrastructure to store and distribute water in the Limari Basin is the Sistema Paloma which comprises a 700 km network of canals connected to three reservoirs: La Paloma (750 hm^3 capacity), Recoleta (100 hm^3) and Cogoti (150 hm^3) (Ribbe et al., 2018).

The system allocates water volumes to user organizations based on the accumulated volume in the three reservoirs which the user organizations then distribute among its members proportional to the number of water rights held by each user. The allocation of water follows operational rules established and approved by the Directorate of Hydraulic Works (DOH) and the General Water Directorate (DGA) and accepted by all beneficiary organizations of the La Paloma reservoir.

The rules state that the maximum annual allocation of water to user organizations is 320 hm^3 when the accumulated volume in the reservoirs is above 500 hm^3. 80 hm3 of the allocation is sourced from the Cogoti and Recoleta reservoirs equally, while the La Paloma Reservoir supplies the remaining 240 hm3. If the accumulated reservoir volume falls below 500 hm^3, the maximum water allocation to the user organizations is half the accumulated reservoir volume. The maximum annual allocation is revised yearly on the 1st of May based on reservoir levels on September the previous year to account for the winter recharge (Angel, 2010). The applied allocation is distributed distributed among the user orgnisations according to the percentages indicated on Table B.2.

Table B.2. Percentage distribution of the Sistema Paloma Water Storage to Water User Organisations

User Organisation	Percentage (%)
Asociación de Canalistas del Embalse Recoleta	35.75
Asociación de Canalistas del Embalse Cogotí	31.09
Junta de vigilancia del Río Grande, Limarí y Afluentes	19.63
Asociación de Canalistas del Canal Camarico	7.90
Junta de Vigilancia del Río Huatulame	2.96
Asociación de Canalistas del Canal Punitaquí	2.67
Total	100

B.3. Primary Water Use

The primary water use in the basin is for agriculture, potable water, mining and energy. With agriculture using 97% of the consumptive water.

B.3.1. Agriculture

This semi-arid basin cultivates 64,056.05 ha of land according to the 2007 Agricultural census grown mainly along the rivers and irrigation channels (Figure B.1).

The main crops grown are forage plants (i.e. alfalfa) to support the regions goat livestock followed by fruit tree cultivation (mostly table grapes cultivation, avocado, clementines and olives) and vineyards for pisco and wine production (ODEPA, 2018). To support this industry, Geohidrología Consultores LTDA (2014) estimates an annual irrigation demand of 517.0 hm^3 considering evaporative losses. From the agricultural survey of 2006/2007, 45% of the area is irrigated with gravitational irrigation, 1.12% is irrigated with sprinkling, reel or pivot irrigation and 54% is irrigated with drip and microspray irrigation.

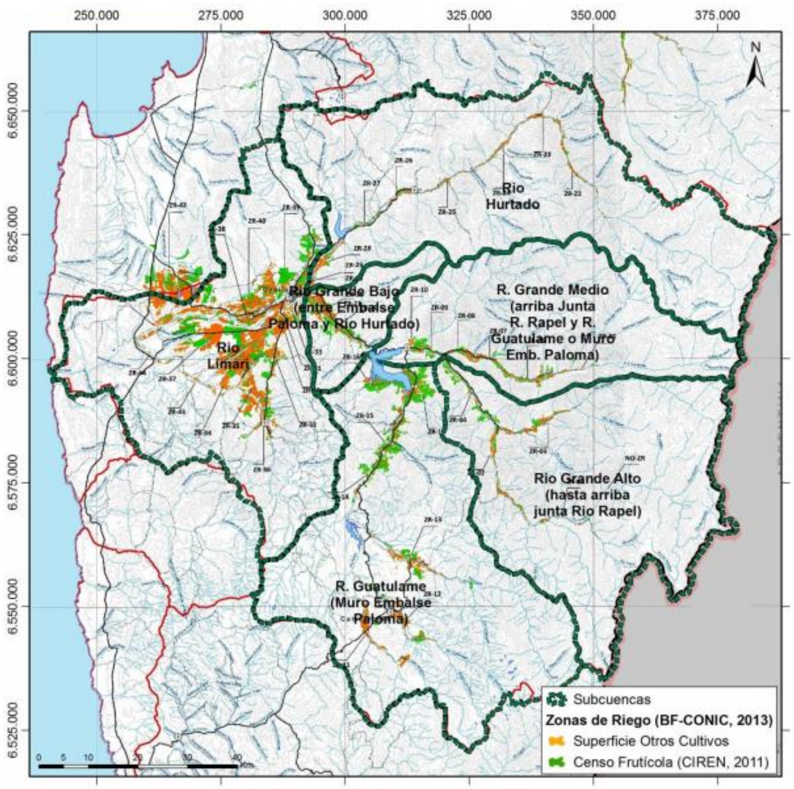


Figure B.1 Cultivated land in the Limari Basin. (Source: Geohidrología Consultores LTDA (2014))

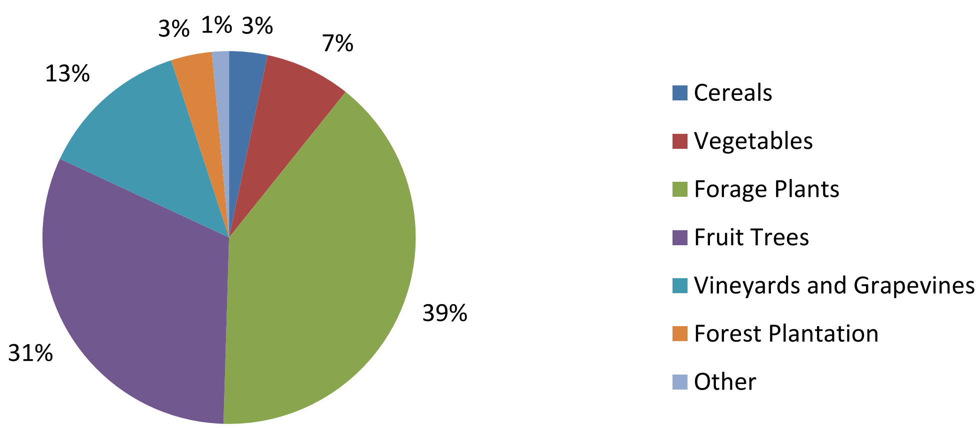


Figure B.2. Crops grown in Limari Basin. (Source: Elaborated from the 2007 Agricultural census published by INE (2007))

B.3.2. Potable Water

Almost 200,000 people live in the Limari basin, distributed across its 5 communes, the most populated of which is the commune of Ovalle (Table B.3). Potable water is supplied by the private company Agua Del Valle in urban or semi-urban areas using a combination of surface and groundwater sources. A local collaboration called the APRs (Agua Potable Rural) supply rural potable water. APRs extract groundwater from 63 wells then distribute supply through water delivery trucks (Ribbe et al., 2018).

Table B.3. Rural and Urban Populations in the Communes of the Limari Province. (Source: Censo 2017 from Instituto Nacional de Estadísticas (2018))

	Rural	Urban	Total
Ovalle	23,733 [21.3%]	87,539 [78.7%]	111,272
Combarbalá	7,324 [55.0%]	5,998 [45.0%]	13,322
Monte Patria	15,413 [50.1%]	15,338 [49.9%]	30,751
Punitaqui	5,108 [46.6%]	5,848 [53.4%]	10,956
Río Hurtado	4,278 [100.0%]	0 [0.0%]	4,278
Total	55,856 [32.7%]	114,723 [67.3%]	170,579

The potable water demand in 2017 for the Limari basin is estimated at 11.94 hm^3/year. This is calculated assuming a population of that the per capita potable water allocation (125 l/inhabitant/day) and efficiency of the water distribution (65.2%) estimated by Ilustre Municipalidad De Ovalle (2012) for the city of Ovalle is applicable for the entire basin. The assumption for the distribution efficiency may not hold for the rural areas, where 32.7% of the population lives, as different APRs are likely to have varying qualities of distribution networks. However, due to limited information on the efficiency of APR networks the aforementioned efficiency value is used.

B.3.3. Mining

Table B.4 lists the mine sites in the Limari province. Together these mines are estimated to use 1.173 hm^3 per year (Equipo Técnico Fundación Chile, 2018)

Table B.4. Mine Sites in the Limari Basin

Name of the Company Comune	Name of the installation plant	Material exploited	UTM North	UTM East
Minerales del Sur S.A., Punitaqui	Mina los Mantos	Copper	6.584.200	286.950
Cia. Explotadora de Minas Cemin, Monte Patria	Mina Los Pingos	Copper	6.581.500	350.100
Cia. Mra. Domino Trucco, Punitaqui	La Poderosa	Calcium Carbonate	6.565.000	265.000
Flor de Los Andes S.A., Monte Patria	Flor de Los Andes	Lapiz lazuli	6.542.200	354.100
Minera Altos de Punitaqui, Punitaqui	Cinabrio	Copper	6.588.735	288.540
Cia. Minerial Tierra Del Fuego, Ovalle	El Dorado	Iron	6.617.500	286.500

B.3.4. Energy

In the main Paloma reservoir, a small hydro power plant was constructed in 2010 to generate energy only from the water released for irrigation and so does not compete with this industry. The plant consists of two turbines and an installation capacity of 4.5 MW, with a designed discharge of 12 m3/s and an average energy production of 19.000.000 Kw/h. Currently it is not operating due to water scarcity (Ribbe et al., 2018). Furthermore, there is a small hydropower plant in the river Los Molles, that has been in place since 1952 (Central Los Molles, 1952) with a capacity of 16.000 kW.

B.4. Response to Historical Droughts

The common actions employed by the farmers in past droughts are listed on Table B.5. However, in the latest drought, the portfolio of options available to farmers to accommodate stressed conditions were more limited as farmers continued to increase farmed acreage devoted to high value permanent crops with the improvement in irrigation infrastructure and technology. This is a typical consequence of basin closure, as stated by Molle et al. (2010), where the slack in water resources availability is reduced due to basin overdevelopment. The basin aquifers have also since been declared '*Restricted*', limiting the water rights allocated for legal groundwater extraction (Vicuña et al., 2014).

Table B.5. Survey responses for adaptation strategies employed by farmers in past droughts.

Adaptation Strategy	Vicuña et al. (2014) survey percentage of responses[1]	Roco et al. (2016) survey percentage of responses [2]
Reducing cultivated acreage	58%	12.1%
Deficit Irrigation	20%	
Trade in water-volume market	15.5%	
Groundwater Extraction	14%	-
Improved Irrigation Efficiency	12.5%	8.3%
Investments for water accumulation	-	31.5%
Partnership Activities	-	2.4%
None	16%	38.7%[3]

[1] Averaged statistics from survey responses in Monte Patria, Ovalle and Punitaqui.
[3] Only the percentage of farmers that acknowledged the drought but did nothing are included in this statistic. The remaining 7% of farmers did not acknowledge a droughts and therefore did nothing.

As a result of a limited capacity to adapt, farmers were forced to cut their permanent trees to the base in order for these to survive the drought while others abandoned or sold their fields (partially or entirely) unable to meet the water requirements and chose to sell their allocations in the water-volume market. As a consequence, the agricultural industry and water resource ownership which are symbols of weath has become more and more concentrated indicating increasing inequality in the region (Urquiza and Billi, 2018). There is evidence of plantations sold to developers for road and residential construction or rented out to accommodate solar energy fields. Those with additional plots planted horticultural crops at reduced acreage to generate income during the drought or opted for deficit irrigation. However, due to low productivity, many small to medium scale farmers chose to sell their water allocation to larger enterprises instead of cultivating. Large enterprises often have larger water allocation and enough capital to buy water during drought periods making them less vulnerable than small to medium scale farms which make up the majority of the agro-business in the basin. In addition to the above responses, the government offered monetary support to small scale farmers, rural communities and farmsteads with employees while larger farms received pay-outs from private insurances.

Many illegal wells were dug during the drought worsening the already stressed aquifer resource which rural communities depend on for their potable water supply. The government responded by deploying water delivery trucks to these communities to meet potable water demand. The capital of the region, Ovalle, also experienced a deficit in its potable water supply, forcing the private drinking water supplier (Agua del Valle) to draft a contract with the Juntas de Vigilancia to maintain a certain flow rate in the Limari River so that the potable water demand is met. The water law has since been revised to ensure that potable water supply is the first priority for water allocation.

B.5. National and Local Plans for Climate Change

Plan de Adaptación al Cambio Climático del Sector Silvoagropecuario (Muck et al. (2013))

The report recognises that future climate scenarios suggest a decrease [increase] in precipitation [temperature] and that the 0 isotherm is likely to rise in the Andes causing shifts in the water flow regime. While the impact of the new climate scenarios in agricultural production varies according to crops, species and regions of Chile, it is expected to cause an overall decrease in agricultural yields across the country due to increased erosional processes, changing crop life cycles, proliferation of pests/disease and/or changing water availability/seasonality. Therefore, the report notes that strong action is required to improve this sector to compensate for the changing climate.

The proposed plan aims to improve the efficiency, flexibility, sustainability and tolerance of this sector whilst protecting the most vulnerable (i.e. subsistence farms) and significantly improving the sector's contribution to the national economy. The actions related to water resource management established by the authority of forestry and agricultural in order to achieve this goal are a combination of direct measures which reduce the vulnerability of the system to climate change and indirect measure to support the implementation of direct measures.

The direct measure proposed may be summarised to:

- Building new irrigation infrastructure and improving current efficiency
- Changing crop types and schedules
- Improving soil quality
- Employing the use of radiation reducing meshes and other technologies with the same; and
- Building rain water harvesting systems.

The Indirect measures to support the application of the above mentioned direct measures are:

- Monitoring the effects of the environmental conditions on the agricultural production

- Promote research on the current system (i.e. system water demands, identifying zones of high risk etc)
- Promoting research on improving the application of the direct measures
- Increasing the technical and legal capacity of farmers and user organisations to implement and properly manage direct measures through education and financing
- Improving insurance policies
- Setting up information systems and databases with work plans for preventive management and contingency plans against agricultural emergencies

Estrategia Regional de Recursos Hidricos por Cuenca, 2014-2030. (CAZALAC)

This strategy presents 5 strategic guidelines which is in line with the regional vision:

- Manage land use planning, relieving sustainability as an essential criterion and integrated management of water resources at regional and basin level, through a regulatory framework applied to all productive sectors
- Strengthen the institutional framework for water governance
- Move towards a modern and efficient infrastructure and water technology
- Ensure the quantity and quality of water necessary to ensure conservation flora, fauna and ecosystem services
- Raising the water culture of urban and rural population through transfer knowledge and awareness of the benefits of sustainable water use.

In line with the above mentioned guidelines the priority projects recommended in this plan are:

- Construction of reservoirs: Valle Hermoso, Muralles Viejas and La Tranca.
- Study and construction of dams or medium reservoirs: 2 reservoirs of 2.5 - 2.0 million m3 + 6 lagoons of 1.5 million m3 in total.
- Implement monitoring: Aquifers, glaciers, snow and fluviometric.
- Increased use of telemetry
- Improve channel efficiency and move to more efficient irrigation systems

Table B.6. Table of proposed reservoir construction [Source: Ribbe et al. (2018) & (Corporación Regional de Desarrollo Productivo, 2016)]

Reservoir	River	North	East	Storage Capacity	Status	Scheduled Construction	Purpose
Reservoir “Valle Hermoso”, in the Pama river catchment	Pama	6537043	314929	20 hm3	Contract signed and under construction	2015-2017* (priority 1 of 19)	Irrigation to Pama Valley Hydroelectric Power APR

Reservoir "Murallas Viejas"	Combarbala	6540761	319709	50 hm3	Feasibility study	2019-2022 (priority 14 of 19)	Irrigation Hydroelectric Power APR
Reservoir "La Tranca"	Cogoti	6555900	322366	50 hm3	Feasibility study	2018-2021 (priority 10 of 19)	Irrigation Hydroelectric Power APR
Rapel Reservoir	Rapel River	6597518	344482	14 hm3	Feasibility study	2019-2022 (priority 15 of 19)	---
Piedra del Barco	Estero Punitaqui			5 hm3	Prelimary studies	-	---
***Completion is delayed to 2019 [Source: Semanario Tiempo (2017)]**							

C System model review

The solution testing model must be accurate in representing the elements of the system listed by Mendoza et al. (2018). System elements specific to the Limari case are listen on Table C.2. The WEAP model by Vicuña et al. (2012) used in the 2016 CRIDA application is reviewed whether it represents the conditions of the system elements on this table.

The review showed that the WEAP model by Vicuña et al. (2012) does not represent the current socio-economic conditions in the area. This model was designed according to conditions from 1970-1985 and therefore assumes a population in the basin of 87,791 while the current population according to the last census (2017) is 170,579. Furthermore, the crop pattern modelled which is shown on Figure C.1, is also significantly different to the crop pattern reported in the Census of 2007 (Figure B.2). The modelled pattern more closely resembles the pattern before the construction of the Sistema Paloma. The irrigation network has since shifted the crop pattern from cereals to more high value crops such as fruit trees and vineyards.

Due to these reasons another WEAP model was sourced from the Laboratorio de Prospección, Monitoreo y Modelación de Recursos Agrícolas y Ambientales (PROMMRA Lab) associated with the University of La Serena's Department of Agronomy. The crop pattern in this model shown on Figure C.1 more closely resembles the real crop patters on Figure B.2. The total agricultural area modelled in the PROMMRA model is 51,659.23 ha, only 80.6% of the area reported in the 2007 agricultural census, 64,056.05 ha. The mismatch may be due to the WEAP model not including agricultural areas not connected to the Sistema Paloma such as substinence farmers. The average flow through transmission links supplying irrigation to catchment is 555.5 hm^3 per year which is not far from the 517.0 5 hm^3 per year calculated by the DGA. The irrigation efficiency modelled overestimates the efficiency reported in the agricultural census of 2007. According to the census 44.94% of the area is irrigated with gravitational irrigation, 1.12% is irrigated with sprinkling, reel or pivot irrigation and 53.94% is irrigated with drip and microspray irrigation. The model is parametrized however with 9.14% of the area irrigated with gravitational irrigation, 37.98% irrigated with sprinkling, reel or pivot irrigation and 52.88% irrigated with drip and microspray irrigation. The efficiencies of each irrigation type is assume to 30% for gravitation irrigation, 50% for sprinkler irrigation and 90% for drop and microspray irrigation. The potable water demand is assumed to be 4.9 hm^3/year, which is almost half of the real demand calculated in Appendix B.3.2. However, since potable water demand is 2 orders of magnitude less than agricultural demand, this is unlikely to cause significant changes in the analyses. The PROMMRA lab model for agricultural and potable water demand is time varying reflecting historical conditions from 1990 to 2014. For this purpose however we aim to model current conditions and how they behave in the future therefore these demands are stabilised to their 2014 values in this study.

The PROMMRA lab model consists of 7 upper basin models to simulate the snow-melt regime in the higher altitude. These models use spatially distributed temperature and precipitation data from the stations listed on Table C.2 to calculate the flow. Many of these stations however are at lower altitudes and may not be representative of conditions at higher altitudes. The resulting streamflow outputs of these models are input to the main catchment model which is designed with infrastructure, agricultural and social components of the basin. The temperature and precipitation series in the upper basin are scaled and shifted to test the effects of climate change in the snow-melt regime. Ideally, temperature and precipitation in the main model should also be scaled and shifted to change the soil moisture content, evaporation and crop transpiration in the basin. However, the model is currently not set up to account for this. Precipitation in the lower basin is already extremely small, and the majority of the source comes from snow melt, hence not having climate change effects on precipitation included in the lower basin is unlikely to cause significant errors. On the other hand, climate change effects on temperature causing an increase in crop transpiration may have significant influence. A sensitivity analyses is recommended in future works to test this sensitivity. But since this model is much better at simulating the agricultural demand in the basin, it will be used to continue with the analysis in place of the model by by Vicuña et al. (2012).

Table C.1 Meteorological stations used in the upper basin model of PROMMRA

Upper Basin Model	**Station Used**
Rio Hurtado en San Augustin	Pabellon DGA (Precipitation) Hurtado DGA (Temperature)
Rio Rapel en Palomo	Las Ramadas DGA
Rio Mostazal en Caren	Las Ramadas DGA
Rio Grande en Las Ramadas	Las Ramadas DGA
Rio Combarbala en Ramadillas	Cogoti (Precipitation) Las Ramadas DGA (Temperature)
Rio Cogoti en Fraguita	Cogoti (Precipitation) Las Ramadas DGA (Temperature)
Rio Tascadero en Desembocadura	Las Ramadas DGA

Table C.2. Assessment on the model's representation of system elements. A: Vicuña, McPhee et al. (2012) Model. B: PROMMRA Lab Model.

System Elements	A	B
Natural System		
The model reflects the snow-melt driven regime dependent on both precipitation and temperature.	Yes	Yes
The model reflects changes in the soil moisture content, evaporation from open water bodies and transpiration from crops as a result of changes in temperature and precipitation	Yes	No
Institutional System		
The model includes operational and distribution rules for Sistema Paloma.	Yes	Yes
Drinking water allocation is prioritised in the model.	Yes	Yes
Infrastructure		
The model includes the three primary reservoir and the main canals making up the Sistema Paloma	Yes	Yes
Socio-economic conditions		

The model must reflect current socio-economic conditions and their associated water demands in the sectors which are the main water users in the basin as described in appendix B.3.	No	Yes
Management		
The model must include adaptation strategies in place or support the testing of adaptation strategies.	Yes	Yes

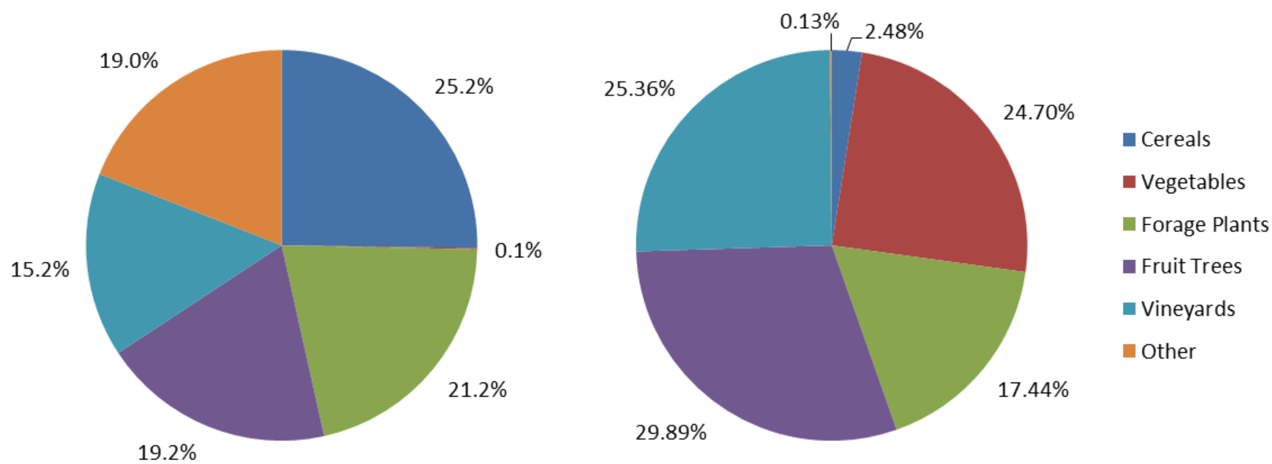


Figure C.1. Crop Patters modelled in the Vicuña, McPhee et al. (2012) Model (left) and PROMMRA Lab Model (Right). Crop Patters are constant over the modelling period (1970-1985) of the Vicuña, McPhee et al. (2012) Model. Crop Patterns varied with time over the modelling period (1990-2015) of the PROMMRA lab model and the crop pattern shown in the image was the pattern in the year 2007.

D Stakeholder Workshop and Interviews

The initial three stages of CRIDA require information from the stakeholders to supplement the participatory aspects of the methodology. Therefore, a mission was organised with the following goals:

1. Revisit the 2016 decision context.
2. Gather information of current adaptation strategies by stakeholders and their effectiveness to populate the adaptation strategy library.
3. Gather information of future plans/expectations and goals in the basin as well as limitations to plan implementations in the basin to inform the acceptability criteria.
4. Gather stakeholder risk perceptions for the LOC analyses including impact indicators.
5. Further knowledge transfer from/to knowledge institutes (PROMMRA Lab WEAP Model).

Representatives of relevant stakeholders in the basin identified through a literature review (See Appendix B.1) and based on recommendations from the local partner CAZALAC were invited to face-to-face interviews and a focus group/workshop day. In the semi-structured interviews, the stakeholders were asked to explain their perspectives on the issues related to water in the past and the future, their roles and attitudes to improving these issues, limitations to implementing projects, and their plans and goals for the basin. Interview questions are on Appendix D.1. During the workshop, a group modelling session was done to revisit the decision context to identify appropriate impact indicators and adaptation strategies in the basin. The workshop program is on Appendix D.2. A survey (Appendix D.3) was done during the workshop and sent out to interviewed stakeholder to gather risk perceptions the level of concern analysis. Furthermore, as agriculture is main water use in the basin, field visits to farms were organized to identify their past response to drought, their attitudes to droughts and adaptation strategies that they are considering in the future. A list of stakeholders surveyed, interviewed and/or attended the workshop is on Appendix D.4.

D.1. Questions in Interviews

Main Water Uses

- What are the most important industries in Ovalle?
    - Agriculture
        - What kind of agriculture? And is it mainly small scale?
    - Mining
        - Do the mines use a lot of water?
    - Potable Water
        - Does it come only from groundwater

    - Environmental
        - Is it important that environmental flow is met?
- What are the future plans for the industry in the basin? How is agriculture planned to evolve, how is mining?

Policies

- What are the main climate change policies in the basin that the government has put in place.
    - Is it law to be responsible for the amount of water that is used.
    - No more permits are being given for groundwater extractions.
- What are the climate goals of Chile in the future? How is the government planning for climate change adaptation? What is the planning horizon? How far ahead are you planning (planning horizon)?
- Are locals and also district office capable of applying solutions? Are they open to it? Is the problem understood enough that people are eager to help?
- What is missing now in policies or institutions for climate change adaptation? What is the biggest hindramce?
- What is the planning horizon in Chile?

Past

- Past Drought.
    - Why was this drought different from the previous droughts?
    - What were the effects? Economic effects (Agriculture, Mining, drinking water)? Social effects (Migration, loss of livelihood, increase in poverty? Environmental effects (Lower environmental services?
    - Who were the most vulnerable? What demographic? Was there a big difference in vulnerability upstream and downstream the reservoirs?
- What were the plans already in place in the past to cope with the drought?
    - Think of supply side or demand side plans? Local (small-scale) or regional scale?
    - How effective were they? What were the most effective? Think of failure and success stories?
    - Was it small-scale adaptation strategies at the local level or regionally/nationally
        - implemented policies?

Adaptation Strategies

- What are current adaptation strategies being implemented in the future?
    - Realistic and proposed?
- How are adaptation strategies implemented. Are there institutions assigned for this task?
- What are your opinions of the planned and proposed future plans? Effectiveness? Economic? Pros and Cons?
- What are adaptation strategies that you would have liked to see implemented but is not?

- Thing of supply/demand side, local/national, technical(i.e. improved irrigation)/social(i.e. migration, change of lifestyle)/financial (incentives to change).

- What are the the characteristics of adaptation strategy that would increase the chances of it being implemented.

D.2. Workshop Program

Activity	**Description**	**Materials**	**Discussion Script**
Group Mapping Session	Full description of the basin and its vulnerabilities	Base map of the basin (inc. land use map, cities, irrigation channel, national parks, reservoirs) Stickers • Three different colors representing economic, social and environment Transparent paper (Areas of Importance) Transparent paper (Areas Vulnerable)	**Introduction**: "The purpose of this session is to get a physical and socio-economic description of the basin. Then identify areas of importance and vulnerabilities related to future water scarcity in the region." "In front of you, you will find a map of the basin with the primary land use classes overlaid on top (i.e. agricultural areas, industrial, national parks, and populated areas). As well as the irrigation network" "This information will help identify areas of importance and areas that are vulnerable so that we have specific locations to focus on when we assess how effective the adaptation strategies are" **Activity 1:** Discuss the base map. • Is there anything important missing? ○ Think of big economic/industrial areas, residential areas and nature reserves. **Activity 2:** Each person to identify "important locations" for economic, social and environmental reasons in the basin.

			Activity 3: Each person to identify "vulnerable locations" for economic, social and environmental reasons. **Note: Focus of vulnerabilities related to a reduction in water supply in the future.** **Activity 4:** Overlay the areas of importance and areas of vulnerabilities layer. Discuss locations where they overlay. (why do you think they are important and vulnerable?) **Activity 5:** Show the slide again of the current indicators used in the assessment. Discuss whether they think they are representative of the areas of importance/vulnerable that they identified. If yes: Continue to next exercise If no: Why? Chose a better indicator Discuss a critical threshold • Critical threshold is the quantitative point where if the indicator reach this point, there will be system failure (i.e. large economic losses). **Note:** Maximum of three indicators.
Collaborative Discussion	Qualitative Risk Assessment	Large paper (for risk assessment) Post its Pens and Markers	**Introduction**: "A critical step in CRIDA is to define the LOC rating which indicates the type of adaptation strategies fit for application" "To define the LOC, the future risk is assessed which is based on impact and

			plausibility that the critical threshold is reached" "This study employs a participatory semi-quantitative approach and engages stakeholders is defining the impact and plausibility" "In this session we will ask what you think the main indicators of impact" "So here we want to ask the question, what indicator would best inspire actions" **Activity 6:** Each person to identify possible indicators of impact. The indicators must be applicable for all key performance indicators (i.e. instead of agricultural crop lost, keep it broad to economic loss). The indicators must also be capable of being assesed either qualitatively or quantitatively. Table 1 is a guide on how to find indicators. Vulnerability is defined as the propensity or predisposition to be adversely affected which can encompass a variety of elements including sensitivity or susceptibility to harm and lack of capacity to cope. While Exposure is defined simply as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. **Activity 7:** Group similar indicators together. Then: • Prioritize the indicators (Chose the best 5). Which indicator of impact fits the case study best. Think of it terms of what would

			inspire the most action among the people. • Determine how to measure indicators. Will this be qualitative or quantitative. Do we have the information to measure this indicator? • Assign weight factors to each indicator if some indicators are obviously more important than others. At the end of the session we should have a table filled out as shown on **Table 2**. (Apart from the threshold, this will done individually in the perception survey)
Perception Survey	Define thresholds of high, medium, and low plausibility and impact for each indicator.	Survey Forms	**Introduction**: “In this exercise, we want to gauge what your perception is on impact and plausibility” “Risk attitude varies from culture to culture and within cultures also from person to person. Hence it is important to consider the perception of stakeholders when proposing an adaptation plan. A group of stakeholder that is risk averse will likely be more keen on applying a “robust” adaptation strategy that deals with a whole range of ucertainty.” “What would you consider a high, medium or low impact for each indicators (i.e. how much economic losses would you consider high). And also what would you consider a low, medium and high plausibility of the impact occurring (i.e. would you consider a 50% plausibility that the critical threshold is reached to be high?).” “We ask you to think of it in terms of the level of actions it would inspire”

			"For the impact thresholds, think of it as follows: • High – would immediately inspire action. • Medium – would commence talks on appropriate actions • Low – would not inspire any action." "Similarly, for the plausibility thresholds, think of it in a similar way: • High – would immediately inspire action. • Medium – would commence talks on appropriate actions • Low – would not inspire any action." "After you have filled in the thresholds, we also ask you to approximate the resulting impact of each vulnerability that we have identified on Activity 5". (i.e. for the vulnerability that is a reduction in the Paloma reservoir volume, what is the impact of the reservoir volume reaching the critical threshold in terms of the impact indicators that we have identified." **Activity 8:** Participants fill out the impact and plausibility thresholds for low, medium and high rating. Then for each impact indicator, they can discuss during the coffee break, how much they think the impact would be of each key performance indicator. **Activity 9:** Compare Risk Rating Between Individuals. (Anonimously)

Group Mapping Session	Adaptation Responses in the Basin	Base map of the basin (inc. land use map, cities, irrigation channel, national parks, reservoirs) Transparent paper (Areas of Adaptation Strategies) Post-its Pens and Markers	**Introduction**: “Finally, in this exercise we will discuss possible adaptation solutions in the basin with respect to climate change.” “This exercise will populate the list of adaptation strategies tested, and will give an idea of the kind adaptation strategy that is best suited for this basin.” “We have compiled a list of adaptation strategies that we have gathered through personal interviews in the past few days.” “These solutions you will find on the map in front of you. More general solutions for the entire basin are to the left and locations specific solutions are found throughout the base map.” **Activity 10:** First call on the people who did not have the chance to be interviewed to offer their solutions. (If they want to) What were the success stories of adaptation strategies implemented? What are the failure stories of adaptation strategies being implemented? **Activity 11:** Discuss the pros and cons of each adaptation strategy presented. What worked and what did not? For each adaptation strategy create a table of pros and cons. **Activity 12:** Discuss important characteristics of adaptation strategies (i.e. specific cost-benefit ratio, amount of jobs that it can add, traditional barriers, focus on small scale of large scale industries, locally

			managed plans (privately) or publicly organized) that stakeholders determine would increase the chance of implementing the strategy and its success.

D.3. Survey

Umbral o valor límite de probabilidad

El umbral o valor límite que defina en esta sección mostrará que tan probable considera usted que un evento ocurra.

Imagine que hay 100 futuros posibles donde una falla crítica en el sistema pueda o no ocurrir.

¿Cuántos de estos 100 escenarios de fallas críticas le llevarían a **tomar acción inmediata**? Escriba el número en el recuadro bajo la categoría de **Probabilidad alta**.

¿Cuántos de estos 100 escenarios de fallas críticas le llevarían a **conversar y discutir** sobre qué acciones tomar? Escriba el número en el recuadro bajo la categoría de **Probabilidad media**

¿Cuántos de estos 100 escenarios de fallas críticas puede **tolerar** (no lo llevaría a hacer nada)? Escriba el número en el recuadro bajo la categoría de **Probabilidad baja**

Umbral o valor límite de probabilidad		
Probabilidad baja	Probabilidad media	Probabilidad alta

Umbral o valor limite de impacto Impact Threshold

El umbral o valor límite que defina en esta sección mostrara que considera usted como bajo, medio o alto impacto para cada indicador de impacto.

Paso 1: Llene en los recuadros azules los indicadores de impacto identificados y priorizados.

Paso 2: Para cada indicador, en los recuadros grises llene que percibe como impacto bajo, medio o alto. Por ejemplo, si su indicador es pérdidas monetarias, usted puede decidir que pérdidas monetarias de 10,000 pesos son bajas, de 10,000 a 50,000 pesos son bajas y más de 50,000 pesos son altas.

¿Qué tan grande debe ser el impacto para que lo lleve a **tomar acción inmediata**? Escriba esto bajo la categoría **Impacto alto.**

¿Qué tan grande debe ser el impacto para que lo lleve a **conversar y discutir** sobre qué acciones tomar? Escriba esto bajo la categoría **Impacto medio.**

¿Qué tanto impacto podría **tolerar** (no lo llevaría a hacer nada)? Escriba esto bajo la categoría **Impacto bajo**

Nota: El umbral o valor limite de impacto puede ser cualitativo o cuantitativo, dependiendo del indicador de impacto definido.

Paso 3: Llene en los recuadros verdes los indicadores clave de desempeño que han sido identificados y priorizados.

Paso 4: Considere cada indicador clave de desempeño por separado e imagine un escenario donde el umbral o valor límite es sobrepasado. ¿Cuál cree que sería el impacto para cada uno de estos indicadores? Por ejemplo, considere que el indicador clave de desempeño es el volumen del reservorio y que las pérdidas monetarias son el indicador de impacto. ¿Cuáles son las perdidas monetarias que podría esperar si los niveles del reservorio están por debajo del nivel crítico? Llene en los recuadros rojos sus estimaciones para cada indicador clave de desempeño.

Indicador de impacto	Umbral o valor límite de impacto			Indicador clave de desempeño					
	Impacto Bajo	Impacto Medio	Impacto Alto						

D.4. Stakeholder Attendance List

Name	Institution	Workshop	Interview	Survey
Llara Kritzner	The Nature Conservancy (TNC)	x		x
Raúl Díaz	Comunidad de Aguas Sistema Embalse Paloma (CASEP)	x		x
Carlos Araya	Comunidad Agrícola de Romerlacillo	x		x
Alejandra Barraza	Comunidad Agrícola de Romeralcillo	x		x
Christopher Vivanco	Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe (CAZALAC)	x	x	x

Héctor Maureira	Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe (CAZALAC)	x	x	x
Cristian Felmer	Secretaría Regional Ministerial de Medio Ambiente – Región de Coquimbo		x	
Carolina Herrera	Dirección General de Aguas – Oficina Provincial Ovalle		x	
Pablo Álvarez	Universidad de La Serena – Depto. de Ingeniería Agronómica – Lab. PROMMRA		x	
Sebastian Norambuena	Universidad de La Serena – Depto. de Ingeniería Agronómica – Lab. PROMMRA		x	
Eric Castro	Ilustre Municipalidad de Ovalle – Fomento Productivo		x	
Daniela Soto	Ilustre Municipalidad de Ovalle – Turismo		x	
Jandry Castillo	Comunidad Agrícola de Punitaqui		x	
Jaime Tello	Comunidad Agrícola de Punitaqui		x	
Rosa Moroso	Comunidad Agrícola de Punitaqui		x	
Carlos Araya	Comunidad Agrícola de Romerlacillo		x	

Alejandra Barraza	Comunidad Agrícola de Romeralcillo		x	
Gabriel Mancilla	Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe (CAZALAC)		x	x
Adrián Lillo Zenteno	Dirección General de Aguas – Central Level		x	

E Kernel Density Estimation

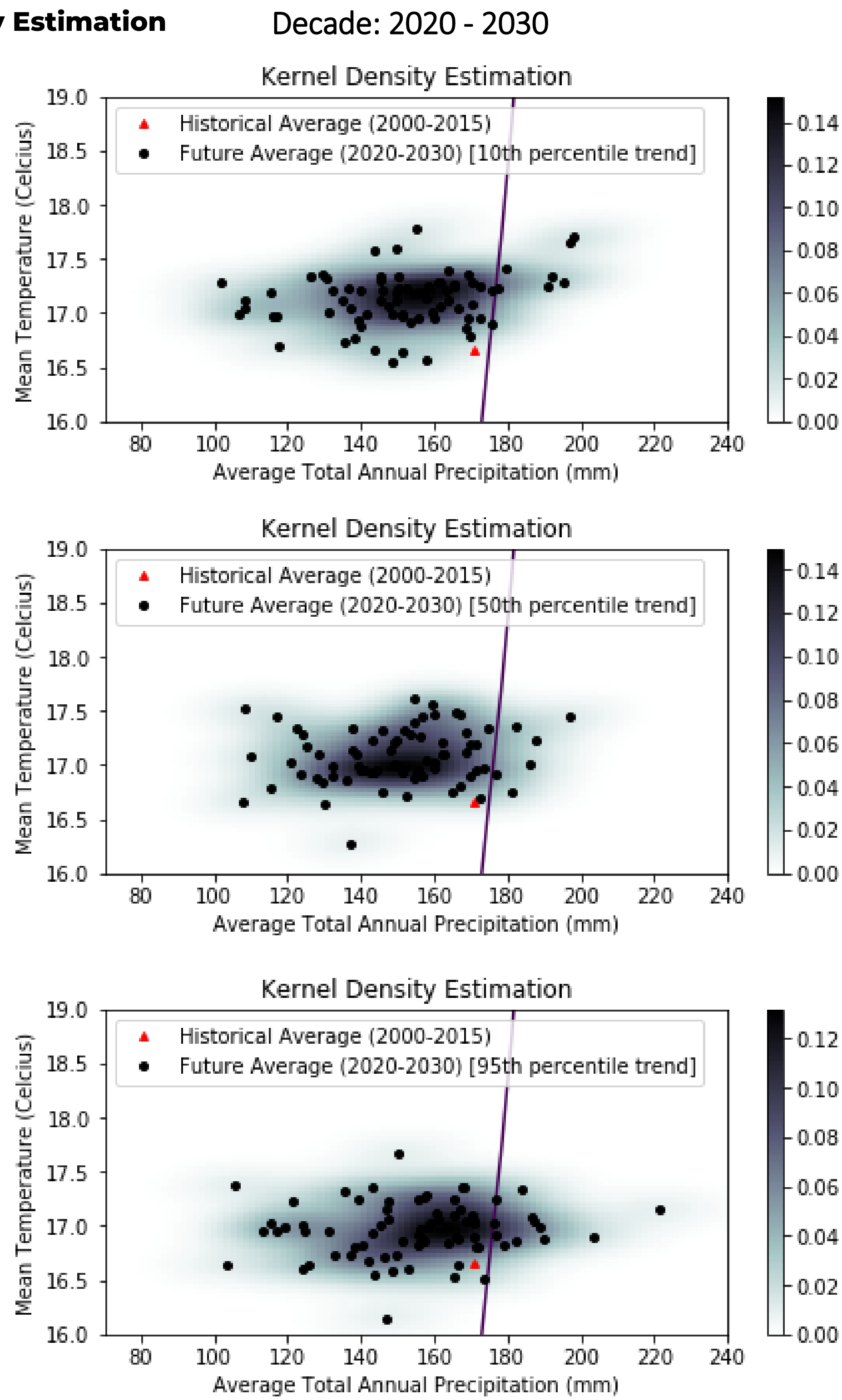


Figure E.1. KDE of future projections averaged over the years 2020-2030. The critical line for KPM: Total Annual Inflow to the La Paloma Reservoir is shown. The critical line for KPM: Total Annual Unmet Demand in the Grande Region is outside of the surface domain (i.e. all future scenarios are in the critical domain).

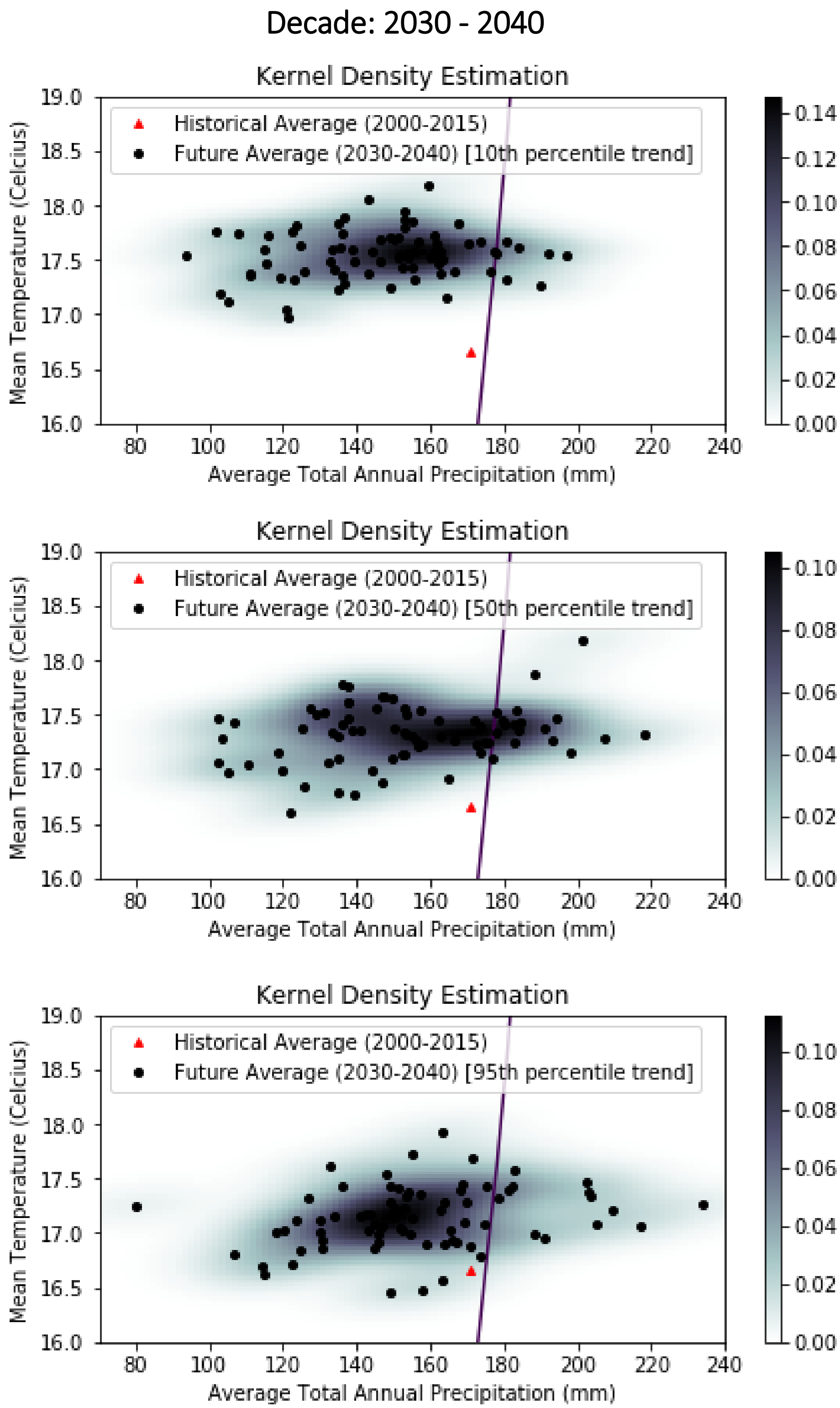


Figure E.2. KDE of future projections averaged over the years 2030-2040. The critical line for KPM: Total Annual Inflow to the La Paloma Reservoir is shown. The critical line for KPM: Total Annual Unmet Demand in the Grande Region is outside of the surface domain (i.e. all future scenarios are in the critical domain).

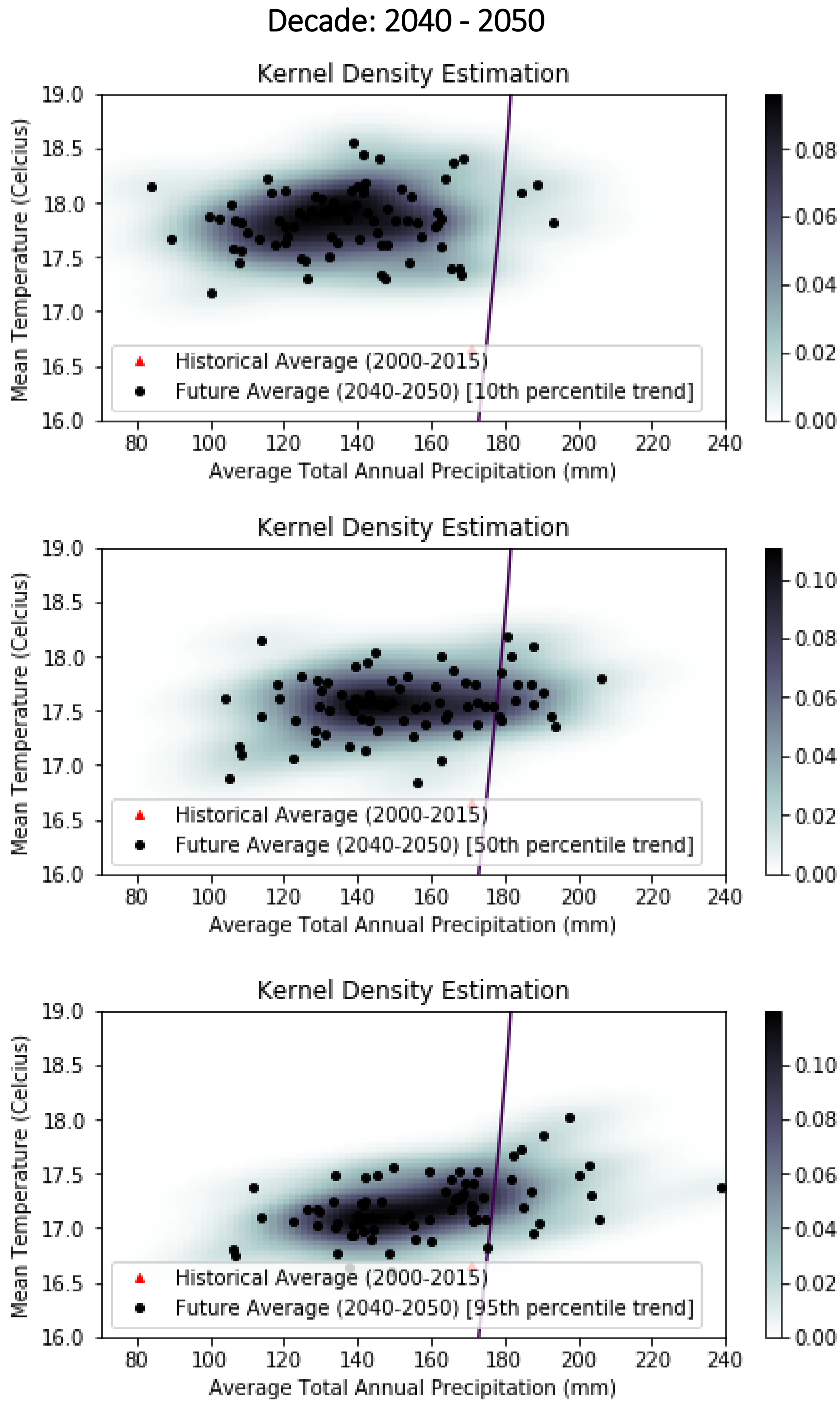


Figure E.3. KDE of future projections averaged over the years 2040-2050. The critical line for KPM: Total Annual Inflow to the La Paloma Reservoir is shown. The critical line for KPM: Total Annual Unmet Demand in the Grande Region is outside of the surface domain (i.e. all future scenarios are in the critical domain).

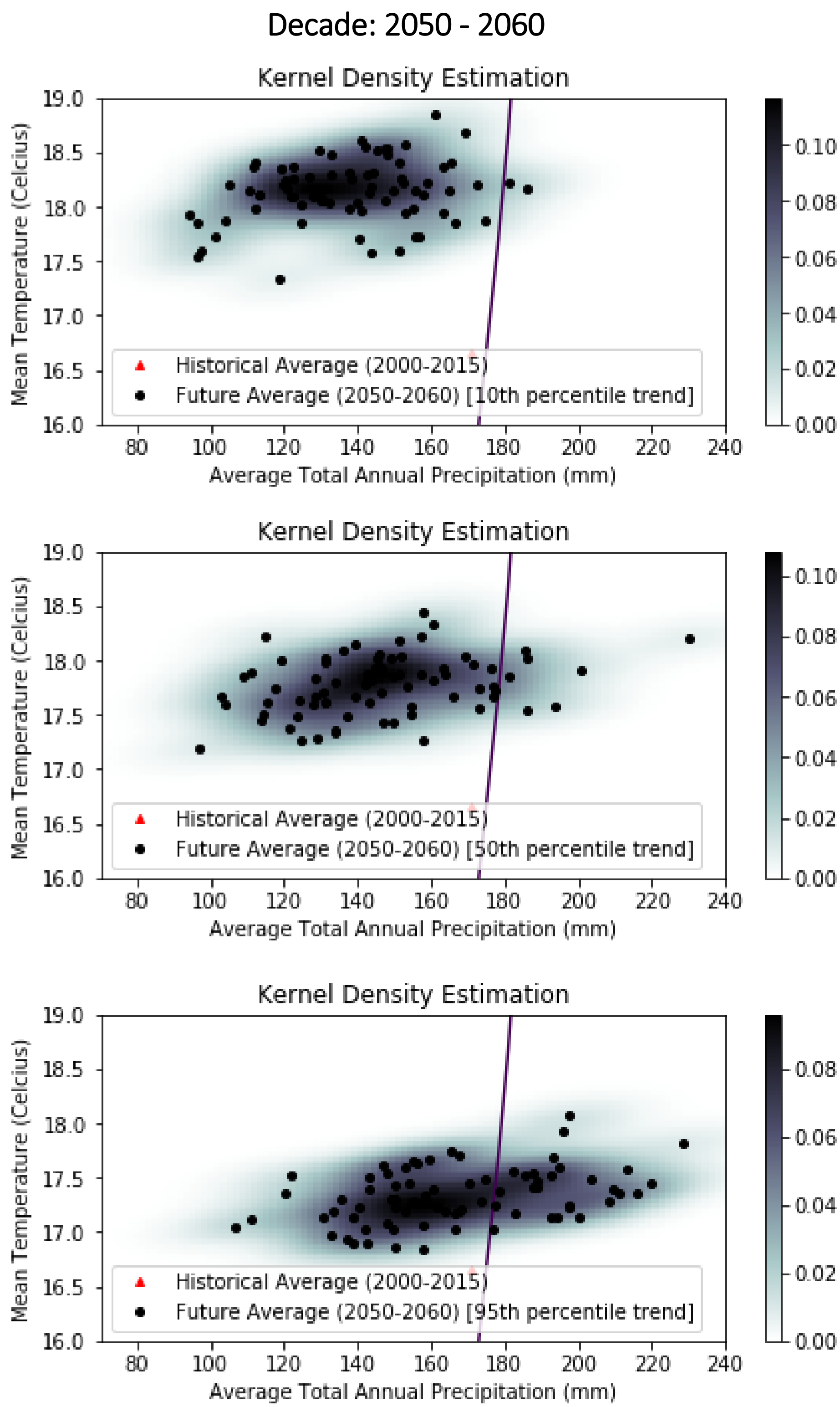


Figure E.4. KDE of future projections averaged over the years 2050-2060. The critical line for KPM: Total Annual Inflow to the La Paloma Reservoir is shown. The critical line for KPM: Total Annual Unmet Demand in the Grande Region is outside of the surface domain (i.e. all future scenarios are in the critical domain).

F Strategy Parameterisation

D1: Deficit Irrigation

Deficit irrigation is a strategy to drought in arid to semi-arid climates. The deficit irrigation regime depends on climate, soil type, crop and also the specific genotype of crop. Therefore local studies are required to draft the optimal irrigation pattern to ensure little to no losses in production. While the strategy is usually applied re-actively, there is a possibility of applying the strategy pro-actively if the deficit irrigation schedule is optimized so as not to reduce production. Since local studies were not found during the literature review, deficit irrigation regimes for the main crop types in the basin is modelled based on best practices from published work with study areas of similar climates (i.e. semi-arid to arid). The crop types with a deficit irrigation regime applied is vineyards, alfalfa, and Avocado which together occupy ~50% of the cultivated area in the basin. A summary of the deficit irrigation regimes are on the table below.

Crop	Deficit Irrigation Regime*	Area	Source
Alfalfa [16.5% of cultivated area]	Terminate irrigation during January and February.	California, USA	(Hanson et al., 2007, Hanson et al., 2008)
Avocado [11% of cultivated area]	Reduce irrigation by 25% from January to March.	North-East Israel	(Levin et al., 2011)
Vineyards [25% of cultivated area]	Reduce irrigation by up to 50% through either deficit irrigation or partial root drying throughout the life cycle.	Portugal	(Chaves et al., 2007)
*Months are corrected to southern hemisphere equivalents.			

D2 & D3: Changing Cropping Pattern

The crops grown in the Limari Basin and their expected revenues per hectare are organized according to their spring/summer water requirements in the table below as they are modelled in WEAP.

Type	Crop	K_c Total	Revenue/ha*
Cereals	Wheat	2.0	241,675.00
Vegetables	Bean	2.3	653,686.34
Vegetables	Pomegranate	2.7	2,616,656.00

Vegetables	Green beans	3.1	1,751,408.65
Cereals	Maize	3.1	2,604,544.41
Vegetables	Corn	4.0	1,647,616.25
Vegetables	Tomato	4.0	7,801,530.68
Vegetables	Cantaloupe	4.2	6,273,521.80
Vegetables	Cucumber for salad	4.2	15,760,744.00
Fruit Trees	Olives	4.2	3,012,327.71
Vegetables	Zucchini	4.4	3,832,077.83
Vineyards	Grapes for Wine, Pisco and Fruit	4.5	2,952,026.32
Vegetables	Aji	4.7	3,737,510.19
Vegetables	Pepper	5.2	4,977,541.35
Fruit Trees	Citric	5.6	16,556,359.00
Vegetables	Lettuce	5.8	2,436,628.18
Vegetables	Artichokes	5.8	6,165,070.01
Fruit Trees	Walnut	5.9	5,362,909.48
Vegetables	Potatoes	6.0	2,464,166.25
Fruit Trees	Avocado	6.0	7,762,385.78
Pasture	Alfalfa	6.2	1,419,907.00
Vegetables	Cucumber (sweet)	6.4	4,671,183.48
***INDAP (2018)**			

Fruits, vineyards and pasture crops use more water during the summer (when water shortage is expected) than cereals and some vegetables.

Changing the crop pattern can be manifested in three ways; reducing permanent crop acreage and switching to annual crops with lower water requirements, switching annual crops with high water requirements to crops with lower water requirements and switching to other crop cultivars.

Permanent crops which use a lot of water such as fruit trees (except Olives) and vineyards may be replaced with annual crops, such as cereals and vegetable crops shaded in grey on the table above. This not only reduces the water requirements in the basin but also increases adaptation flexibility during drought years. This strategy is modelled by changing the land use areas of these crops in WEAP. The loss in acreage of the crop types replaced are equally distributed to the other crop types. Several percentage reductions of permanent crops are tested (25%, 50% & 75%). This is strategy D2.

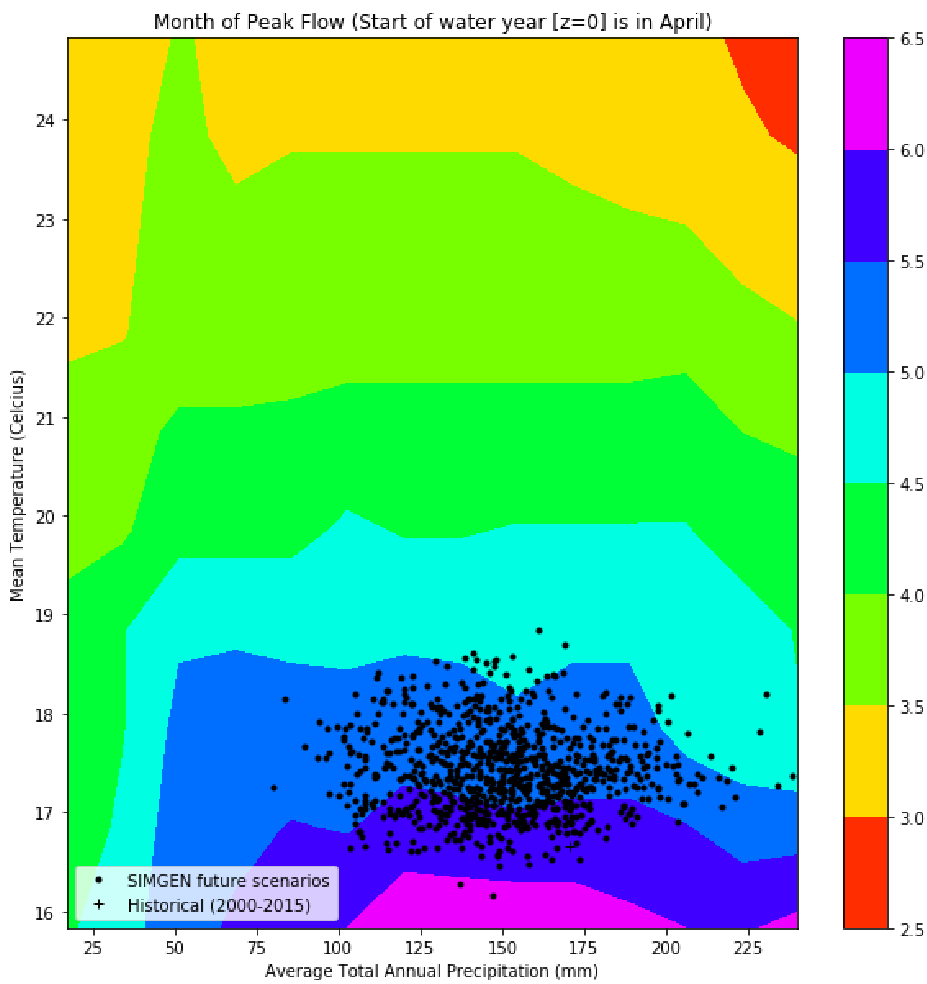
Where annual crops are planted, the farmers may choose to adapt to drought conditions by temporarily or permanently switching to annual crops with lower water use requirements (i.e. crops shaded in grey in the table above). This is ideal for farmers so that they do not lose their permanent. Several percentage reductions of high water requirement annual crops are tested (25%, 50% & 75%). This is strategy D3.

Finally, the farmer may choose to switch to alternative crop cultivars which are found to have lower water requirements. This strategy may be employed pro-actively for all crop types but also re-actively only during drought years where annual crops are concerned. However, there is limited information on the crop coefficients for different crop varieties/cultivars which are required for this strategy to be modelled and tested through WEAP.

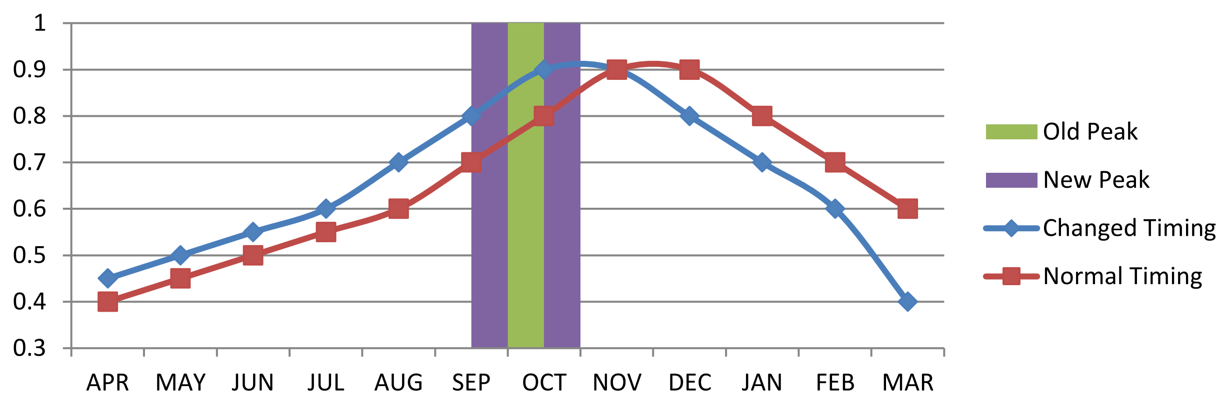
D4: Changing Crop Schedule

Several studies have indicated that a rise in temperature in the Limari Basin moves peak flows forward. In addition, the rise in temperature will cause lifecycle changes in the crops (higher temperatures may mean earlier maturation of crops). With these factors considered, an adaptation strategy proposed in the Plan de Adaptación al Cambio Climático del Sector Silvoagropecuario (Muck et al., 2013) is to revisit the cropping schedules in the area to coincide more with peak flows.

A response surface showing the changing in the timing of the peak flow with changing precipitation and temperature conditions is shown in the figure below. It may be concluded from this analysis that in most future scenarios by 0.5 to 1 month forward.



A strategy that may be employed is to move planting schedules 1 month forward to correspond with the shift in peak flows and temperatures. This strategy is modelled in WEAP by shifting the crop coefficient monthly values of annual crops one month forward. An example on the shifted Alfalfa regime on the figure below shows that higher water requirements corresponds better to higher water availability for future scenarios.



D5: Reduce Evapotranspiration with Meshes and Screens

One of the goal of covering crops with screens is increasing the water use efficiency through microclimate modification. This is most important in arid and semi-arid regions where water scarcity is one of the limiting factors for year-round agricultural production (Tanny, 2013).

Reference evapotranspiration (ETo) (ETo is used along with the crop factor (Kc) to calculate the evapotranspiration of a crop) under netting was found to reduce by 35% in a banana plantation and 38% is a sweet pepper plantation (Möller and Assouline, 2007, Moratiel and Martínez-Cob, 2012).

It is noted that changes in the reference ET under netting is also a function of the hydric properties of the specific crop and the type of netting used (Tanny, 2013). However, due to limited literature on the subject for the purpose of this strategy test, a netting factor of 0.65 is applied to the reference ET in all catchments of the basin.

S1: Improve Irrigation Efficiency

Modelled irrigation efficiency ranges from 30% (Traditional Flood irrigation), 50% (Sprinkler Irrigation), 90%(Drip Irrigation) (Vicuña et al., 2014). The test involves setting the minimum irrigation efficiency to 90%.

S2: Improve Canal Efficiency

Water is lost in the delivery to the farm level through infiltration (from 6% to 20%) and evaporation (20%). To test the possible effectiveness of adding canal linings and covers to reduce these lossess, the loss for both infiltration and eveporation reduced to 5% a total delivery efficiency of 90%.

S3: Building Reservoirs

The Department of Hydraulic works is prioritizing the construction of four large reservoirs in the Limari Basin. Of those proposed, three reservoirs are at a sufficient stage of planning where operational rules and volume elevation curves required by the WEAP model is available (Corporación Regional de Desarrollo Productivo, 2016). The reservoirs are incorporated into the model along with their operational rules and are programmed to release their excess water at a constant rate throughout the year to the rivers in order to recharge the La Paloma Reservoir in years of drought. A drought year is identified similarly to the operation rules of the Sistema Paloma. When the accumulated volume in all three reservoirs(La Paloma, Recoleta and Cogoti) is below 500 hm3 in September, then this strategy is invoked.

Reservoir	Status [as of 2015]	Storage Capacity [hm³]	Operational Rules
Valle Hermosa	Under Construction	20	$10\ hm^3 \leq V_{April}$; $Q_{year} = 9\ hm^3$ $10\ hm^3 \geq V_{April}$; $Q_{year} = 0.7 \times V_{April}\ hm^3$
Murallas Viejas	Feasibility study	50	$25\ hm^3 \leq V_{April}$; $Q_{year} = 19.3\ hm^3$ $25\ hm^3 \geq V_{April}$; $Q_{year} = 0.7 \times V_{April}\ hm^3$
La Tranca	Feasibility study	50	$30\ hm^3 \leq V_{April}$; $Q_{year} = 24.4\ hm^3$ $30\ hm^3 \geq V_{April}$; $Q_{year} = 0.7 \times V_{April}\ hm^3$
Rapel	Feasibility study	14	n/a

S4: Building Additional Sources

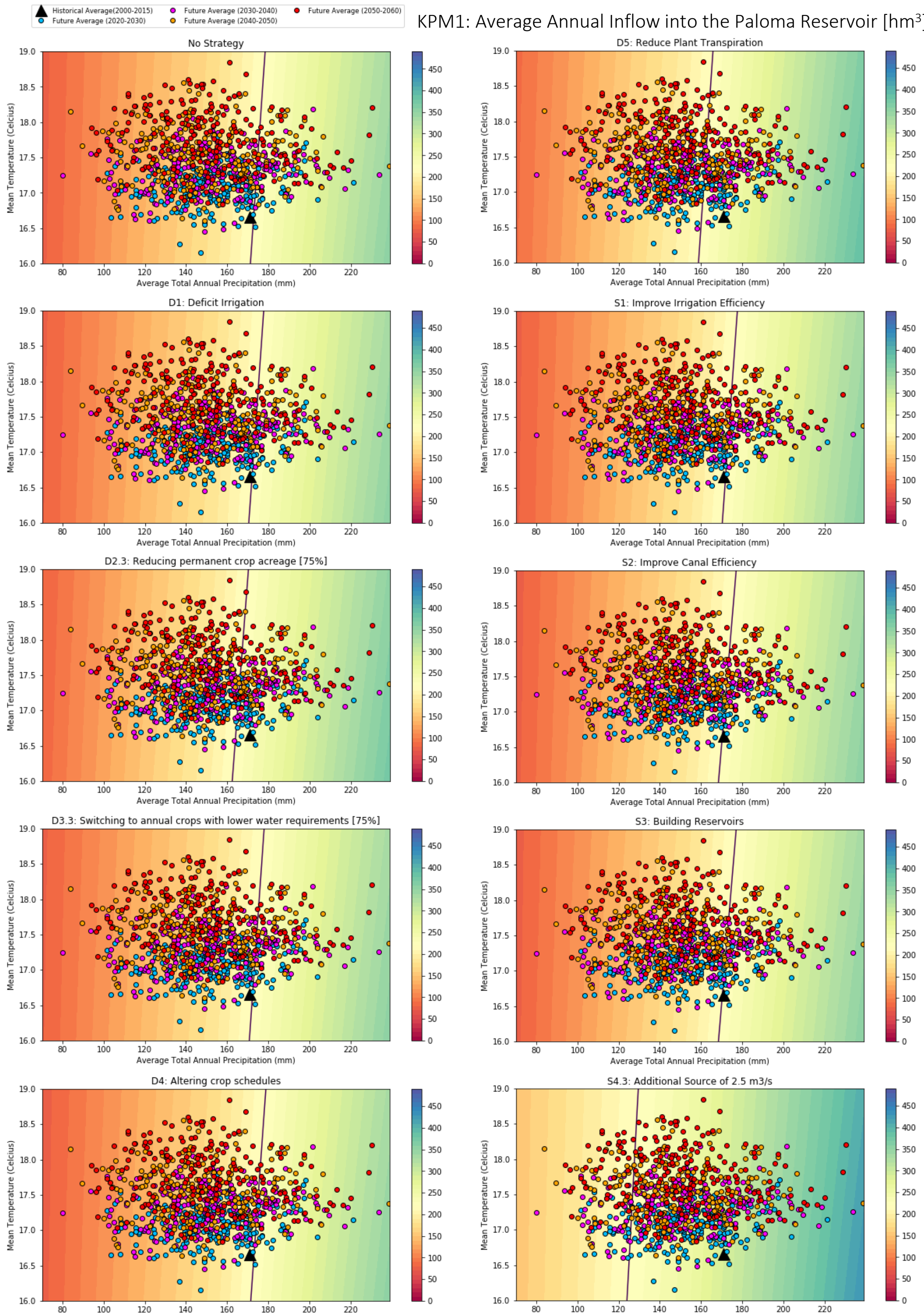
Additional water may be sourced from waste water treatment and re-use, desalination plants and a water highway transferring water from the south of Chile to the more Arid North. The following information acts as a guide regarding how much these sources can supply:

- Waste Water Treatment and Reuse - The reusable waste water in the Limari Basin is calculated to be 2.19 hm3/year [0.069 m3/s] based on information from Equipo Técnico Fundación Chile (2018).
- Desalination Plants - Reverse osmosis desalination plant of sea water currently in operation in Chile ranges from deliveries 120 l/s [0.12 m3/s] to 3,200 l/s [3.2 m3/s] (Álvarez and Benavides, 2013)

- Water Highway - The Aquatacama project currently in its feasibility study phase is being designed to transfer up to 1.5 km^3/year [47.5647 m3/s] of water from Chiles water-rich south to the arid north (Shumilova et al., 2018).

Additional sources are modelled in WEAP by adding a head flow just upstream of the Paloma reservoir feeding 1.5,2, 2.5 and 3 m^3/s [mimicking either a desalination plant or water highway input].

G Response surface with individual strategies



KPM2: Average Annual Unmet Demand in the Grande Region [m^3]