Informing Many-Objective Decision-Making for Water Rights Allocations and Trading Dynamics Conditioned on a Streamflow Prediction Regime in the Elqui River Basin

by

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Thesis Directed by Professor Joseph Kasprzyk

The Elqui Valley in northern Chile faces increasing water stress due to a growing agricultural sector. This study evaluates how improvements in season-ahead forecasting skill and changes in water rights trading dynamics impact the ability for seasonal reservoir management to meet the water needs of various actors in the basin. By establishing a baseline forecast of perfect foresight of observed streamflow data, the analysis evaluates how the use of an updated forecasting technique compares to climatology in its ability to meet management needs. Using the RiverWare river system modeling tool, multiple scenarios representing different suites of trade and reservoir operating policies are simulated, with multiple performance metrics and objectives calculated. Results of the study demonstrate that forecasting significantly affects objective performance and that a statistical forecast outperforms climatology. Additionally, results indicate that although increased trading leads to economic gain, tradeoffs must be considered and trading cannot make up for overly conservative management.

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1. Introduction

Increasing demand for freshwater resources for agriculture, drinking water, and other competing uses, and growing concern over long term water availability has led to new approaches for water management. In the early twentieth century, water management followed what has been called the “hard path”, in which large, centralized, water resource projects were developed to promote agricultural expansion in arid regions (Gleick, 2002). This led to the construction of large dams, reservoirs, and pipelines, and modifications to river systems that delivered mostly potable water in large volumes. In the late twentieth century, recognition of the environmental and social impacts of such management encouraged a paradigm shift to the “soft path” for water, in which the objective changed from simply delivering water to addressing water “needs” in innovative and efficient ways. This has been accomplished using centralized and decentralized systems, innovative technologies and economic approaches, and collaborating and communicating with communities to determine needs (Gleick, 2002).

One outcome of this new style of water management has been to take advantage of the economic properties of water, and treat water as an economic good such that free market forces promote its to transfer from lower to higher value uses (Donoso, 2006, Characklis et al., 2006). Previous work has found that the use of portfolios of temporary and permanent rights transfers, spot leases and options can reduce water supply costs while maintaining high reliability (Charaklis et al., 2006, Kaspryzk et al., 2009). Additionally, Kasprzyk et al., 2009 found that water markets can improve resiliency under extreme conditions (Kasprzyk 2009). These studies combine equations representing the reservoir systems and the associated objectives with streamflow simulations to identify optimal solutions. River system modeling tools such as RiverWare (Zagona et al., 2001), have the potential for furthering these types of studies by incorporating the spatial distribution of water across river systems and incorporating hydropower capabilities through complex, rule-based simulation that can more specifically represent management decisions and priorities. This study uses RiverWare to examine the effects of water rights trading dynamics on a river system in Chile.

Chile is often cited as an illustrative example of the economics of water markets. The Chilean Water Code of 1981 established a free water market in Chile that has been claimed to have accomplished this objective (Donoso, 2006). However, while researchers have agreed there are certain economic benefits gained through such a system, some have suggested that limitations to the Chilean Water Code and its success exist (Donoso, 2006, Rios and Quiroz, 1995, Bitran et al., 2014). The Elqui River Basin (ERB) in north-central Chile is one basin in which the effects of the Chilean Water Code have been heavily studied; it is the focus of this research.

The ERB is a semi-arid basin facing increasing water stress due to its growing agricultural sector. Farmers of both high and low value crops dominate the region and are the primary consumers of water in the basin. However, many conflicting uses also exist within the basin, including hydropower production, recreation on the primary reservoir, and a drinking water municipality serving the growing population. The already limited water supply is further stressed by high inter-annual variability in precipitation leading to large seasonal variations in water supply availability – conditions that lend themselves to a water market with the goal of incentivizing efficient water use.

While the Chilean Water Code has generally facilitated the transfer of water rights amongst private and public entities in the ERB, limitations to the effectiveness of its application have reduced the ability for decision makers to meet the needs of water users. Limited seasonal streamflow forecasting skill has resulted in suboptimal projections of streamflow, curbing the ability for water managers to make accurate allocations (Delorit et al., 2017). The effectiveness of water rights transactions is directly tied to the accuracy of streamflow projections such that failures to accurately forecast result in economic loss and residual consequences for the livelihoods of those involved (Bauer, 2010). Additionally, decision-making about how forecasts are interpreted and applied to determine allocation values has historically been subjective and not followed a consistent operating policy (Delorit et al., 2017). Information has been insufficiently transferred to water rights holders, limiting the ability for them to make informed decisions about whether to engage in trade. While additional barriers to market success exist (Donoso, 2006), this work focuses on addressing the issues of forecasting, reservoir operations, and trading within the ERB.

This work addresses three main issues: how changes to the (1) forecasting methodology, (2) allocation and operating policy, and (3) trading dynamics might impact the ability for decision makers to meet the various needs within the ERB. A model of the ERB is created in RiverWare to spatially represent the basin and its water users, and scenarios that include combinations of policy variables representing possible management decisions are run and analyzed for performance. Three streamflow prediction methodologies are evaluated, including a statistical forecast provided by collaborators at the University of Wisconsin (Delorit et al., 2017). Various reservoir operation policies are explored including those related to reservoir storage and release. Finally, the implications of trading are assessed by evaluating different levels of trading between low and high value crops.

1.1. Summary of Chapters

The following sections review the layout for the sections of the remainder of the document.

1.1.1 Chapter 2: Characteristics of the Elqui River Basin

Chapter 2 provides the reader with background information on the region of interest, including the geography, climate, water resources, water policy, and relevant actors. It reviews the physical constraints of the ERB and how they motivate the need for improved management techniques. It also provides historical context for policy within the ERB and the social and economic motivators for improved water management.

1.1.2 Chapter 3: Methodology

Chapter 3 presents the methods used to construct and analyze management scenarios for this study. Specifically, it explains which policy variables are chosen and why, and reviews the data sources, modeling tool, and post-processing methods used to evaluate the performance of each scenario.

1.1.3 Chapter 4: Results and Analysis

Chapter 4 presents results for all scenario runs and their performance regarding the identified management objectives. It is separated into three parts for each group of management decisions: (1) Forecasting, (2) Reservoir Operations, and (3) Trading. Impacts from each group of management decisions is isolated and analyzed for their individual contributions to overall scenario performance.

1.1.4 Chapter 5: Conclusions and Future Work

Chapter 5 summarizes the findings of this research, what implications may exist for management of water resources in the ERB and larger water resource community, and how future work may contribute to deeper understanding of these findings.

2. Characteristics of the Elqui River Basin

To provide context for this study, the following sections review the physical, historical, and political landscape of the ERB.

2.1. Geography and Climate

The Elqui River Basin, shown in **Figure 1**, is in the Coquimbo region of northern Chile. Its headwaters are in the Andes Mountains to the east from where it descends 4,800 m over 150 km to the Pacific Ocean to the west (Young et al., 2010). The basin is relatively small, constituting less than 10,000 km^2. It is bordered by the Atacama Desert to the north and the wet Central Valley to the south. Glacier el Tapado, a retreating glacier in the Andes, is the source of ice-melt in the valley. As it melts, it is contributing a short-term increase in streamflow to the region; however, there is concern over long-term impacts from its eventual disappearance (Young et al., 2010). There are two main tributaries originating in the Andes: The Turbio River to the northeast and the Claro River to the southeast. Groundwater is not readily available for use due to the depth of the water table and shallow bedrock.

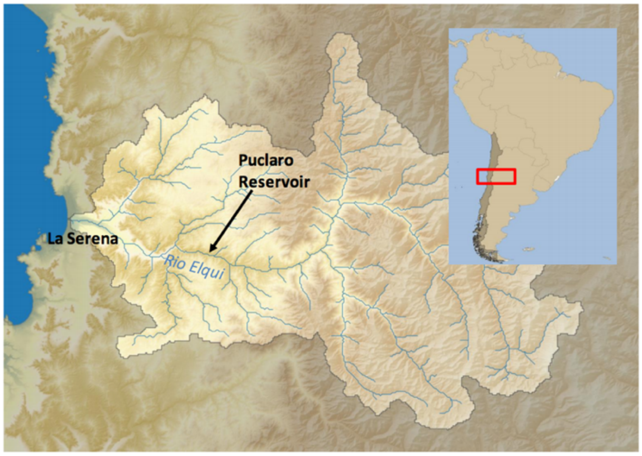

Figure 1: Map of the Elqui River Basin in Chile.

Climate in the region is dominated by the El Nino Southern Oscillation (ENSO), causing long, dry periods (La Nina) and short, intense, wet periods (El Nino) (Young et al., 2010), as shown by negative and positive precipitation anomalies, respectively, in **Figure 2** below. Average annual precipitation is 90mm, with high variability (Delorit et al., 2017). Most precipitation falls in the austral winter (May – August) as snow in the mountains and rain in the valley. The remaining months of the year are extremely dry, although the watershed continues to receive incoming flows from snow and ice-melt during this period (Delorit et al., 2017). The highest streamflow occurs from October through January, opposite the precipitation season and coinciding with the agricultural growing season, when snowmelt feeds the valley. A plot of the total annual precipitation and streamflow regime can be found in **Figure 2**.

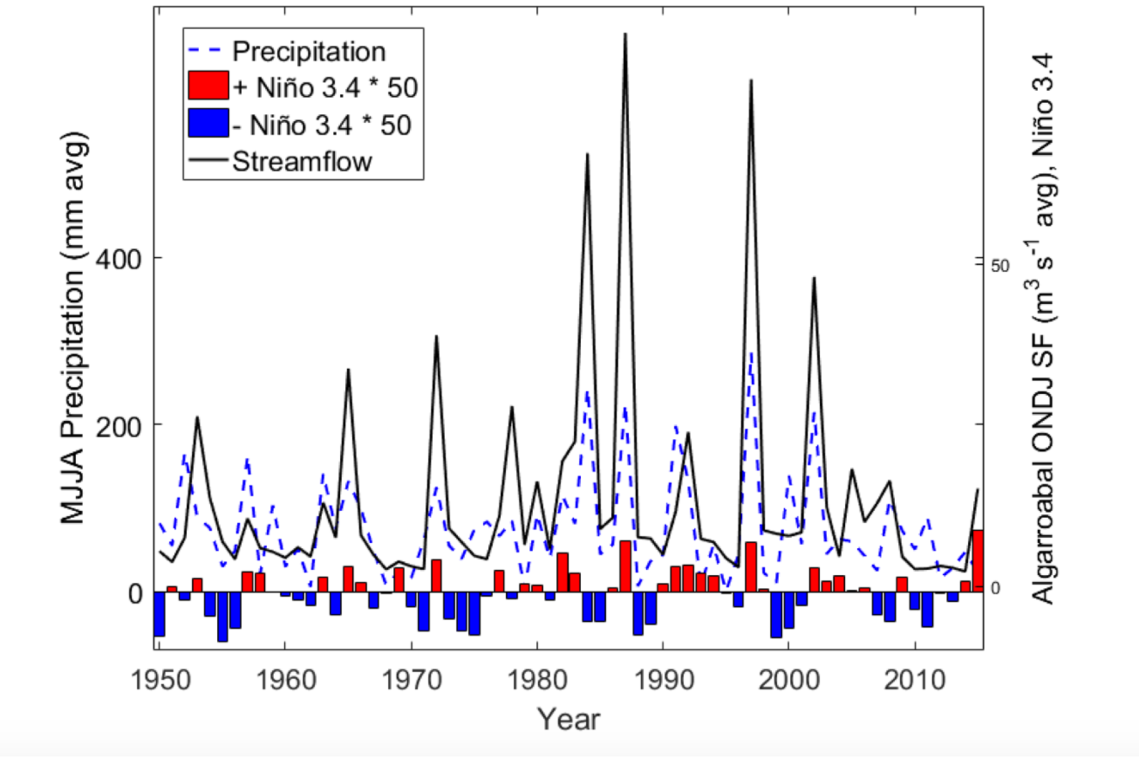

Figure 2 *Total annual precipitation (dashed), streamflow (solid)*, and May-August Niño 3.4 sea-surface temperature anomalies (bars) (Delorit et al. 2017).

Water managers within the ERB have traditionally used a simple streamflow prediction models conditioned on the multivariate ENSO index at the Algarrobal streamflow gage, just upstream of the Puclaro reservoir. Their subjective application of the forecast, paired with limited forecasting skill has led to limited success (Delorit et al., 2017). Delorit et al., 2017, developed an improved statistical streamflow prediction model using a suite of predictor variables including, but not limited to, sea surface temperatures, sea level pressure, local soil moisture, and the Multivariate ENSO Index, paired with principal component regression. They then applied this to a leave-one-out cross validated hindcast to produce deterministic streamflow predictions for each year, from 1950-2015. The work concluded that the Stat-PCR model could provide improved forecasts at a September 1st, 1-month lead-time over Climatology.

2.2. Water Resources

There are two primary reservoirs in the Elqui River Basin: The Puclaro reservoir and La Laguna reservoir. The Puclaro reservoir is the primary source of water for users in the basin. It is located halfway down the Elqui River and has a maximum storage capacity of 210 Mm^3 (Orhanopoulos et al., 2013). The Puclaro reservoir's functions include flow regulation, water storage for approximately 21,000 hectares of agricultural land (Cepeda et al., 2004, Delorit et al., 2017), recreation, and hydropower, with an installed capacity of 5.2MW (CDM Executive Board, 2012). La Laguna reservoir is upstream of the Puclaro reservoir and is used primarily in periods of drought ("Junta de Vigilancia del Rio Elqui y sus Alfuentes, Region de Coquimbo, Chile," n.d.) It has a maximum storage capacity of 40 Mm^3. For the purposes of this study, the La Laguna reservoir is excluded due to a lack of sufficient observed historical streamflow data at surrounding gages and the ability to separate the Puclaro reservoir's operations from La Laguna's by a gage above and below the Puclaro reservoir. The uses of both reservoirs are governed by the 1981 Chilean Water Code as well as a set of statutes created in 1993 specific to the Elqui Valley.

2.3. Water Policy

Since the establishment of the National Water Code of 1981 (Water Code), Chile's water market has driven the allocation of water resources within the Elqui Valley. Water rights are granted through the national water authority, the Direccion General de Aguas (DGA) and managed by both the DGA and the Junta de Vigilancia de Rio Elqui (JVRE), the local water council. Although prospective users initially obtained rights at no cost through an approval process with a valid application, the government has since stopped issuing new water rights (Donoso, 2006). The water market is set up to be independent of land ownership and relatively unrestricted, such that the rights can be leased, bought, sold, and priced amongst individuals. Permanent water rights transactions are managed by the DGA, who also operates and maintains an extensive hydro-climate monitoring system reporting real-time data, supervises the local water councils, and approves water infrastructure development. Temporary water rights transactions are managed by the JVRE, which is controlled by fee-paying members who elect a supervisory board and regional directors that represent the water rights holders in the basin. The council is also responsible for setting the annual water right allocation, managing channel flow, and handling conflict resolution between water users.

Water rights holders within the basin each own a certain number of rights, based on how many they applied for originally and how many they have bought, sold, or leased once the rights were all allocated. These water rights are treated as "shares" and valued equally, regardless of ownership or the date of acquisition. Water rights are converted into flowrate units of 1 l/s called "acciones" so that they may easily be leased and sold. All acciones have been allocated, constituting a total demand of 25,000 l/s. Each year, acciones are given an allocation value between 0 and 1 l/s during the growing season, determined by the JVRE. This apportioning scheme is based on the JVRE's desire to maintain a target capacity of about half-full, or 100Mm^3 in the Puclaro reservoir. If the JVRE interprets that the season's forecast will not meet this goal, actual allocations, the amount of water let out per water right, are reduced proportionally to account for low flow conditions (e.g. 0.5 L/s). If the reservoir is lower than the target at the end of the growing season, the next year's allocation amount may be reduced as compensation. It has been common for the JVRE to reduce the allocation value to around 0.5 l/s in normal years, such that the reservoir is often unable to meet the demands of the entire basin (Delorit et al., 2017).

The JVRE typically issues two projections of water allocations for the growing season based on seasonal forecasts: an early projection in May and a more accurate projection in September, just before the growing season. Rights holders then have two decision points where they may engage in the water market if necessary to supplement their water supply (Beya & Olivares, 2010). Although all water rights are valued equally by law, the drinking water municipality is given unofficial priority for full allocation of its water rights to accommodate the population's drinking water demand. JVRE determines how much water is diverted through the nonconsumptive hydropower plant throughout the year. Sometimes water is spilled because of intense rainfall and flooding hazards, in which case it is not captured by hydropower.

2.4. Actors

Various actors in the ERB have conflicting needs and objectives for the basin's water supply. Agricultural rights-holders in the basin include farmers and irrigators. Farmers of low-value sustenance crops such as potatoes have more flexible water needs than those of high-value boutique crops such as pisco grapes and exotic fruits that require consistent water each season. The valley has only one municipal water supplier, the Water Supply and Sanitation Company of Coquimbo (ESSCO). Municipal demand for drinking water is expected to be between 660 l/s (from water use per capita (Fry et al., 2006) and population expectations (Dittmar, 2004) and 1,800 l/s (Delorit et al., 2017). For the purposes of this study, 1,800 l/s is used to capture the maximum likely demand.

Because the DGA and the JVRE manage water rights allocations and the trading and leasing of rights, they are both interested in minimizing conflicts between water users. Because it is an elected group, JVRE is also interested in setting the best possible water allocation per year to satisfy water rights holders. In addition to these water demands, the Puclaro reservoir's storage provides recreation opportunities for boaters and hydropower capabilities.

3. Methodology

This study is organized into three main phases: policy variable formulation, river system simulation, and objective formulation and evaluation. A workflow of the methodology is shown in **Figure 3** below. Observed streamflow data and a series of scenarios constructed of management decisions, called policy variables, that may be made for forecasting (Section 3.1.), reservoir operations (Section 3.2), and water rights trading (Section 3.3.) are run through a river system model of the basin. Finally, objectives that represent conflicting basin needs are used to assess the performance of the different scenarios.

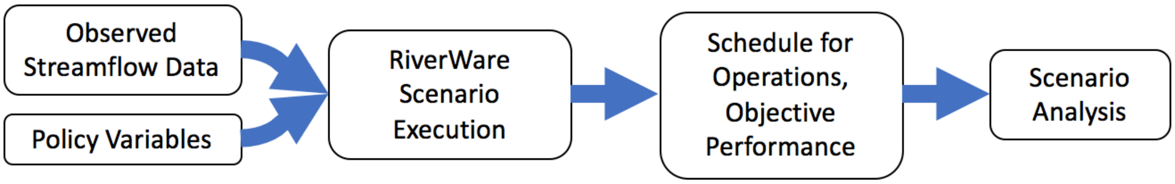

Figure 3: Workflow of methodology.

3.1. Forecasting

This study evaluates the performance of the simulations under three different streamflow prediction methodologies: A baseline of observed values referred to as "Perfect Foresight", historical averaged streamflow values representing a "business-as-usual" strategy referred to as "Climatology", and an updated forecasting technique developed by our collaborators referred to as

"Statistical Forecast" (Delorit et al., 2017)[1], detailed in Section 2.1. These techniques are listed in **Figure 4** with their sources.

Perfect Foresight assumes perfect knowledge of future streamflow is available by using observed monthly streamflow values from the Algarrobal gage station as forecasted values. Thus, it is used as a baseline with which to compare the other forecasting methods.

The Climatology method uses monthly averages of streamflow for all years as the forecast for each year's October – January (ONDJ) streamflow. Technically, this technique is not strictly a "forecasting" technique as it does not attempt to predict how the variables will change in the future; it can also be thought of as a "business-as-usual" approach. However, this technique is often used as a comparison with other forecasting techniques to evaluate skill because it assumes no formal forecast is available and relies entirely on historical data. This method only has values for four different timesteps – each of the ONDJ streamflow months. These values are the same each year. Comparing the methods that have more information to this method that only has constant information for each of the months provides a useful comparison for the benefit of the other techniques.

To improve upon this technique, the "Statistical Forecast" was used based on the Stat-PCR method developed by Delorit et al., 2017, described in Section 2.1., above. This method is used here, and simply called "Statistical Forecast" throughout the rest of the study. This method includes 65 timesteps of different

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[1] As described in Section 2.1., the JVRE currently uses different hydro-climatic seasonal forecasts than analyzed here. However, these forecasts were not made available for our use.

forecasted values by predicting a new value for each of the 65 ONDJ seasonal streamflow totals. The median forecast, or 50th percentile forecast, was used in this study, although 99 other realizations exist such that there are 100 in all. This is discussed further in the Future Work section of this paper.

In summary, Perfect Foresight is used to understand how decision makers might act if given perfect information, while the Statistical Forecast was compared with Climatology to see if it could again offer improved performance under a different modeling technique. Perfect Foresight includes 260 timesteps to incorporate each ONDJ month over the simulation period.

Figure 4: Forecasting Technique Breakdown

Forecasting Technique	**Source**	**# Timesteps**	**Forecasted/Observed**
Perfect Foresight	Observed streamflow gage data at Algarrobal Gage	260	Observed
Climatology	ONDJ monthly averaged observed streamflow gage data at Algarrobal Gage	4	Observed
Statistical Forecast	Forecasted streamflow values for the growing season, ONDJ (Delorit et al., 2017)	65	Forecasted

3.2. RiverWare Simulation Tool

The RiverWare modeling tool was used for this study due to its capacity for complex, spatial representation of river systems, including built-in data slots that can be populated with reservoir properties, the ability to include hydropower capabilities, and rule-based scenario execution that allows for complex representation of management priorities. RiverWare has been used in previous studies primarily for reservoir operation analysis, but its capacity for water rights trading analysis has not yet been explored. RiverWare is an object-oriented, data-driven river system modeling tool capable of modeling hydrology, hydrologic processes, water quality, hydropower and other energy production, and water accounting information such as water rights allocations for a system (Zagona et al., 2001.). Objects represent different features and actors on a river system such as reservoirs, stream reaches, stream gauges and hydropower plants. When running simulations, data passes through links between objects according to user-defined rules that represent the operating policy of the river system.

3.3. Elqui Basin Model

3.3.1. Design

The Elqui River Basin model runs on a monthly timestep and spatially divides the basin into different agricultural sectors and users, simulating flow paths from the upper basin to its termination at the Pacific Ocean. A diagram of the model is shown by **Error! Reference source not found.**. The model is partly based on a technical report on the hydrology of the Elqui Valley (Zunino et al., n.d.) that details the hydrologic processes, spatial distribution of water rights within the basin, and stakeholders and policymakers involved in water resource allocation. It also briefly describes previous studies on reservoir operations performed in the region[2]. The report divides the basin into 10 agricultural sectors with different crop distributions. For this study, Sectors 1 through 4, above the confluence of the Rio Turbio and the Rio Claro, have been omitted due to gaps in available historical data. The lower sectors and Puclaro reservoir can be isolated by a gage at Algarrobal, above sector 5. Sectors 5 through 10 are represented as aggregate diversion sites in this model, each separated into five water users representing different crop types. Crop types include grapes, vegetables, fruit, grains, and dual cultivation, and were chosen based on data provided in a comprehensive report on the region's distribution of agricultural land and diversions (Zunino et al., n.d.).

Agricultural users are separated into upstream and downstream sectors. The upstream allocation includes only water delivered upstream to Sector 5 while the downstream allocation includes water delivered downstream to Sectors 6 through 10. The model also includes a diversion to ESSCO, the drinking water municipality, below Sector 10. The municipal demand for drinking water is modeled as 1,800 l/s for every timestep.

The model simulates the transport of water through the basin and accounts for it at different gage checkpoints. The Algarrobal gage is located above the Puclaro Reservoir and populated with observed monthly streamflow values from January, 1950 to December, 2015 (Delorit et al., 2017) for a total of 791 monthly timesteps. This run period includes 65 years of data based on the historically observed gage data available. The Almendral gage is located below the Puclaro Reservoir and

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[2] The details of previous studies are not available for public access. Therefore, we only had access to summaries of these studies discussed in the report.

records the outflow of the reservoir. The Puclaro Reservoir is modeled to match the characteristics of the existing reservoir. Its initial storage is set to 160 Mm^3 based on observed data and a simple guide curve controls its mechanics. The Puclaro Reservoir pool elevation (h) to volume (V) relationship was determined in accordance with Delorit et al., 2017. This relationship is defined as:

$$h = 0.0000103414 \times V^3 - 0.00484991 \times V^2 + 0.866452 \times V + 443.266$$

$$where\ h = pool\ elevation\ above\ sea\ level\ (m.a.s.l.)\ and\ V = volume\ of\ water\ (Mm^3)$$

The Puclaro Reservoir includes a maximum floodgate flow of $40m^3/s$ and spillway capabilities of $2{,}500m^3/s$ (Beya & Olivares, 2010), and a minimum operating pool elevation of 10 Mm^3. The reservoir's hydropower generation capabilities are modeled using operating head and turbine release data from (Beya & Olivares, 2010). Because power generation is not a significant factor in water rights allocations, energy produced during simulations was recorded as a byproduct of water released from the reservoir for downstream users and environmental flows.

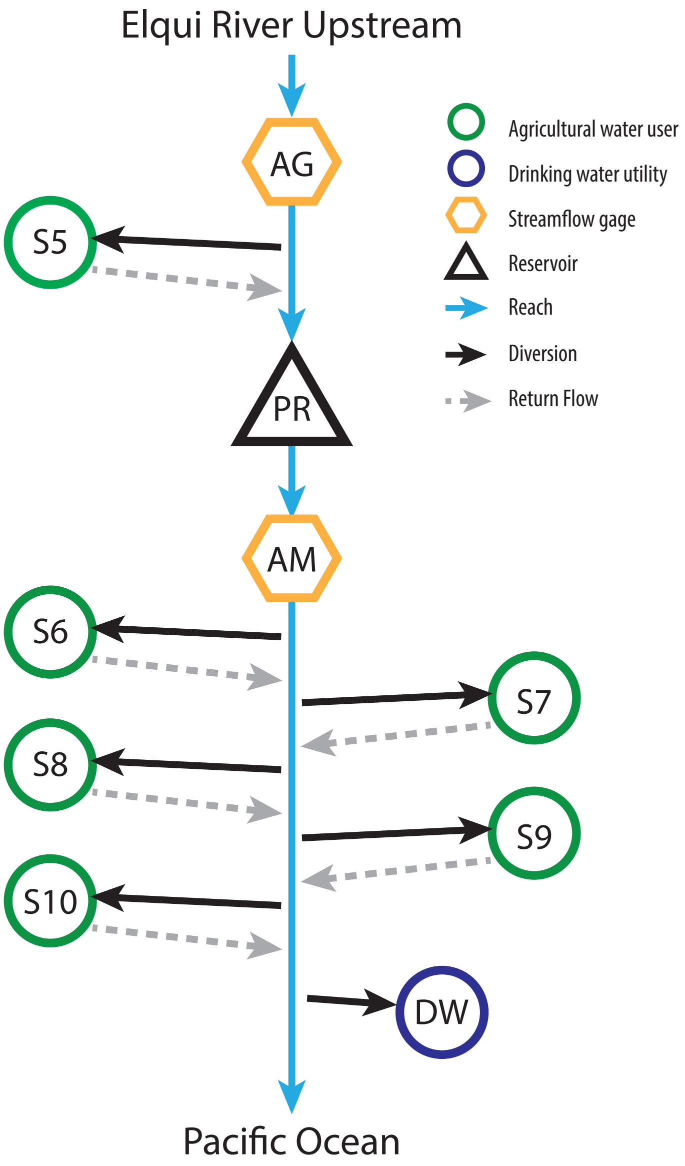

Figure 5: RiverWare model layout. The two streamflow gages, Algarrobal and Almendral are represented by "AG" and "AM", respectively. The drinking water municipality is represented by "DW", and the sectors are represented by "S" followed by the number of the sector. The Puclaro Reservoir is represented by "PR".

3.3.2. Rules

The model is run using RiverWare's rulebased simulation, with which rules control the operation of Puclaro reservoir, the trading that occurs between agricultural users, and the percentage reduction of water allocations during low flow years. Rules in RiverWare are executed according to their priority as set by the modeler, such that the higher priority rules overwrite lower priority rules when necessary.

The Elqui Basin model's ruleset is driven by a set of scenarios found in **Figure 6** that control four major decision variables: 1) Forecasting Method; 2) Allocation Reduction Trigger; 3) Trading Priority; and 4) Trading Cap. The Forecasting Method determines which of the three methods previously discussed is used to predict streamflow in the coming agricultural season. The Allocation Reduction Trigger is the percentage of average summed ONDJ streamflow over the 65-year period that must be met by the forecasted ONDJ streamflow to prevent an allocation reduction in the coming agricultural season. The Trading Priority determines if grapes will be prioritized in the simulation. The Trading Cap determines how much water non-prioritized crops can give up, or lease, to the prioritized crop.

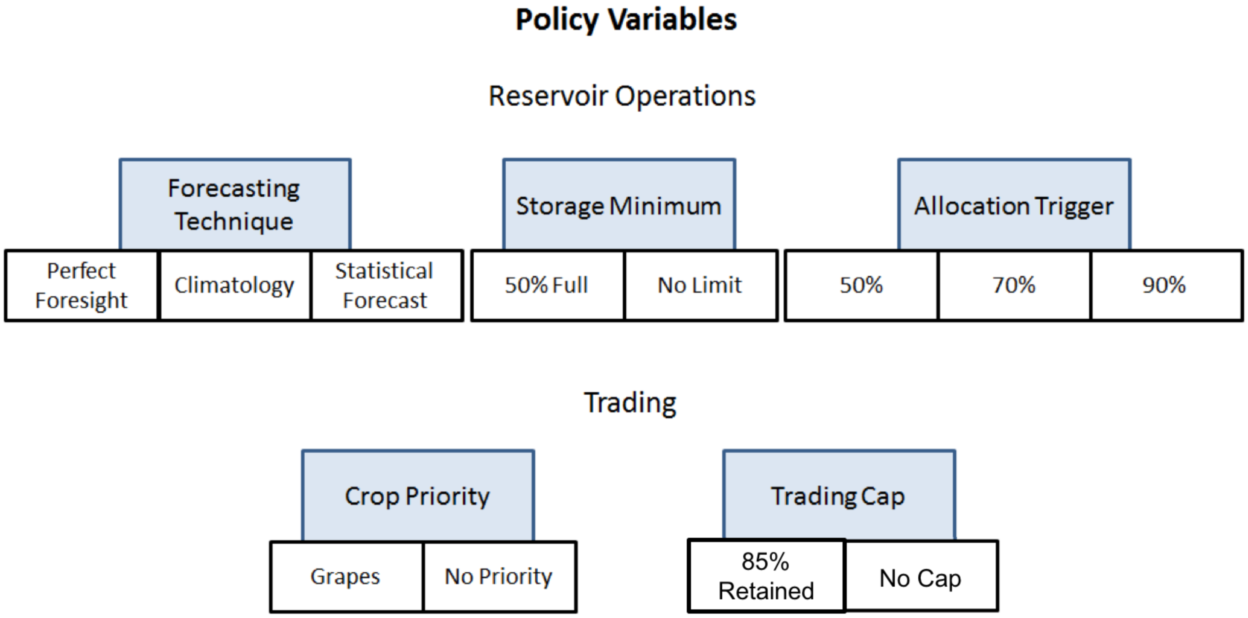

Figure 6: Policy variables depicting different suites of management decisions.

The ruleset executes at every timestep in order from the lowest priority rule to the highest priority rule, ensuring that every rule is executed at every timestep. A complete summary of the ruleset can be found in Appendix A: RiverWare Ruleset in **Figure 19**. Rules were organized in a tiered structure of priorities such that rules that depend on physical constraints on the river system or constitute emergency situations are given the highest priority. These include rules such as Drought Control, Flood Control, and Minimum Spill. The second tier of rules controls how trading is incorporated between prioritized and non-prioritized crops. The last tier of rules controls the allocation percentage for all users and corresponding reductions related to expected low flows in the coming season or existing low reservoir levels.

The simulation executes following the structure laid out in

Figure *7*. The simulation begins on January 1st, 1950. This month is used to initialize the model and is purposefully not considered part of the growing season, so no agricultural allocations are released. However, streamflow begins filling the reservoir in accordance with the observed data at the Algarrobal gage. Simultaneously, the reservoir releases water to meet the monthly municipal demand along with environmental flow requirements subject to storage availability in the reservoir. The reservoir may also release water as necessary if it reaches its maximum capacity of 210 Mm^3. The simulation continues executing this way on a monthly timestep until it reaches October 1st, the start of the agricultural season.

On October 1st, the simulation determines whether it has been forecasted to be a low flow year based on the policy variable chosen for that scenario. If the forecasted streamflow is less than the Allocation Trigger chosen (either 50%, 70%, or 90% of the 65-year average flow), the allocation is reduced equally for all users. In **Figure 7**, because the Allocation Trigger is 90% and streamflow is forecasted to be only 85% of the average, the allocation is reduced by 15% to 0.85 l/s. If the forecasted streamflow is projected to be at or above the Allocation Trigger, the allocation remains at 100%, or 1 l/s. For the Climatology forecasting case, the total ONDJ streamflow predicted is always equal to the 65-year average seasonal streamflow. Thus, under Climatology, there will never be a reduction in the allocation based on streamflow, and reductions will only be issued based on storage levels – what is understood to be a primary driver of reductions under current management.

The simulation then checks to see if there is a Storage Limit on the reservoir. If there is not, as in **Figure 7**, the allocation remains at the current amount. However, if there is a Storage Limit of 50%, the simulation checks the level of the reservoir on October 1st and compares it to the 50% level of 105 Mm^3. If it is above the limit, the allocation value is not changed. However, if it is below, the allocation is reduced by a factor of 50% of the difference of the storage level and the Storage Limit. The allocation value calculated from both the Allocation Trigger and Storage Limit is applied for the entire growing season such that the total outflow to agriculture remains the same for October, November, December and January pending any reservoir storage or outflow capability limitations.

Next, the simulation considers the amount of trading that may occur given the Crop Priority and Trading Cap chosen for that scenario. If no trading occurs, all crops will receive approximately the percentage of their acciones dictated by the allocation percentage calculated above. This percentage may be slightly different if the forecasted allocation amount is more than what is ultimately available for storage. This would represent a management error of over-allocating available storage.

If trading does occur and grapes are prioritized, the simulation refers to the Trading Cap to determine how much water the other crop farmers can give up, or trade, to the grape farmers. Trading only takes place between farmers within the same sector, so if a sector does not contain grape farmers, trading will not occur in that sector. In **Figure 7**, the Trading Cap is 85%, so for sectors that contain grape farmers, the other crop farmers must retain 85% of their acciones and can only give up 15% to the grape farmers. The simulation then looks at what percentage the grape farmers require to fulfill their entire water demand. If the grape farmer's deficit is less than 15% of all the other crops' acciones combined, the grape farmers will proportionally receive just enough water from each other crop type to fulfill their demand. If the demand is greater than 15% of all the other crops' acciones combined, grape farmers will receive the 15% from all other crop farmers.

This trading scheme continues each month until February 1st, when the simulation functions again as explained above for the non-growing season. The simulation then continues to execute for the full 65-year period until it completes on December 31st, 2015.

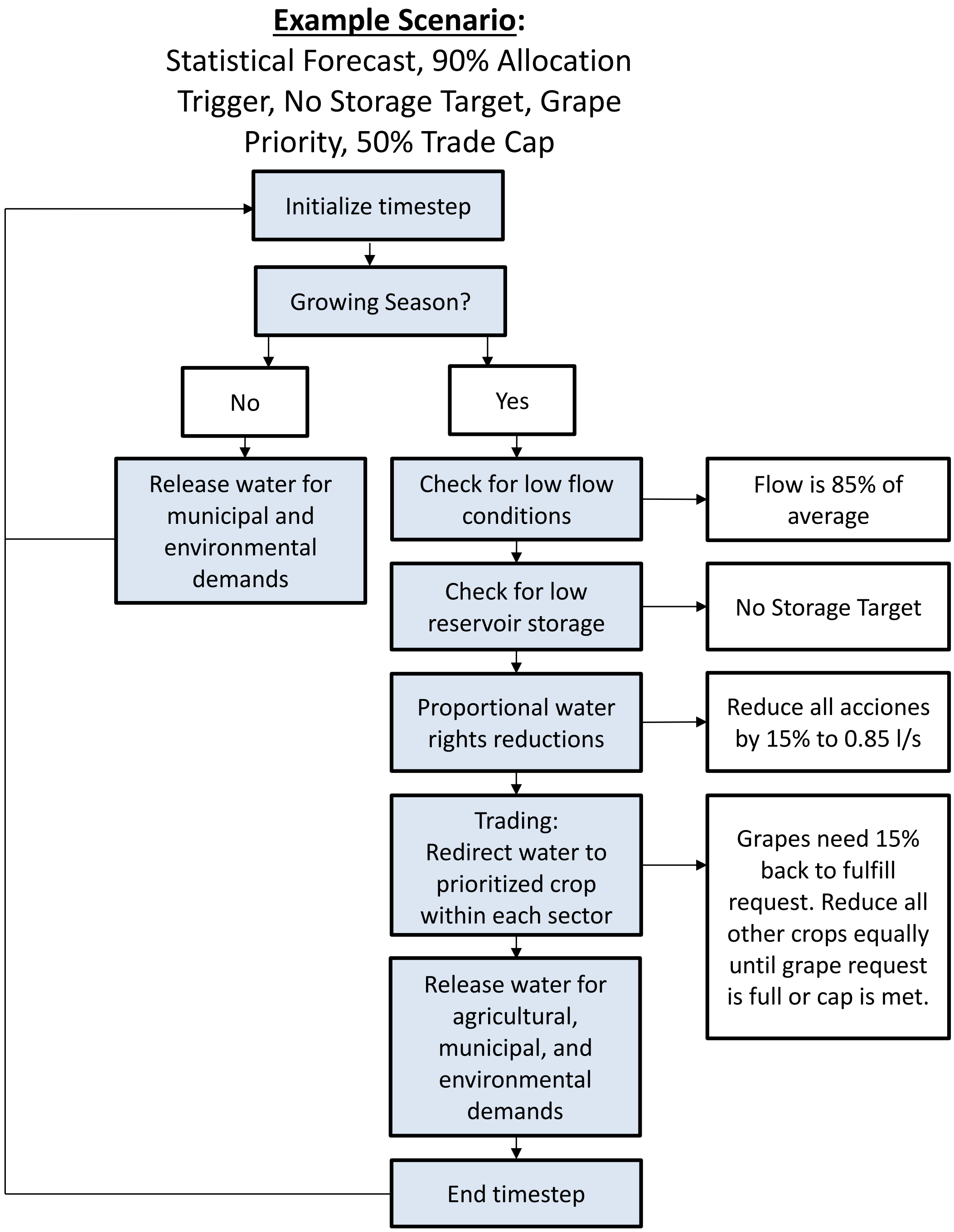

Figure 7: Example scenario walk-through

3.4. Objectives

A set of seven objectives, shown in **Figure 8**, were developed to represent the conflicting needs of stakeholders in the basin. Some of the objectives can be divided into groups based on their dependence on either the allocation percentage being delivered to farmers (allocation-dependent) or the storage level in the reservoir (storage-dependent).

3.4.1. Allocation-Dependent Objectives

Three objectives were determined to benefit from increased allocation values and decreased storage in Puclaro reservoir: Gross Agricultural Revenue, Agricultural Demand Realization, and Flood Vulnerability.

Gross Agricultural Revenue is intended to evaluate the overall economic gain of the basin throughout the simulation period. This was included to evaluate how scenarios perform in meeting of the primary goals for the implementation of water markets – to move water from low to higher value uses. It is calculated as the product of the average annual yield[1] of a crop for a specific sector and its selling price[2]. Prices in this study have been assumed to be static, based on current market prices. This does not account for the effects of changing market conditions but captures the general relationship between high and low value crop pricing. Additionally, prices associated with the leasing of rights have not been captured in this model.

$$\frac{\text{Yield}\left(\frac{\text{kg crop}}{\text{m}^3}\right)*\text{Cost}^2\left(\frac{\$}{\text{kg crop}}\right)}{65\text{ Years}}^3\left(\sum_{1950}^{2015}\text{Flow}_{delivered,month}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)$$

Agricultural Demand Realization is intended to evaluate the average overall fulfillment of accion requests throughout the basin. It is intended to assess how scenarios perform in meeting the needs of the basin’s agricultural users, primary stakeholders within the basin. It is calculated as the annual average of the percentage of the requested flowrate that is delivered to all crops.

$$\frac{1}{65\text{ Years}}\left(\left(\left(\sum_{1950}^{2015}\text{Flow}_{requested,month}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)-\left(\sum_{1950}^{2015}\text{Flow}_{delivered,month}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)\right)/\left(\sum_{1950}^{2015}\text{Flow}_{requested,month}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)\right)$$

Flood Vulnerability is intended to evaluate the risk of flooding throughout the simulation period. Flooding has been a concern within the valley due to the periods of intense, heavy rainfall brought on during El Nino events (Young et al., 2010). It has been suggested that precipitation events will increase in intensity as

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[1] Yield values from: (Steduto et al., 2012)

[2] Cost Ratios from: (Bureau of Labor Statistics, 2017; U.S. Wheat Associates, n.d.; USDA, 2015)

an effect of climate change (Young et al., 2010). It is calculated as the average number of times storage in the Puclaro reservoir reaches the flood limit and must be spilled.

$$\frac{1}{65\ \text{Years}}\sum_{1950}^{2015}\text{IF}\big(\text{Storage}\ (\text{m}^3) \geq \text{MaxStorage}(\text{m}^3)\big)\ \text{return a 1, (if not return 0)}$$

3.4.2. Storage-Dependent Objectives

Conversely, two objectives were determined to benefit from increased storage in Puclaro reservoir and decreased allocation values: Hydropower Production and Drought Vulnerability.

Hydropower Production is intended to determine how much power is by the reservoir as an annual average over the 65-year simulation period, and is included to address the basin's targets for using renewable energy. As earlier described in section 3.3.1., hydropower is modeled as a byproduct of reservoir outflow subject to the physical capabilities of the reservoir.

$$\frac{1}{65\ \text{Years}}\sum_{1950}^{2015}\text{Power (MW)}$$

Drought Vulnerability is intended to evaluate the risk of running out of water in the Puclaro reservoir during dry years or an extended dry period. Drought has been an ongoing threat in the basin, most recently indicated by a prolonged period of drought between 2009 and 2015 (Delorit et al., 2017). It is calculated as the average number of times storage in the Puclaro reservoir reaches the dead storage limit on the reservoir and cannot supply water.

$$\frac{1}{65 \text{ Years}} \sum_{1950}^{2015} \text{IF}\big(\text{Storage } (\text{m}^3) \leq \text{MinStorage}(\text{m}^3)\big) \text{ return a 1, (if not return 0)}$$

3.4.3. Other Objectives

The remaining objectives are not specifically allocation-dependent or storage-dependent.

Storage Variation determines how much fluctuation in storage happens annually in the reservoir and is meant to account for needs of recreationists who depend on consistent storage in the basin for windsurfing and sailing (Cepeda and Lopez-Cortez, 2004). It is calculated as the standard deviation of the storage over the entire period.

$$\text{Standard Deviation}\left(\text{Storage}_{\text{All Monthly Values}}(\text{m}^3)\right)$$

Finally, Low Value Crop Disadvantage is intended to measure the impact of trading on low value crop farmers, specifically for application to social consequences. As discussed in the introduction, social inequity has been one of the criticisms of the Chilean Water Code. This objective is calculated as the average difference in the percentage of acciones fulfilled between grapes and all other crops in sectors that have grapes. A negative value means that low value crops receive a greater percentage of their rights while a positive value means that grapes receive a greater percentage.

$$\frac{1}{65\text{ Years}}\left(\left(\left(\sum_{1950}^{2015}\%\text{Flow}_{not\ delivered,month,all\ low-value\ crops}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)-\left(\sum_{1950}^{2015}\%\text{Flow}_{not\ delivered,month,grapes}\left(\frac{\text{m}^3}{\text{s}}\right)*3{,}600\frac{s}{hr}*24\frac{hr}{day}*30\frac{day}{month}\right)\right)\right)$$

Figure 8: Objective Calculations

Objective	**Calculation**	**Minimize or Maximize**
Gross Agricultural Revenue	Annual average gross revenue for all crops produced based on yield and market price.	Maximize
Agricultural Demand Realization	Annual average percentage of water rights delivered to all crops.	Maximize
Hydropower Production	Annual average power generated in MW.	Maximize
Flooding Reliability	Annual average # of times flood limit on reservoir is reached.	Maximize
Storage Reliability	Annual average # of times dead storage is reached.	Maximize
Storage Variance	Measure of fluctuations in storage over time	Minimize
High vs. Low Value Crop Disparity	Measure of disparity between how much high value crop demand is met vs. low value crop demand.	Minimize

4. Results and Discussion

After developing the scenarios and running them in RiverWare, simulation results were collected and analyzed. A verification of the model setup was run prior to the full scenario execution to ensure the model was performing as expected. After running the scenarios, model outputs were analyzed and evaluated for objective performance metrics.

4.1. Model verification

To verify that the model simulations were running properly, we ran a limited set of scenarios to verify that water moved through the river system as expected based on the ruleset. First, we made sure that the reservoir storage, outflow, and inflow changed as expected under different reservoir operations rules. For example, **Figure 9** (left) shows a comparison of Puclaro Reservoir storage, outflow, and inflow over time for two different scenarios, one with a 90% Allocation Trigger and one with a 50% Allocation Trigger. The blue line displays storage over time for Puclaro Reservoir. As expected, for the same time period, the storage for the more conservative trigger (90%) is greater than that of the less conservative trigger because seasons are more frequently triggered as low flow years and more water must be conserved.

Next, we verified that the trading portion of the model was working properly by comparing trading and non-trading scenarios. **Figure 9** (right) shows the distribution of water between different crops within the model for scenarios where grapes are prioritized with no trading cap, and one in which there is equal priority for all crops and trading is not occurring. In this plot, grape rights are shown in purple, while the other crops are represented by the remaining colors. Taller lines represent greater diversions to that crop. As anticipated, we found that incorporating trading by prioritizing grapes led to increased diversions to grape farmers and decreased diversions to other farmers in comparison to the non-trading scenario.

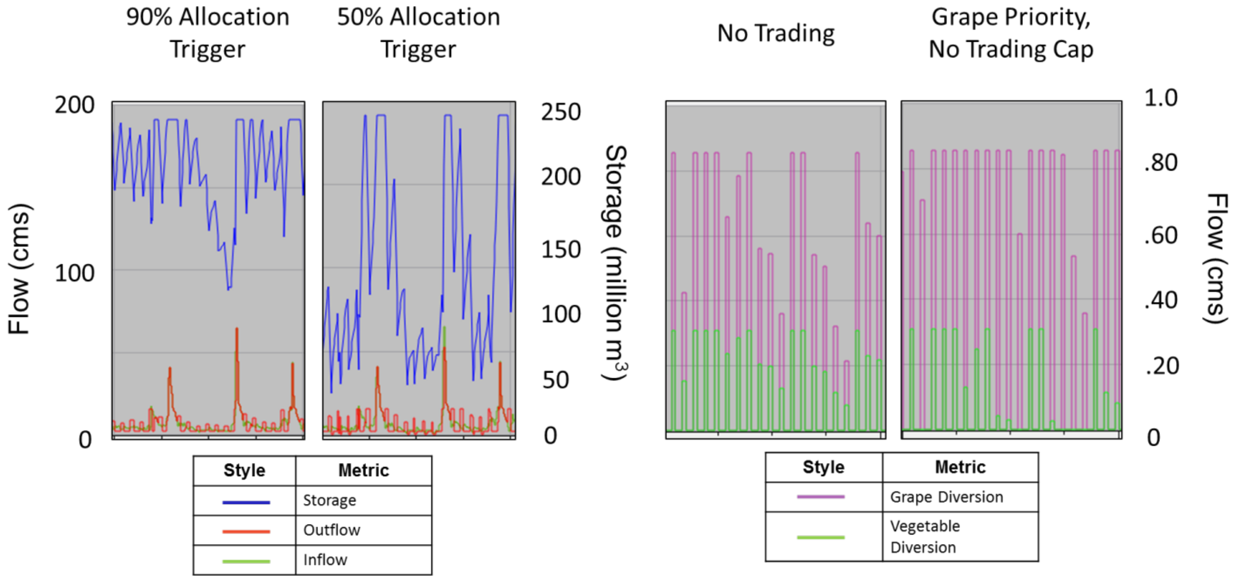


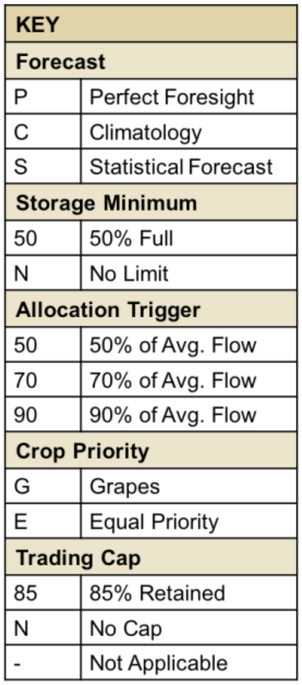
Figure 9: RiverWare outputs for Puclaro reservoir storage and outflow (left) and crop type allocation distributions (right).

4.2. Tradeoff Analysis

The Tradeoff Analysis demonstrates how values of the scenario variables affect the multiple performance objectives for the ERB. The first set of results focuses on scenarios with Perfect Foresight. These scenarios represent the choices management would make if they knew what the streamflow values for the coming season would be, dictated by the scenario's suite of other policy variables. Thus, these scenarios represent the best-case decisions, since the managers would know exactly how much flow that would arrive in a growing season. Although this is impossible in real life, it is used as an ideal baseline by which to compare the results under other forecasting techniques.

Figure 11 is a parallel coordinate plot that includes results for all the Perfect Foresight scenarios that were run. Scenarios have been named with a set of numbers, letters, and symbols representing the different policy variables, explained in **Error! Reference source not found.**. Specifically, the forecasting techniques are shown with different line types. The seven objectives are listed across the bottom of the plot and correspond to the vertical axis directly above them. Performance of the scenarios across the objectives is shown by the vertical position on each axis. The figure focuses on the Perfect Forecast results, with remaining results for the other forecasting methods plotted in grey; these results will be discussed later. Objectives are oriented such that the bottom of the figure represents the best performance. Thus, performance decreases when lines have a higher vertical position on an axis. Tradeoffs between objectives can be seen where scenario lines cross (in other words, a tradeoff denotes that one cannot achieve higher performance on multiple objectives simultaneously). Note that the order of the objectives along the bottom axis affects how the lines and tradeoffs show up on the plot. At the end of this chapter, **Figure 18** includes all the scenario results.

Recall from the Objectives section earlier, that storage-dependent objectives include Hydropower Production and Drought Vulnerability, whereas allocation-dependent objectives include Gross Agricultural Revenue, Agricultural Demand Realization, and Flood Vulnerability. Tradeoffs between these two suites of objectives can be seen for most scenarios by the zig-zagging of lines between objectives. This is intuitive because storage and allocations are inversely related such that a decrease in storage corresponds to an increase in outflow and allocations, and vice versa.



KEY	
Forecast	
P	Perfect Foresight
C	Climatology
S	Statistical Forecast
Storage Minimum	
50	50% Full
N	No Limit
Allocation Trigger	
50	50% of Avg. Flow
70	70% of Avg. Flow
90	90% of Avg. Flow
Crop Priority	
G	Grapes
E	Equal Priority
Trading Cap	
85	85% Retained
N	No Cap
-	Not Applicable

Figure 10: Scenario key.

Additionally, greater variability in performance can be seen for Gross Agricultural Revenue, Agricultural Demand Realization, and Low Value Crop Disadvantage than for the remaining objectives. It appears that the performance of Hydropower Production, Flood Vulnerability, Drought Vulnerability, and Storage Variation trends toward one of three general levels, suggesting that fewer policy variables are likely driving the performance than for the more variable objectives. The effects of the other policy variables will be explored in subsequent figures.

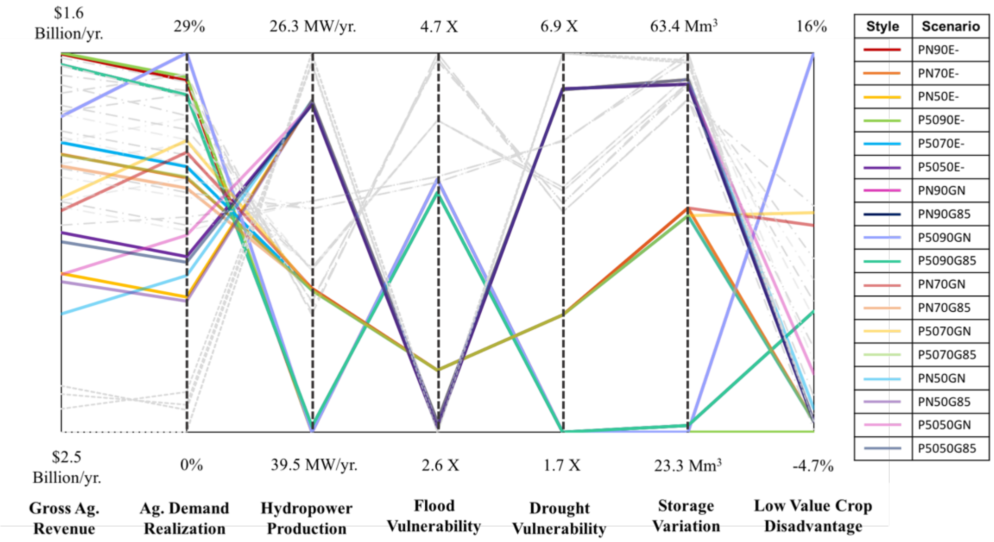


Figure 11: Parallel Coordinate Plot of all scenario results for Perfect Foresight forecasting technique.

4.2.1. Forecasting

We first examined these results more closely by looking at the performance of the other two forecasting methods in comparison the baseline Perfect Foresight method explored above. **Figure 12** compares results for the three different forecasting techniques. To isolate the effects of forecasting, values for the other policy variables are held constant. In other words, all solutions shown in **Figure 12** have the same values for the other variables – no limit on the Storage Minimum, 70% of average flow for the Allocation Trigger, and equal priority for Crop Priority. Perfect Foresight is shown by the solid line (PN70E-), Climatology is shown by the dashed line (CN70E-), and Statistical Forecast is shown by the variable dashed line (SN70E-), while all remaining scenarios are shown in grey.

First, comparing the two other forecasting methods to each other in **Figure 12** reveals that the Statistical Forecast outperforms Climatology for storage-dependent objectives. This is a result of the Statistical Forecast predicting lower streamflow on average than Climatology, resulting in reduced allocations relative to Climatology. Climatology outperforms the Statistical Forecast for allocation-dependent objectives for the same reason.

When comparing to the baseline Perfect Foresight scenario, the Statistical Forecast performs more similarly than Climatology for six out of the seven objectives, including Gross Agricultural Revenue, Agricultural Reliability, Hydropower Production, and Low Value Crop Disadvantage. This suggests that the Statistical Forecast may be more reliably predicting streamflow than Climatology and implies that if decision makers had complete knowledge of future streamflow, they would make decisions at each timestep more like those under the Statistical Foresight scenario. Since Climatology does not allow for reductions in allocations based on streamflow, this also suggests that basing decisions on reservoir storage alone results in outcomes quite different than when incorporating a true streamflow forecast. Increased allocations under Climatology also likely contribute to worse performance for Storage Variation due to frequent drawing down of the reservoir, leading to a pattern of storing then releasing water.

However, Climatology outperforms the Perfect Foresight method for allocation-based objectives. Again, this is likely due to Climatology over-predicting streamflow at most timesteps and not reducing allocations based on streamflow, resulting in a greater allocation to farmers at many timesteps. Consequently, Climatology performs the worst for storage-based objectives.

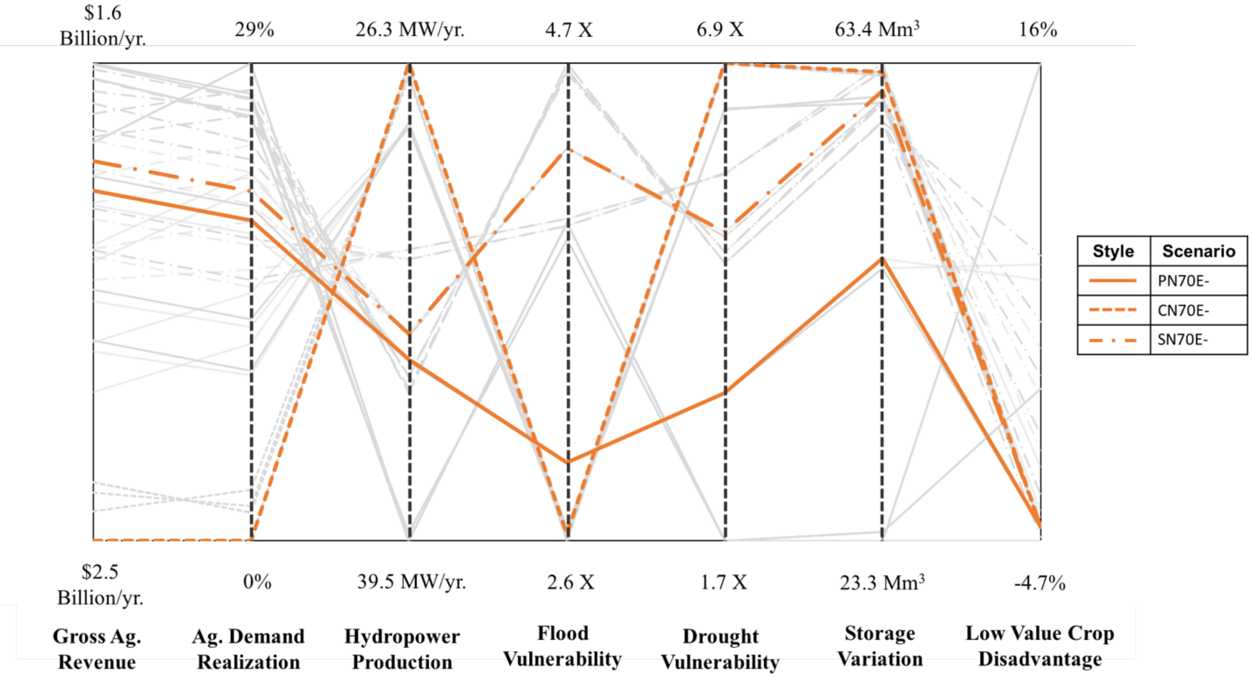


Figure 12: Parallel Coordinate Plot comparing three forecasting scenarios.

Figure 13 further investigates the tradeoff between Drought Vulnerability and Flood Vulnerability that can be seen by comparing the Climatology and the Statistical Forecast scenarios from above. This figure shows a time series of the entire simulation period for both scenarios. Reservoir storage is shown by the blue line in both figures. The yellow line indicates the target storage level the JVRE hopes to meet at the beginning of every growing season, while the magenta line indicates the maximum level of the reservoir at which water must be spilled. Under Climatology (CN70E-), the reservoir storage is more frequently below the target storage than under the Statistical Forecast (SN70E-). Similarly, under the Statistical Forecast, storage is more frequently reaching the spill level of the reservoir than under Climatology. Managers must determine their priorities regarding these conflicting objectives to determine which outcomes are most acceptable for meeting their needs.

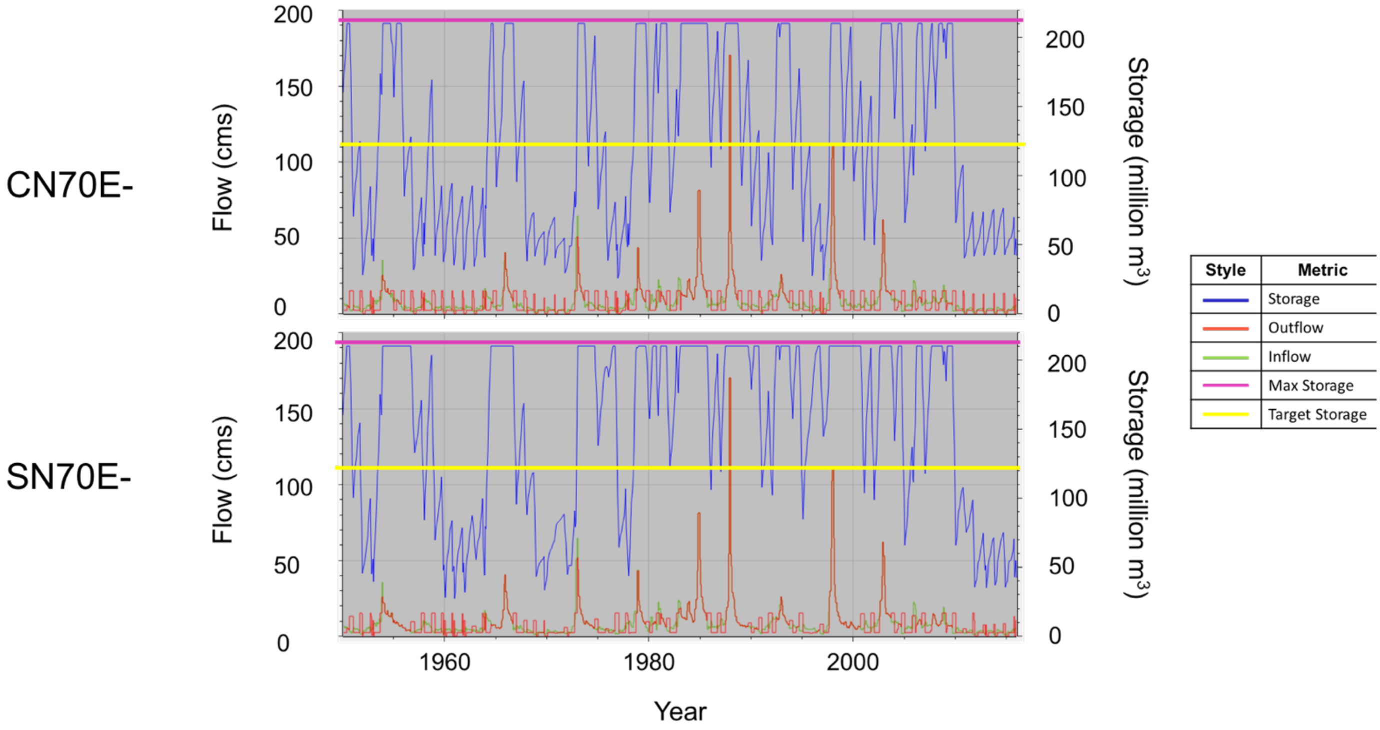


Figure 13: Comparison of Puclaro Reservoir storage levels for Climatology and Statistical Forecast forecasting techniques.

4.2.2. Reservoir Operations

Next, **Figure 14** compares the performance of different Allocation Triggers. To isolate the effects of the Allocation Trigger, values for the other policy variables are held constant such that the Statistical Forecast is used, there is no Storage Minimum, and there is equal priority for the Crop Priority. The most conservative Allocation Trigger of 90% is shown in red (SN90E-), the middle value of 70% is shown in orange (SN70E-), and the least conservative value of 70% is shown in yellow (SN50E-), while all remaining scenarios are shown in grey.

Tradeoffs between the storage-dependent and allocation-dependent objectives can be seen for more and less conservative management. More conservative management for the Allocation Trigger results in better performance of the storage-dependent objectives, whereas less conservative management results in better performance of the allocation-dependent objectives. This is intuitive because more water is released for less conservative Allocation Triggers while more water is stored for more conservative Allocation Triggers. For five of the seven objectives, including Gross Agricultural Revenue, Agricultural Demand Realization, Hydropower Production, Drought Vulnerability, and Storage Variation, the discrepancy between the 70% and 50% Allocation Trigger is greater than that of the discrepancy between the 90% and 70% Allocation Trigger. This requires further investigation but may indicate that there is some management threshold at which impacts to objectives are greater. The much poorer performance of the 90% Allocation Trigger for the Low Value Crop Disadvantage objective indicates that if management is very conservative and farmers are receiving less water, much more trade is occurring, resulting in a greater disparity between how much water grape farmers and other farmers are receiving.

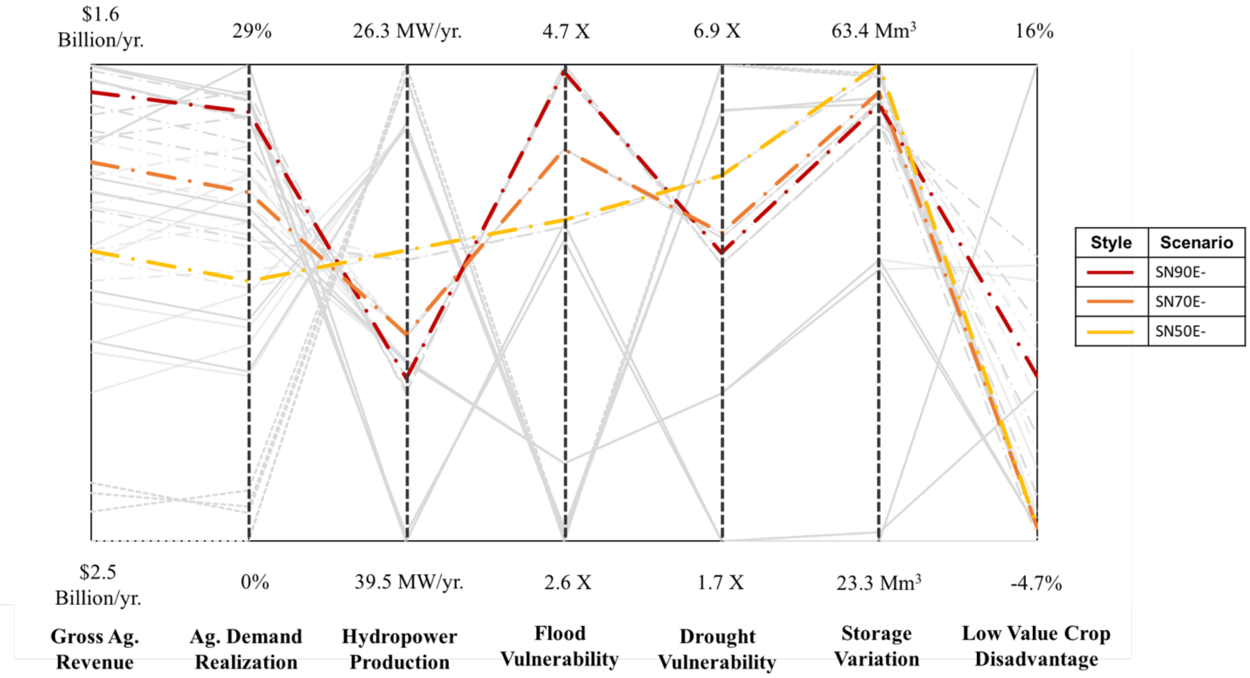


Figure 14: Parallel Coordinate Plot Allocation Trigger comparison.

Next, **Figure 14** evaluates the effect of incorporating a Storage Minimum. In this figure, multiple scenarios are compared to show the subtler effect of this policy variable. By comparing like scenarios while varying the Storage Minimum policy variable (e.g. PN90E- vs. P5090E-), performance is similar for many of the objectives apart from Gross Agricultural Revenue, Agricultural Demand Realization, and Low Value Crop Disadvantage. This is likely because the reduction to the allocation release in the model for low storage is minimal and does not impact the overall storage or allocation for the reservoir much.

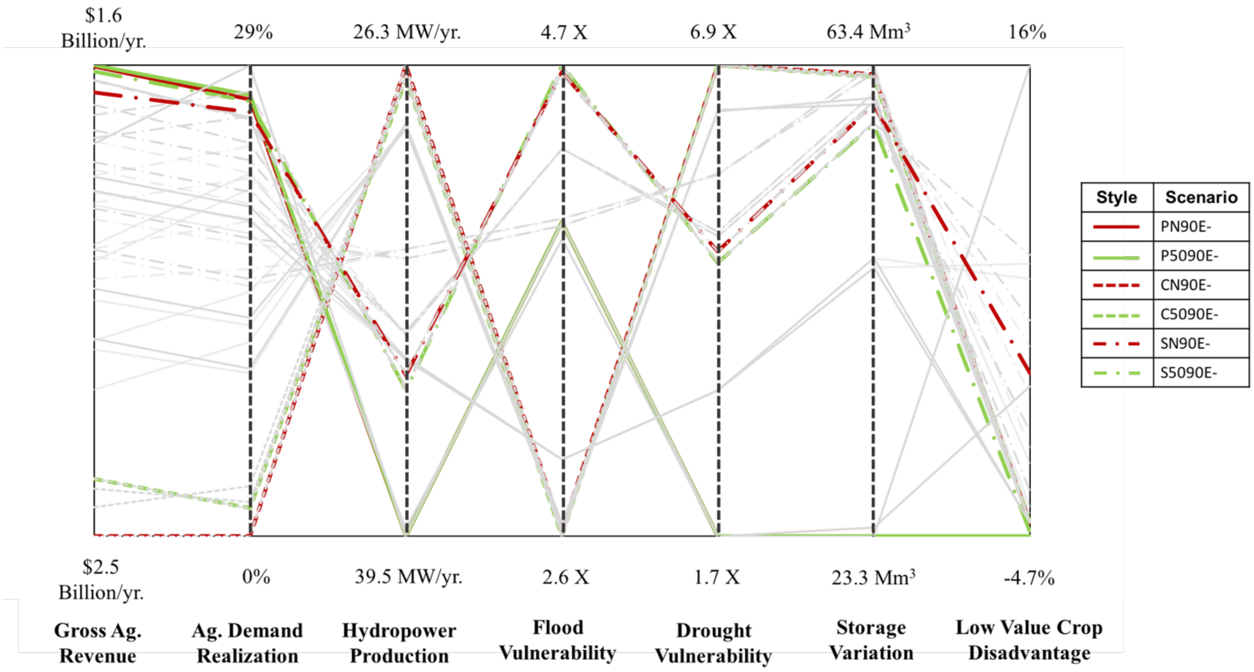


Figure 15: Parallel Coordinate Plot Storage Minimum comparison.

To better understand the compound effects of the Allocation Trigger and Storage Minimum, **Figure 16** compares the reservoir storage for a less conservative scenario with a 50% Allocation Trigger and no Storage Minimum (SN50E-), and a more conservative scenario with a 90% Allocation Trigger and a 50% Storage Minimum (S5090E-). The lower plot shows that highly conservative storage and allocation management results in a more frequent storage volume at the spill level, outside of the growing season. This means that under this scenario, management would be limiting the release of water to users during the growing season, limiting the number of crops that could be grown. Management would then be forced to release water at a time when it could not be used for farming, likely upsetting the agricultural community. Conversely, in the upper plot, less conservative management results in more frequent storage below the target level. Thus, management must again weigh the conflicting storage- and allocation-dependent objectives and determine acceptable levels of failure for each.

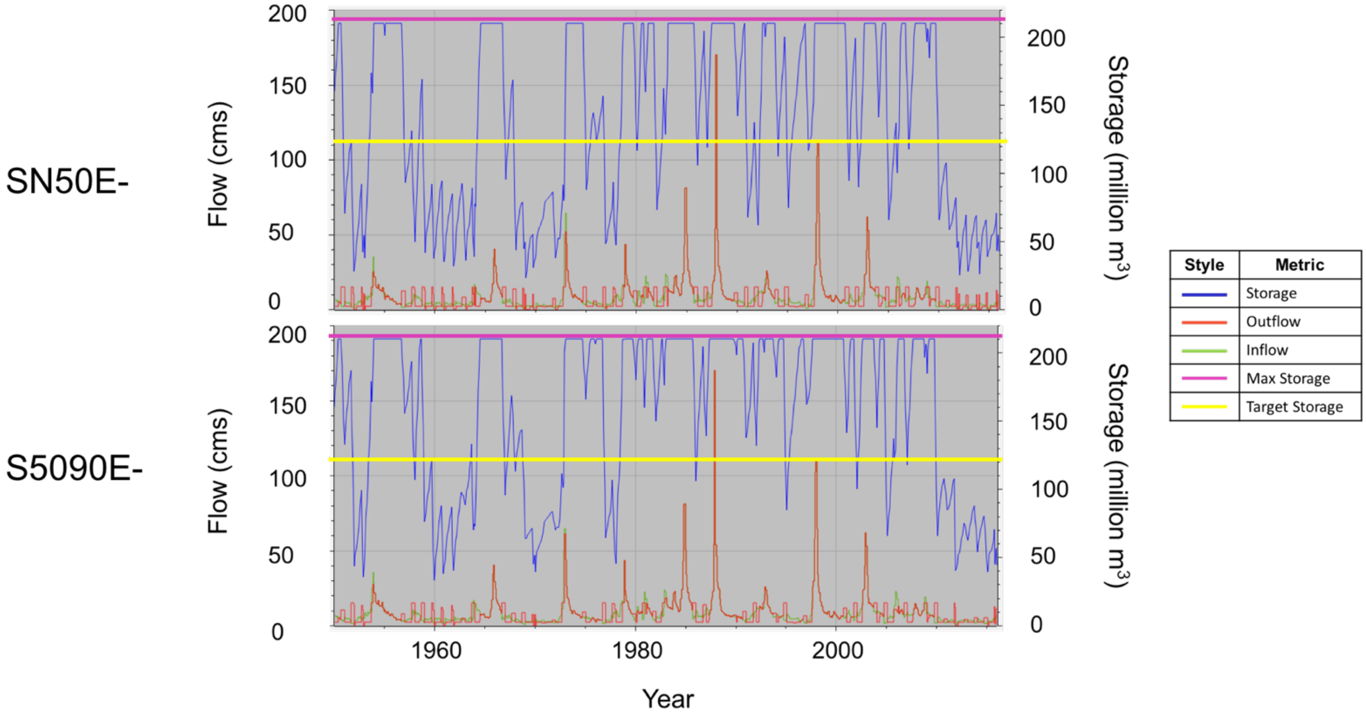


Figure 16: Comparison of spill frequencies for more and less conservative reservoir operation regimes.

4.2.3. Trading

Figure 17 investigates the effects of trading on objective performance. To isolate the effects of the Crop Priority and Trading Cap, values for the other policy variables are held constant such that Perfect Foresight is used, there is no Storage Minimum, and there is a conservative Allocation Trigger of 90%. Equal priority, or no trading, is shown in red (PN90E-), grape priority with an 85% trading cap is shown in indigo (PN90G85), and grape priority with no trading cap is shown in magenta (PN90GN). Recall that an 85% Trading Cap means that the non-prioritized crops must stop trading once they have given up 15% of their acciones. As the amount of trading allowed increases, the Low Value Crop Disadvantage performs worse and Gross Agricultural Revenue improves. This makes sense because when trading occurs, low value crops are transferring their water to the higher value grape farmers, reducing the percentage of acciones they have fulfilled in comparison to grapes and increasing the revenue earned.

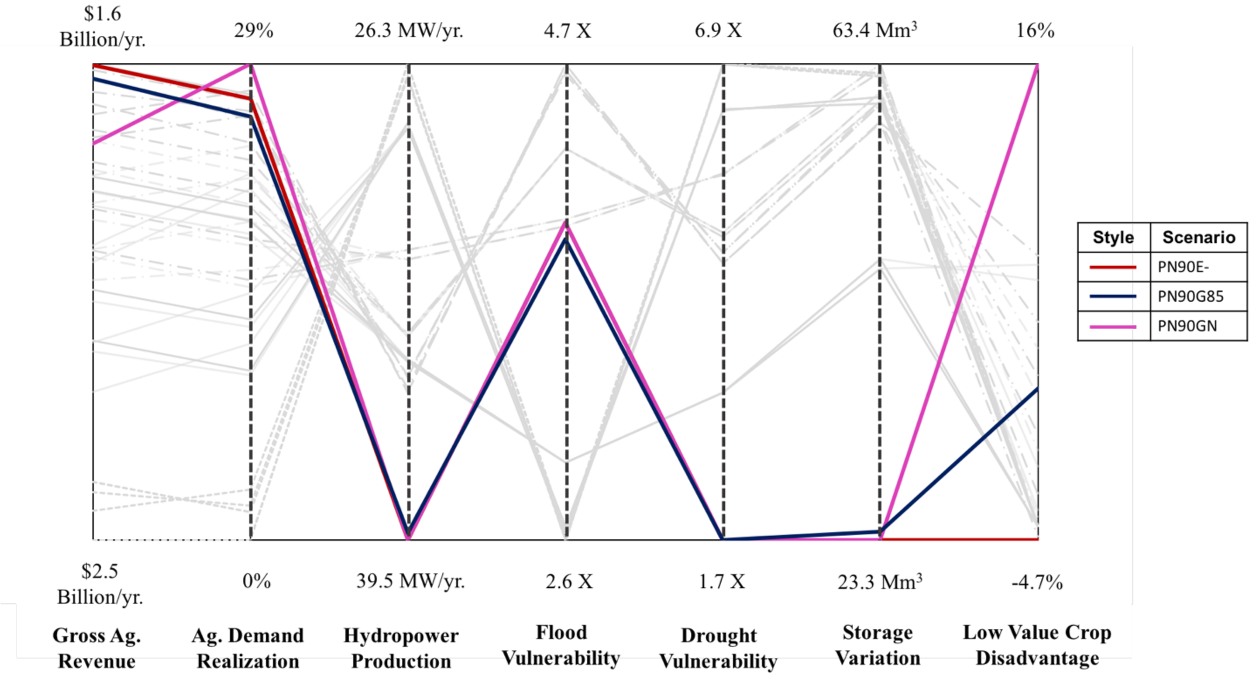


Figure 17: Parallel Coordinate Plot comparison of Trading options.

4.2.4. Scenario Summary

Figure 18 displays the complete set of scenario results. It can be seen that none of the solutions are perfect options. Tradeoffs always exist and are generally significant for at least one combination of objectives. Managers can apply different techniques to determine which of these solutions is most appealing for their priorities. One such example could be to apply a weight to each objective based on their relative importance, then total up the scores and compare them. However, we would recommend that this is not done blindly, so that tradeoffs are evaluated in case objectives are below what might be an acceptable performance level.

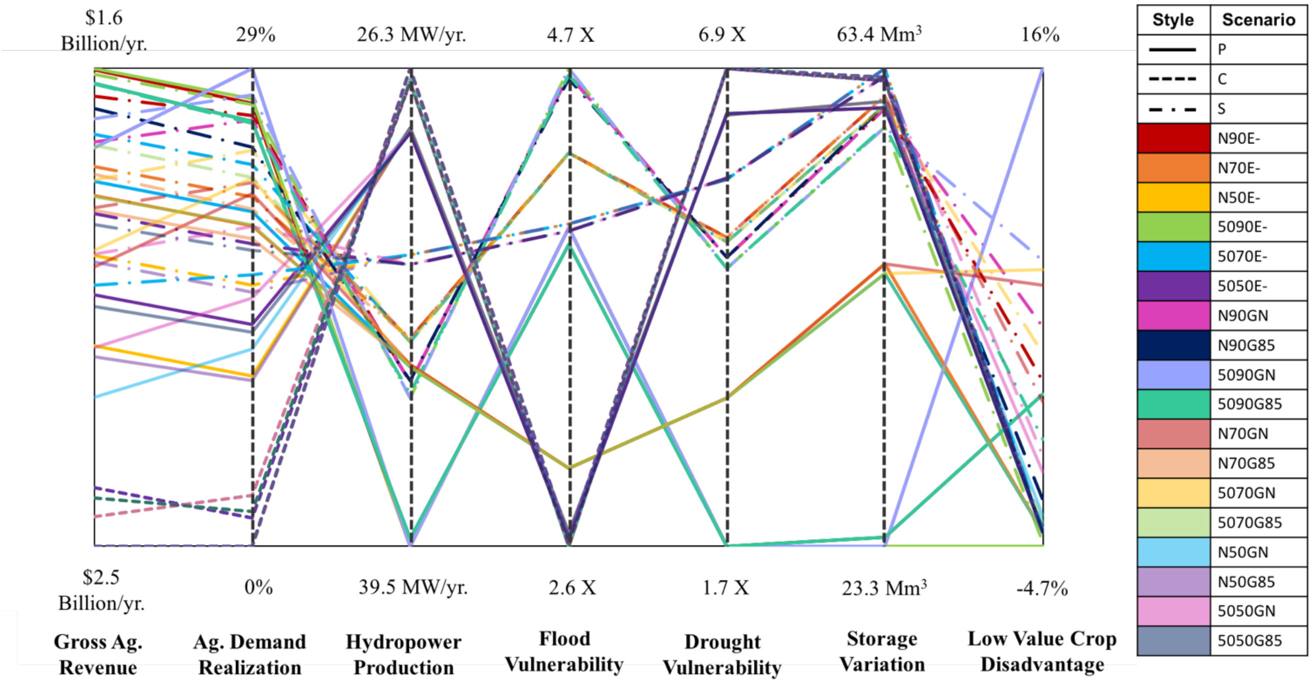


Figure 18: Parallel Coordinate Plot of all scenario results. The line style (solid or dashed) represents the forecasting technique, while the line color represents the other policy variables chosen. Tradeoffs can be seen where lines cross. The best performance is toward the bottom of the plot.

5. Conclusions and Future Work

5.1. Conclusions

This study sought to understand and evaluate the impacts of various management decisions within the ERB while also generally exploring the integration of water rights trading and forecasting analysis with the RiverWare modeling tool. By applying the forecasting technique from Delorit et al., 2017, this work found that a statistical forecast can provide objective performance more similar to that of having perfect knowledge of future streamflow conditions within the ERB than that of Climatology. Additionally, because the Statistical Forecast is outperformed by Perfect Foresight for most objectives, an investment in improved forecasting skill would translate into improved performance across various needs within the basin and could be supported by all stakeholders.

Although Climatology results in improved performance for some objectives over Perfect Foresight, it appears to be due to an over-allocation of water to farmers in many timesteps. This is likely because Climatology does not account for temporal variability, resulting in forecasted streamflow values that are influenced by wetter periods that do not persist throughout the time period. This results in performance tradeoffs that should be considered and weighed.

Next, an evaluation of reservoir management impacts revealed that decisions regarding the Allocation Trigger result in noticeable impacts to objective performance across all objectives. As this trigger is dependent on the Forecasting Technique discussed above, cascading effects of the implementation of Climatology or the Statistical Forecast must be considered. However, it was found that even independently, the decision to be more or less conservative in responding to a chosen forecast and determining an allocation reduction affects the performance of all objectives. The conservativeness of the chosen method determines whether storage-dependent or allocation-dependent objectives are favored, indicating that management should evaluate the tradeoffs between these objective types and determine levels of acceptable performance for both.

Finally, analyzing the impacts of different amounts of trading within the basin suggest that moving water from lower to higher value uses does improve the economic performance of the basin as a whole, as shown by the Gross Agricultural Revenue objective. However, management may want to consider how the disparity between low and high value crops affects social dynamics within the basin. Literature on the region suggests that farmers who sell their rights often do not reinvest their money and end up worse off (Donoso, 2006). This could result in indirect impacts to the economic performance of the basin later on as poor farmers lose their farms. Additionally, the improved performance of Gross Agricultural Revenue from trading does not make up for the effects of a more conservative Allocation Trigger, such that a scenario that incorporates trading but is more conservative performs worse than a scenario that is less conservative but does not incorporate trading. Thus, while trading may provide incremental economic benefits, it will likely not make up for overly conservative reservoir management decisions or poor forecasting skill that directly ties into those decisions.

Generally, this study found that incorporating forecasting and water rights policy into RiverWare can help inform water managers about tradeoffs that exist between needs within a basin. Further analysis can reveal the relative effect of certain decisions on objectives and can identify the most impactful decisions that can be made. This can help management prioritize limited resources in addressing water resource management issues.

5.2. Future Work

Opportunities for further analysis and expansion of this work exist. First, it is likely that closer temporal analysis of the existing simulation data could reveal important details about objective performance. During the sixty-five year simulation period, wetter and dryer periods occurred, including a drought at the end of the simulation (2009-2015) (Delorit et al., 2017). Further analysis of scenario performance during the extreme periods of drought and high flows might reveal the robustness of different management decisions over changing conditions. Additionally, it is possible that certain scenarios are preferable during specific climatic periods but not preferable for others. Such analysis would require breaking down the existing data outputs into different temporal periods and re-analyzing the objectives.

Next, there is room for further investigation into forecasting methodologies. The Climatology forecast overestimates streamflow for many of the timesteps. It might be interesting to adopt a moving average for Climatology and compare its performance to the Statistical Forecast. Because this method relies on few resources to evaluate, it would be helpful to understand how it compares to the more resource-intensive Statistical Forecast. Further work could evaluate how stochastic climate assessment might affect objective performance. By considering sequences of years not seen in the historical record, management might need to respond differently to new extremes in streamflow or to extended periods of drought or high flows. Additionally, more realizations of the Statistical Forecast could be evaluated. In this study, only the median forecast was used. However, ninety-nine more realizations exist and could be run through the simulation to find the optimal forecast. Finally, all of the forecasts could be evaluated temporally as described above to see if certain forecasts perform best under certain conditions, allowing management to pivot between forecasts when beneficial.

The potential for additional trading scenarios exists as well. The current model only includes trading within sectors, due to the existing infrastructure in the region. However, it could be helpful to evaluate trading across sectors by incorporating the required infrastructure options that would enable such trade. More detailed infrastructure analysis could be included to account for repairing leakages that are currently an issue in the ERB. Additionally, trading currently only occurs in one direction – from low value crop farmers to grape farmers. There may be certain years in which low value crop farmers want to increase their yields and grape farmers have excess water to sell to other users. Also, if dynamic pricing were included, there may be years in which other crops are valued higher than grapes.

Finally, a multi-objective evolutionary algorithm (MOEA) could be incorporated to translate the existing discrete scenarios into a much more extensive set of scenarios. MOEAs remove the manual process of updating policy variables by systematically updating these variables based on their performance, and continuing the process until an optimal solution set is found (Maier et al., 2014). This optimal solution set is typically referred to as the Pareto optimal set, meaning that each solution is non-dominated with respect to one another and satisfies the problem's constraints (Kollat et al., 2012). This allows for the exploration of management decisions that would result in optimal performance of the objectives and the elimination of scenarios that are outperformed for all objectives by other scenarios. Each of the solutions is equally viable, so it is then up to the decision maker to determine which solutions are preferable based on his or her subjective needs. This could allow for scenarios that span a nearly continuous set of policy variable values, and could reveal where benefits are maximized for each objective and what the expected opportunity cost might be for incremental changes between objective performance.

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Appendix A: RiverWare Ruleset

Figure 19: RiverWare Rules

Priority	Rule	Description
1	Puclaro Drought Control	If reservoir storage is less than the minimum storage requirement, sets outflow to minimum outflow possible given all constraints.
2	Puclaro Flood Control	If reservoir storage is greater than or equal to the maximum storage, sets outflow to minimum required to meet maximum storage or maximum outflow constrained by the reservoir.
3	Minimum Spill Requirement	If reservoir outflow is less than 25% of the regulated spill, sets outflow to minimum of two quantities: 25% of regulated spill or maximum outflow constrained by reservoir.
4	Puclaro Outflow	During growing season, sets outflow to minimum of total diversions requested for each sector and ESSCO requirement or maximum outflow constrained by reservoir. Outside of growing season, sets outflow to minimum of two quantities: environmental flow requirement plus ESSCO requirement or maximum outflow constrained by reservoir.
5	User Return Flows	Adjusts for return flows from agricultural production.
6	Municipal Water	Sets ESSCO drinking water request to minimum of either municipal demand set by rule 13 or maximum flow rate available.
7-12	Sector 5-10 Diversions	Sets total available water for given sector to minimum of two quantities: water available for diversion or requested flow rate.
13	Municipal Request	Sets ESSCO drinking water request to its set demand.
14-19	Sector 5-10 Trade Diversion Reductions	Modifies each crop in each sector's requested flow rate to account for rules 21-26.
20	Run Control	Checks timestep.
21-26	Sector 5-10 Reduction Variables	If turned on, simulates trading of acciones between water users. During growing season, if prioritized crop in sector is getting less water than its acciones require, all other crops in sector will give up proportional percentages of their flow rates to help prioritized crop reach its full request.
27-28	Run Control	Checks timestep.
29-34	Sector 5-10 Reductions	Sets given Sector's requested flow rate to total acciones in sector reduced by percent reduction calculated in rule 35 during growing season. Outside of growing season, it is set to 0.
35	Low Storage Reduction	Compares reservoir storage prior to growing season (ONDJ) to target storage. If it is less, then percent reduction is decreased by a set amount.
36	Diversion Reduction	Compares forecasted seasonal (ONDJ) average flow to low flow limit set by allocation trigger. If it is less, then percent reduction is set to difference between forecasted average and low flow limit.