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WATER INFRASTRUCTURE PLANNING FOR THE UNCERTAIN FUTURE IN LATIN AMERICA

A COST- AND TIME-EFFICIENT APPROACH FOR MAKING ROBUST INFRASTRUCTURE DECISIONS, WITH A CASE STUDY ON MENDOZA, ARGENTINA

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INTRODUCTION

Water managers in many regions of Latin America are facing increasing challenges meeting societal needs due to rapid demographic and economic growth, expansion of irrigation, changes in climate and hydrology, and degradation of groundwater resources and ecosystems. However, how these conditions will evolve over the coming decades is deeply uncertain and not predictable. In response, development banks and utilities in Latin America are investing billions of dollars on water management over the coming decades. Before such investments should be made, however, a prudent lender or planner should ask:

- How could changes in future conditions affect these investments?
- Will these investments be robust—or perform sufficiently well over a wide range of plausible futures?

Answering these questions requires thinking differently about evaluating water resources needs and solutions. First, because important drivers of future conditions are highly uncertain (and not easily characterized with probabilities), a planner or funder should consider how proposed investments might perform across a wide-range of plausible futures. Second, it is also increasingly important and necessary to involve stakeholders in the planning and decisionmaking process. As such, bringing the analysis to stakeholders and involving them in evaluating infrastructure and decisionmaking tradeoffs is critical. Lastly, while data and models are never as comprehensive as would be desired, the complexities of water resources planning require a quantitative evaluation of future water resources and local needs.

Recently, development banks and water funds have commissioned studies to evaluate climate and other risks to Latin American water systems and proposed infrastructure.[1] These studies have used new methods for Decision Making Under Deep Uncertainty (DMDU) (Marchau et al. 2019) to stress test water management systems over many plausible futures and identify robust strategies. Recognizing that these studies are often costlier and more time consuming than could be replicated widely across all of Latin America, the World Bank developed the Decision Tree framework (Ray and Brown 2015) to help identify situations for which a full robustness analysis is warranted, based on expected climate effects. For systems facing significant climate sensitivity, a thorough robustness analysis is recommended.

This study builds on these prior studies and presents a time- and cost-efficient, replicable approach to applying DMDU methods to support a robustness analysis of water systems in Latin America. This approach is based on Robust Decision Making (RDM) (Lempert 2019) and is consistent with other versions of DMDU methodology. Importantly, while this approach is designed to address climate risks, it also incorporates other important uncertainties in a consistent and systematic fashion. This approach is demonstrated through a case study application to Mendoza, Argentina.

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[1] Lima, Peru (Groves et al. 2018; Kalra et al. 2015); Monterrey, Mexico (Molina-Perez et al. 2019); Mexico City, Mexico (on going); and La Paz, Bolivia.

CASE STUDY BACKGROUND: MENDOZA, ARGENTINA

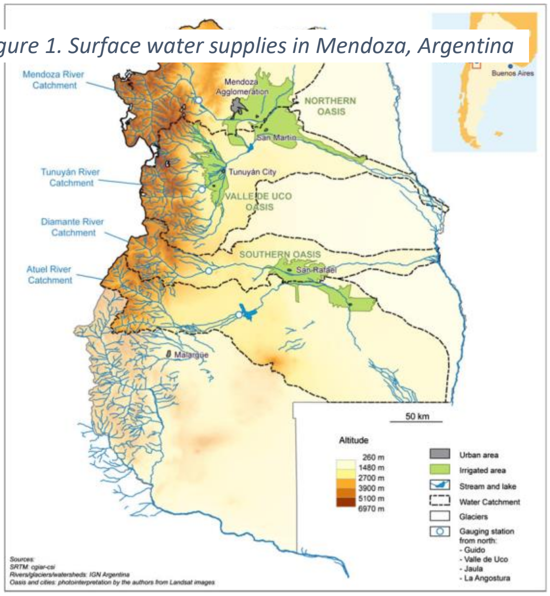


Figure 1. Surface water supplies in Mendoza, Argentina

Sources:
SRTM: cgiar-csi
Rivers/glaciers/watersheds: IGN Argentina
Oasis and cities: photointerpretation by the authors from Landsat images

The Mendoza, Argentina region sits at the foothills of the Andes Mountains (Figure 1) and supports an expansive and nationally-important agricultural industry that is predominantly focused on wine production and other fruit crops. The region's surface water supplies, which originate in the upper mountain zone and are largely fed by snow and glacial melt, flow into an arid lower plain with interconnected, underlaying alluvial groundwater basins. Together, these serve as the principal supply sources used to meet the region's predominantly agricultural demands. Urban areas also require water for residential and commercial and industrial use. While these water resources have been sufficient to meet urban demand over the past several decades, during dry periods, irrigated agricultural areas do not have the water required for full agricultural production. Specifically, the Mendoza region is experiencing its tenth consecutive year of water crisis, which began in 2009 when average annual streamflow dropped below the region's historical average due to scarce snowfall and below normal snowpack.

Complicating the scarcity of surface water are a number of other long-term challenges, which include: i) rising temperatures that increase crop water demand and heighten irrigation needs; ii) declining average annual precipitation; iii) melting glaciers; iv) unregulated use of groundwater resources, leading to groundwater declines in some sub-basins; among others. Mendoza is already considering a number of potential strategies to mitigate these problems, chiefly: a large new reservoir to buffer seasonal and interannual variability and/or a series of small reservoirs along the floodplain to store water and recharge groundwater resources.

Local stakeholders, including the Departamento General de Irrigación (hereafter, Irrigación), would benefit by better understanding which of these approaches, or others, would cost-effectively address their water management needs throughout an uncertain future. That is, infrastructure and management strategies that are designed or implemented such that they will perform their needed function regardless of how future climate and demographics change into the future.

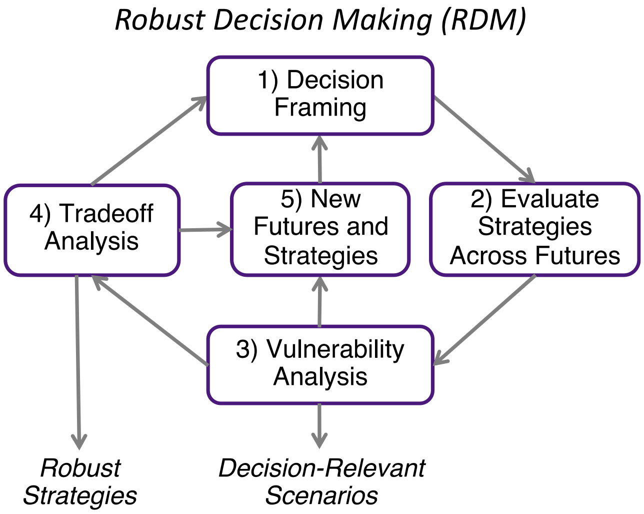
A REPLICABLE DMDU APPROACH

The study presents a standardized approach to using Robust Decision Making (RDM) to characterize the long-term threats to water management and evaluate the robustness of different management and investment options. This approach is intended to take one year, and it includes important direct engagements with stakeholders. This study illustrates this approach through a case study in Mendoza, Argentina.

RDM is an iterative process that includes a combination of stakeholder engagement, modeling, and analysis to account for difficult-to-address uncertainties, such as climate change, and to facilitate consensus on actions comprising a robust strategy. It has been successfully used in multi-year engagements to support water planning in Latin America.

Figure 2 shows the different iterative steps as typically presented in RDM studies.

Figure 2. Iterative steps of a Robust Decision Making process



RDM studies generally use an approach similar to that shown in Figure 2 and adapt it for their own needs. For the purposes of this study, we applied this iterative framework in Figure 2 to form five steps to be conducted over a 12-month period.

1. **Engage Stakeholders Over Key Issues, Decisions, And Available Technical Information (month 1)**: Step 1 of the analysis begins with the Decision Framing Workshop with in-country with local partners. This workshop discusses the key decision framing elements to be evaluated during the study, including key uncertainties (Xs), relevant performance measures (Ms), potential water management strategies and infrastructure options (Ls), and available water system models and data (R). This information is summarized in an XLRM table.
2. **Compile Data And Models (months 2-4):** Next, the study team quantifies the key uncertainties from Step 1 as a range of plausible futures by assembling available climate information to form future climate scenarios and developing alternative demographic and water demand scenarios. With this information, researchers then design experiments and employ models to test water systems under these futures.
3. **Characterize the Key Vulnerabilities (months 5-6):** The team then identifies key vulnerabilities in water systems by evaluating how the system would perform across the range of plausible futures previously defined. The results are analyzed to identify the key uncertain future conditions that would stress the water management system. The results are shared with stakeholders during an interactive stakeholder workshop.

4. **Evaluate Benefits And Costs Of Infrastructure Proposals (months 7-9):** Based on the vulnerability analysis and stakeholder engagements, one or a few water management or infrastructure proposals to improve the performance of the water system are identified. These strategies are then evaluated across the range of plausible future conditions (as in Step 3) to quantify the benefits and costs of each proposed option. Changes in system robustness are calculated and compared to the costs of each option or combination of options and then presented as tradeoffs for the stakeholders to consider.
5. **Deliberate over Robustness and Cost Tradeoffs (months 10-12):** In the last step, the study team works directly with in-country partners to deliberate over the cost and robustness tradeoffs of the infrastructure options analyzed in Step 4. Depending on resources available, such deliberations could occur via a final in-country workshop or via a series of targeted video conferences.

The approach systematically evaluates the vulnerabilities of current water infrastructure and management systems as well as the effectiveness of proposed water management investments in reducing those vulnerabilities. The results of this evaluation are detailed in a final in-country workshop and a study report. These provide a concise overview of the entire project, targeted to different audiences—policymakers, technical stakeholders, and the public—as well as present and discuss the final robust water management adaptation strategy. This cost- and time-efficient approach to making robust infrastructure decisions can be thus deployed to support both development banks and water entities Latin America where budget, time and partner engagement may be limited but investment and infrastructure decisions must be climate-smart and perform well in the face of changing conditions in the coming decades.

MENDOZA CASE STUDY PROGRESS

STEP 1) ENGAGE STAKEHOLDERS OVER KEY ISSUES, DECISIONS, AND AVAILABLE TECHNICAL INFORMATION

Step 1 of the analysis began with the Decision Framing Workshop, held at Irrigación headquarters in Mendoza during the week of October 15, 2018. The workshop participants discussed the key decision framing elements to be evaluated during the study—the uncertainties (X); performance measures (M); water management and infrastructure options (L); and models (R). The stakeholders agreed that the major uncertain factors driving management conditions are related to urban demand, agricultural demand, climate conditions, and groundwater resources. Other uncertainties were discussed, as well. The most critical metrics used to measure the performance of the Mendoza system include unmet water demand, infrastructure cost, availability of groundwater resources. The stakeholders described a range of different management options, but follow-on discussions with Irrigación led to a focus on surface storage and comparing two alternative approaches—a large, multi-purpose reservoir projects and a system of smaller, distributed reservoirs. Lastly, Irrigación provided an existing model of the Mendoza River Basin to modify to support this study. The “XLRM” matrix below (Table 1) summarizes the resultant scope of the analysis.

Table 1. XLRM matrix for Mendoza, Argentina case study

Uncertainties (X)	Options (L)
• Trends in temperature and precipitation reflecting climate change • Alternative sequences of wet and dry years reflecting climate change • Change in urban water uses (domestic/commercial and industrial) • Irrigated acreage, by crop type • Land use transition from irrigation to urban	• Current system (CS) • CS + one large, multi-purpose reservoir project • CS + system of smaller, distributed reservoirs
Models (or relationships) (R)	**Performance measures (M)**
• Modified WEAP model of the Mendoza River Basin	• Monthly water demand by node • Unmet water demand (absolute and percent of demand on an annual basis) • Groundwater depletion • Water use by sector and the affiliated supply from surface water or groundwater • Annual agricultural production (proxied by irrigated acreage by crop type) • Cost of projects under consideration

STEP 2) COMPILE DATA AND MODELS

In the second step, the project team worked with Irrigación to adapt the WEAP model for this study and develop data to define a set of uncertain futures.

ADAPT EXISTING WATER MANAGEMENT MODEL

The project team made a number of updates to the WEAP model of the Mendoza Basin. Specifically, the project team:

- Extended the model to 2050
- Reconnected the upper watershed to enable WEAP to calculate the climate effects
- Removed anticipated climate change effects from the baseline hydrology
- Added uncertainty dimensions for population, municipal water use rates per person, industrial activity, groundwater storage, and climate change (in the form of changes to average precipitation and temperature over time)
- Added mechanisms to support running the model in batch mode using a discrete scenario set for each uncertainty
- Generated WEAP scenario data tables for:
    - Population and municipal water use rates: based on existing model scenarios
    - Industrial activity and groundwater storage: based on illustrative scenarios

    - Climate change: based on gridded, downscaled GCM runs
- Updated input datasets to include the most up-to-date observations (for example, population, precipitation, etc.)
- Provided well-documented scripts, which run WEAP in batch mode with updated input parameters, to Irrigación as part of a capacity building step

DEFINING PLAUSIBLE FUTURES

Hydrologic conditions

The project team developed scenarios to evaluate the Mendoza management system that reflect future hydrologic conditions using a modified Delta approach. The project team started with available historical time series data (2000-2016) of monthly temperature and precipitation from 18 locations in the Mendoza River Basin. These data were used to develop a baseline future precipitation time series by cycling historical years to 2050. The historic and future times series for 18 locations were then spatially interpolated to form temperature and precipitation inputs for each of the WEAP model's 76 catchments.

To reflect trends in temperature and precipitation due to climate change and possible longer droughts, different hydrologic futures were developed by modifying the baseline timeseries. First, two alternative precipitation time series were developed that reflect recurrence of a drought that is 1 and 2 years longer, respectively, than in the baseline. Then a set of futures were developed that vary precipitation and temperature by the changes, or deltas, in these variables shown in the AR-5 IPCC global climate model output by 2050.

Land use scenarios

The following scenarios describe six alternative futures that represent potential changes in land use and urbanization. We apply these scenarios to the Mendoza river basin. The data requirements for each scenario are detailed below.

- **Current trends:** this scenario is the "base case" and uses historical growth trends for urban and industrial users and changes in land use as a forecasting tool. This scenario also assumes a constant crop composition in the agricultural area.

- **Accelerated urbanization**: this scenario represents a faster development of the urban population and industrial users, as well as a uniform retreat of irrigated land in the agricultural areas of the Mendoza river basin.

- **Expansion of agriculture**: this scenario represents a slower urbanization rate and includes the expansion of new irrigated areas (through the rehabilitation of abandoned land or expansion of agriculture to new areas). While there is growth in the agricultural zone, this scenario assumes that the composition of the crops in the agricultural zone is constant. We apply the expansion of agriculture to Wine, Horticulture, Fruit, and Olive crops. We also keep the total area in each agricultural node constant by eliminating area from other land uses ("Recent", "Old", Forest, Pasture) in each node.

- **Conversion of crops**: this scenario represents a rate of urbanization that reflects historical trends and includes a change in crops from mostly wine to mostly fruit in only the northwest area of the Mendoza basin.

- **Rapid growth:** this scenario represents increases in urbanization (through greater density in the urban area and the conversion of land for urban use) and an expansion of agricultural land. This is achieved by combining the details of the "Accelerated Urbanization" and "Expansion of Agriculture" scenarios.

Table 2 presents the initial values for these scenarios.

Table 2. Initial values of land use scenarios

	Current Trends	***Accelerated Urbanization***	***Expansion of Agriculture***	***Conversion of Crops***	***Rapid Growth***
Urban population *(percent change per year)*	Historical trends	2.2	0.5	Historical trends	2.2
Number of industrial users (percent change per year)	Historical trends	1	0	Historical trends	1
Land use for agriculture *(percent change in* acreage per year)	Historical trends	-1	1	Historical trends	1
Domestic per capita water use *(percent change* per year)	Historical trends	-1.5, 0.2	-1.5, 0.2	Historical trends	-1.5, 0.2
Industrial per customer water use *(percent change* per year)	Historical trends	-1, 0.2	-1, 0.2	Historical trends	-1, 0.2
Percentage of acreage with wine grapes **out of total**	Static at last year in model	Static at last year in model	Static at last year in model	50% lower than last year in model for the northwest of Mendoza	Static at last year in model

Plausible Futures

Combining the variations in land use and hydrologic conditions, the study team developed the following set of futures:

Land Use Projections	X	Hydrological Variability	X	Climate Trends	=	Total
Current Trends + 4 other scenarios (5)		Historical + 2 extended drought (3)		No trend + 55 temperature & precipitation trends (56)		840

A base case future was defined with the following specifications: Current Trends land use scenario + historical hydrological variability, and no climate trends.

BASE CASE RESULTS

The water system model generates information about many aspects of the Mendoza water system for each future. For Mendoza, some key results include available supply from the Mendoza River, changes in groundwater availability, demand at the various urban and agricultural nodes, and any unmet demand. Figure 3 shows total demand for all the nodes in the model from water years 2002-2049, grouped by irrigation nodes (green), domestic nodes (blue), and commercial nodes (orange) for the base case future. Note that there is a gradual increase in projected demand and considerable interannual variability.

Figure 3. Demand by node for base case future

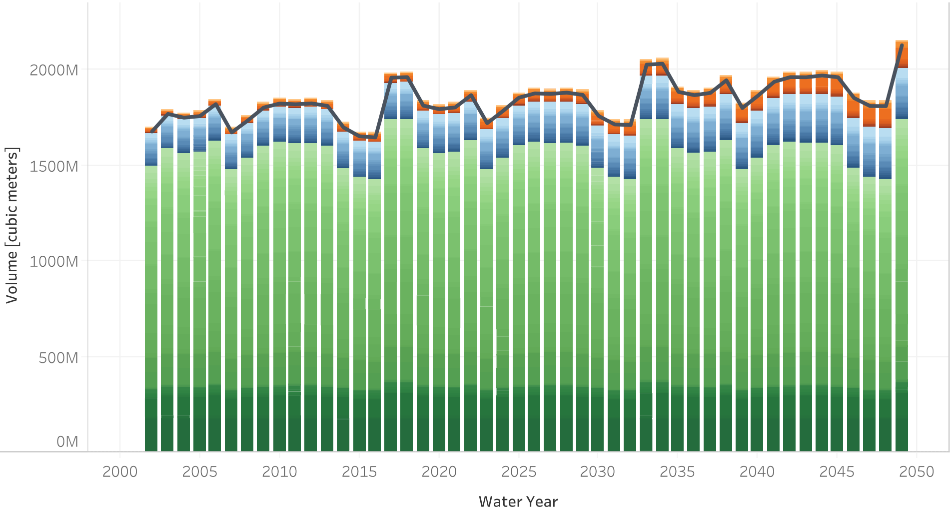


Figure 4 next shows the projected Mendoza River flow (cubic meters per year), the annual total volume of the region’s reservoirs, and the annual net groundwater extractions under base case assumptions. The Mendoza streamflow panel shows significant interannual variability and an extended dry period between 2011 and 2018 (consistent with measured historical records) which is repeated again starting in 2027 and then 2043. The total surface storage (middle panel) shows some interannual variability and also a slow decline due to sedimentation of Mendoza’s main reservoir—Potrerillos. Lastly, changes in groundwater storage from a 2018 baseline shows declines reflecting groundwater pumping rates that are greater than replenishment rates.

Figure 4. Mendoza River streamflow, total reservoir storage, and change in groundwater volumes

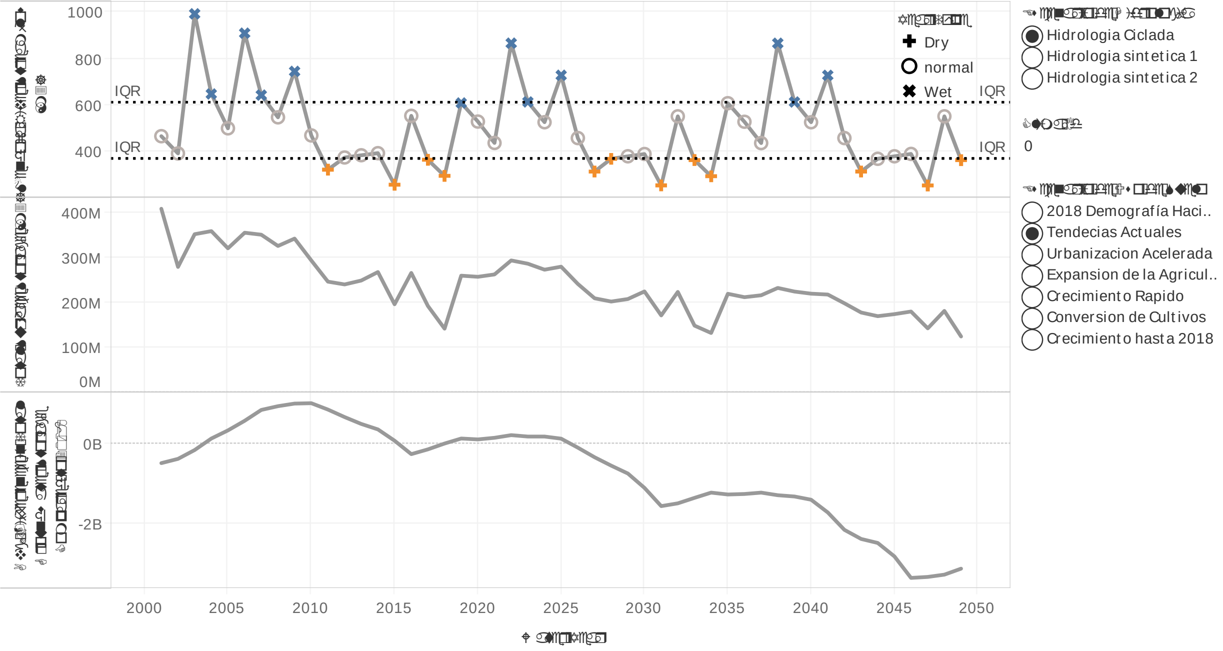
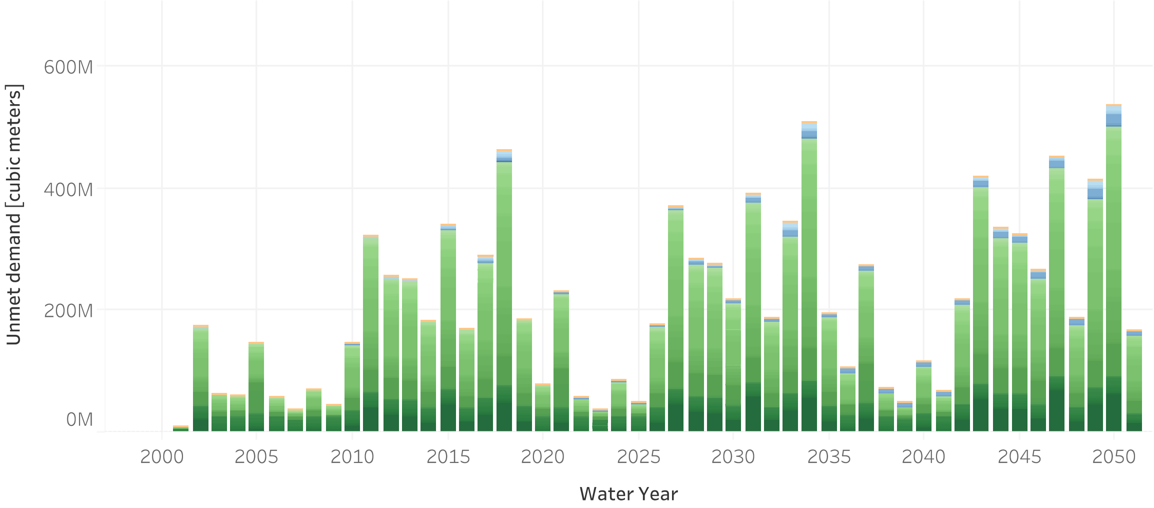


Figure 5 shows the projected unmet demand for all sectors (agricultural, commercial, and residential) under base case assumptions. The vast majority of unmet demand occurs in the agricultural sector, with a small amount in a few residential nodes. Unmet demand grows significantly during the drought periods and exhibits a general increase over time as well.

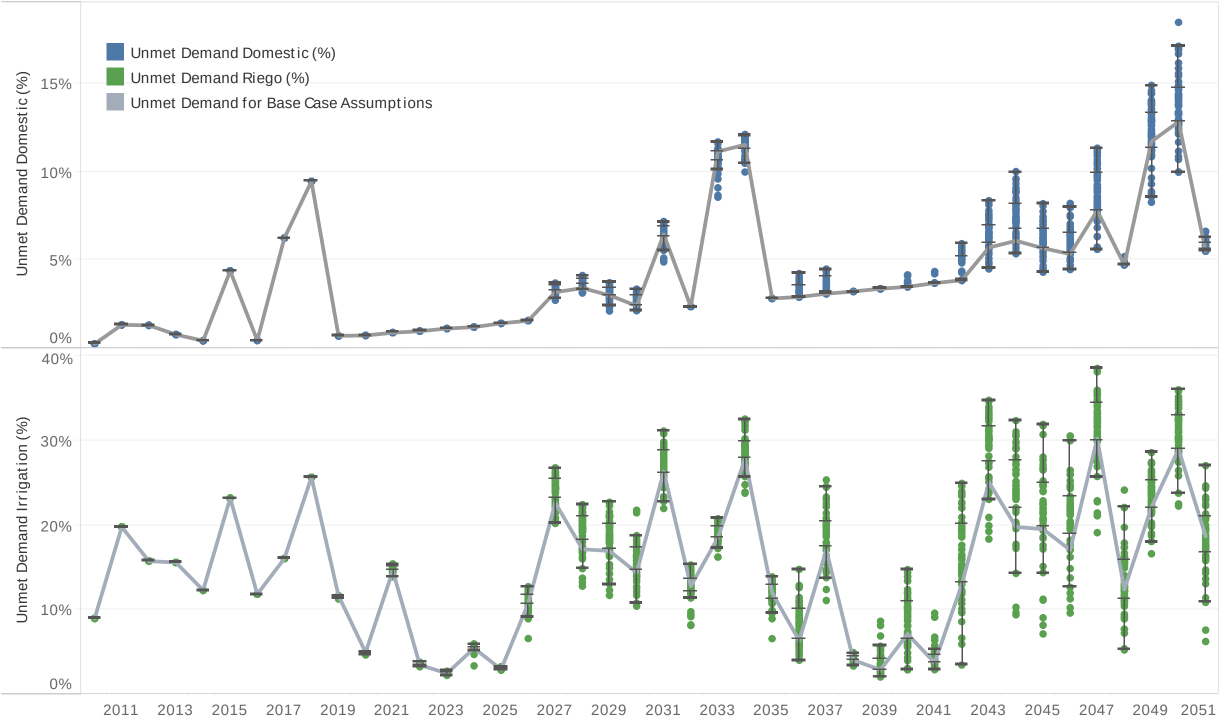
Figure 5. Projected unmet demand under base case assumptions



Note: colors correspond to different node types—green = agricultural; blue = domestic; orange = commercial.

Unmet demand at domestic and irrigation nodes varies across the futures as shown in Figure 6. For the domestic nodes, shortages peak during dry years. During wet periods, shortages are small, with a steadily increasing minimum associated with one node that has an infrastructure constrain on delivered water. Urban unmet demand is generally below 5 percent, except during dry years and late in the simulation period. Agricultural unmet demand ranges between just a few percent to almost 40 percent late in the simulation period. The vulnerability analysis, below, will explore how these patterns of unmet demand change under different land use and climate conditions.

Figure 6. Projected unmet demand under full range of plausible futures for domestic and irrigation nodes



STEP 3) CHARACTERIZE THE KEY VULNERABILITIES

How well Mendoza’s water management system performs in the future is highly dependent on the assumed future conditions. This suggests that while it is possible that the system will perform satisfactorily in the future, it is also plausible that the system will not. The vulnerability analysis step of an RDM analysis is designed to highlight what parts of the system are vulnerable to low performance and under what future conditions. This information can then inform the development of and comparison of adaptations.

DEFINING A VULNERABLE OUTCOME

The Mendoza water system is highly dependent upon groundwater produced from individual basins and surface supplies provided by a disaggregated infrastructure that leads some areas to be more secure in their water supply than others. Thus, where and under which conditions shortages might occur is quite different across the system. Modeled performance of the system also differs depending on the time of year and future time period. To illustrate these disparities in system performance, we focus on the absolute amount of unmet demand and the percentage of demand that is not serviced at a given node. This dual approach to quantifying unmet demand recognizes that (1) for a given node, the ability to accommodate shortages is proportional to the percentage of service reduction and (2) investments should be weighed in terms of their absolute benefits.

We first define and use a set of performance thresholds to aggregate system performance at each node across time. We average demand, unmet demand, and percent unmet demand by three seasons—peak demand (October-February), off-peak demand (May-July), and transitional demand (March-April and August-September)—and two future time horizons—near-term (2021-2035) and long-term (2036-2050). We then classify outcomes at urban nodes using the following two levels:

- **acceptable performance**: average unmet demand below 10 percent
- **poor performance**: average unmet demand greater than 10 percent

For agricultural nodes we use two different levels:

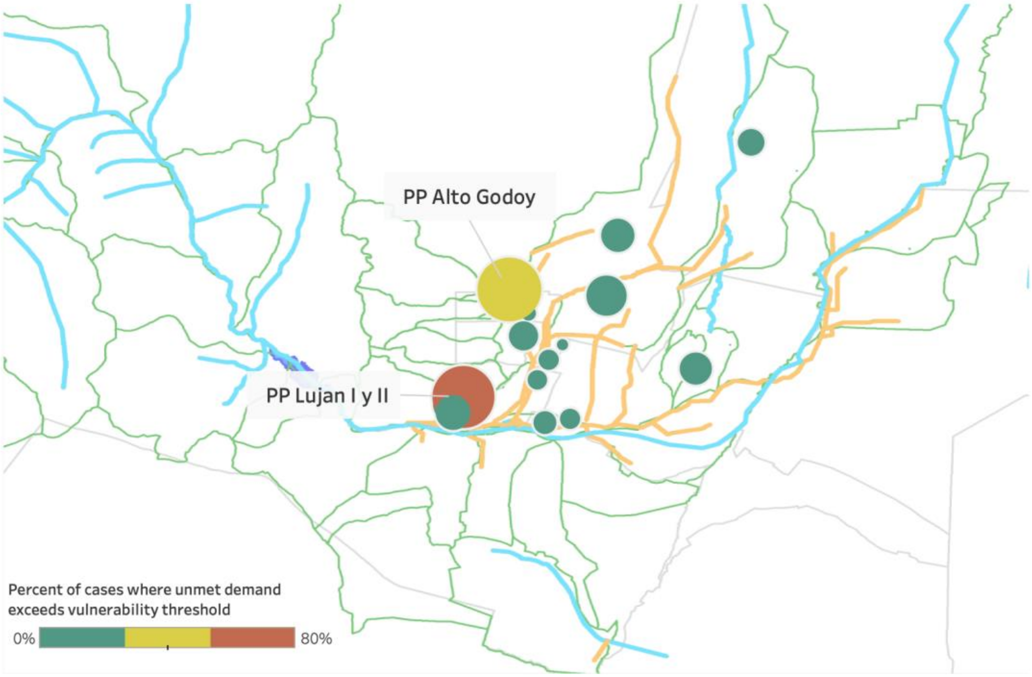
- **acceptable performance**: average unmet demand below 20 percent
- **poor performance**: average unmet demand greater than 20 percent

These thresholds were set in collaboration with the Mendoza water managers.

Urban vulnerabilities

Due to the prioritization of supplying water for urban water use over agricultural water use, all but a few urban zones are completely reliable across the future simulations. The exceptions are two fairly large areas—PP Alto Godoy and PP Lujan I y II (Figure 7). In both these areas, there are some futures in which performance is acceptable and some in which it is poor. Water managers at Irrigación have concerns that the model is not representing properly the available supplies at these nodes. Therefore, we did not continue with the vulnerability analysis for urban nodes.

Figure 7. Domestic demand nodes, sized by relative demand and colored by vulnerability



Agricultural vulnerabilities

Supply to meet agricultural demands is less sufficient than it is for urban demands in the Mendoza River Basin. Figure 8 shows the range of modeled outcomes in the near-term and long-term across all the futures for each agricultural node. The coloring indicates the performance levels for unmet demand for the peak demand season. The width of the symbols is proportional to the average demand for the node. For about a quarter of the nodes, outcomes are modeled to be favorable across all futures in the near-term (all symbols are green)—nodes listed at the top in Figure 8. There are also a number of nodes that are modeled to have very high unmet demand—nodes listed at the bottom of Figure 8. Some of these results are due to constraints in the model that do not allow adequate supply to be used to meet demand, e.g. S Lavalle 1, S Lavalle 3, and S San Martin. The outcomes for others depend on assumptions about the future and are of particular interest for this study.

Figure 8. Ranges of performance across the uncertainties in the Near-term and Long-term for the irrigation nodes

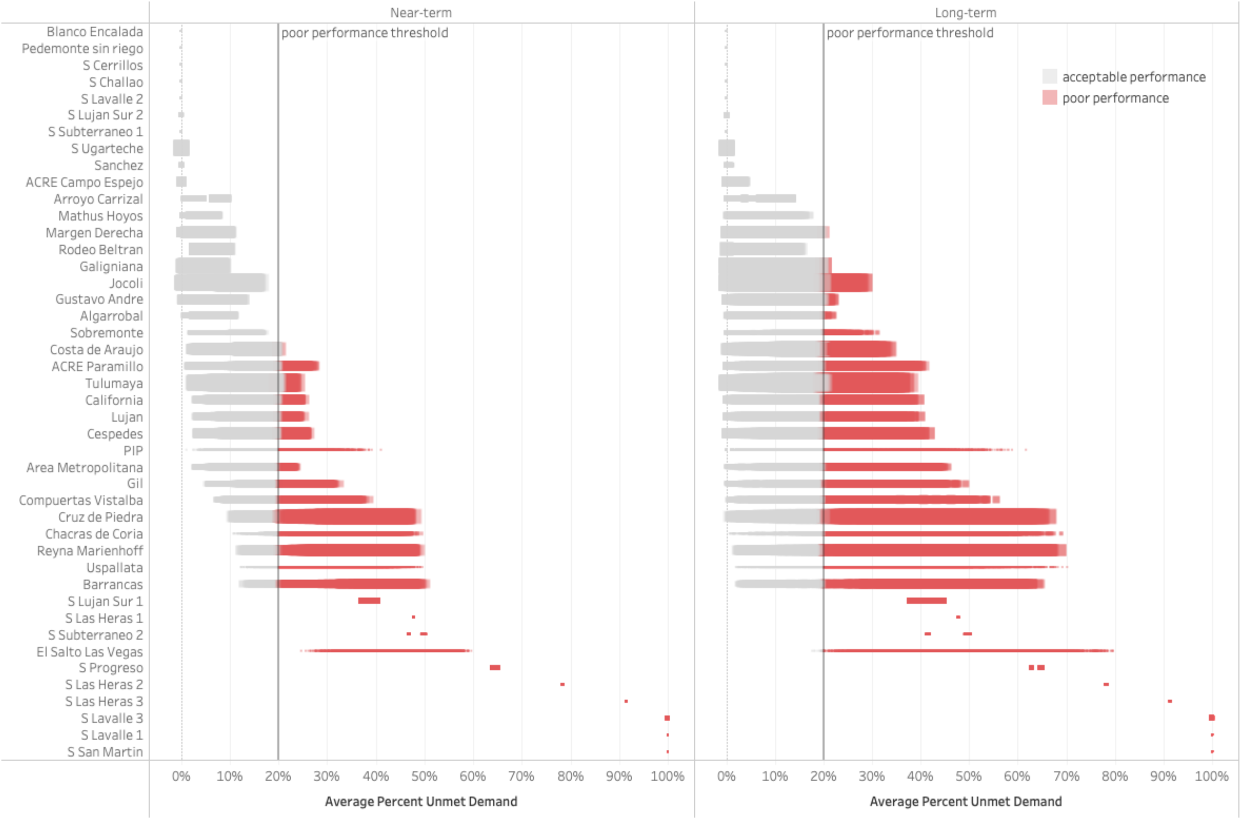
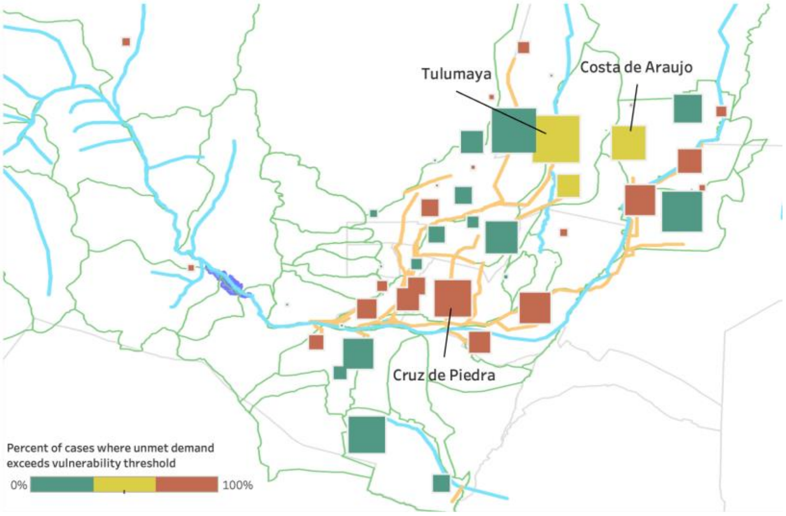


Figure 9 summarizes the system performance in the agricultural sector geographically. We highlight three nodes—Tulumaya, Costa de Araujo, and Cruz de Piedra—which are described in more detail below to illustrate the vulnerability analysis method.

Figure 9. Irrigation demand nodes, sized by relative demand and colored by vulnerability



Notes: Nodes are colored based on the percent of cases in which unmet demand exceeds the 20 percent threshold. Green shaded results have high unmet demand in less than 33 percent of the cases. Red shaded results have high unmet demand in more than 67 percent of cases.

Figures 10 through 12 show the long-term vulnerability maps for three large agricultural regions that would experience shortages in many plausible futures—Tulumaya, Costa de Araujo, and Cruz de Piedra. The first two are downstream irrigation nodes that exhibit high unmet demand across many, but not all futures. The vulnerability maps show the long-term performance of the system across the different uncertainty dimensions. The broad columns indicate the assumed land use scenario (ordered by the amount of increase in agricultural land) and the broad rows correspond to the climate variability scenarios—the length of the longest drought. The inner horizontal dimension represents precipitation trends and the inner vertical dimension represents temperature trends. Cases of interest—those with poor performance—are indicated by red Xs. Note that there are poor performance outcomes scattered throughout the vulnerability maps for Tulumaya and Costa de Araujo, suggesting that all three uncertainty dimensions play a role in the vulnerability at these irrigation nodes. For Cruz de Piedra, unmet demand exceeds the vulnerability threshold under all but a few futures (Figure 12).

Figure 10. Vulnerability map for the Tulumaya irrigation node

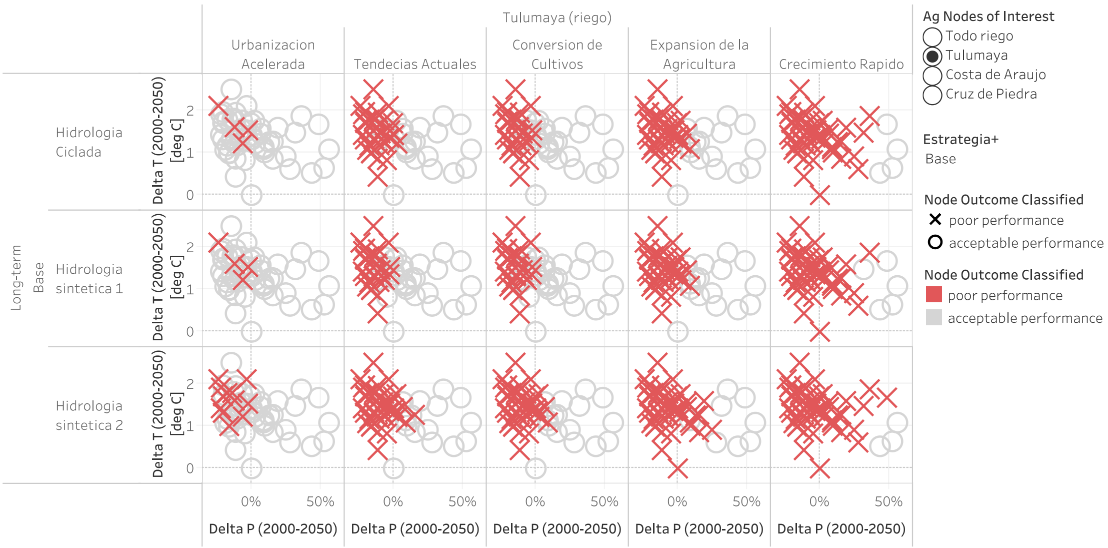


Figure 11. Vulnerability map for the Costa de Araujo irrigation node

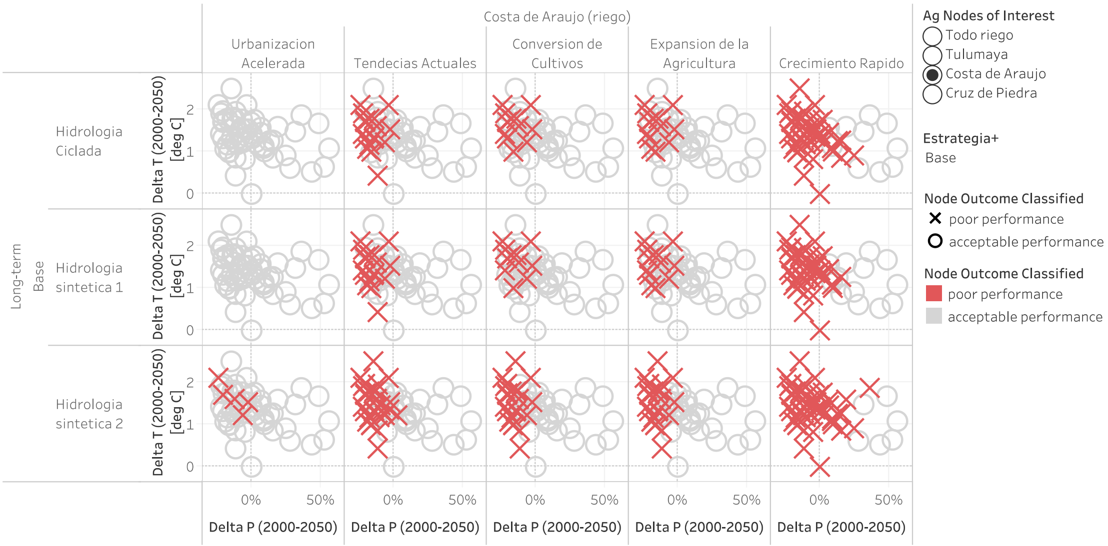


Figure 12. Vulnerability map for the Cruz de Piedra irrigation node

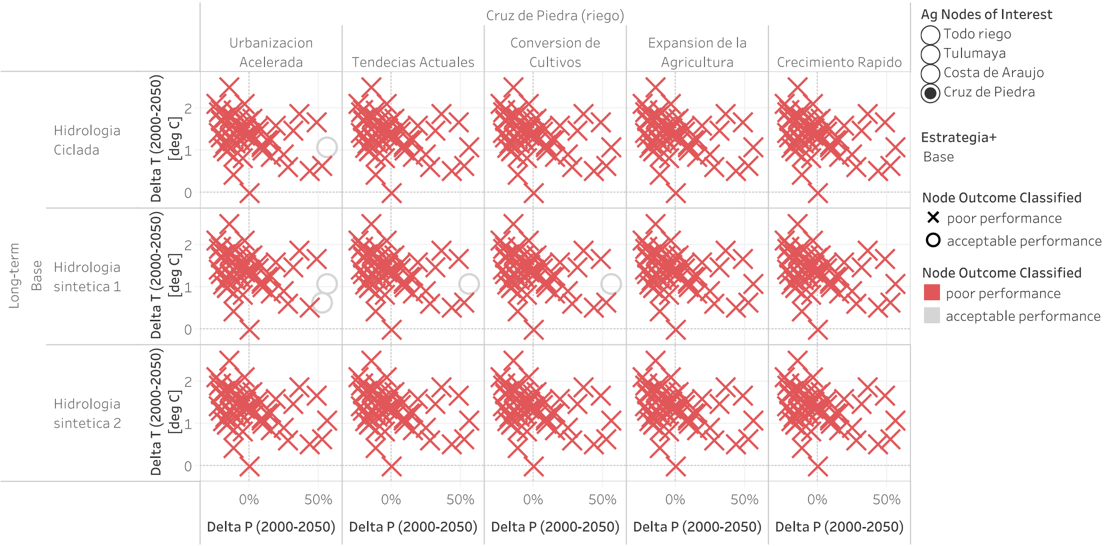
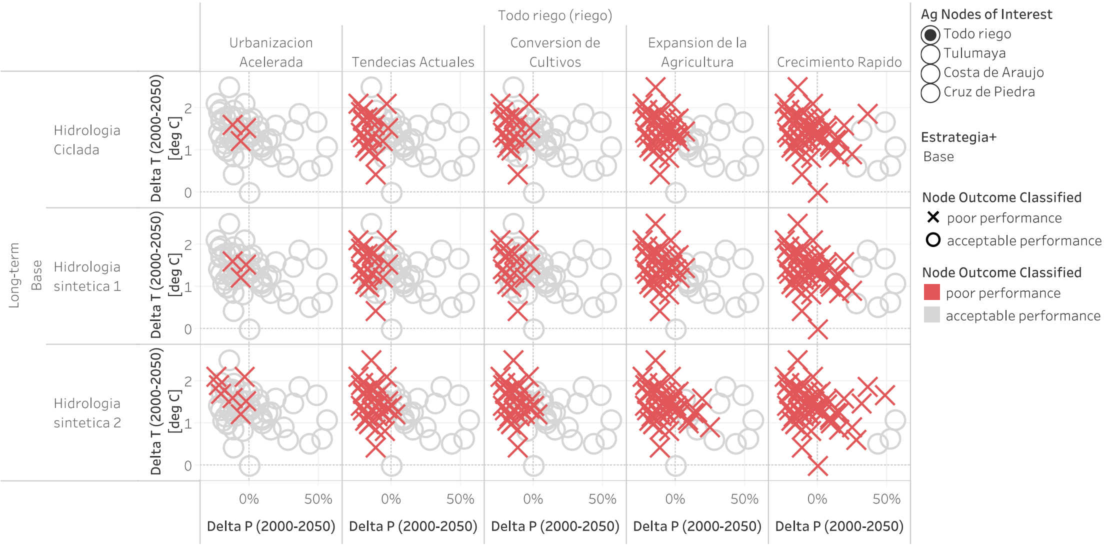


Figure 13 shows the vulnerability map for all irrigation nodes in aggregate, which mirrors the vulnerability patterns for Tulumaya and Cruz de Piedra. We use the performance across all irrigated areas to compare mitigation strategies below.

Figure 13. Vulnerability map for all irrigation nodes

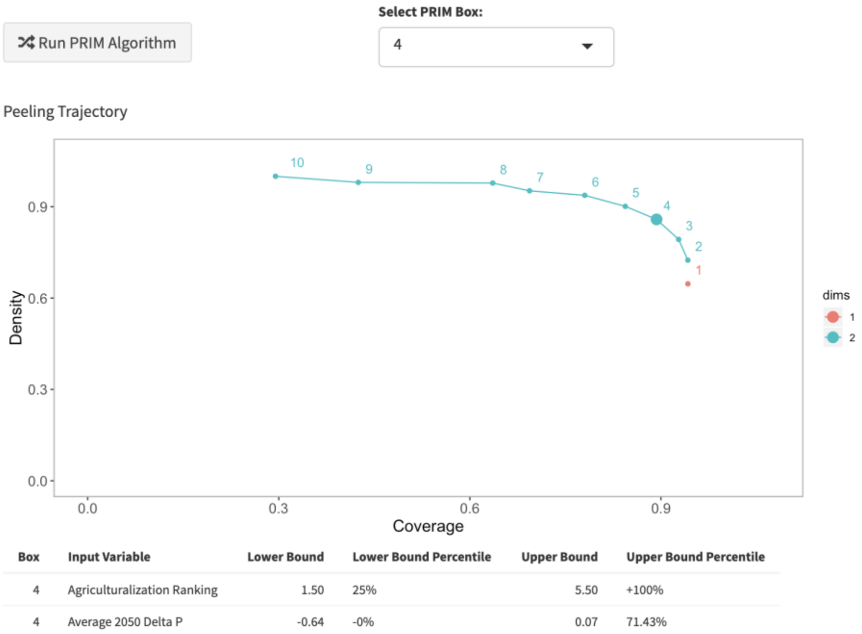


Using RDM "scenario discovery" tools, we can further define conditions that lead to poor performance. These tools include the PRIM algorithm are used to: (1) identify which uncertainties or characteristics of those uncertainties present future vulnerabilities; (2) define a small group of factors that describe the range of uncertainty. With PRIM, the sets of futures are defined by ranges of uncertainty values and thus define multi-dimensional "boxes" within the uncertainty space. PRIM identifies boxes that balance density—the percentage of cases that are of interest within the box—and coverage—the percentage of all cases of interest that are within the box. An ideal “box” would include all the cases of interest and no cases that are not of interest, having 100 percent density and 100 percent coverage. In practice, there are often multiple regions in the uncertainty space that lead to poor outcomes and they usually are not always completely comprised of poor outcomes. Thus, scenario discovery include subjectivity on the part of the analyst and is iterative. Importantly, the analyst has to employ their own judgement to select boxes identified by PRIM that are easy to interpret for decisionmakers. In general, the number of uncertainties included in a box can serve as a proxy for interpretability – the fewer the number of uncertainties, the greater the interpretability. For this study, a custom-built PRIM tool was developed to interactively show the statistics for each box on the peeling trajectory and also a visualization of the outcomes and defined “box”.

For Tulumaya, the PRIM algorithm was used to identify three vulnerabilities:

- The first vulnerability includes futures for which the land use conditions are restricted to the *Crecimiento Rapido* scenario and precipitation trends are less than +30%.
- The second vulnerability is defined based upon the “peeling trajectory” of boxes along the coverage and density frontier shown in Figure 14. Box 1 is a single dimension box—simply restricting the land use scenario to all those except for *Urbanizacion Acelerada* (*Crecimiento Rapido* was removed, as it is mostly covered by the first vulnerability). The density of this box is 65 percent, and coverage is 94 percent. Boxes 2 through 11, successively increase density at the expense of coverage by restricting futures to those with increasingly negative precipitation trends. The selected Box 4 limits precipitation increases to less than +7 percent and has a density of 86 percent and includes 89 percent of the remaining poor outcome cases—a useful future characterization.
- The third vulnerability describes the remaining poor outcomes under the *Urbanizacion Acelerada* scenario. Under this land use scenario, only futures with the extended drought (+ 2 years) and negative precipitation trends are included.

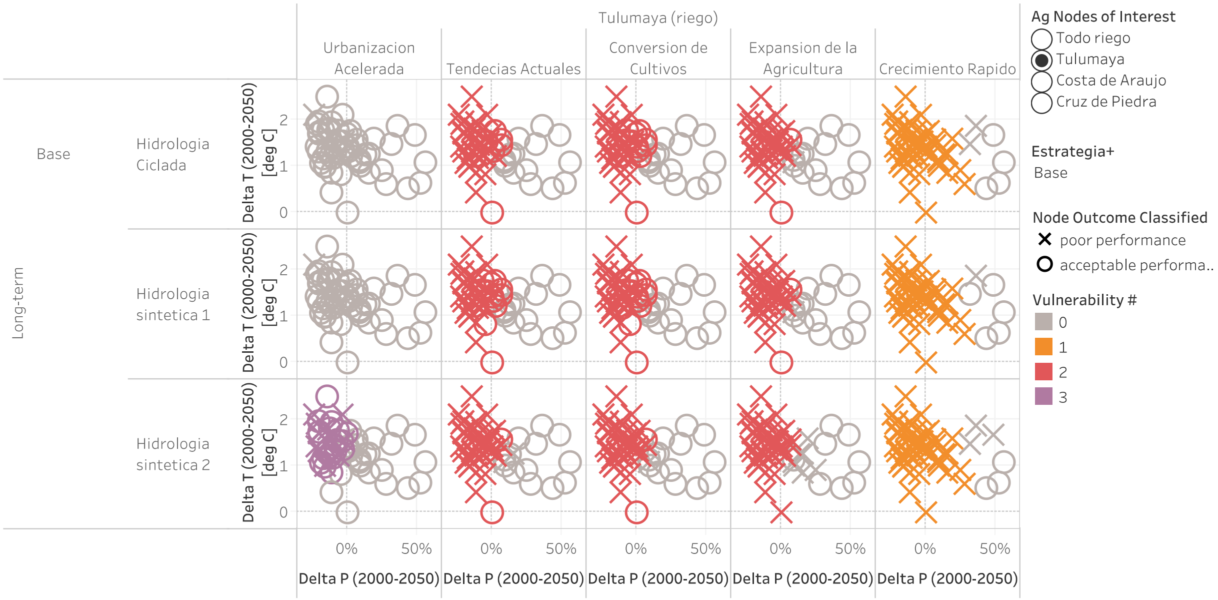
Figure 14. Peeling trajectory for PRIM analysis of Tulumaya irrigation node



Box	Input Variable	Lower Bound	Lower Bound Percentile	Upper Bound	Upper Bound Percentile
4	Agriculturalization Ranking	1.50	25%	5.50	+100%
4	Average 2050 Delta P	-0.64	-0%	0.07	71.43%

Figure 15 shows again the vulnerability map for the Tulumaya irrigation node, but this time colors the results to show the three PRIM-identified boxes. This graphic shows that these three vulnerabilities include almost all poor performance outcomes (the Xs) and few acceptable performance outcomes (the Os).

Figure 15. Vulnerability scenarios for the Tulumaya irrigation node



This same scenario-discovery process was used to identify vulnerabilities for the other two nodes and aggregated irrigation results, summarized in Table 2. Tulumaya, Costa de Araujo, and the All Irrigation

Aggregated nodes all are highly vulnerable in the *Rapid Growth* land use scenario, indicating that either or both supplemental supply or lower demand will need to be supported by additional management. For the moderate growth land use scenarios, these nodes are also particularly sensitive to trends in precipitation—negative trends would lead to poor or very poor performance in the long-term. For the least-stressing land use scenario—*Accelerated Urbanization*—the current management approach is vulnerable when droughts are longer than what has been experienced in the recent historical record and drying and warming trends prevail.

The Cruz de Piedra node is vulnerable under all conditions.

Table 2. Vulnerability definitions and statistics for three agricultural nodes plus aggregation of all irrigation nodes

Irrigation Node	Vulnerability	Definition	Density	Coverage
Tulumaya	1	*Rapid Growth* land use scenario Precipitation trend <= +30%	100%	30%
	2	Land use scenarios except *Rapid Growth* and *Accelerated Urbanization* Precipitation trend <= +7%	85%	63%
	3	*Accelerated Urbanization* land use scenario Drought length + 2 years in length Precipitation trend <= 0% Temperature trend => +0.84	38%	2%
Costa de Araujo	1	*Rapid Growth* land use scenario Precipitation trend <= +13%	96%	43%
	2	Land use scenarios except *Rapid Growth* and *Accelerated Urbanization* Precipitation trend <= +0%	51%	52%
	3	*Accelerated Urbanization* land use scenario Drought length + 2 years in length Precipitation trend <= 0% Temperature trend => +1.2	20%	2%
Cruz de Piedra	1	All futures	99%	100%
All Irrigation (aggregated)	1	*Rapid Growth* land use scenario Precipitation trend <= +30%	99%	35%
	2	Land use scenarios except *Rapid Growth* and *Accelerated Urbanization* Precipitation trend <= +7%	69%	60%
	3	*Accelerated Urbanization* land use scenario Drought length + 2 years in length Precipitation trend <= 0% Temperature trend => +1.22	28%	2%

STEP 4) EVALUATE BENEFITS AND COSTS OF INFRASTRUCTURE PROPOSALS

The vulnerability analysis suggests that unmet demand during the peak water use months would increase across many, but not all, plausible futures across the agricultural sector. Informed by discussions with Mendoza water resource managers, the research team defined and modeled three different management options:

- **Single large reservoir**: new reservoir on Rio Mendoza near Uspallata with capacity of 862 hm^3, of which 757 hm^3 is usable—a simplification of *Alternativo 2a* from Mendoza planning documents.[2]
- **Set of smaller reservoirs:** Addition of several (around 10-20) smaller reservoirs (between 200 km^3 and 1 hm^3) strategically placed on irrigation canals to reduce unmet demand at key irrigation nodes identified through the vulnerability analysis—called *Embalses Pequeños*.
- **Pressurized irrigation:** Represented by an increase in irrigation efficiency to simulate the conversion of irrigation from flood to drip techniques for a different percentage of each node. The study considered 20, 50, and 80 percent conversion—called *Incrementa Riego Pressurizado*. This study did not consider the energy requirements for drip irrigation and only focused on reduction in energy demand.

These options were grouped together in several different strategies, and simple cost estimates were developed, as shown in Table 3. The cheapest strategy is the *Embalses Pequeños*, at a modest $27 million.[3] The most expensive strategy—***Incrementa Riego Presurizado +80% + Alternativo 2a***—includes the cost of the single large reservoir ($3,385 M) plus an additional $85-89M to convert 80 percent of irrigated land to pressurized techniques.[4]

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[2] Alternative 2a calls for three moderate-sized reservoirs (Tupungato Superior, Punta de Vacas, and Uspallata) and one small reservoir (Punta Vacas). All four reservoirs are primarily designed for hydropower but could also have water supply benefits. We simplify this strategy by modeling a single large reservoir. An extension of this analysis could be to model the filling of the reservoir over a longer time period, particularly for longer than one hydrologic cycle.

[3] Note that this cost estimate is based on a simple assumption that per capacity cost for these small reservoirs would be equal to the per capacity costs of the large reservoirs--$4.47/cubic meter. The analysis below shows that the effects of these reservoirs is negligible, so a more refined cost estimate is not needed for this analysis.

[4] The exact cost of the irrigation strategies varies across the land-use scenarios due to the projected extent of irrigated land area. The costs for the most expansive irrigation scenario—*Crecimiento Rapido*—is about 20 percent higher than for the least expansive irrigation scenario—*Urbanization Acelerada*.

Table 3. Assumed costs for each strategy evaluated

Strategy	Reservoir capital costs ($M)	Conversion area to pressurized irrigation (hectare)	Irrigation pressurization costs ($M)[c]	Total strategy cost ($M)
Alternativo 2a	3,385	n/a	n/a	3,385
Embalses Pequeños	27	n/a	n/a	27
Incrementa Riego Presurizado +20%	n/a	21,143[a] – 22,284[b]	106 - 111	106 – 111
Incrementa Riego Presurizado +20% + Alternativo 2a	3,385			3,491 – 3,496
Incrementa Riego Presurizado +20% + Embalses Pequeños	27			133 – 138
Incrementa Riego Presurizado +50%	n/a	52,857[a] – 55,710[b]	265 - 279	265 – 279
Incrementa Riego Presurizado +50% + Alternativo 2a	3,385			3,650 – 3,664
Incrementa Riego Presurizado +50% + Embalses Pequeños	27			292 – 306
Incrementa Riego Presurizado +80%	n/a	84,571[a] – 89,136[b]	423 – 446	423 – 446
Incrementa Riego Presurizado +80% + Alternativo 2a	3,385			3,808 – 3,831
Incrementa Riego Presurizado +80% + Embalses Pequeños	27			450 – 473

[a] Corresponds to the *Urbanizacion Acelerada* land use scenario.

[b] Corresponds to the *Crecimiento Rapido* land use scenario.

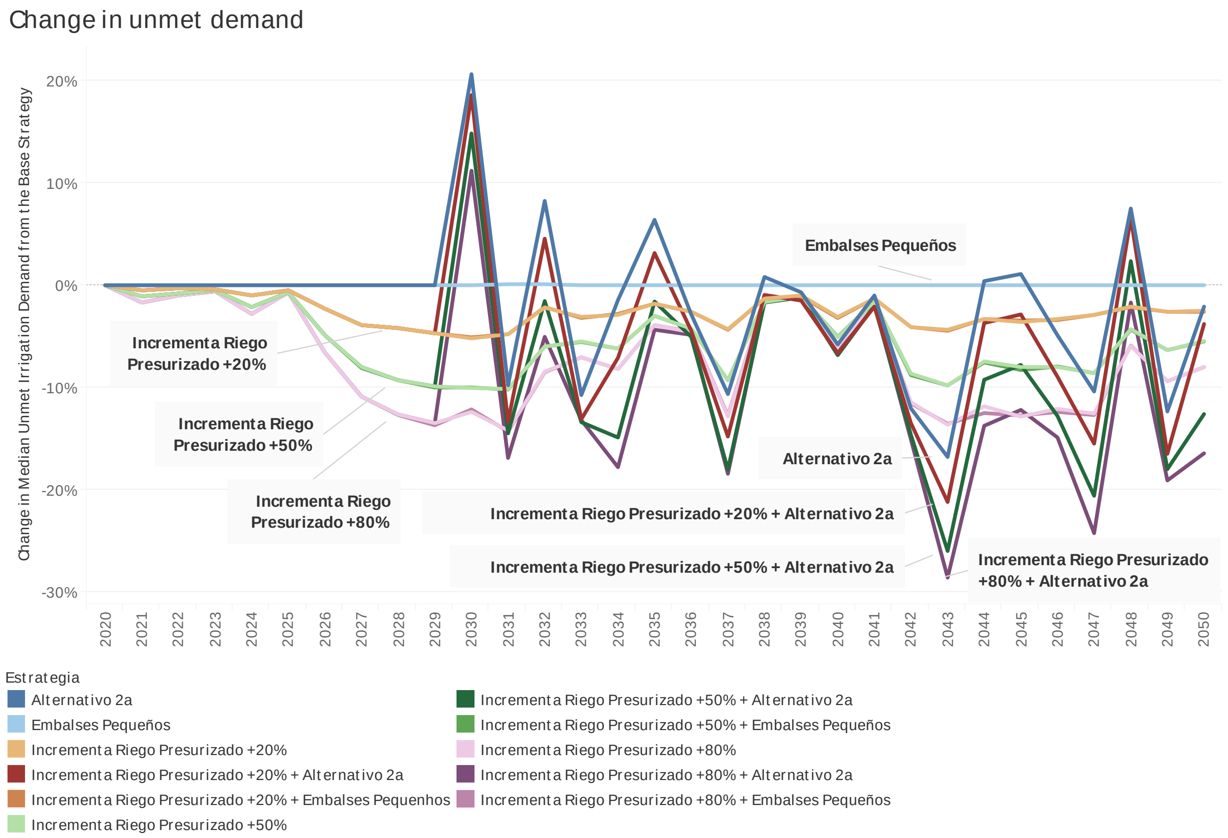
[c] Based on a conversion cost of $5,000/hectare.

These strategies were then evaluated across all the futures to evaluate how well they would reduce vulnerabilities and, in the process, increase resilience to climate and land use changes. Figure 16 shows how unmet irrigation demand would change over time in response to the implementation of the different strategies. For all strategies that include *Alternativo 2a* (the single, large reservoir), change in unmet demand oscillates as the reservoir is filled and drawn down to meet future demand. This behavior is the result of the system not having significant unused water, even during the wet season and years, to fill or re-fill a large reservoir quickly. The reservoir could be operated to have a more consistent impact, but it would then likely not be filled fully and this would reduce its ability to generate hydropower. In this study, we only considered the benefits of the addition of one large dam in Uspallata as they related to unmet demand. Other benefits could include the generation of hydroelectric power, reduction of downstream rates of sedimentation, or mitigation of drought risk. Due to the time and resource constraints of this study, these benefits were not considered but could be incorporated in future work.

Another key finding from Figure 16 is the very minimal effect that the Embalses Pequeños strategies would have on unmet demand—virtually indistinguishable from other strategies that exclude this option. It is important to note that reservoir management is on the order of 10 to 20 day cycles, but the time period in WEAP is monthly, suggesting that there may be some loss in the ability of the model to meaningfully capture the dynamics of these smaller reservoirs. Additionally, these small reservoirs provide additional benefits for farmers in the region, as they can use them to fill even smaller reservoirs on their property. This gives greater flexibility to the secondary distribution network as well as can increase the frequency of irrigation for farmers. The WEAP model does not consider this secondary irrigation network, but it could be included in future work.

Finally, the strategies that increase pressurized irrigation all have a noticeable effect on reducing unmet demand, both alone (e.g. *Incrementa Riego Presurizado +20%, +50%, and +80%*) and in conjunction with *Alternativo 2a.*

Figure 16. Change in unmet irrigation demand from the Base Strategy over time for a range of strategies

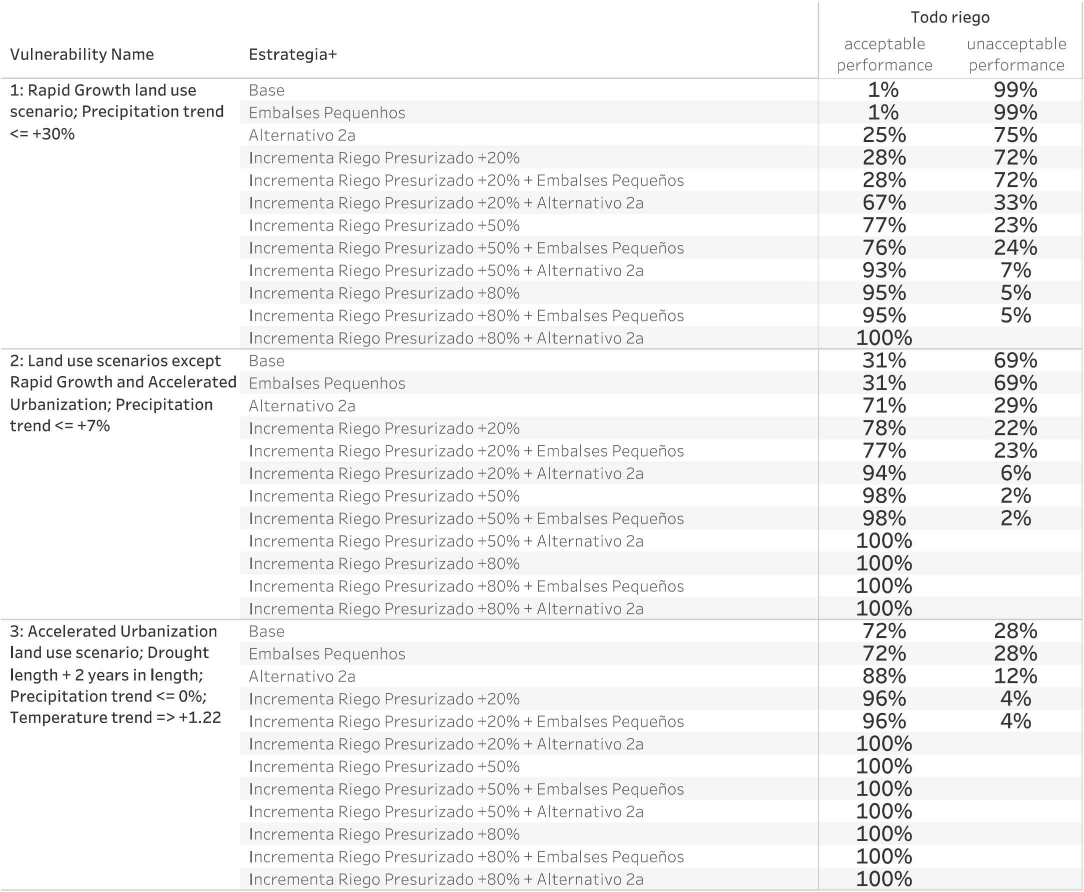


The next section describes a simple approach for comparing the costs and performance improvements for each strategy.

STEP 5) DELIBERATE OVER ROBUSTNESS AND COST TRADEOFFS

One useful measure of robustness and robustness improvements due to alternative strategies is the percentage of acceptable (or unacceptable) cases for each of the three vulnerabilities identified in Step 3, in this case, for the entire agricultural region. Table 4 summarizes the percentage of cases that are acceptable and unacceptable for the three vulnerabilities described in Table 2 (above) for each strategy. The results for the Base strategy match the statistics shown in Table 2. For the first vulnerability, the percentage of unacceptable outcomes declines from 99 percent for the Base strategy to 0 percent for the *Incrementa Riego Presurizado + 80% + Alternativo 2a* strategy. Note, however, that only 5 percent of outcomes are unacceptable with 80% pressurization and no *Alternativo 2a* reservoir. Robustness is dramatically increased as well for vulnerabilities 2 and 3. For these vulnerabilities, less intervention is required to eliminate bad outcomes.

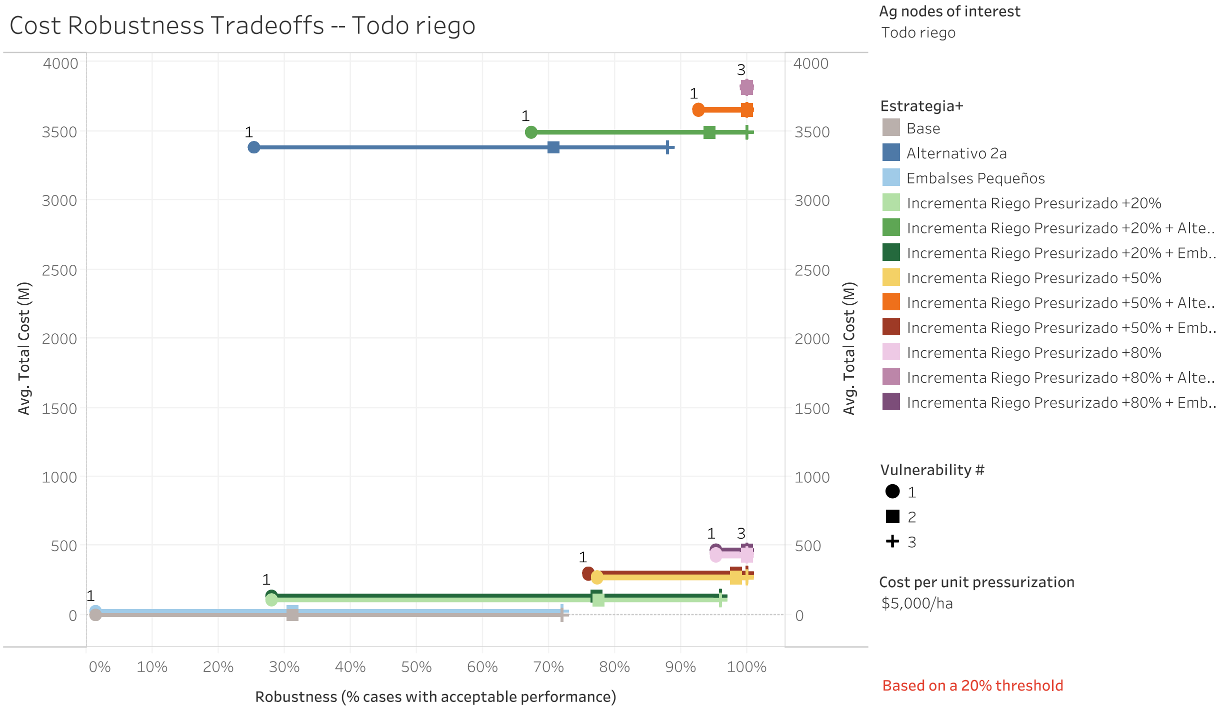
Table 4. Robustness measures for the three vulnerabilities for the irrigation sector across all strategies



		Todo riego	
Vulnerability Name	Estrategia+	acceptable performance	unacceptable performance
1: Rapid Growth land use scenario; Precipitation trend <= +30%	Base	1%	99%
	Embalses Pequenhos	1%	99%
	Alternativo 2a	25%	75%
	Incrementa Riego Presurizado +20%	28%	72%
	Incrementa Riego Presurizado +20% + Embalses Pequeños	28%	72%
	Incrementa Riego Presurizado +20% + Alternativo 2a	67%	33%
	Incrementa Riego Presurizado +50%	77%	23%
	Incrementa Riego Presurizado +50% + Embalses Pequeños	76%	24%
	Incrementa Riego Presurizado +50% + Alternativo 2a	93%	7%
	Incrementa Riego Presurizado +80%	95%	5%
	Incrementa Riego Presurizado +80% + Embalses Pequeños	95%	5%
	Incrementa Riego Presurizado +80% + Alternativo 2a	100%	
2: Land use scenarios except Rapid Growth and Accelerated Urbanization; Precipitation trend <= +7%	Base	31%	69%
	Embalses Pequenhos	31%	69%
	Alternativo 2a	71%	29%
	Incrementa Riego Presurizado +20%	78%	22%
	Incrementa Riego Presurizado +20% + Embalses Pequeños	77%	23%
	Incrementa Riego Presurizado +20% + Alternativo 2a	94%	6%
	Incrementa Riego Presurizado +50%	98%	2%
	Incrementa Riego Presurizado +50% + Embalses Pequeños	98%	2%
	Incrementa Riego Presurizado +50% + Alternativo 2a	100%	
	Incrementa Riego Presurizado +80%	100%	
	Incrementa Riego Presurizado +80% + Embalses Pequeños	100%	
	Incrementa Riego Presurizado +80% + Alternativo 2a	100%	
3: Accelerated Urbanization land use scenario; Drought length + 2 years in length; Precipitation trend <= 0%; Temperature trend => +1.22	Base	72%	28%
	Embalses Pequenhos	72%	28%
	Alternativo 2a	88%	12%
	Incrementa Riego Presurizado +20%	96%	4%
	Incrementa Riego Presurizado +20% + Embalses Pequeños	96%	4%
	Incrementa Riego Presurizado +20% + Alternativo 2a	100%	
	Incrementa Riego Presurizado +50%	100%	
	Incrementa Riego Presurizado +50% + Embalses Pequeños	100%	
	Incrementa Riego Presurizado +50% + Alternativo 2a	100%	
	Incrementa Riego Presurizado +80%	100%	
	Incrementa Riego Presurizado +80% + Embalses Pequeños	100%	
	Incrementa Riego Presurizado +80% + Alternativo 2a	100%	

Lastly, we combine the information presented in Table 4, with the cost estimates from Table 3, to show the tradeoffs in robustness reduction and costs (Figure 17). The percentage of cases with acceptable performance under the conditions of the three vulnerabilities are shown along the horizontal axis. The vertical axis represents the approximate cost for a given strategy. The Base strategy, for example, has no additional costs, and very low robustness in the first vulnerability (1%), low robustness in the second vulnerability (31%), and moderately high robustness in the third vulnerability (72%). The most favorable strategies would be those that improve the robustness across the three vulnerability at the least cost. As seen in the figure, the next least expensive strategy that reduces robustness is the *Incrementa Riego Presurizado +20%* strategy. Continuing up the cost-robustness frontier is the *Incrementa Riego Presurizado +50%* strategy. This strategy all but eliminates the 2nd and 3rd vulnerabilities and increases the percentage of favorable outcomes in the 1st vulnerability to 77 percent. The strategy that also adds the *Alternativo 2b* reservoir does improve the robustness to the 1st vulnerability but does so at an extremely high cost (plus $3,385 M), and thus it is not on the frontier. The last strategy on the frontier is the *Incrementa Riego Presurizado +80%*, which increases robustness to the first vulnerability to 95 percent. This is achieved at a total cost of $423 - 446M.

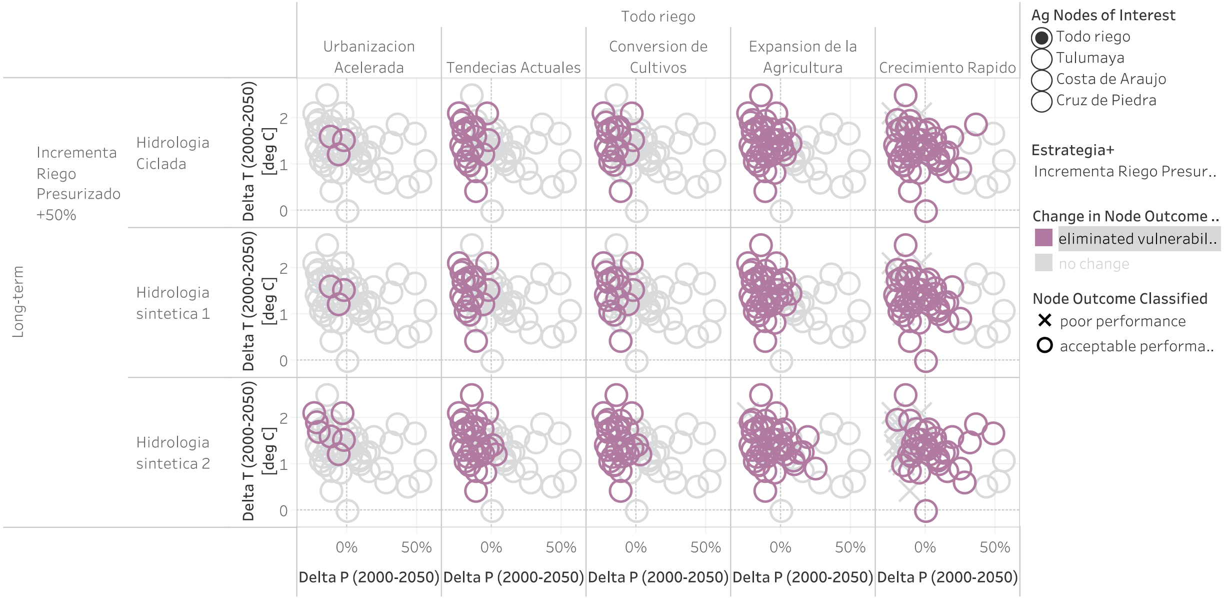
Figure 17. Tradeoffs between Cost and Robustness



Figures 17 strongly suggests that the main decision facing Mendoza related to reducing expected future unmet demand across the wide range of plausible futures, is how much irrigated area to convert to pressurized systems. Based on the analysis here, the reservoir cannot be justified on the basis of improving supply reliability.

To aid decisionmaking regarding this choice, Figure 18 shows the vulnerability map again, but highlights the cases in which the *Incrementa Riego Presurizado +50%* strategy changes performance from unacceptable to acceptable. Figure 19 complements Figure 18 by highlighting the remaining cases in which performance is poor.[5] As can be seen in the figures, *Incrementa Riego Presurizado +50%* strategy provides significant performance improvement across the moderate land use scenarios and some cases for the *Crecimiento Rapido* land use scenario (those in which precipitation increases). This suggests that it would only be justified pressurize irrigation beyond 50 percent, if Mendoza sought to hedge against futures in which irrigated areas increase as projected in the *Crecimiento Rapido* land use scenario and against declining precipitation conditions.

Figure 18. Change in performance across futures for the *Incrementa Riego Presurizado +50%* strategy



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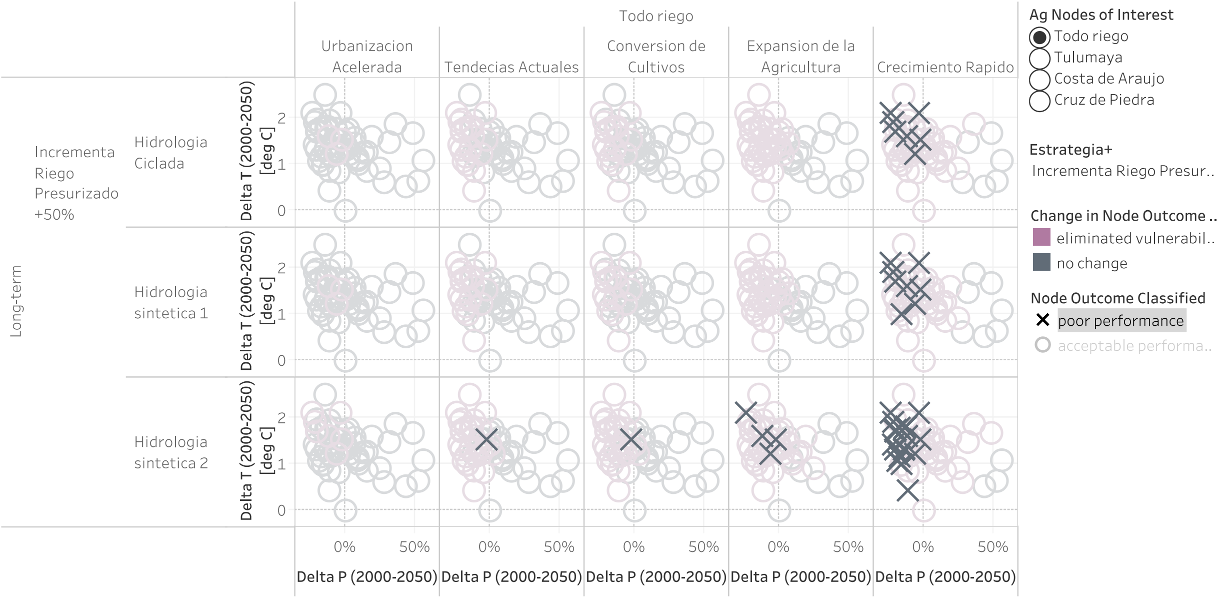
[5] In both figures, an acceptable threshold for unmet demand is defined as less that 20 percent, and an indicator of poor performance is an unmet demand greater than 20 percent.

Figure 19. Remaining poor performance cases for the *Incrementa Riego Presurizado +50%* strategy



CONCLUSION

This report describes an RDM-based approach to evaluating vulnerability and adaptation for water resources management and illustrates it with a case study for the Mendoza region of Argentina. RDM is shown to be a useful method for supporting long-term water resources planning, as it is capable of considering uncertainties that are difficult to understand and analyze in traditional planning approaches. In addition, RDM provides information on the tradeoffs that arise when weighing different policy options.

The analysis confirms that Mendoza's water system is vulnerable to changes in land use and climate change. This was determined by evaluating how Mendoza's current water management system would perform under almost 900 different plausible futures; each future reflecting a different assumption about climate trends, climate variability and land use change. The simulation results showed that unmet demand grows significantly during dry periods and also exhibits a general increase over time.

The vast majority of unmet demand occurs in the agricultural sector, with a small amount in a few residential nodes. However, a concern of the Departamento General de Irrigación is that the current WEAP model may need further improvements to fully capture operations and allocations to the urban sector, so these uncertainties were not explored in more detail. In the agricultural sector, the results show plausible shortages that increase significantly over time, exceeding 35 percent in some future years.

Significant variations in projected scarcity are observed between agricultural sectors, and with different climatic and land use assumptions. For this reason, a vulnerability analysis was carried out to understand under which conditions the system would not perform adequately. For this, performance thresholds were defined for urban demand and for agricultural demand for three seasons, in the long and short term. The system performance was then ranked for each future using these thresholds. A detailed vulnerability analysis was carried out in two large agricultural localities — Tulumaya and Costa de Araujo — and the agricultural sector as a whole. Both of these locations are downstream irrigation areas that exhibit high unmet demand in many, but not all, futures.

Using RDM tools, three general conditions were identified that would lead to high unmet demand in these locations and in the industry as a whole:

1. Rapid growth / Wetter
2. Current urban growth trends / Medium or dry conditions
3. Accelerated urbanization / Dry and hot conditions

From this analysis, we explored how land use and climate interact and together effect the agricultural sector. Under combined land use and climate conditions, different strategies were evaluated based on how they reduced vulnerabilities. These included: a large reservoir, a series of smaller reservoirs, and investments in drip irrigation. These three options have been previously evaluated for the region, but this analysis represents the first comparative exercise between them, and across a wide range of plausible futures that reflect climate and land use uncertainties.

Increasing surface storage, either through one or a few large reservoirs or a network of smaller reservoirs, would not significantly mitigate vulnerabilities and would constitute a high-cost investment. The simulations showed that in many plausible futures there is not enough excess water available during rainy seasons or wet years. Without this excess water, reservoirs cannot capture and store water for future dry spells without also causing shortages.

Investments in drip irrigation could result in a more meaningful reduction in vulnerabilities identified in this work. The analysis finds that converting approximately half of the irrigated area to drip irrigation would significantly reduce all three vulnerabilities identified above. Investments in drip irrigation are also a way to reduce water demand, which in turn increases the availability of water for other parts of the distribution system. More detailed analysis would be needed to know where to best focus irrigation improvements and to quantify additional energy demand and infrastructure limits and capacities.

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Water Infrastructure Planning for the Uncertain Future in Latin America: A Cost- and Time-Efficient Approach for Making Robust Infrastructure Decisions, with a Case Study on Mendoza, Argentina

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